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Research Article

Properties of a Laminated Wood Composite Produced with Thermomechanically Treated Veneers

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The paper aimed at evaluating the properties of plywood made from thermomechanically treated wood veneers. Veneers from Amescla (*Trattinnickia burseraefolia*) wood were treated in a hydraulic press with electric resistance heating. Two temperature levels were applied, 140°C and 180°C, for 1 and 2 minutes with 2.7 N/mm^2 of pressure. A total of 30 plywood boards were produced, including six boards produced from untreated veneers. The results showed that the thermomechanical treatment did not have any deleterious effect on glue line strength and most of the mechanical properties of plywood made from treated veneers were improved. On the other hand, plywood made from untreated veneers presented better dimensional stability. Dimensional stability properties were most affected by the temperature of the treatment, while mechanical stability, represented by the glue line shear strength, was positively affected by temperature and duration of the treatment.

1. Introduction

Densification and dimensional stability improvement are among the main objectives of producing thermomechanically treated wood. Thermomechanical modification is a densification technique combining heat treatment with mechanical compression. Wood compression mainly causes a reduction in empty spaces between cells and cell lumen. During compression, the cell structure is permanently modified resulting in new material exhibiting new properties. The number and type of collapsed cells are the main factors influencing mechanical and physical properties of thermomechanically modified wood [1]. Such collapse may occur to bend or break the cell wall or by breaking and crushing the cell, depending on test conditions and nature of cell wall material [2]. Heat affects wood's viscoelastic polymers; as the cell wall is deformed without fracture, the vessels flatten out and radii are bent. The wood compression without cell collapse is the ultimate factor in enhancing mechanical and physical properties of densified materials [1, 3].

Springback is the main negative effect of compression, which is the tendency of the material to return to its original thickness after the compression stresses are released. It is caused by the elastic deformation energy storage during the compression of semicrystalline microfibrils and hemicelluloses [4]. Nevertheless, compressed wood retains its shape after pressing due to the union of microfibrils deformed with lignin and cellulose by means of strong covalent bonds and hydrogen bonds of hemicelluloses [4].

Despite this negative effect caused by compression, the increase in density is the most influential effect on physical and mechanical properties of thermomechanically treated wood. Narayanamurti and Kaul [5] observed that mechanical properties were improved by an increase in compression ratio and density. Similarly, we have studied the effects of thermomechanical treatment on physical properties of *Trattinnickia burseraefolia* veneers [6] and an improvement in bulk density ranging from 9% to 14% was obtained. However, in plywood production, veneer surface quality is just as important as other physical properties. Plywood quality depends on, among other things, the quality of the veneers employed in the composition and the incidence of defects, adhesive type, and surface roughness. Adhesive application on veneers during plywood production is the most influent parameter among panel properties [7]. Veneer roughness has an important role in penetration depth, uniform adhesive distribution, and, hence, the bonding quality of veneers.

However, one of the most known side effects of the thermal treatment is the surface inactivation, which can impart negatively the glue line strength of the consolidated wood product. It happens, because veneer wettability is significantly reduced even when short-time treatments are applied, as presented by Bekhta and Krystofiak [8]. It can explain why modification of the veneers has received less attention than solid wood, although it has an excellent potential to improve properties of the plywood produced with this material, as stated by Antikainen et al. [9].

In this context, in our first work (Arruda and Del Menezzi [6]), we verified that veneer roughness was significantly reduced; thus, it has been hypothesized that it could improve gluing quality leading to improvement of the mechanical properties. In this way, in this paper, we present the results of physical and mechanical properties of plywood produced with thermomechanically treated veneers, where the main objective was to enhance the quality of a native species from Brazil.

2. Materials and Methods

2.1. Production of Plywood. Veneers from Amescla (*Trattinnickia burseraefolia*) wood were thermomechanically treated in a hydraulic press under two temperature levels (140°C and 180°C), for 1 and 2 minutes, with 2.7 N/mm^2 of pressure. After being removed from the hot-press, the veneers were kept at ambient temperature for cooling down without pressure. Each temperature-time combination was considered as one treatment (Table 1). The veneers were obtained in two thicknesses, 1.5 mm and 3.5 mm, and cut into 250 mm × 250 mm ($w \times l$). More details regarding the thermomechanical treatment of the veneers can be found in Arruda and Del Menezzi [6].

Veneers were bonded using phenol-formaldehyde at 200 g/m^2 spread rate. The adhesive was formulated following a 100 : 5 : 8 : 7 ratio of resin, wheat flour, coconut flour, and water, respectively. Mixture viscosity was about 840 cP and solids content was 59%. The boards were manufactured in a hydraulic press at 150°C, for 7 minutes, with 1.0 N/mm^2. A thermocouple was placed inside the board to measure the glue line inner temperature. Afterwards, the boards were placed in a conditioned room (20°C, 65% relative humidity) until equilibrium moisture content was reached.

