Effects of the Corona Treatment of Rubber Tire Particles on the Properties of Particleboards

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The aim of this study was to evaluate the effect of corona treatment and rubber tire particle substitution proportion on the properties of particleboard. Treatments consisted of replacing 10%, 20%, and 30% *Pinus oocarpa* with rubber tire particles, as well as a treatment without added rubber. Rubber particles were submitted to corona treatment. Panels were produced with a nominal density of 650 kg.m^{-3}, a 7% urea-formaldehyde adhesive, a temperature of 200 °C, a specific pressure of 3.92 MPa, and pressing time of 8 min. Panels were evaluated to determine their physical properties, including water absorption and thickness swelling after 2 h and 24 h of water immersion (TS2h and TS24h), and for mechanical properties including internal bond strength (IB), modulus of rupture (MOR), and modulus of elasticity (MOE) in static bending. Using a 30% rubber tire particle substitution proportion significantly improved the TS24h and non-return rate in thickness (NRRT) of the panels. However, rubber addition significantly decreased the mechanical properties, and only panels with up to 10% rubber met the minimum requirements of the EN 312 (2003) standard for MOR, MOE, and IB in panels for internal use (including furniture).

Keywords: Composites; Residue; Physical and mechanical properties

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INTRODUCTION

Recently, the generation, handling, and storage of solid residues have become major environmental concerns. This, coupled with the concept of sustainable development by industrial sectors, has opened an area for scientists to research alternative uses for industrial residues. Tire residues are of great interest because the available amount is on the rise with increasing demand for tires, which have a short life (Nehdi and Khan 2001; Fioriti and Akasaki 2004; Azmi *et al.* 2008; Ayrilmis *et al.* 2009; Zhao *et al.* 2010).

One of the first forms of reusing tires was for power generation by burning. However, with technological advances, new applications have emerged, such as mixing with asphalt, incorporation in plastic or concrete composites, use as a raw material for carbon production, and even in nature by creating artificial environments for the protection of marine life (Nehdi and Khan 2001; Kongsuwan and Phetcharat 2003; Abduh Dahlan 2007; Sadek and El-Attar 2015).

According to Macedo (2008), such residue used in manufacturing composites can present advantages, such as the reduction of the deposit of this material in landfills because of the long degradation time for tires (up to 240 years), and the reduction in atmospheric emissions of some pollutants, among others. Galle *et al.* (2010) state that a large number of tires stored in open spaces can serve as a breeding ground for mosquitos (*Aedes aegypti*), which are vectors of diseases like dengue, zika, and chikungunya fever. Thus, rubber used in particleboard panels, in addition to contributing to minimizing an environmental and public health problem, may enable the creation of new products (Ayrilmis *et al.* 2009).

According to Fu (2003), waste tire rubber is an excellent raw material for the production of wood panels, because it presents unique properties such as, absorption, better sound insulation, durability, and abrasion resistance; it is also anti-caustic and anti-rot. However, only a few studies deal with rubber used for reconstituted wood panel production. Zhao *et al.* (2010) assessed panels produced from wood and particles of rubber tire and found an improvement in soundproofing properties when compared with commercial particleboards. According to Bertolini (2014), the adhesive used in preparing particleboard is responsible for the largely mechanical adhesion between the particles of wood and rubber.

To improve the adhesion of rubber tire particles with other materials, researchers have been studying different procedures, such as corona treatment (Briggs *et al.* 1980; Amoroux *et al.* 1982; Stehling and Meka 1994). According to Witmann (2010), corona treatment involves the application of electrostatic discharges on a material's surface to increase its surface energy, allowing a good anchoring between materials. Giraldi and Campos (2004) treated natural rubber surfaces with corona discharge and concluded that as the treatment time increased, the value of the contact angle on the surface decreased. However, there are no reports on corona discharge treatment of rubber tire particles in the literature.

In this context, the aim of this study is to evaluate the effect of corona treatment and rubber tire particle substitution proportion on the properties of particleboard.

EXPERIMENTAL

Raw Materials

Wood particles of *Pinus oocarpa* and rubber tire residue were used for panel production. Twenty-eight-year-old *P. oocarpa* trees were obtained at the campus of the Federal University of Lavras (UFLA), in Lavras, MG, Brazil.

After being felled, the trees were divided into logs and selected for lamination. In total, 10 logs with diameters between 25 and 40 cm and lengths of 1.20 m were used. Logs remained inside a tank, submerged in water over 10 days before processing to avoid attack by fungi and xylophagous organisms, to prevent the emergence of top cracks, and to relieve growth stresses. The entire procedure for determining the basic density of wood was conducted according to the standard NBR 11941 (2003).

Blades obtained by the lamination process were crushed in a knife mill and subsequently sieved in a particle agitator. Particles used were those that passed through a sieve with a 4.76 mm opening and were retained in a sieve with an opening of 1.19 mm.

Rubber tire particles were obtained from a tire retreading company located in Lavras, MG, Brazil. After collection, the rubber was prepared and sieved using a 1.19 mm opening sieve. Unitary rubber weight determination was performed according to the standard requirements of NBR NM 45 (2006).

Corona Treatment

Particles were divided into two groups, and one group went through a surface modification process by means of grafting functional groups and/or intertwining chains of atoms on the rubber particles' surface (corona treatment) for a period of 5 min, aiming at improving the interaction between wood particles and rubber. The corona treatment excites the free hydroxyl groups and also changes the surface energy, which serves to improve the compatibility between the fiber and the matrix (Bledzki and Gassan 1999).

The equipment used was the company Plasma-Tech, model P-1, Corona Brasil Ldta., using an applied potential of 12 kV, a current of 60 mA and a frequency of 60 Hz. The discharge was performed in air (25 ± 3 °C, 70 ± 5% relative humidity) at an average distance of 2 cm between the sample and the electric source. About 5 min after the corona treatment, the panels were produced.

