Surface Modification of Tire Rubber Waste by Air Plasma for Application in Wood-Cement Panels

Alan Pereira Vilela, Danillo Wisky Silva, Lourival Marin Mendes, Maria Alice Martins, Lívia Elisabeth Vasconcellos de Siqueira Brandão Vaz, and Rafael Farinassi Mendes *

Much research has been carried out to improve the wettability and to overcome the low adhesion of tire rubber for use in developing new building materials, such as wood-cement panels. Corona surface treatment (air plasma) of rubber particles was used in this study with various application times to improve adhesion and the interface between the particles and the cementitious matrix. Another aspect evaluated in this study was the partial replacement of wood particles by tire rubber waste in wood-cement panels. The particulate rubber residue was subjected to various corona application times to determine the most suitable treatment; the samples showed the most desirable qualities after 20 min of air plasma treatment. Then, panels were produced using *Pinus oocarpa* particles associated with various contents of tire rubber after corona treatment. Overall, after 20 min of air plasma treatment, the wettability and adhesion properties of tire rubber waste improved. The use of 5% rubber to replace pine wood in wood-cement panels led to a substantial improvement in the physical-mechanical properties evaluated, making its production feasible and promoting the reuse of a material harmful to the environment.

Keywords: Waste rubber; Corona treatment; Wood; Cement; Alternative composite

Contact information: Engineering Biomaterials, Federal University of Lavras (UFLA), Lavras-MG, Brazil;
** Corresponding author: rafael.mendes@deg.ufla.br*

INTRODUCTION

The construction sector has been investing in clean technologies, presenting a growing number of studies focused on the development of green materials, such as waste used in the composition of composite materials (Shu and Huang 2014; Goh *et al.* 2016; Xiaowei *et al.* 2017). The number of discarded tires has attracted the interest of this sector because it is estimated that 1.5 billion waste tires are generated each year as a result of the fast growth of the automobile industry. Approximately 60% of these tires come from China, the USA, and Europe (Lo Presti 2013; Shu and Huang 2014; Zhu 2015). The numbers of discarded tires are increasing each year, leading to environmental pollution caused by the inadequate disposal of such wastes (Zhu 2015), as well as possible health problems related to vectors' proliferation on the inside of tires (Galle and Lopes 2010). One of the first methods proposed to reuse tires was to generate energy by burning them. However, with technological advances, new applications have emerged. In the USA, waste tires are blended with asphalt and incorporated into plastic composites as a raw material for carbon production, merged into concrete, or even used in nature for creating artificial environments for marine life protection (Cao 2007; Shu and Huang 2014; Liang *et al.* 2016; Rahimi *et al.* 2016).

Numerous studies have been performed with the incorporation of rubber tire waste as an aggregate in cementitious composites (Khatib and Bayomy 1999; Guneyisi *et al.*

2004; Papakonstantinou and Tobolski 2006; Zheng *et al.* 2007; Gesoglu and Guneyisi 2007; Balaha *et al.* 2007; Khaloo *et al.* 2008; Farhan *et al.* 2016; Xiaowei *et al.* 2017). However, these studies point to some disadvantages for this composite type, as rubber particles are difficult to disperse in cement and form a weak bond with the cement matrix because of their hydrophobicity, resulting in a decrease in the strength of the cement (Topcu 1995; Huang *et al.* 2004; Liang *et al.* 2016). The poor interaction between rubber particles and cement generates microcracks that reduces the mechanical strength of the composite (Khatib and Bayomy 1996; Huang *et al.* 2004; Kaloush *et al.* 2005; Bignozzi and Sandrolini 2006; Mohammadi *et al.* 2014; Shu and Huang 2014). One solution is the chemical treatment of rubber particles. Positive results have been reported by increasing the mechanical properties of rubber-cement composites (Rostami *et al.* 1993; Yu *et al.* 2010, 2012; Kocaman *et al.* 2017). However, these treatments have some disadvantages, such as the complex process involved, a prolonged treatment period, and environmental problems (Albano *et al.* 2005; Xiaowei *et al.* 2017). Therefore, physical treatment has attracted attention. Some common physical treatment principles include improving surface activity and roughness, or the elimination of weak interfaces. To reach this goal, techniques such as ultrasonic cleaning, plasma modification, ultraviolet radiation, ozone treatment, and corona discharge have been developed (Tyczkowski *et al.* 2003; Romero-Sánches *et al.* 2003; Liao *et al.* 2003; Romero-Sánches and Mártin-Martínez 2006; Romero-Sánches *et al.* 2007).

Corona treatment (air plasma) consists of applying a low voltage (10 and 40 kV) at a high frequency (1 and 4 kHz), which generates a visible electrical discharge from a linear array of electrodes on the polymer surface. The corona discharge causes partial ionization of the surrounding atmosphere, producing excited species (*e.g.*, free radicals, ions, or electrons). These chemical species are able to react and oxidize the molecules exposed on the polymer surface, forming new polar functionalities, such as hydroxyl, carboxyl, carbonyl, and amide groups on the surface. These new functionalities have a strong compatibility with hydrophilic materials and increase adhesion (Ozdemir *et al.* 1999; Kurek and Debeaufort 2015). Another well-known effect of this partial ionization of the atmosphere is nano-modification of the polymer physical surface resulting from an abrasion phenomenon called chemical attack (Pankaj *et al.* 2014; Rocca-Smith *et al.* 2016).

Thus, corona treatment may aid in the bonding between tire rubber particles and the cementitious matrix. Another relevant aspect is an evaluation of the incorporation of particles with greater modulus into the composite, reducing the "hole" effect that is often observed in composites with rubber and cement (Xiaowei *et al.* 2017). In this sense, the aim of this research was to investigate the optimal time for corona treatment in rubber particles that would increase affinity with hydrophilic materials and subsequently use the rubber particles with *Pinus* wood particles in the production of wood-cement panels.