2.2. Physical and Mechanical Properties. Following the conditioning stage, the samples were measured and weighed for density determination (D, g/cm^3). Twenty-four samples of 50 mm × 50 mm were used per treatment, and their apparent volumes were determined according to ASTM D2395 [10] standard. Other physical properties were also analyzed such as thickness swelling (TS, %), in 2 and 24 hours, water absorption (WA, %), in 2 and 24 hours, and permanent thickness swelling (PTS, %). PTS measures the thickness swelling caused by the release of compressive stresses. TS and WA were determined according to ASTM D1037 [11] standard and 24 samples had the dimensions adjusted to 25 mm × 90 mm (width × length) and were used per treatment. Finally, equilibrium moisture contents (EMC, %) were calculated according to ASTM D4442 [12] for the same samples used in the PTS test.

Table 1: Experimental design applied for plywood production.

Treatment	Number of veneers	Veneers by board	Number of boards
Control	30	5	6
140°C, 1 min, 2.7 N/mm^2	30	5	6
140°C, 2 min, 2.7 N/mm^2	30	5	6
180°C, 1 min, 2.7 N/mm^2	30	5	6
180°C, 2 min, 2.7 N/mm^2	30	5	6
Total	150		30

The following mechanical properties were evaluated: bending modulus of rupture (f_m, N/mm^2), bending modulus of elasticity (E_M, N/mm^2), compression strength parallel to the surface ($f_{c,0}$, N/mm^2), Janka hardness (f_H, N), and the shear strength of glue line in dry condition ($f_{\mathrm{gv},0}$, N/mm^2) according to EN 314-1 [13] standard. Moduli of rupture and elasticity were evaluated following EN 310 [14] standard while $f_{c,0}$ and f_H were evaluated according to ASTM D1037 [11] standard. These tests were performed in a universal testing machine EMIC with 300 kN maximum load capacity. For each mechanical testing, 24 samples were used. In order to assess f_H, the samples were glued in pairs to comply with the minimum thickness requirement of the abovementioned standard. Thus, 12 samples were tested for each treatment.

2.3. Image Analysis. The images were first made in a manual stereomicroscope Leica S8APO model with 75 cm working distance and 80x apochromatic zoom magnification. Samples were analyzed in the cross section which allowed us to compare glue lines between samples and to view the overall densification of the material. Then, the samples were analyzed in cross section and the surface of the cover was offset with a Scanning Electron Microscope (SEM), low vacuum (0.45 torr), using detector backscattered electrons (BSE) and 20 kV voltage from the Brazilian National Institute of Criminology. This analysis enabled us to visualize vessel size and to more accurately detect possible reduction in voids of the densified veneers.

2.4. Statistical Analyses. The properties were analyzed by Dunnett's test at 5% significance level, which compares averages of properties between treatments and control, in pairs. Factorial ANOVA at 5% significance level with two factors (temperature and time) and two levels each (140°C and 180°C, 1 minute and 2 minutes) was applied to identify the effect of

Table 2: Physical properties of plywood made from thermomechanically treated veneers.

	Thickness mm	D g/cm^3	TS2h	TS24h	PTS	WA2h %	WA24h	EMC
Control	8.88	0.61	3.56	6.03	3.50	17.62	52.77	10.46
140°C, 1 min, 2.7 N/mm^2	8.47*	0.65*	4.82	9.66*	6.51*	16.87	50.89	10.75
140°C, 2 min, 2.7 N/mm^2	8.29*	0.64*	6.31*	10.02*	7.52*	20.14*	56.97*	10.55
180°C, 1 min, 2.7 N/mm^2	8.10*	0.66*	7.21*	11.89*	7.97*	19.25	52.49	9.84*
180°C, 2 min, 2.7 N/mm^2	7.96*	0.65*	7.14*	10.86*	6.80*	21.36*	53.16	10.06*

*Significant difference between control and treatment at 0.05 level by Dunnett's test. D: density; TS2h and TS24h: thickness swelling after 2 and 24 hours of water immersion; WA2h and WA24h: water absorption after 2 and 24 hours of water immersion; EMC: equilibrium moisture content.

Table 3: Factor analysis of plywood physical properties.