Characterization of Rubber Tire Particles

After corona treatment, the rubber particles were characterized regarding the modifications obtained after electrical discharge. To evaluate such effects, the treated particles were compared with untreated particles.

Aiming to identify chemical groups present on the rubber particle surface, a Fourier transform infrared spectroscopy (FTIR) analysis was carried out using a mid-infrared spectrometer with Fourier transform (Vertex 70, Bruker). Also, attenuated total reflectance (ATR) equipment, with crystalline zinc selenide (ZnSe) and 20 internal reflections, was used. In addition, 32 scans with a resolution of 4 cm^{-1} were performed.

To assess the thermal stability and decomposition of rubber tire components, an analysis by thermogravimetry (TG) was performed in a nitrogen atmosphere with a flow rate of 40 mL min^{-1} using a thermogravimetric analyzer TGA Q500 (TA Instrument, USA, with a heating rate of 10 °C/min and an ambient temperature range (30 °C) up to 700 °C. In addition, a scanning electron microscopy (SEM) (JEOL JSM-6510 series) operating at 10 kV analysis was used to determine the material surface morphology.

Experimental Plan and Panel Production

Treatment conditions included different substitution proportions of wood particles by rubber particles with or without corona treatment, as described in Table 1.

For each treatment, three panels were produced with a nominal density of 650 $kg.m^{-3}$, 7% urea-formaldehyde adhesive, and dimensions of 480 mm × 480 mm × 15 mm (length, width, and thickness, respectively).

Table 1. Experimental Design

Treatment	Combination of material		Rubber treatment
	Rubber tire (%)	*Pinus oocarpa* (%)	
Control	0	100	No treatment
10% rubber	10	90	No treatment
20% rubber	20	80	
30% rubber	30	70	
10% rubber	10	90	Corona treatment
20% rubber	20	80	
30% rubber	30	70	

Before manufacturing the panels, wood particles were placed in an oven with forced air circulation until a moisture content of 5% (base of particle dry weight) was reached. Subsequently, rubber and wood particles were placed in a gluing machine with a rotating drum, where an adhesive was sprayed on the material. After 5 min of mixing in the gluing machine, particles went to a mattress-forming box with dimensions 480 mm × 480 mm. This mattress was then cold pressed with a 0.4 MPa pre-press to provide better panel conformation. Subsequently, the mattress was taken to a hot press machine with a pressing cycle at 200 °C and pressure of 4 MPa for 8 min.

Assessment of Physical and Mechanical Properties of Panels

Panels were conditioned in a climatized room with a temperature of 20 ± 2 °C and relative humidity of 65 ± 5% to constant weight. Initially, panels were squared to remove any edge effect caused in the manufacturing process. Samples were subsequently removed using a circular saw to assess physical and mechanical properties by various methodologies, as denoted in Table 2. For the bending test, the three point's method with maximum extension between the 200 mm end points was used. The loading speed applied for the bending and internal bonding tests was 2 mm / min. All mechanical tests were carried out on the Arotec 20KN universal testing machine.

Table 2. Assessed Tests and Execution Standards

Test	Methodology
Water absorption after 2-h immersion (WA2h)	ASTM D–1037 (2012)
Water absorption after 24-h immersion (WA24h)	ASTM D–1037 (2012)
Thickness swelling after 2-h immersion (TS2h)	ASTM D–1037 (2012)
Thickness swelling after 24-h immersion (TS24h)	ASTM D–1037 (2012)
Moisture	NBR 14810–3 (2006)
Apparent density	NBR 14810–3 (2006)
Static bending – Modulus of elasticity (MOE)	DIN–52362 (1982)
Static bending – Modulus of rupture (MOR)	DIN–52362 (1982)
Internal bond strength (IB)	NBR 14810–3 (2006)

Table 3 shows the tests performed, as well as the dimensions of the specimens. Figure 1 shows the scheme for removal of the specimens in the panel.

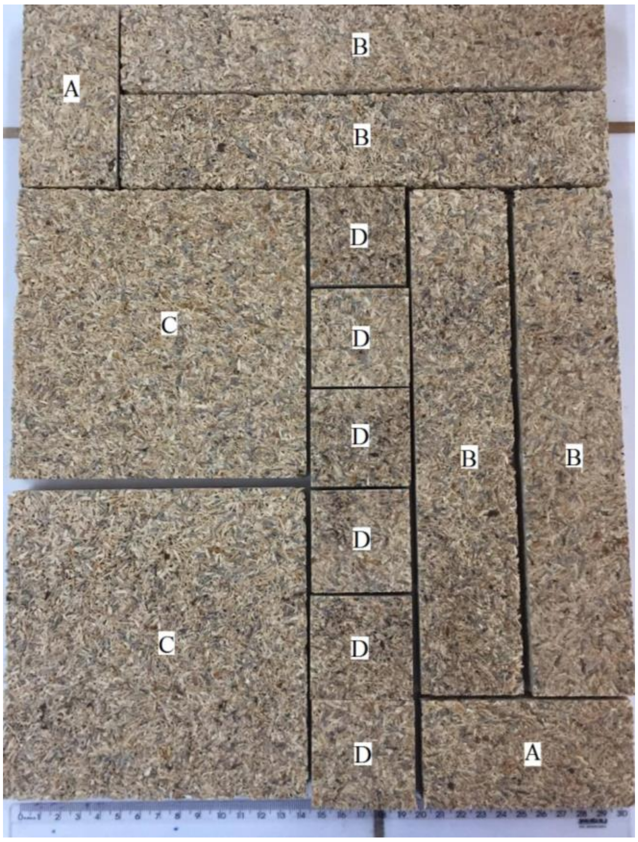

Fig. 1. Specimens in the panel. (A) Apparent density; (B) Static bending; (C) Water absorption; (D) Internal bond strength and Moisture

Figure 2 shows the panels produced only with wood particles and with 30% added rubber tire.