EXPERIMENTAL

Raw Material

The wood particles used in this study were extracted from roughly 28-year-old *Pinus oocarpa* by a mechanical process. The process consisted of sectioning the timber into 55-cm-long small logs. The logs were then steamed at 60 °C for 24 h, and 2.0-mm-thick rotary cut veneers were obtained from these steamed timber logs. The veneers were turned into particles using a hammer-mill with a 2.0-mm-aperture sieve. The tire rubber particles were obtained from BKERP (tire retreading company), located in Lavras, MG-Brazil. The unitary rubber weight determination was performed in accordance with the NBR NM 45 Brazilian standard requirements (ABNT 2006). The wood and tire rubber particles were sieved through a combination of two superposed sieves to remove the fines content (less than 1.19 mm), resulting in particle sizes of 4.76 mm (top sieve) and 1.19 mm (bottom sieve).

Surface Particles Modification by Air Plasma

The previously sifted tire rubber particles were treated with air plasma *via* the corona treatment. The air plasma exposure time was varied (5 min, 10 min, 15 min, or 20 min) while the equipment configuration for surface modification of the tire rubber particles were kept constant at 12 kV, 0.06 A, and 60 Hz at 25.6 ± 2 °C ambient atmosphere, 60% moisture, and a 3-cm distance between source and sample.

Tire Rubber Particle Characterization

To evaluate the possible physical-chemical modifications that occurred in rubber particles after exposure to air plasma, the particles were characterized and compared with rubber particles without any treatment. To identify the chemical groups present in the rubber particle surface before and after the corona treatment, a Fourier transform infrared spectroscopy (FTIR) analysis was carried out using a Bruker mid-infrared spectrometer with Fourier transform, Vertex 70 model (Bruker, Germany). Also, attenuated total reflectance (ATR) equipment with zinc selenide (ZnSe) crystal and 20 internal reflections were used. A total of 32 scans was performed, with a 4 cm^{-1} resolution. To evaluate the thermal stability and decomposition of rubber tire components when submitted to temperature control, the analysis was performed in a nitrogen atmosphere with a 40 mL min^{-1} flow rate. A thermogravimetric analyzer TA Instruments, Q5000 model (TA Instruments, USA), with a 10 °C/min heating rate and an ambient temperature range to up to 700 °C was used. In addition, scanning electron microscopy (SEM) analysis was used to determine the material surface morphology before and after corona treatment. These characterizations were performed to evaluate which duration of exposure to air plasma most effectively modified the rubber particles. Subsequently, the selected rubber particles were used in the production of wood-cement panels.

Experimental Plan and Panel Production

The best air plasma treatment condition was evaluated for wood-cement panel production. Rubber particles were used as a replacement in proportions of 5%, 10%, 15%, and 20% relative to the total weight of the wood particles in the panel. Air plasma treatment was applied to rubber particles for 20 min because the greatest change in the material surface occurred under this condition.

For each treatment, three panels were produced with a 1200 $kg.m^{-3}$ nominal density and dimensions of 480 mm × 480 mm × 15 mm (length, width, and thickness, respectively). Cement Portland V – Alta Resistencia Inicial (CPV–ARI) cement was used for glueing the wood-cement panels, as it reaches high resistance at a young age. This was seen as a benefit because it prevents time loss in the production process and inhibition of cement curing with wood. In addition, calcium chloride ($CaCl_2$) was used as an additive to accelerate curing of concrete and cement-based mortars. Parameters used for fabricating wood-cement panels are shown in Table 1.

Table 1. Parameters for Fabricating Wood-Cement-Rubber Panels

Parameter	Ratio
Density	1200 kg/m^3
Wood: cement	1:2.75
Water: cement	1:2.5
Cement hydration rate	0.25
Additive	4%

After weighing, the materials were mixed in a concrete mixer. Initially, wood and rubber particles were added (when necessary), followed by cement. After mixture homogenization, water was added with premixed additive using a container with a pressurized system. Subsequently, the material was removed from the concrete mixer, weighed, and molded with 4-MPa pressing for 24 h. Afterward, the panels were demolded and left for 28 d in a controlled environment chamber set at 65 ± 5% humidity and 20 ± 2 °C for curing. In total, three panels were obtained per treatment.

Physical-Mechanical Characterization of Panels

Finally, square-shaped panels were obtained to remove any edge effects from the manufacturing process. Samples were subsequently analyzed to determine their physical and mechanical properties, as shown in Table 2.

Table 2. Assessed Tests and Implementation 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)

After the physical and mechanical tests were performed, SEM analysis was carried out in the proof bodies of panel internal bond strength to assess rubber-wood-cement association. After the physical and mechanical tests were carried out, SEM analysis was performed on internal bond test-bodies to evaluate the rubber-wood-cement association.

The results were submitted to both descriptive and experimental analyses, with the aid of SISVAR software version 5.6 (Lavras – MG, Brazil). The experiments were assessed in a completely randomized design. The results were submitted to variance analysis and, when deemed significant, a regression analysis was performed at a 5% significance level.

RESULTS AND DISCUSSION

Tire Rubber Particle Characterization

To analyze changes in rubber structure after applying the corona treatment, comparisons were made between the FTIR spectra of untreated and treated rubber (Fig. 1).

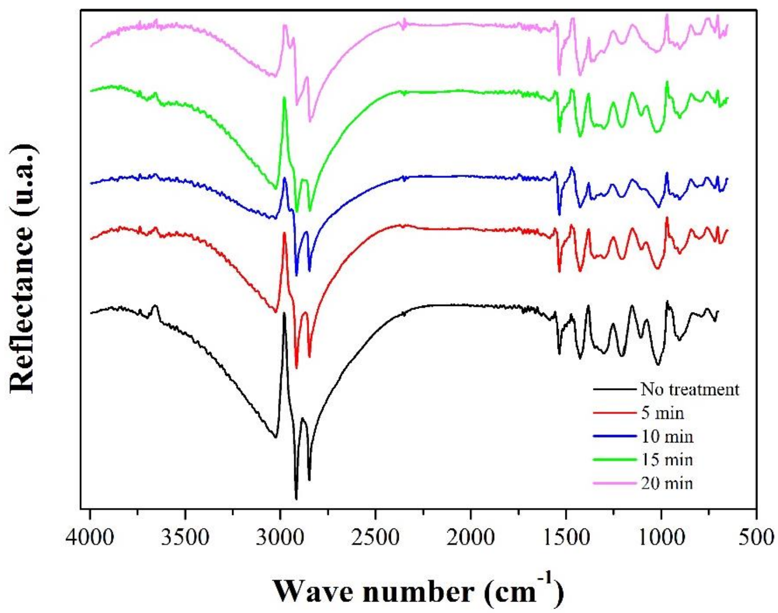

Fig. 1. FTIR spectra of untreated tire rubber and after corona treatment for 5, 10, 15, and 20 min