Source	Property	SS	DF	MS	F	Sig.
Temperature	Thickness	2.82	1	2.81	71.96	0.000*
	D	0.002	1	0.002	2.45	0.121^{NS}
	TS2h	37.00	1	37.00	16.99	0.000*
	WA2h	45.09	1	45.09	8.90	0.004*
	TS24h	33.64	1	33.64	13.37	0.001*
	WA24h	17.71	1	17.71	1.36	0.248^{NS}
	PTS	2.16	1	2.16	1.10	0.299^{NS}
	EMC	6.68	1	6.68	63.26	0.000*
Time	Thickness	0.61	1	0.61	15.51	0.000*
	D	0.001	1	0.001	1.24	0.269^{NS}
	TS2h	2.13	1	2.13	3.27	0.076^{NS}
	WA2h	100.79	1	100.79	19.89	0.000*
	TS24h	1.54	1	1.54	0.61	0.438^{NS}
	WA24h	164.80	1	164.80	12.68	0.001*
	PTS	0.098	1	0.098	0.05	0.824^{NS}
	EMC	0.002	1	0.002	0.02	0.989^{NS}
Temperature × time	Thickness	0.02	1	0.02	0.39	0.532^{NS}
	D	0.00	1	0.00	0.12	0.728^{NS}
	TS2h	8.69	1	8.69	3.99	0.058^{NS}
	WA2h	4.69	1	4.69	0.92	0.341^{NS}
	TS24h	6.96	1	6.96	2.76	0.102^{NS}
	WA24h	105.73	1	105.73	8.14	0.006*
	PTS	17.90	1	17.90	9.12	0.004*
	EMC	0.60	1	0.60	5.67	0.021*

*,NS Significant and nonsignificant, respectively, in factor analysis at 0.05 level. D: density; TS2h and TS24h: thickness swelling after 2 and 24 hours of water immersion; WA2h and WA24h: water absorption after 2 and 24 hours of water immersion; EMC: equilibrium moisture content; PTS: permanent thickness swelling.

increased temperature, time, or interaction between factors on properties. Mechanical properties and density were correlated by Pearson's correlation coefficient (r).

3. Results and Discussion

3.1. Physical and Mechanical Properties. The average thickness of the plywood produced with untreated veneers was 8.88 mm. The boards produced with densified veneers are significantly thinner than the control and these values are decreasing with increasing treatment intensity (temperature or time). Thickness values ranged significantly from 8.47 mm (140°C for 1 minute) to 7.96 mm (180°C for 2 minutes). The difference in thickness between the plywood treated at 180°C for 2 minutes and the control was 10.36% (Table 2). Plywood density increased by 8.2% in the treatment using veneers treated at 180°C for 1 minute (Table 2). The apparent density of treated plywood ranged from 0.64 g/cm^3 to 0.66 g/cm^3. The variation between treatments was not statistically significant; that is, density was not influenced by an increase in temperature or time (Table 3). This result had been previously observed by Arruda and Del Menezzi [6] and shows that the 140°C, 1-minute treatment in veneers was appropriate to reach an increase in density.

Table 4: Mechanical properties of plywood made from thermomechanically treated veneers.

Material	E_M	f_m	$f_{c,0}$	$f_{gv,0}$	f_H
	N/mm^2				N
Control	8604	81.1	40.2	3.35	4054
140°C, 1 min, 2.7 N/mm^2	8704	81.7	42.6	3.88	4882*
140°C, 2 min, 2.7 N/mm^2	9300	86.2	41.5	4.08*	4704*
180°C, 1 min, 2.7 N/mm^2	9036	84.0	42.9*	4.03	4869*
180°C, 2 min, 2.7 N/mm^2	9654*	80.9	43.6*	4.72*	4610*

*Significant difference between control and treatment at 0.05 level by Dunnett's test. E_M: bending modulus of elasticity; f_m: bending strength; $f_{c,0}$: parallel compression strength; $f_{gv,0}$: glue line shear strength; f_H: Janka hardness.

The results of dimensional stability properties of the plywood are also presented in Table 2. Usually, in all wood products submitted to mechanical compression and then immersed into water, there is release of compression stresses which impair the material's dimensional instability. In this context, densified wood products are not stable in comparison with untreated material and the deformation due to the compression can be almost fully recovered when they get in contact with water [15]. This was verified in TS, WA, and PTS test results. In 2 hours, TS values varied between 4.82% and 7.21%, while the untreated material reached 3.56%. In 24 hours, TS values ranged between 9.66% and 11.89% while the control reached 6.03%. The TS tests evinced significant difference between treatment and control, and such effect was significantly higher when compression temperature went up to 180°C. Similarly, PTS values of the treated materials are significantly higher than the control, which showed 3.5% PTS. Since PTS regards that swelling caused by stresses release, this means that treated plywood housed the veneers' stresses leading to higher PTS. The factorial analysis for PTS showed that lower temperature and time lead to lower PTS (Table 3). If temperature rises up to 180°C, there will be a greater effect on increase in PTS compared to a time increase up to two minutes.