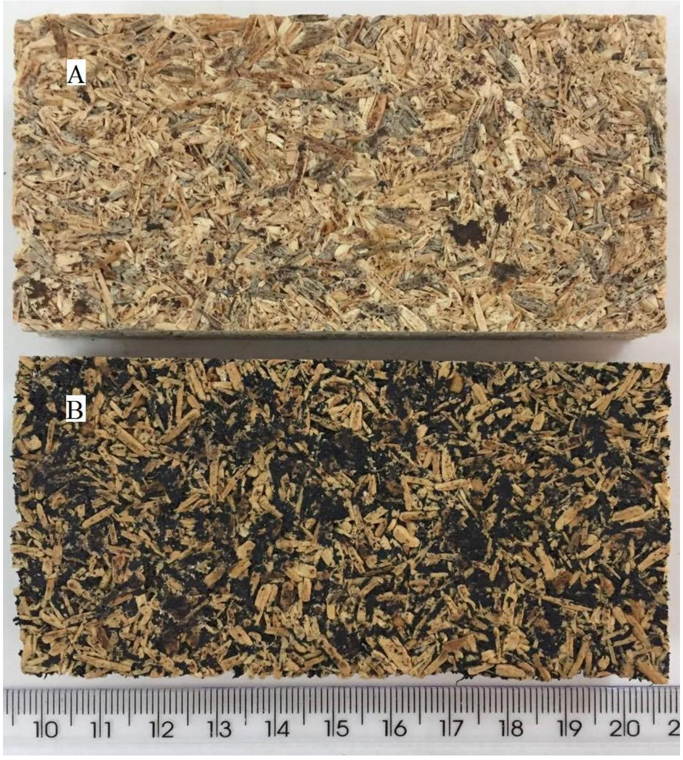

Fig. 2. Wood panels. (A) Only wood particles; (B) 30% rubber particles

Table 3. Assessed Tests and Dimensions of the Specimens

Test	Dimensions of specimens (mm)
Water absorption after 2-h and 24-h immersion	152 x 152
Thickness swelling after 2-h and 24-h immersion	152 x 152
Moisture	50 x 50
Apparent density	50 x 50
Static bending – Modulus of elasticity (MOE)	250 x 50
Static bending – Modulus of rupture (MOR)	250 x 50
Internal bond strength (IB)	50 x 50

Analysis of the results was performed considering a completely randomized design, in which treatments were arranged in a 3 × 2 factorial scheme (three rubber percentages, namely 10%, 20%, and 30%, and two types of treatments, with and without corona treatment, in addition to a control treatment (no addition of rubber). Statistical analysis was performed using the SISVAR program (Version 5.6). For comparison between panels with rubber addition and those without rubber, Dunnett’s test at 5% significance was carried out. In addition, Tukey’s test at 5% significance was performed to assess the effect of rubber proportion or corona treatment.

RESULTS AND DISCUSSION

Characterization of Rubber Tire Particles

Aiming to evaluate the changes to the rubber tire particle structure after corona treatment, a comparison of the spectra obtained by the FTIR technique was conducted for treated rubber (5 min) and untreated rubber (Fig. 3).

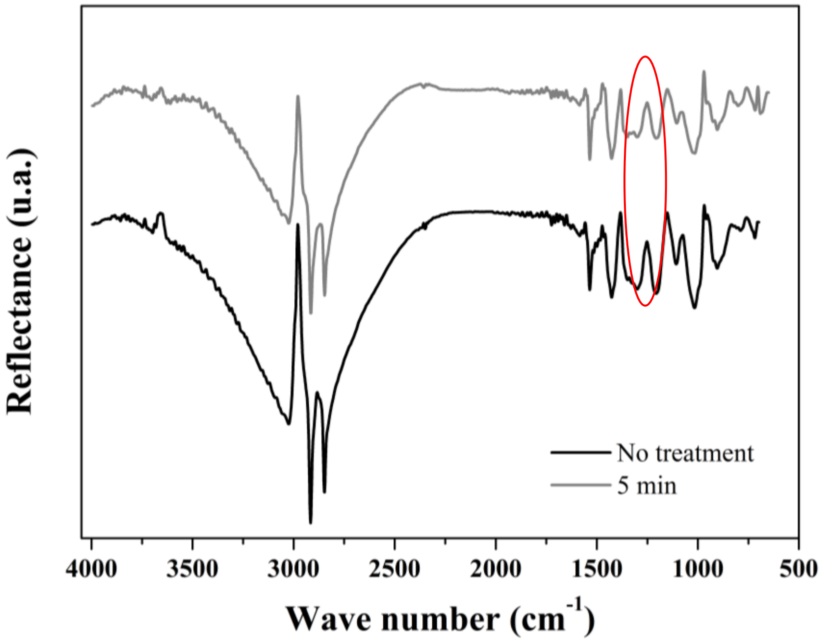

Fig. 3. FTIR spectra of untreated rubber tire and after corona treatment

A peak elongation can be observed between bands 1100 and 1200 cm^{-1} related to a C–O bond vibration when corona treatment is applied to the rubber. This fact may be related to rubber tire oxidation caused by the corona discharge application. Furthermore, a reduction in intensity of C–H bonds can also be observed between bands 2850 and 3000 cm^{-1}, which is related to the breaking of aliphatic and aldehydic C–H group bonds (CH, CH_2, and CH_3) arising from rubber oxidation.

Figures 4 and 5 show weight loss values by thermogravimetry (TG) in an inert atmosphere (N_2) and the derivative weight loss curve (DTG), respectively, of both untreated and corona-treated rubber.