A peak elongation formed by band vibration can be observed in the 1100 to 1200 cm^{-1} range, which is related to C–O bonds with increased corona treatment time. This fact may be related to tire rubber oxidation caused by the corona discharge application. Vibrations related to bands in the 1100 to 1370 cm^{-1} range showed lower intensities for treated samples, particularly those treated for 10 min. This may indicate a decrease in the number of compounds containing sulfur-oxygen bonds because sulfur atoms are joined together to linear rubber structures, culminating in sulfur bonds, which increase the material strength and hardness.

Bands at 1020, 1100 to 1200, 1100 to 1370, and around 1600 cm^{-1} are the main peaks for rubber surface oxidation. Bands close to 1400 cm^{-1} were also reduced because of oxidation and double bond C=C breaking.

Reduction in the intensity of C–H bonds (region between 3000 and 2850 cm^{-1}) was obtained with increasing time of material exposure to corona treatment. A new band was observed at 2930 cm^{-1}, attributed to the CH_2 group C–H bond. Reductions in bands at 2916 and 2846 cm^{-1} were associated with aliphatic breaking and aldehydic C–H group bonds (CH, CH_2, and CH_3 groups) caused by rubber oxidation.

Thermogravimetric analysis was used to determine the mass variation of samples, which are affected by chemical or physical transformations depending on temperature or time (Sibilia 1988; Hunt and James 1993). Figures 2 and 3 show mass loss values by thermogravimetry (TGA) in an inert atmosphere (N_2) and the derivative mass loss curve (DTG), respectively.

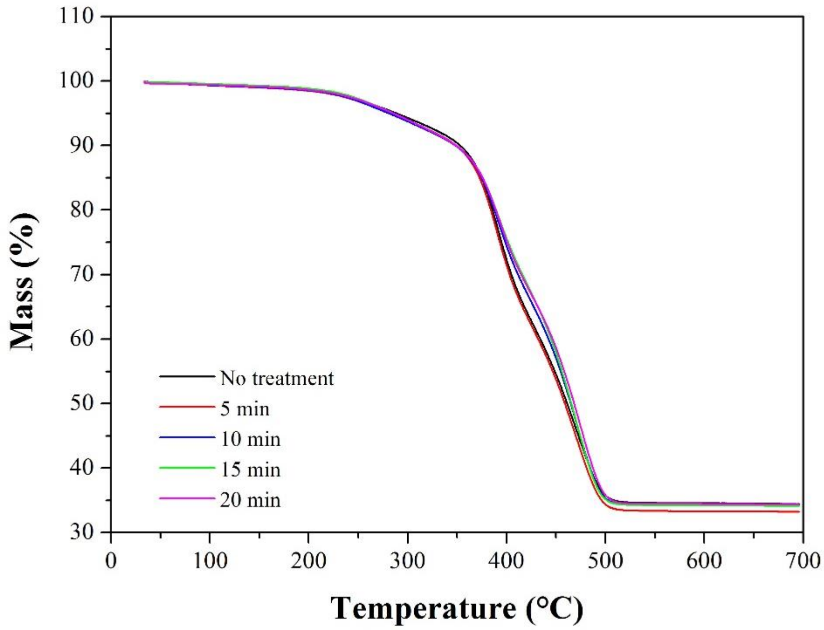

Fig. 2. TG curves for tire rubber before and after corona treatment at intervals from 30 to 700 °C

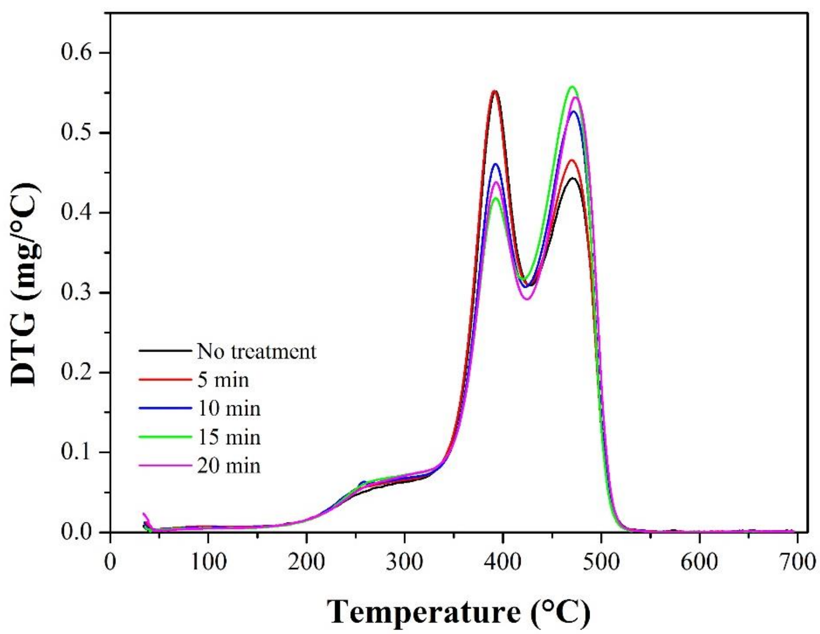

Fig. 3. DTG curves for tire rubber before and after corona treatment at intervals from 30 to 700 °C

In general, even after corona treatment, the tire rubber showed two maximum mass loss peaks, at 60 to 400 °C and 400 to 520 °C. These peaks were in agreement with those found by Silva *et al.* (2006), who performed a compositional analysis using thermogravimetry of microwave-devulcanized tire rubber. All samples showed an approximate 60% mass loss at approximately 450 °C. According to Segre (1999), such mass loss is related to volatile oils released from tire rubber.