Regarding WA in 2 hours, only the two-minute treatments were significantly higher than the control (20.14% and 21.36%, resp., at 140°C and 180°C). In WA in 24 hours, only 140°C, 2-minute treatment was significantly different (56.29%) from the control. The factorial analysis indicated that, for WA in 2 hours, the effect of the rise in temperature or time was significant (Table 3). For WA in 24 hours, the increase in time caused greater effect on WA than the rise in temperature up to 180°C.

In terms of hygroscopicity, the EMC significantly decreased when the 180°C temperature was employed (Table 2). When the 140°C temperature was used, there was no reduction in EMC in relation to the untreated material. The greatest decrease in EMC was by 5.93% verified in the 180°C, 1-minute treatment. When time was increased to 2 minutes, there was a 3.82% decrease in relation to the untreated material, but the difference (1×2 minutes) was not statistically significant. The statistical analysis confirms that only the rise in temperature was enough to cause reduction in EMC, without effects of increase in time (Table 3). Although it might be a controversial result, some authors have found that in fact the utilization of higher temperature is more effective than extending the treatment [16]. It happens because, to reduce the water adsorption and consequently the EMC, the degradation of the wood polymer must occur and it is dependent on the temperature used. The duration of the treatment might be important mainly when long-term processes are used, which is quite different from that employed here.

The reduction in EMC, according to Del Menezzi and Tomaselli [17], has many benefits and indicates that the veneers are more stable when submitted to changes in moisture content since they are less susceptible to water adsorption. The main cause for a reduction in EMC is the loss of hygroscopic polymers such as hemicellulose, which are more sensitive to temperature rise [18, 19]. This polymer degradation can be quantified by mass loss which in the veneers was 0.22% and 0.38% at the 180°C, 1-minute and 180°C, 2-minute treatments, respectively, as previously presented by Arruda and Del Menezzi [6]. Despite such small loss, it may have been sufficient to decrease the hygroscopicity of the material when treated at higher temperature in comparison with plywood made with untreated veneers, as seen in Table 2.

The results of the mechanical properties are presented in Table 4. E_M of the plywood made with untreated veneers was 8604 N/mm^2. Lower E_M values, between 4,548 N/mm^2 and 6,356 N/mm^2, were, however, verified by Iwakiri et al. [20] for similar untreated plywood of *Pinus tecunumanii* and *Pinus oocarpa*. On the other hand, plywood from 11 species of the genus *Eucalyptus* analyzed by Bortoletto Junior [21] showed higher average stiffness of 14,918 N/mm^2. Plywood made with treated veneers showed rise in E_M in relation to the control, but only the most severe treatment showed significant difference. E_M increased by 12.2% in the 180°C, 2-minute treatment and, according to the ANOVA, time was the most important factor for this variable. The employment of a 140°C temperature for veneer treatment did not significantly affect E_M of the plywood.

The mean f_m in the untreated plywood was 81.2 N/mm^2, which is higher than that found by Iwakiri et al. [20] for similar untreated plywood of *P. tecunumanii* and *P. oocarpa*. After the treatment, the Amescla plywood showed certain improvement in strength compared to control. The greatest improvement was 6% verified in the 140°C, 2-minute treatment, followed by 180°C, 1-minute treatment with a 3.4% rise.

Regardless of those improvements, there was no significant difference between plywood of treated veneers and the

Table 5: Factor analysis of the plywood's mechanical properties.

Source	Property	SS	DF	SM	F	Sig.
Temperature	E_M	2483216.18	1	2483216.18	3.45	0.067^{NS}
	f_m	43.90	1	43.90	0.50	0.480^{NS}
	$f_{c,0}$	28.05	1	28.05	2.29	0.134^{NS}
	$f_{gv,0}$	3.27	1	3.27	4.56	0.036*
	f_H	30379.15	1	30379.15	0.07	0.791^{NS}
Time	E_M	7779230.83	1	7779230.83	10.80	0.001*
	f_m	8.00	1	8.00	0.09	0.762^{NS}
	$f_{c,0}$	1.25	1	1.25	0.102	0.750^{NS}
	$f_{gv,0}$	4.11	1	4.11	5.72	0.019*
	f_H	508883.65	1	508883.65	1.19	0.281^{NS}
Temperature × time	E_M	2354.62	1	2354.62	0.003	0.955^{NS}
	f_m	304.33	1	304.33	3.49	0.065^{NS}
	$f_{c,0}$	16.46	1	16.46	1.34	0.250^{NS}
	$f_{gv,0}$	1.30	1	1.30	1.81	0.182^{NS}
	f_H	17591.53	1	17591.53	0.04	0.840^{NS}

^{*,NS}Significant and nonsignificant, respectively, in factor analysis at 0.05 level. E_M: bending modulus of elasticity; f_m: bending strength; $f_{c,0}$: parallel compression strength; $f_{gv,0}$: glue line shear strength; f_H: Janka hardness.

control, nor has the rise in temperature or time significantly affected f_m (Table 5). On the other hand, the thermomechanical treatment of veneers did not lead to a decrease in f_m of the plywood, which could have happened owing to the rate of degradation and mass loss following thermal treatments. The lower strength is mainly attributed to depolymerization reactions which wood polymers undergo, especially hemicelluloses, which are less stable than lignin and more temperature sensitive. According to Hillis [22], changes in the composition or loss of hemicelluloses may significantly contribute to changes in strength properties of wood treated at high temperatures.