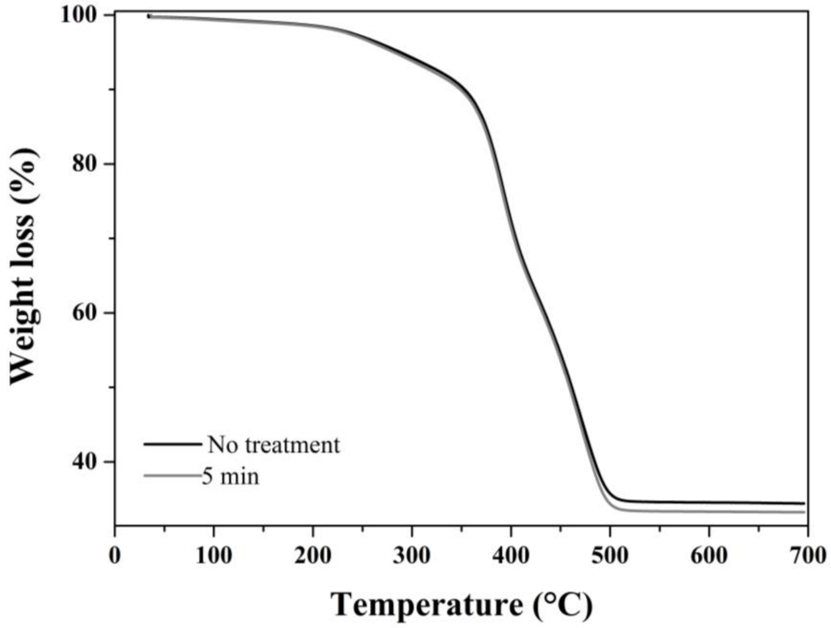

Fig. 4. TG curve for untreated and corona-treated rubber tire at intervals from 30 to 700 °C

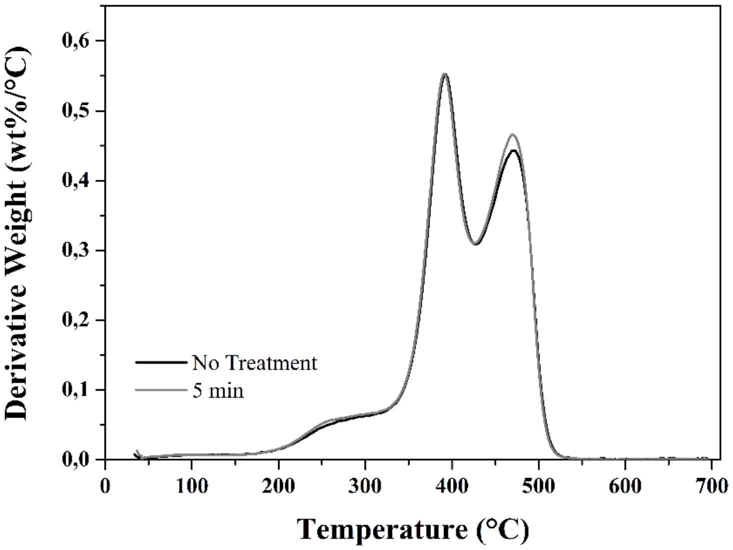

Fig. 5. DTG curve for untreated and corona-treated rubber tire at intervals from 30 to 700 °C

The rubber tire showed two peaks of maximum weight loss: one between 60 and 400 °C and the other between 400 and 520 °C, even after corona treatment. According to Maurer (1981), the weight loss near 380 °C is related to natural rubber degradation, whereas a weight loss between 448 and 470 °C is attributed to synthetic rubber degradation.

A weight loss of approximately 60% near 450 °C was observed for both untreated and rubber treated with corona discharge. According to Segre (1999), this weight loss is related to the release of volatile oils present in rubber tires. However, no change in thermal stability of the material was observed when submitted to corona treatment.

Rubber particles were observed by SEM before and after corona treatment to observe surface changes. Figure 6 shows the micrographs of these rubber particles.

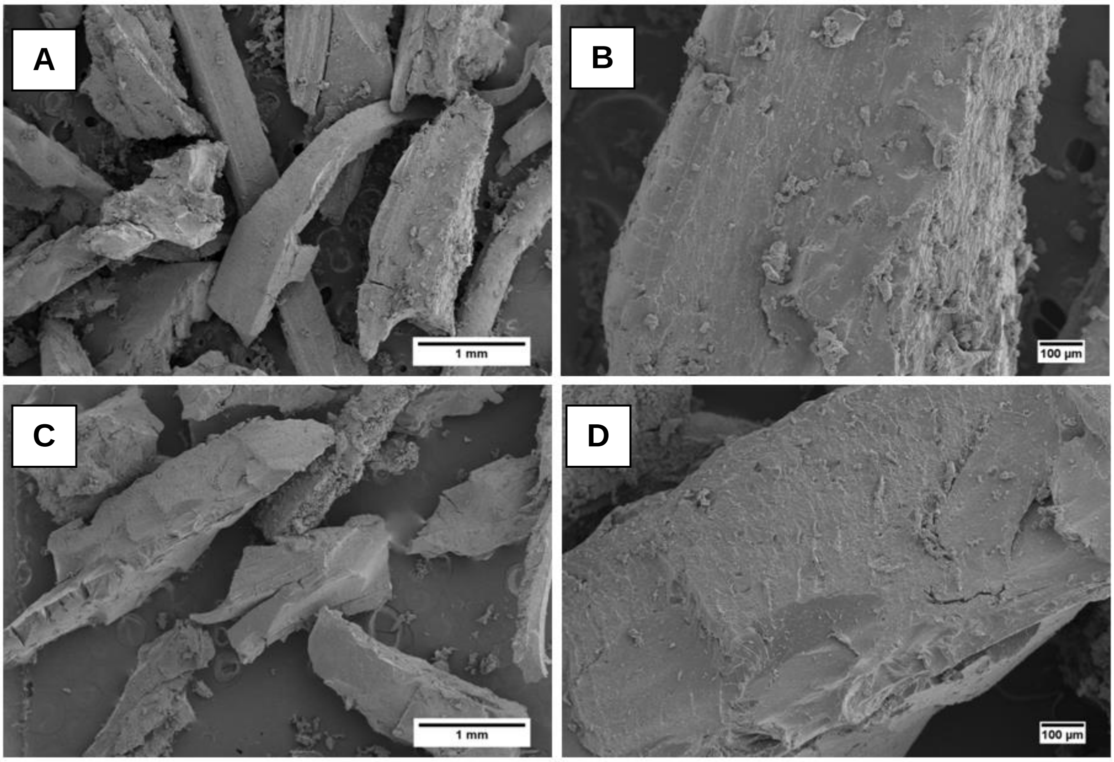

Fig. 6. A and B – SEM of rubber particles without corona treatment; C and D – SEM of rubber particles exposed to corona treatment for 5 min

Rubber particles have no uniformity, as can be observed by means of micrographs. According to Lima (2008), the texture of rubber fragments is also diversified, probably because of differences in the formation of these fragments. Corona discharge application for 5 min had no effect on the surface morphology of the rubber tire particles, *i.e.*, treatment time was short enough to avoid causing surface roughness that would hinder rubber adhesion with other panel components.