Two rubber degradation peaks can also be observed. In the first stage, a mass loss about 10% was observed within a 60 to 400 °C temperature range. Moreover, in the second stage, the mass loss was about 55% within a 400 to 520 °C temperature range.

The rubber particles were analyzed by scanning electron microscopy for morphological characterization, and changes were observed on their surface after corona discharge treatment. Figure 4 shows the micrographs of the rubber particles.

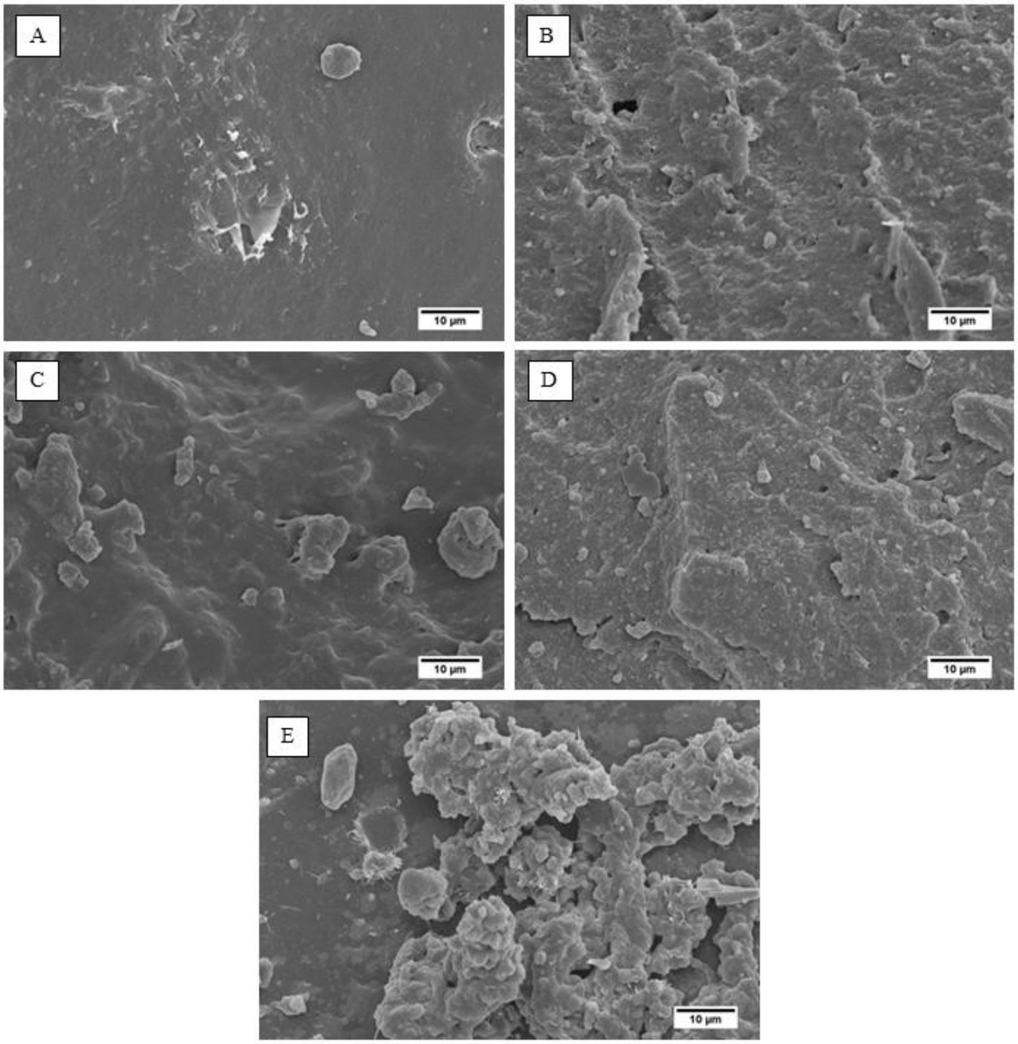

Fig. 4. A – SEM micrographs of rubber particles without corona treatment; B, C, D, and E – SEM micrographs of rubber particles exposed for 5, 10, 15, and 20 min to corona treatment, respectively

The effect of corona treatment could be detected on the surface of rubber particles, *i.e.*, as material exposure time to electrical discharge increases, rubber roughness increases because of material surface oxidation. This roughness positively affects the connection between the rubber and binding material (cement) for panel production.

Considering the entire characterization process of tire rubber before and after treatment at different periods, the corona treatment was satisfactory with respect to material surface modification. Thus, the 20-min treatment was chosen because it led to greater surface roughness, which facilitates anchorage between rubber particles and the cementitious matrix.

Panels' Apparent Density and Moisture Content

Figure 5 shows the average values of apparent density, compaction ratio, and moisture content of wood-cement panels obtained from the various analyzed treatments. Basic densities calculated for *Pinus oocarpa* wood and tire rubber were 500 ± 20 kg/m^3 and 340 ± 40 kg/m^3, respectively.

Apparent density is a factor that directly influences physical, mechanical, and thermal behavior. In this sense, no statistical difference between treatments was observed when the apparent density values of panels were analyzed, *i.e.*, tire rubber addition did not change the final product density. The amplitude of the average values found was from 1.12 to 1.14 g/cm^3, which indicated homogeneity in panel production between treatments. According to Eleotério (2000), a reduction in apparent density, when compared with the 1.2 g cm^{-3} nominal density, is related to material loss and weight dispersion for a larger area during the production process.