Moreover, those authors report that in thermal treatments f_m is more affected than E_M, which was not verified in this work, since f_m did not decrease. This evinced the notion that the employment of thermomechanical treatment of veneers enhanced static bending since the material turned out to be more resistant to elastic deformation without lowering the rupture load. Similar results were found by Chen et al. [23]. The authors observed that bending strength of plywood manufactured using heat-treated veneers was higher than that obtained in untreated material.

Plywood hardness improved with thermomechanical treatment (Table 4). In the control, f_H was 4054 N and went up by 20.4% (4882 N) with the employment of the 140°C, 1-minute treatment. The lowest value was found in the most severe treatment, 4610 N, which was 13.7% higher than the control. The factorial analysis did not show that hardness was influenced by a rise in temperature or time (Table 5). It seems that the mechanical compression of veneers themselves, regardless of the treatment employed, was responsible for an improvement in plywood hardness. The same behavior was observed for $f_{c,0}$. Regardless of the treatment employed, only the mechanical compression was enough to improve the compression resistance of the plywood. Compression strength was 40.2 N/mm^2 in the control samples, which significantly increased in the 180°C temperature treatments, whereas it was 42.9 N/mm^2 in 180°C, 1-minute treatment and 43.6 N/mm^2 in 180°C, 2-minute treatment (Table 3).

Narayanamurti and Kaul [5] verified that the thermomechanical treatment of veneers enabled the increase in $f_{c,0}$ in plywood up to 46.92%. Yet, in thermal treatments without mechanical compression, a drop in $f_{c,0}$ has been reported. For instance, Yildiz et al. [24] verified that $f_{c,0}$ went down by nearly 40% when the thermal treatment reached 200°C during a period of 10 hours. Gündüz et al. [25] correlated a decrease in $f_{c,0}$ and loss in wood density during the thermal treatment and verified that, after 12 hours at 210°C, $f_{c,0}$ decreased by 34.7% due to a 16% loss in density.

At last, the shear strength of the plywood's glue line also increased after the thermomechanical treatment of the veneers. In the control, such variable was 3.35 N/mm^2 and went up by 41% (4.72 N/mm^2) when the most severe treatment was employed. The second-greatest rise was found in the 140°C, 2-minute treatment, where $f_{gv,0}$ went up by 21.8% (4.08 N/mm^2) (Table 4). Considering the factorial analysis, the rise in $f_{gv,0}$ was significantly influenced by an increase in both temperature and time, whereas 140°C for 2 minutes and 180°C for 2 minutes were those which provided the highest values (Table 5).

Arruda and Del Menezzi [6] have also found that an increase in temperature or in time resulted in significant reduction in roughness. According to those authors, the veneers' roughness decreased by 43.4%, which supported the reduction of stresses points between the surface of the veneer and the glue line. Several studies [26–29] have reported that the improvement of roughness may improve gluing quality thus raising $f_{gv,0}$. However, roughness cannot decrease so that the veneer surface becomes inactivated, harming the adhesion between wood and glue [30]. This was verified by

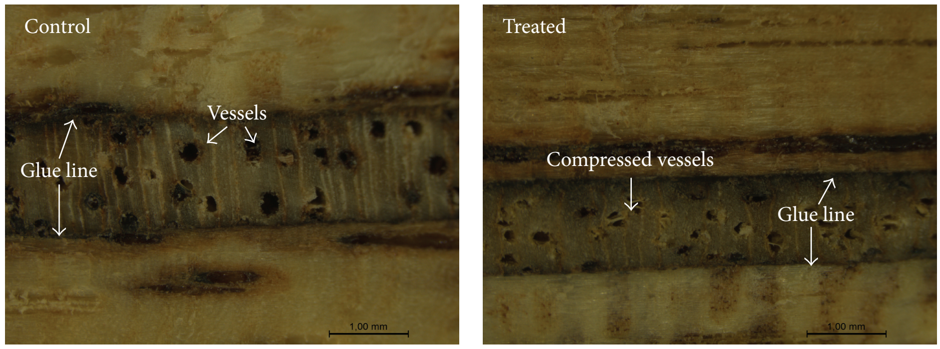

Figure 1: Stereomicroscopy (20x) images for general analysis of plywood densification and glue line. Scale: 1.0 mm.