Apparent Density and Compression Ratio of Panels

The basic densities calculated for wood of *Pinus oocarpa* and rubber tires were 500 ± 20 and 560 ± 40 kg.m^{-3}, respectively. Table 3 shows the average values of the apparent densities and compression ratios for the panels.

Table 3. Average Values for Apparent Density and Compression Ratio of Panels

Treatment	Apparent density (kg.m^{-3})	Compression ratio
Control	605 ± 25 a	1.21 ± 0.05 a
10% rubber	601 ± 26 a	1.25 ± 0.02 a
20% rubber	593 ± 5 a	1.26 ± 0.01 a
30% rubber	604 ± 9 a	1.34 ± 0.02 a
10% treated rubber	604 ± 21 a	1.26 ± 0.04 a
20% treated rubber	589 ± 16 a	1.26 ± 0.03 a
30% treated rubber	576 ± 24 a	1.28 ± 0.05 a

Means followed by the same letter in the column are statistically equal by Tukey's test at 95% significance level.

The average densities are lower than the pre-established value of 650 kg.m^{-3}, as shown in Table 3. Iwakiri *et al.* (2005) explain that this difference is due to the panel manufacturing process, specifically material loss during particle handling in adhesive application stages, mattress forming, and panel pressing, as well as during thickening after pressing.

The apparent densities of panels ranged from 576 to 605 kg.m^{-3}. Thus, all panels were classified as having medium density, which corresponds to densities between 550 and 750 kg.m^{-3}, according to NBR 14810 (2008). Panel compression ratios ranged from 1.11 to 1.21. However, no significant difference was observed between treatments.

Table 4. Average Values of Water Absorption of the Particleboard

Treatment	WA2h	Δ	WA24h	Δ
	%			
10% rubber	92.64 $^{(5.98)\ ns}$	−1.5	96.93 $^{(8.26)\ ns}$	−4.5
20% rubber	99.80 $^{(4.08)\ ns}$	6.2	102.88 $^{(4.67)\ ns}$	1.4
30% rubber	85.66 $^{(5.54)\ ns}$	−8.9	92.55 $^{(7.10)\ ns}$	−8.8
10% treated rubber	88.62 $^{(5.93)\ ns}$	−5.7	92.51 $^{(5.08)\ ns}$	−8.9
20% treated rubber	91.00 $^{(5.16)\ ns}$	−3.2	94.74 $^{(4.90)\ ns}$	−6.7
30% treated rubber	92.18 $^{(7.85)\ ns}$	−1.9	93.39 $^{(4.07)\ ns}$	−7.9
Control	94.02 $^{(5.13)}$		101.49 $^{(4.93)}$	

^{ns} Values do not differ statistically from control treatment by Dunnett's test (α=0.05). Values in parentheses are the standard deviation.

Physical Properties

Results of water absorption after immersion for 2 h and 24 h (WA2h and WA24h, respectively) are shown and compared with the control treatment in Table 4. The positive values of delta of 6.2% and 1.4% indicate an increasing of the ratio of the water absorption (WA2h and WA24h) in case of the panels with 20% rubber with respect to the values recorded in case of the control panels. In case of other contents of rubber (10% and 30%) one can observe a decreasing of the water absorption and negative values of delta.

Macedo (2008) observed a significant reduction in water absorption of approximately 14% after 24-h immersion for panels containing 30% rubber compared with panels without rubber. Santos *et al.* (2011) evaluated different percentages of PET (polyethylene terephthalate) in panel production and observed WA24h values of 72.87, 64.12, and 56.54% for 0%, 25%, and 50% PET, respectively, indicating an increase in the amount of PET particles in the panel results in a decrease in water absorption. Table 5 shows the average values for thickness swelling after 2-h and 24-h water immersion (TS2h and TS24h), the non-return rate in thickness (NRRT), and Dunnett's test for both properties.

Table 5. Average Values for Thickness Swelling and Non-Return Rate in Thickness of the Particleboard

Treatment	TS2h	Δ	TS24h	Δ	NRRT	Δ
	%					
10% rubber	12.67 $^{(2.68)\ ns}$	−4.0	14.47 $^{(2.57)\ ns}$	−5.6	8.36 $^{(2.04)\ ns}$	−14.7
20% rubber	11.26 $^{(1.42)\ ns}$	−14.7	12.27 $^{(1.97)\ ns}$	−19.9	7.94 $^{(1.48)\ ns}$	−18.9
30% rubber	10.16 $^{(1.26)\ ns}$	−23.0	11.30 $^{(1.89)}$ *	−26.3	6.96 $^{(1.22)\ ns}$	−28.9
10% treated rubber	13.15 $^{(2.87)\ ns}$	−0.4	12.93 $^{(1.61)\ ns}$	−15.6	8.45 $^{(1.51)\ ns}$	−13.8
20% treated rubber	11.68 $^{(2.26)\ ns}$	−11.5	11.94 $^{(0.50)\ ns}$	−22.1	6.65 $^{(0.28)\ ns}$	−32.1
30% treated rubber	9.70 $^{(2.07)\ ns}$	−26.5	10.44 $^{(1.09)}$ *	−31.9	5.53 $^{(2.27)}$ *	−43.6
Control	13.20 $^{(1.06)}$		15.33 $^{(1.38)}$		9.80 $^{(1.33)}$	

*Values statistically differ from control treatment by the Dunnett's test (α=0.05). ^{ns} Values do not differ statistically from control treatment by the Dunnett's test (α=0.05). Values in parentheses are the standard deviation.