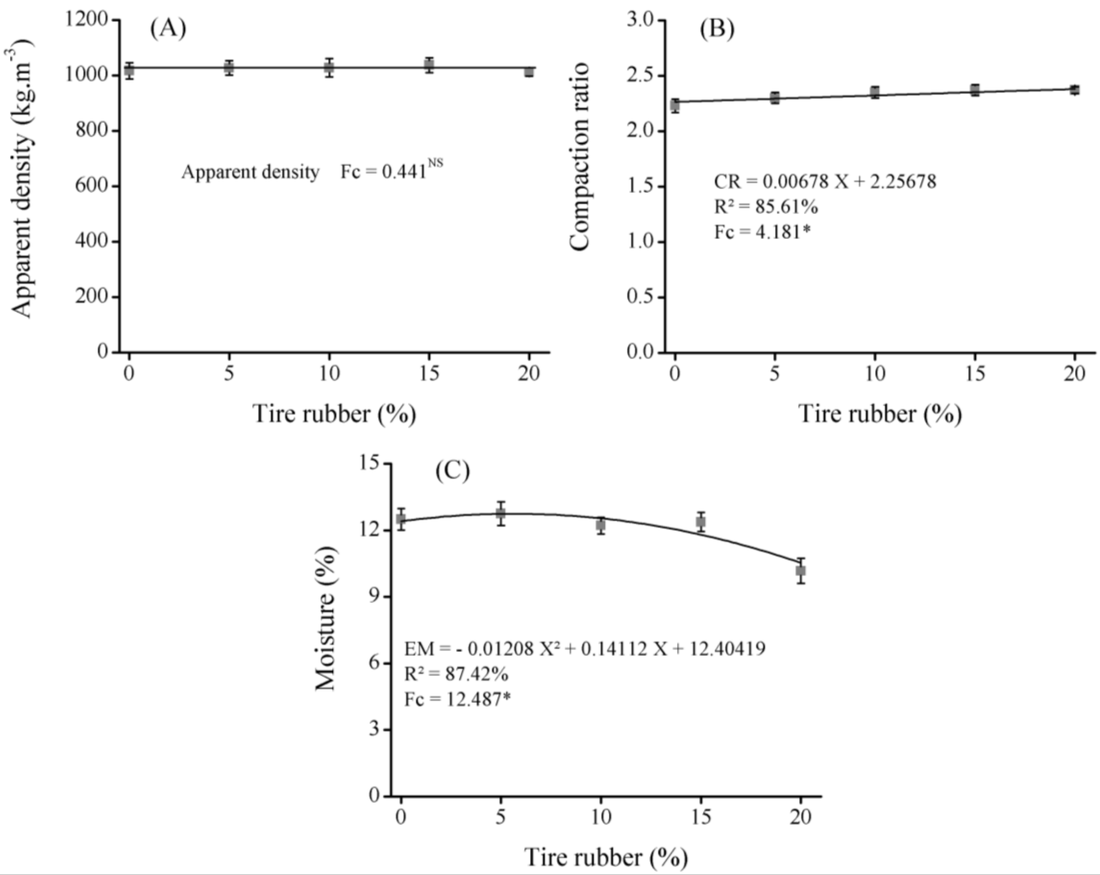

Fig. 5. (A) Apparent density, (B) compaction ratio, and (C) moisture content at various rubber percentage levels assessed for wood-cement panel production. ns Non-significant regression analysis at a 5% significance level

There was a significant difference (P = 0.0507) between the compaction ratios of the different treatments. With an increase in rubber waste particles contents, the compaction ratio increased because tire rubber has a lower basic density than does *Pinus* wood, causing a decrease in the pore contents of wood-cement panels.

The addition of rubber waste also influenced the moisture content of the panels. As tire rubber waste was added, the panels' moisture content decreased from 12.5% (0%

rubber) to 10.2% (20% rubber) because of the hydrophobicity of rubber particles, which indicated a possible increase in the dimensional stability of panels. Savastano Júnior (1992), when studying fiber-matrix interface in cement composites, observed that the decrease in fiber-matrix adhesion is related to low dimensional stability, which in turn indicates that the composite has water affinity.

Physical Properties

The addition of rubber tire particles to wood-cement panels neither influenced water absorption after 2 and 24 h nor influenced thickness swelling after a 2-h immersion period (Fig. 6).

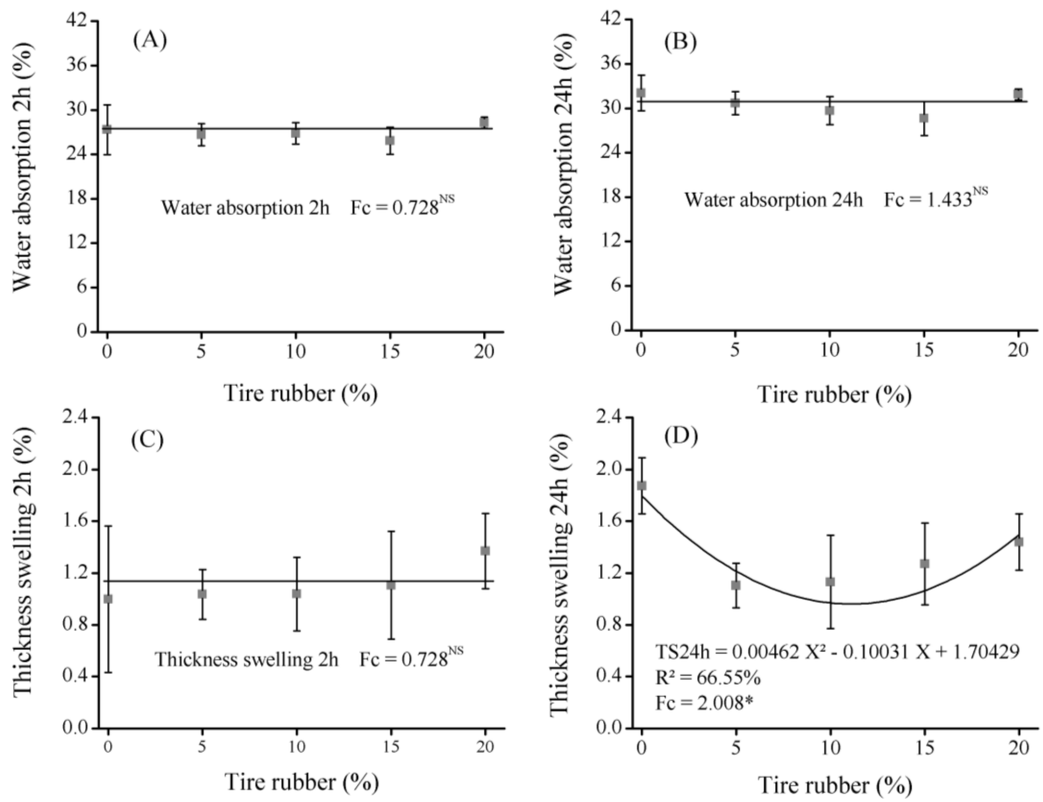

Fig. 6. (A), (B) Water absorption and (C), (D) thickness swelling after 2- and 24-h immersion periods at various levels of rubber percentage for wood-cement panel production. Non-significant regression analysis at a 5% significance level.