Bekhta et al. [27] when thermomechanically treated veneers, above 150°C, produced plywood with low $f_{gv,0}$. Those authors employed similar times, between 0.5 and 2 minutes, and tested birch (*Betula pubescens*) veneers. Considering veneers treated at higher temperatures, those authors recommended a reduction in the adhesive spread rate. Nevertheless, here we employed a 180°C temperature without damaging veneer gluing due to particularities of the Amescla veneers, which were very rough before the treatment.

Grzeskiewicz et al. [31], treating beech (*Fagus* sp.) veneers at 160°C, verified that there was no loss in plywood $f_{gv,0}$. However, when temperature went up to 190°C and 220°C, the shear strength dropped to 3.8 N/mm^2 (control value), 2.1 N/mm^2, and 0.6 N/mm^2, respectively. The authors used a 160 g/m^2 glue spread rate to glue the plywood, which should have been lower as the temperature was raised.

Another complementary analysis of the $f_{gv,0}$ data is the visual analysis of gluing quality. All samples presented 100% failure in the wood, except for one sample at 140°C, 2-minute treatment which showed 90% failure in the wood. This is a visual classification, based on Appendix A of EN 314-1 [13] standard, and, despite being subjective, can provide an idea of adhesion between wood veneers. Kurowska et al. [32] have also verified that plywood made with thermomechanically treated veneers of *Pinus sylvestris* showed 100% failure in the wood. Nonetheless, these results were reached employing lower temperature (105°C) and 1.8 N/mm^2 pressure for only 30 seconds and thinner glue line of 120 g/m^2.

Pearson's correlation coefficient was applied to correlate mechanical properties among themselves and with density (Table 6). This coefficient indicates that density correlated significantly with all mechanical properties. The highest correlation was found between density and $f_{c,0}$ (0.624), which was moderate and positive; that is, the increase in density caused $f_{c,0}$ to increase in the same direction. Compression strength was also positively correlated with $f_{gv,0}$, even though the strength of this relation was low (0.261). This means that high resistance in gluing matched higher compression values. Compression strength, hardness, and the static bending variables were also positively correlated with density, indicating that densification was correlated with the increase in those mechanical properties.

Table 6: Pearson correlation (r) for properties versus apparent density.

Property	D	$f_{c,0}$	$f_{gv,0}$	f_m	E_M	f_H
D	1					
$f_{c,0}$	0.624**	1				
$f_{gv,0}$	0.310**	0.261**	1			
f_m	0.395**	0.357**	0.113	1		
E_M	0.232*	0.248**	−0.061	0.392**	1	
f_H	0.314*	0.247	0.271	0.212	0.044	1

*Significant at 0.05 level; $^{**}r$ coefficient significant at 0.01 level. E_M: bending modulus of elasticity; f_m: bending strength; $f_{c,0}$: parallel compression strength; $f_{gv,0}$: glue line shear strength; f_H: Janka hardness.

3.2. Image Analysis. The transversal details of three out of five veneers of the plywood are shown in Figure 1, in 20x magnification in stereomicroscope. The images showed that the control presented more irregular glue line due to roughness of the untreated wood. Also, the vessels were in cylinder shape, which evinces the nondensification of wood elements. The image of treated wood shows a significant improvement in the glue line, which became thinner and more continuous. The treated sample vessels were also visually compressed.

The densification was more evident by analyzing the SEM images (Figure 2). In fact, in the control, the shape of the vessels is more cylindrical than the treated sample. In the latter, it was verified that the vessel walls were compressed but compression did not lead to collapse. This may be positive to preserve the internal structure of the wood, preserving the mechanical properties. In order to quantify the reduction in vessel size, five vessel diameters were measured, randomly selected within control and treatment. The mean vessel diameter was 224.98 μm while in the most severe treatment this average was 88.72 μm. The SEM analysis also found crystals throughout Amescla wood fibers (Figure 2). The chemical composition was confirmed by SEM, which identified in the crystal the presence of silica (Si), oxygen (O_2), and carbon (C). According to Vasconcellos et al. [33], the presence of silica in tropical woods is common and, for Burseraceae family, silica is exclusively found in fibers.