No significant difference was found between treatments for TS2h. However, a 26.5% reduction was observed for panels containing 30% treated rubber when compared with the control treatment. For WA24h, a significant difference was found between panels containing 30% rubber (treated and untreated) compared with panels without rubber, obtaining reductions of 26.3% (30% rubber without treatment) and 31.9% (30% treated rubber). The treatment with 30% treated rubber was statistically different from the control treatment for NRRT, with a reduction of 43.6%.

The improvements in TS24h and NRRT observed for panels produced with 30% rubber are due to their hydrophobic character and greater dimensional stability, leading to a decrease in hydrophilic sites of pinewood (Ayrilmis *et al.* 2009). According to Macedo (2008), a reduction in TS2h for panels produced from rubber particles is due to lower hygroscopicity of the mixture with the presence of rubber. This author obtained a value of 13.5% for panels containing 45% rubber, which means a decrease of 31% compared with the treatment without adding rubber.

Another factor that improved TS24h was the increase in the panel compression ratio (Table 3). According to Maloney (1993), an increased compression ratio creates an improved panel shape because the shorter distance between particles results in a higher number of particles in the same space. Scatolino *et al.* (2013) assessed corncobs for producing particleboard panels and observed that as the panel compression ratio increased, the thickness swelling value decreased. In addition, the authors stated that an increased compression ratio provides a higher initial barrier to water penetration, thus decreasing panel swelling.

Silva *et al.* (2016) studied sugarcane bagasse in particle composites with a density of 700 kg.m^{-3} and 8% urea-formaldehyde. According to the authors, bagasse's low particle density, which increases the compression ratio and hampers the entry of water into the panels, can explain the physical property improvements seen in composites produced with sugarcane bagasse.

The significant reduction of NRRT in panels with 30% treated rubber can be explained by rubber modification, which improves the bond interface between the adhesive and pine particles. Another important observation is a downward trend in thickness swelling and NRRT as the rubber percentage in the panels increases.

Only the control treatment and the treatment with 10% rubber and no corona treatment failed to meet the requirements (14%) of the standard EN 312 (2003) for MDP panels for general use in wet conditions. No paraffin was used to decrease the hydrophilic character of the wood particles, with the addition of rubber being the main factor to reduce these values.

Analysis of variance of the physical properties showed no interaction between rubber percentages (10%, 20%, and 30%) and treatments applied to rubber (with and without corona treatment). Table 6 presents the results for WA2h, WA24h, TS2h, TS24h, and NRRT as functions of rubber percentage.

Table 6. Average Values of Water Absorption and Thickness Swelling of the Particleboard with Different Rubber Percentages

Treatment	WA2h	WA24h	TS2h	TS24h	NRRT
	%				
10% rubber	90.64 $^{(5.77)*}$ a	94.73 $^{(6.60)}$ a	12.92 $^{(2.50)}$ a	13.71 $^{(2.10)}$ a	8.41 $^{(1.61)}$ a
20% rubber	95.40 $^{(6.37)}$ a	98.81 $^{(6.18)}$ a	11.48 $^{(1.71)}$ a	12.11 $^{(1.30)}$ ab	7.30 $^{(1.19)}$ a
30% rubber	88.93 $^{(7.05)}$ a	92.98 $^{(5.20)}$ a	9.93 $^{(1.55)}$ a	10.87 $^{(1.46)}$ b	6.25 $^{(1.81)}$ a

Means followed by the same letter in the column are statistically equal by the Tukey's test at 5% significance. *Values in parentheses are the standard deviation.

No significant difference was found between different rubber tire percentages for WA2h, WA24h, TS2h, and NRRT. For TS24h, the treatment had a significant effect, resulting in its reduction using 30% rubber tire. This reduction is associated with a combination of factors, such as a reduction of particle hydrophilicity and an increase in the panel compression ratio, as previously discussed.

Mechanical Properties

Results found for MOE, MOR, and IB, as well as a comparison of the treatments with the control, are presented in Table 7. A significant difference in MOE and MOR was observed in treatments containing 20% and 30% rubber when compared with the control treatment, regardless of whether corona treatment was used or not. The reduction in the average MOR for treatments containing 20% treated and untreated rubber was 46.1% and 45.2%, respectively. On the other hand, for panels with 30% rubber addition, with and without corona treatment, this reduction was 74.7% and 71.5%, respectively. The MOE reduction for panels with 20% treated and untreated rubber was 41.2% and 41.1%, respectively, and for panels containing 30% rubber, was 71.6% and 72.1% before and after corona treatment, respectively.

Table 7. Average Values of Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) in Static Bending and Internal Bond Strength (IB) of the Particleboard

Treatment	MOE	Δ	MOR	Δ	IB	Δ
	MPa					
10% rubber	2027 $^{(130)\ ns}$	−10.6	11.65 $^{(1.05)\ ns}$	−32.3	0.59 $^{(0.06)}$ **	−38.1
20% rubber	1528 $^{(564)\ **}$	−32.6	9.45 $^{(3.15)}$ **	−45.2	0.48 $^{(0.13)}$ **	−49.7
30% rubber	737 $^{(86)\ **}$	−67.5	4.89 $^{(1.38)}$ **	−71.5	0.34 $^{(0.06)}$ **	−64.2
10% treated rubber	2116 $^{(341)\ ns}$	−6.7	13.66 $^{(2.69)\ ns}$	−20.6	0.66 $^{(0.12)}$ **	−30.7
20% treated rubber	1198 $^{(321)\ **}$	−47.2	9.28 $^{(2.71)}$ **	−46.1	0.41 $^{(0.09)}$ **	−57.6
30% treated rubber	726 $^{(222)\ **}$	−67.9	4.38 $^{(0.96)}$ **	−74.7	0.27 $^{(0.04)}$ **	−71.7
Control	2267 $^{(373)}$		17.17 $^{(4.54)}$		0.96 $^{(0.04)}$	

**Values statistically differ from control treatment by the Dunnett's test (α=0.01). ^{ns} Values do not differ statistically from control treatment by the Dunnett's test (α=0.05).