Although the rubber had no water affinity, the panels with rubber addition exhibited the same water absorption as the panels with wood particles. This was due to the occurrence of microcracks inside the panels with added tire rubber (Fig. 7); these voids can store water at similar levels to the absorbability of wood particles that have been replaced by rubber particles. The water absorption results from this study were consistent with the water absorption values reported in the literature for wood-cement panels (Iwakiri *et al.* 2015). With SEM, it was also possible to observe an increase in the number of microcracks as the percentage of rubber in the panels increased (Fig. 7). This occurred because of the pressing process of the panels, which deformed the rubber particles inside the matrix. According to Macedo (2008), microcracks are associated with the rebound of the compression of the material at the moment of panel production.

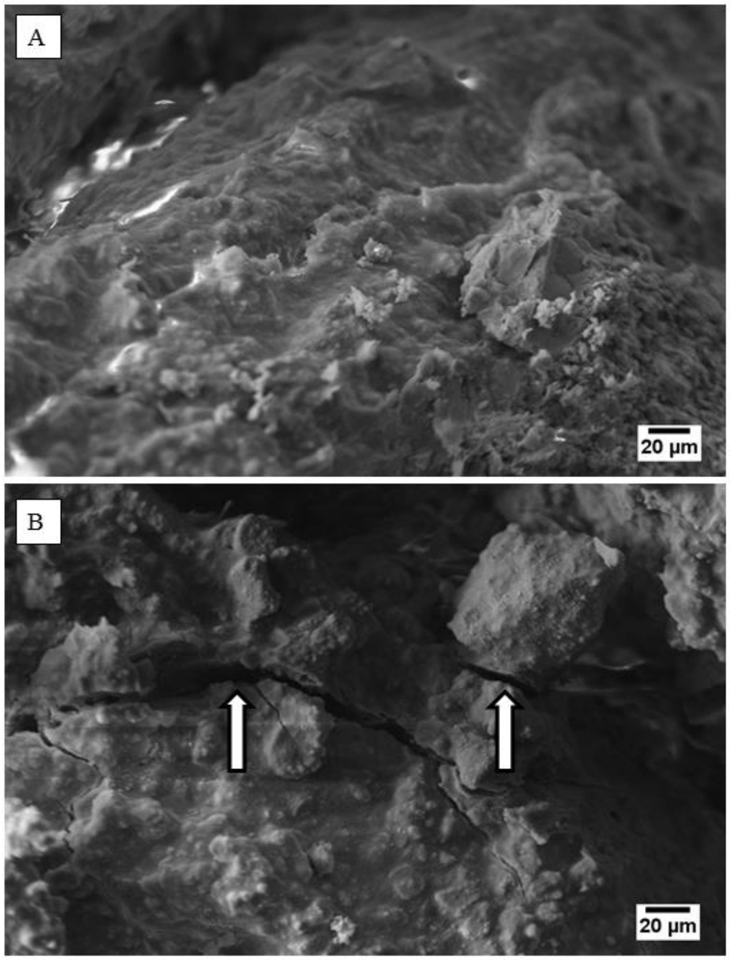

Fig. 7. SEM micrographs of wood-cement panels: (A) 5% tire rubber particles, and (B) 20% tire rubber particles

There was also no variation between treatments in the thickness swelling property after two hours of water immersion. However, thickness swelling tended to increase when rubber percentage was increased. This is probably because the microcracks in the cementitious matrix facilitated the swelling of wood particles, which affected the panels' dimensional stability.

Evaluating the swelling in thickness after a 24-h immersion period, the panels containing rubber obtained results that were similar to those observed after two hours of water immersion. The panels reinforced only with wood particles continued swelling. These results corroborate with the moisture values of the panels, proving the greater dimensional stability of the panels with rubber particles.

The panels with 5% rubber particles were the most stable, and by increasing rubber percentage, the dimensional stability of the panels gradually decreased; however, they were all more stable than the control panel. These results indicated a good rubber-cement adhesion (Fig. 8), which demonstrated the effectiveness of the surface modification of the rubber particles with air plasma. However, higher rubber percentages (10%, 15%, and 20%) caused increases in thickness swelling in relation to other panels with rubber particles (5%). These increases were associated with the re-expansion after the application of pressure during panel production. Such re-expansion led to microcracks that increased wood composite particle swelling as a result of higher water absorption, as observed for WA2h and WA24h (Figs. 5 and 6). Microcracks generated in panels with 20% rubber can be seen in Fig. 7. This fact was also observed by Macedo (2008), who found average values for thickness swelling after a 2-h immersion of 0.2% for wood-cement panels with 15% rubber, 0.7% for treatment without rubber, and 1.5% for panels containing 30% rubber.