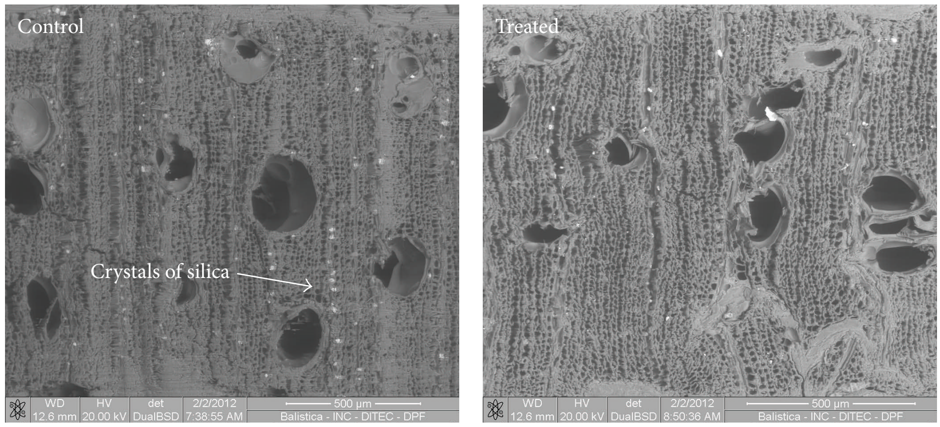

Figure 2: SEM images of the transversal section of the plywood, comparing control and treated samples. Scale: 500 μm; WD 12.6 mm.

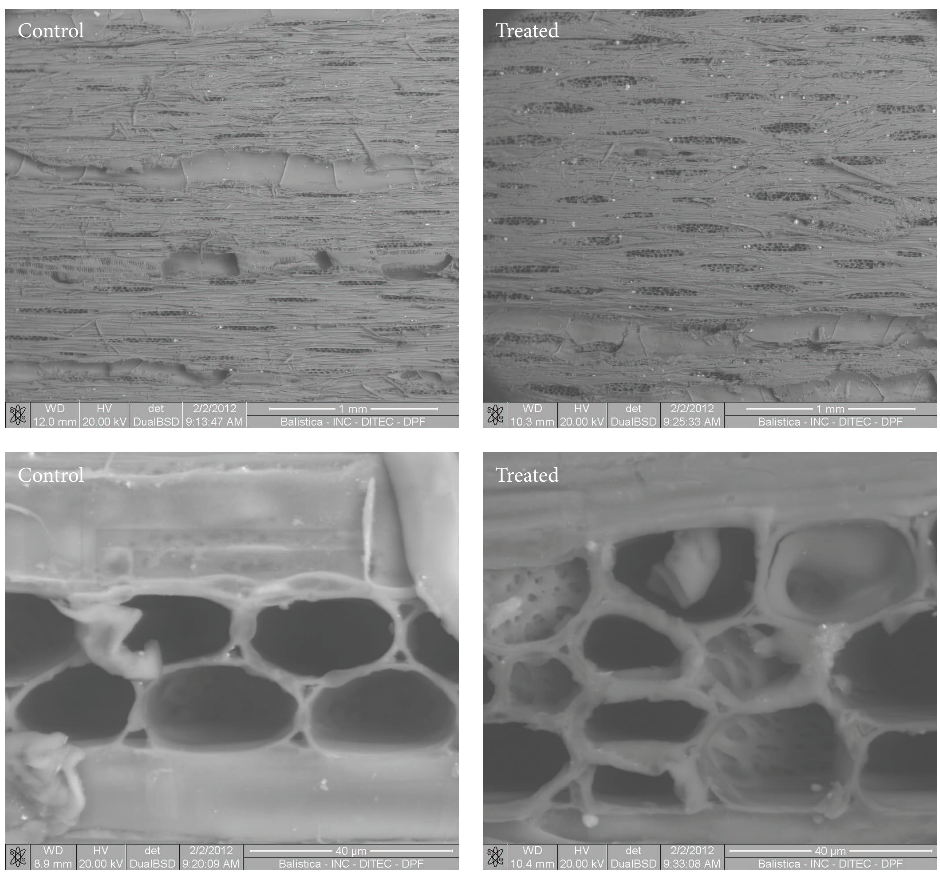

Figure 3: Images of the surface of the samples made by SEM.

Figure 3 shows the plywood surface in images made by SEM. On the surface of the control sample, the wood fibers are more evident, rendering a rough aspect. In the treated sample, radii were visually observed since fibers were flattened, rendering a rough aspect.

The second image (Figure 3) shows the detail of the radii on the surface of the treated sample where it is clearly observed that the edges were flattened due to the mechanical compression. On the treated wood, it was observed that the punctuation is more closed since the vessels were compressed and this was important for the reduction in the porosity of the veneers, reducing the wettability. It is also evident that cell lumen was reduced by the compression; however, fiber cell wall fractures were not identified. Bekhta et al. [15] observed that cell wall lumen was reduced and that cells were deformed and fractured allowing the improvement of the veneer densification. Recently, Bekhta et al. [34] observed significant deformation of vessels and fibers, even in wood veneer subjected to a short-term densification process.