For IB, all treatments differed significantly from the control treatment, with reductions from 38.1% to 64.2% for panels containing untreated rubber and from 30.7% to 71.7% for panels produced with treated rubber.

The reduction in IB values compared with the control treatment is likely related to the reduction in adhesion between wood and rubber particles, which do not establish ionic bonds among each other (Macedo 2008), in addition to their own mechanical characteristics. Thus, corona treatment was not able to provide improved bonding between tire and wood particles.

Santos *et al.* (2011) assessed the addition of 0%, 25%, and 50% PET in particleboard panels produced with candeia wood residues and observed MOR average values of 8.05, 9.02, and 8.33 MPa, respectively. The authors state that the non-use of any substance capable of acting as a link between the raw material surfaces is the main factor for reducing the average MOR value. Jun *et al.* (2008) assessed panels of larch (*Larix gmelini*) particles and rubber tire residues at 40% in relation to the wood, in addition to urea-formaldehyde and PMDI resins, and found an average internal bond strength of 0.52 MPa.

Analysis of variance of the mechanical properties showed no interaction between rubber percentages (10%, 20%, and 30%) and treatments applied to the rubber (with and without corona treatment). Table 8 presents the results for MOE, MOR, and IB.

Table 8. Average Values for Mechanical Properties of Particleboard with Different Rubber Percentages

Treatment	MOE	MOR	IB
	MPa		
10% rubber	2071 $^{(236)*}$ a	12.65 $^{(2.14)}$ a	0.63 $^{(0.09)}$ a
20% rubber	1363 $^{(470)}$ ab	9.36 $^{(2.63)}$ a	0.44 $^{(0.11)}$ b
30% rubber	731 $^{(151)}$ b	4.63 $^{(0.72)}$ b	0.31 $^{(0.06)}$ c

Means followed by the same letter in the column are statistically equal by the Tukey's test at 5% significance. *Values in parentheses are the standard deviation.

A significant difference in mechanical properties was observed between panels produced with different rubber tire percentages. For MOE, MOR, and IB, a significant value reduction can be observed for panels containing 30% rubber.

Panel mechanical resistance loss with increasing rubber percentage is due to greater material ductility (rubber tire) compared with wood. Another important point to be assessed is the interaction between the two raw materials because even with the application of corona treatment on the rubber particles, no change was observed on the material's surface. In addition, the basic density of rubber is lower than that of pinewood, indicating a greater surface area and, consequently, a smaller amount of adhesive per particles that formed the panel.

Ayrilmis *et al.* (2009) evaluated particleboard panels produced with 10% rubber replacing wood and found average MOE, MOR, and IB values of 1821.25, 12.85, and 0.35 MPa, respectively. Increasing the rubber percentage to 30% decreased the MOE, MOR, and IB values to 1161.14, 6.29, and 0.23 MPa, respectively.

Only panels used as a control treatment and those with up to 10% rubber addition met the EN 312 (2003) standard for internal use panels (including furniture), which requires minimum MOE, MOR, and IB values of 1650, 11, and 0.35 MPa, respectively.

Thus, corona treatment of the rubber particles for a period of 5 min does not lead to the improvement of the mechanical properties corresponding to the particleboards. This fact can be justified by the short time of application of the corona treatment in the rubber particles. Moreover, the governing mechanisms of the properties of the particleboard were not critically dependent on the wettability phenomena between rubber and wood.

CONCLUSIONS

1. An increase in the rubber particle composition in particleboard panels improved TS24h and NRRT at the cost of a significant decrease in mechanical properties. Only panels with up to 10% rubber, under conditions proposed in this study, can be used for producing particleboard.

2. Corona-treating rubber particles for 5 min did not provide any significant effect on the properties of particleboard panels, and thus is an unnecessary step in the production process.

3. However, further studies investigating corona treatment on rubber particles should be developed and aimed at improving the interaction between rubber and wood particles to allow for greater rubber particle composition without affecting panel properties.

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REFERENCES CITED

Abduh Dahlan, F. (2007). *Utilization of Coarse Crumb Rubber to Enhance Hot Mix Asphalt Mixture Properties*, Master's Thesis, Department of Civil Engineering, Universiti Teknologi, Malaysia.

NBR 11941 (2003). "Madeira - Determinação da densidade básica," ABNT, Rio de Janeiro, Brazil.

NBR NM 45 (2006). "Agregados - Determinação da massa unitária e do volume de vazios," ABNT, Rio de Janeiro, Brazil.

Amoroux, J., Goldman, M., and Revoil, M. F. (1982). "Modification of the wettability of a poly (ethylene terephthalate) film treated by corona discharge," *Journal of Polymer Science Part A: Polymer Chemistry* 20(6), 1373-1387. DOI: 10.1002/pol.1982.170200601

ASTM D-1037 (2012). "Standard methods of evaluating properties of wood-base fiber and particles materials," ASTM International, West Conshohocken, PA.

Ayrilmis, N., Buyuksari, U., and Avci, E. (2009). "Utilization of waste rubber tire in the manufacturing of particleboard," *Materials and Manufacturing Processes* 24, 688-692. DOI: 10.1080/10426910902769376

Azmi, N., Mohammed, B., and Al-Mattarneh, H. (2008). "Engineering properties of concrete containing recycled rubber tire," in: *International Conf. on Construction and Building Technology e ICCBT*, June 16 to 20, Kuala Lumpur, Malaysia.