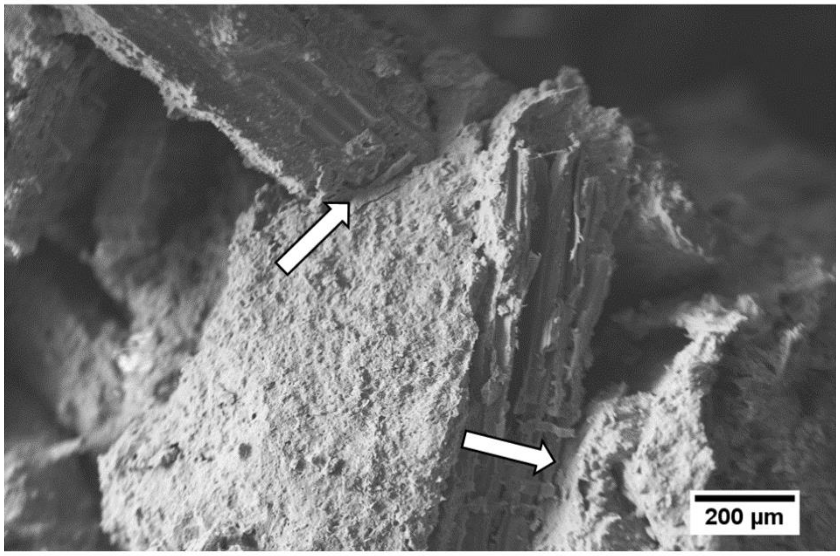

Fig. 8. SEM micrographs of the wood-cement panel with 5% tire rubber particles

According to Viroc (2004), commercial wood-cement panels should present no more than 1% TS2h, with maximum variations of TS24h values between 1.5% and 1.8%. In the BISON process (BISON WOOD-CEMENT BOARD, 1978), panels should present values lower than 1.3% for TS2h and 1.8% for TS24h.

Panels without any tire rubber particles did not achieve the average TS2h and TS24h values determined by the BISON process (BISON WOOD-CEMENT BOARD, 1978) and Viroc (2004). All wood-panels replaced by rubber met the parameters obtained for commercial panels, especially for the treatment containing 15% rubber, which obtained the lowest average values for TS2h and TS24h (0.66% and 1.03%, respectively).

The decrease in thickness swelling of panels containing tire rubber may be associated with tire rubber hydrophobicity, as the cell walls of rubber do not swell as wood does, which leads to a better dimensional stability. In addition, a good adhesion between particles and the cementitious matrix, caused by the roughening associated with corona treatment, may also be influenced by the decrease in thickness swelling, as shown in Fig. 8 (white arrows).

Wood particles can also inhibit cement curing (Simantupang *et al.* 1978; Iwakiri and Prata 2008), which promotes interfacial deterioration between particles and the cement matrix, allows greater dimensional movement between particles, and does not incur inhibition between the rubber and cement. Macedo (2008), studying the properties of wood-cement-rubber composite, concluded by means of a compatibility test that the addition of tire rubber and *Pinus taeda* wood led to a low inhibition in cement hydration. The author pointed out that both materials do not slow down the hydration process, but only decrease cement hydration temperature. In general, the surface modification with air plasma improved the rubber-cement interface. The addition of tire rubber increased the dimensional stability of the panels.

Mechanical Properties

There was variation between the different panels for the internal bonding (IB) properties; however, parallel compression (PC) did not present any statistical variation (Fig. 9).

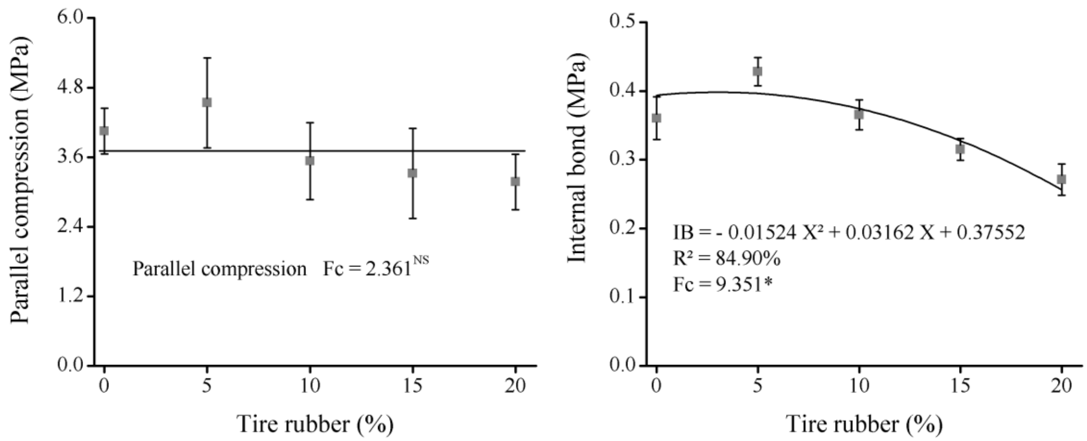

Fig. 9. Parallel compression at different levels of rubber percentages assessed for wood-cement panel production, an internal bond strength at different rubber concentration levels assessed for wood-cement panel production. Non-significant regression analysis at a 5% significance level.

The replacement of wood with rubber particles did not have a significant effect on PC, although there was a decrease in average values with the replacement of 15% and 20%. However, treatments showed significant effects for IB. An increasing trend in average values was observed for panels containing 5% rubber when compared to control treatment, followed by a decrease in average values. Percentage values from 15% to 20% rubber promoted a negative effect on panels, providing lower average values for IB than the ones obtained for panels without any added rubber.

As described for physical properties, wood reduction resulting from replacement by rubber particles caused an improvement in IB because of the good interface obtained between rubber modified with corona treatment and the cement matrix, as well as an inhibition decrease of cement cure with wood replacement. However, with an amount of rubber greater than 10%, a rise in the number of generated cracks was observed, caused by the return of rubber particles' dimensions after removing the pressure used for panel production. Figure 7 shows SEM micrographs of wood-cement panels containing 5% and 20% rubber particles, respectively. Cement cracks on rubber particles can be seen clearly, as shown by the white arrows.

Macedo (2008) also observed a loss resistance to internal bond strength with an increase in the number of rubber particles. The author obtained internal bond strength values of 0.58 MPa and 0.40 MPa for panels without any rubber addition and panels with 15% addition, respectively.

The values observed in this study were satisfactory in relation to the results presented in the literature (Latorraca 2000; Matoski and Iwakiri 2007; Iwakiri and Prata, 2007; Mendes *et al.* 2011). Only panels containing 15% and 20% rubber particles replacing wood did not meet the specifications for commercial panels produced with the BISON process (BISON WOOD-CEMENT BOARD 1978), which determines a minimum internal bond value of 0.40 MPa. No treatment, including the control, met the specifications laid out by Viroc (2004), who stated that commercial wood-cement panels should have an internal bond strength of 0.50 MPa. Thus, improvements in laboratory production processes will be necessary for future research to adjust the control to a commercial standard.