4. Conclusions

The thermomechanical treatment of veneers provided higher density to plywood and lower equilibrium moisture content. As a result of the release of compression tension, thickness swelling and water absorption were higher in plywood made with treated veneers, which caused them to be less dimensionally stable. However, the treatment of veneers improved modulus of elasticity, compression strength, Janka hardness, and glue line shear strength. The image analyses clearly showed that the densification changed the internal structures of the wood, flattening vessels and radii without leading to collapse in cell walls, which was important for maintaining the strength. Dimensional stability properties were most affected by the temperature of the treatment, while mechanical property, represented by the glue line shear strength, was positively affected by temperature and duration of the treatment. Future studies should further investigate any correlation between densification and the reduction in the amount of glue and plywood pressing time. Moreover, economical analyses should bring about insights into the viability of such treatment in the plywood production chain.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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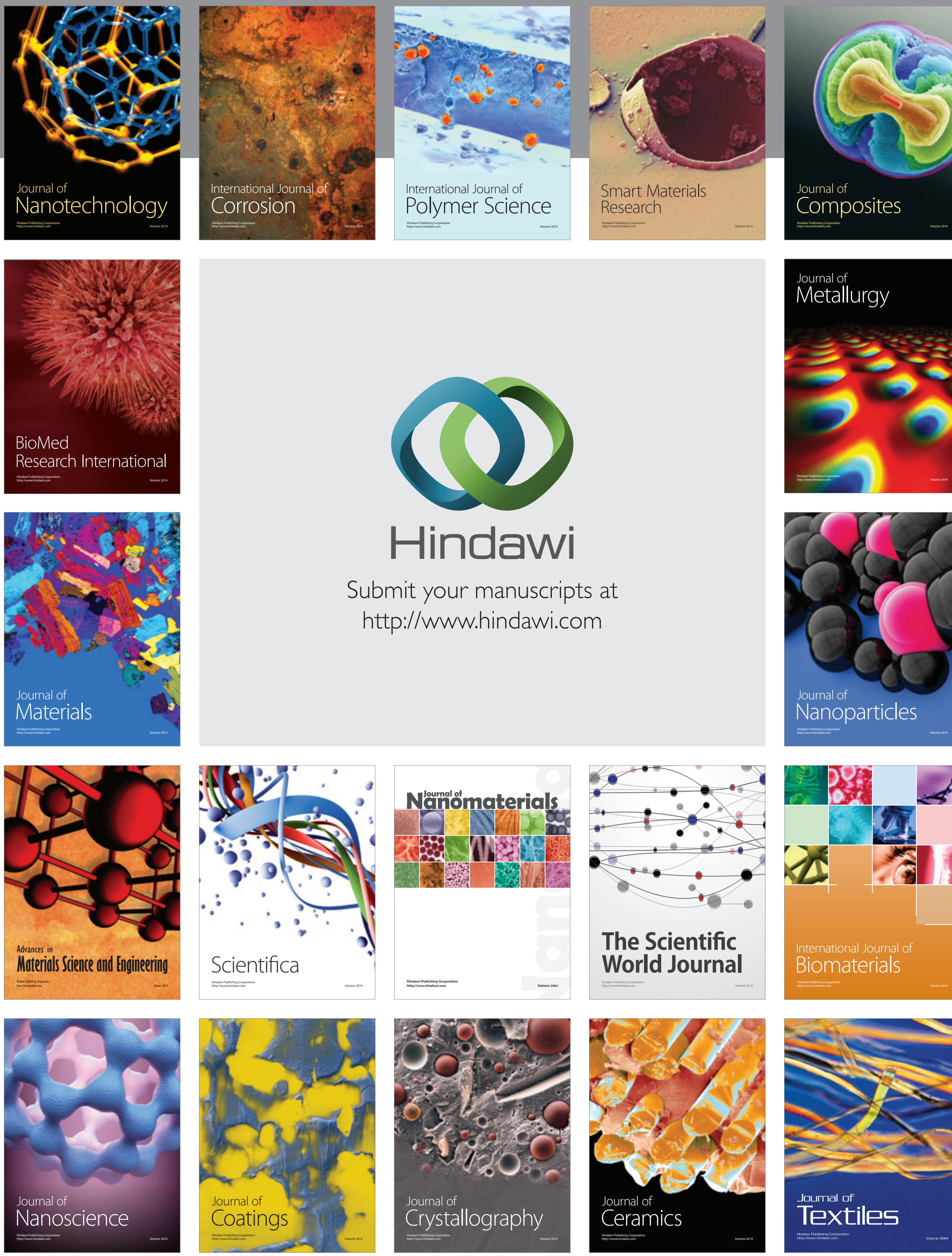
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