Bertolini, M. S. (2014). *Painéis de Resíduos Madeireiros e de Borracha de Pneu Associados à Espuma Poliuretana à Base de Mamona para Aplicação como Composições Termoacústicas.* Doctor's thesis, Programa de Pós-Graduação em Ciências e Engenharia de Materiais, Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, Brazil.

Bledzki, A. K., and Gassan, J. (1999). "Composites reinforced with cellulose based fibres," *Prog. Polym. Sci*. 24, 221-274. DOI: 10.1016/S0079-6700(98)00018-5

Briggs, D., Rance, D. G., Kendall, C. R., and Blythe, A. R. (1980). "Surface modification of poly (ethylene-terephthalate) by electrical-discharge treatment," *Polymer* 21(8), 895-900. DOI: 10.1016/0032-3861(80)90244

DIN 52362 (1982). "Testing of wood particleboards bending test, determination of bending strength," Deutsches Institut für Normung, Berlin, Germany.

EN 312 (2003). "Particleboards – specifications," European Committee for Standardization, Brussels, Belgium.

Fioriti, C. F., and Akasaki, J. R. (2004). "Manufacture of concrete structural blocks with residues of tire rubber," *HOLOS Environment* 4(2), 145-156. DOI: 10.14295/holos.v4i2.349

Fu, Z. *Properties and Designs of Rubber Materials*; Publishing House of Chemistry Industry: Beijing, China, 2003.

Galle, A. da H., Lopes, E. F. S., Araújo, M. J. G., Grama, Y. dos S. (2010). "The influence of the tire on the environment," in: *Simpósio Internacional de Ciências Integradas da UNAERP*, Campus Guarujá - SP. Brasil. September 22 to 24.

Giraldi, D. P., and Campos, J. S. de C. (2004). "Corona treatment in natural rubber," in: *XII Congresso Interno de Iniciação Científica da UNICAMP*, Campinas – SP, Brasil. September 22 to 24.

Iwakiri, S., Andrade, A. S., Cardoso Jr., A. A., Chipanski, E. R., Prata, J. G., and Adriazola M. K. O. (2005). "Production of high density particleboard using melamine-urea-formaldehyde resin," *Cerne* 11(4), 323-328.

Jun, Z., Xiang-Ming, W., Jian-Min, C., and Kai, Z. (2008). "Optimization of processing variables in wood-rubber composite panel manufacturing technology," *Bioresource Technology* 99(7), 2384-2391. DOI: 10.1016/j.biortech.2007.05.031

Kongsuwan, S., and Phetcharat, S. (2003). "Rubber asphalt composition and application in road pavement," in: *Fourth Regional Symposium on Infrastructure Development in Civil Engineering (RSID4)*, Bangkok, Thailand, April.

Lima, C. S. (2008). *Characterization of Modified Ashaltic Ligantes with Tire Rubber and Additive*, Master's thesis, Programa de Mestrado em Engenharia de Transportes, Centro de Tecnologia, Universidade Federal do Ceará, Fortaleza, Brazil.

Macedo, D. G. (2008). *Composites Made with Wood Chips and Tire Rubber Residues*, PhD dissertation, Departamento de Engenharia Florestal, Universidade de Brasília, Brasília, Distrito Federal, Brazil.

Ndazi, B., Tesha, J. V., Karlsson, S., and Bisanda, E. T. N. (2006). "Production of rice husks composites with *Acacia mimosa* tannin-based resin," *Journal of Materials Science* 41(21), 6978-6983. DOI: 10.1007/s10853-006-0220-7

Nehdi, M., and Khan, A. (2001). "Cementitious composites containing recycled rubber tire: An overview of engineering properties and potential applications," *Cement, Concrete and Aggregates* 23(1), 3-10. DOI: 10.1520/CCA10519J

Sadek, D. M., and El-Attar, M. M. (2015). "Structural behavior of rubberized masonry walls," *Journal of Cleaner Production* 89, 174-186. DOI: 10.1016/j.jclepro.2014.10.098

Santos, R. C., Mendes, L. M., Carneiro, A. C. O., Mori, F. A., Castro, R. V. O., and Mendes, R. F. (2011). "Utilization of candeia (*Eremanthus erythropappus* (DC.) Macleish) wood residues in the production of particleboad with addition of pet," *Ciência Florestal* 21(1), 149-158. DOI: 10.5902/198050982757

Scatolino, M. V., Silva, D. W., Mendes, R. F., and Mendes, L. M. (2013). "Use of maize cob for production of particleboard," *Ciência e Agrotecnologia* 37(4), 330-337. DOI: 10.1590/S1413-70542013000400006

Segre, N. C. (1999). *Use of Tire-rubber Particles as Addition to Cement Paste*, PhD dissertation, Universidade Estadual de Campinas, Instituto de Química, Campinas, São Paulo, Brazil.

Silva, D. W., Farrapo, C. L., Mendes, R. F., Mendes, L. M., Tonoli, G. H. D., and Guimarães Jr., J. B. (2016). "Use of castor hull and sugarcane bagasse in particulate composites," *Key Engineering Materials* 668, 381-389.

Stehling, F. C., and Meka, P. (1994). "Heat sealing of semicrystaline polymer films. II Effect of melting distribution on heat-sealing behavior of polyolefins," *Journal of Applied Polymer Science* 51(1), 105-119. DOI: 10.1002/app.1994.070510112

Witmann, G. C. P. (2010). *Tratamento Superficial de Filmes Plásticos,* Revista Tecnologia Gráfica, São Paulo, n° 75. Available in: http://www.revistatecnologiagrafica.com.br/index.php?option=com_content&view=article&id=1481:tratamento-superficial-de-filmes-plasticos&catid=46:como funciona&Itemid=183.

Zhao, J., Wang, X. M., Chang, J. M., Yao, Y., and Cui, Q. (2010). "Sound insulation property of wood–waste rubber tire composite," *Composites Science and Technology* 70(14), 2033-2038. DOI: 10.1016/j.compscitech.2010.03.015

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