The effects of replacing wood by tire rubber particles on the rupture modulus (MOR) and on the elasticity modulus (MOE) in static bending were also significant and can be observed in Fig. 10.

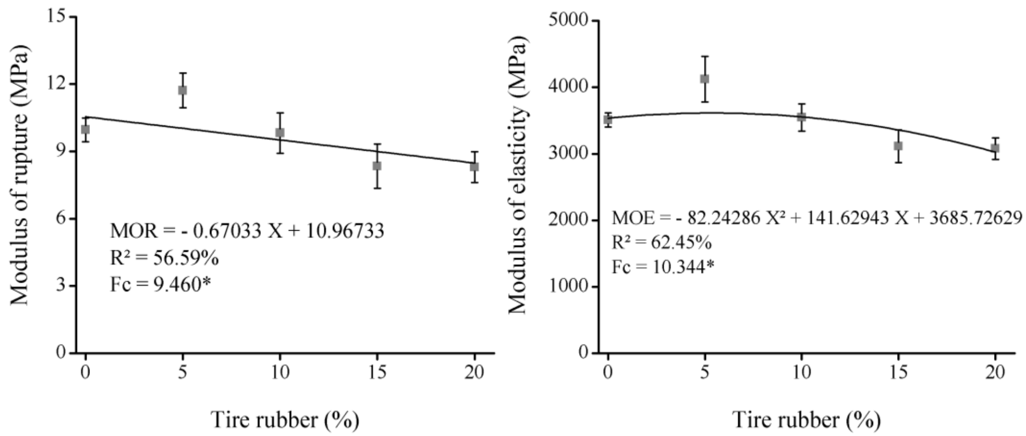

Fig. 10. Rupture modulus in static bending at different levels of rubber percentages assessed for wood-cement panel production, and elasticity modulus in static bending at different levels of rubber percentages assessed for wood-cement panel production. *Significant regression analysis at a 5% significance level.

MOR and MOE results in static bending presented the same trend of internal bond strength, demonstrating the rubber-matrix interface influence on panel properties. Furthermore, MOR and MOE in static bending presented an increase when 5% wood was replaced by tire waste, presented similar values to the control with 10% tire rubber, and presented MOR and MOE reductions in the other wood particles replacement percentages per rubber particles.

Wood-cement panels containing 5% tire rubber particles showed the highest average values for MOR and MOE, with values of 11.52 and 4154 MPa, respectively. The replacement of 15% and 20% of wood by tire rubber proved to be detrimental to the panels since it presented average values lower than those found for the control treatment.

As discussed for internal bond strength, the decrease in wood quantity and 5% tire rubber addition modified using the corona treatment led to an interfacial improvement with the cement matrix. For rubber amounts higher than 10%, crack-generation (Fig. 7) induced a most pronounced effect, providing reductions in composite properties. The crack also influenced the panels' loss of mechanical strength because of the rubber particles' low modulus compared with the wood particles and the cementitious matrix (Kaloush *et al.* 2005; Shu and Huang 2014).

Many previous studies point to different chemical treatments capable of improving the rubber-cement interface by reducing the "hole" effect, as they improve the mechanical strength of cementitious composites compared with untreated rubber composites (Yu *et al.* 2010). In this sense, the surface modification using 20 min air plasma was effective, improving the bond between rubber particles and cement, increasing the MOR, MOE, and

IB properties of the panels with 5% tire rubber, and equaling the properties of 10% rubber tire panels with the ones with 100% wood particles (control).

Macedo (2008) found average values of 9.8 and 2936.1 MPa, respectively, for MOR and MOE in wood-cement panels produced without any rubber addition. However, when 15% rubber was added to panels, values decreased to 3.8 MPa (MOR) and 1138.4 MPa (MOE). Only the treatments with 0%, 5%, and 10% rubber remained above the specifications of wood-cement panels produced using the BISON process (BISON WOOD-CEMENT BOARD 1978), which provides a minimum rupture modulus of 9.0 MPa. In terms of the elasticity modulus values in static bending, only panels containing 20% rubber did not fit the specifications of commercial panels produced using the BISON process (BISON WOOD-CEMENT BOARD 1978), which provides a minimum elasticity modulus of 3000 MPa.

When compared with commercial panels, the minimum value determined is 10.78 MPa for MOR and 4500 MPa for MOE (VIROC 2004). Only the treatment containing 5% rubber fit the MOR value. Regarding MOE, no treatment achieved the requirements. It is worth noting that commercial panels used as a comparison present a wider density ranging from 1.3 to 1.4 g cm^{-3}, which certainly provides improved MOR and MOE. In general, MOR and MOE results for wood-cement panels produced with 5% tire rubber particles were satisfactory when compared to past literature and quality standards.

CONCLUSION

1. Air plasma modified the tire rubber particles chemically and physically. After a 20-min application, it was possible to observe variations in chemical composition of the rubber and a quite apparent superficial modification, thus increasing the particulate material's roughness.
2. Air plasma treatment assisted in the tire rubber particles bonding with the cementitious matrix. Replacement of wood particles by rubber decreased the equilibrium moisture of the panels and increased dimensional stability compared to the control. The panels with 5% rubber particles obtained the lowest TS24h. The TS24h property increased as the rubber percentage in the panels increased, however, all rubber panels had lower values than the control ones.
3. The highest MOR, MOE, and IB values were obtained from panels with 5% rubber when replacing wood particles. Panels with 10% replacement obtained similar results to the control panel, and the other wood particles replacements per rubber presented the lowest MOR, MOE, and IB values, not meeting the standards for wood-cement panels.
4. Overall, there was a good rubber-cement interface due to the air plasma treatment, enabling the use of up to 10% tire rubber particles instead of wood particles. The use of rubber tire waste in wood-cement panels' production secures the correct proportions improving the properties of panels and aids in a more appropriate outcome for materials, avoiding future environmental problems.

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