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Physical and Mechanical Properties of Plywood Produced with Thermally Treated *Pinus taeda* Veneers

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Abstract: Plywood is a structural composite mainly applied in construction. For this purpose, some sort of preservative treatment is recommended to increase its durability. One option of the available treatments is heat treatment, which promotes the modification of the wood properties. This treatment is carried out on the final product (plywood), because it can reduce strength if applied to the veneers. However, no study has proven such a reduction. Therefore, the aim of this work was to evaluate three different temperatures (160 °C, 180 °C and 200 °C) of the heat treatment on the veneer surface and on the physical properties (specific gravity, moisture content and swelling in thickness) and mechanical properties (MOE and MOR in static bending) of *Pinus taeda* plywood. A reduction was observed in the roughness of the veneer's surfaces and the total extractives content changed, with a minimum value reached in the 160 °C treatment. The plywood specific gravity initially increased with the heat treatment and did not change at higher temperatures, moisture content reduced, and thickness swelling was not affected. There was no change in the mechanical properties of the plywood, evidencing that the veneer heat treatment does not prejudice mechanically the final product.

Keywords: heat treatment; chromated copper arsenate; wood panels; bonding quality; mechanical properties

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1. Introduction

Plywood is a type of structural wooden board composed of veneers arranged orthogonally in an odd number of layers [1]. Its main uses are in the furniture and construction industries [2,3]. The wood and its composites should be submitted to a preservative treatment when applied in construction to increase its durability [4]. Currently, *Pinus taeda* L. wood stands out as a great alternative for this application in Brazil, as it is the second largest forest reserve (1.64 million hectares, with a total of 18% of the national area). Moreover, this wood is fast-growing [5].

The main form of wood treatment in Brazil is chemistry based on chromated copper arsenate (CCA). Another treatment option for wood, more studied in wood composites, is the heat treatment [6]. The heat treatment of wood consists of its controlled degradation by exposure in a high temperature environment [7]. In this way, the volatilization of the extractives and the degradation of the hemicelluloses contained in the wood are promoted, reducing the probability of xylophagous attack [8].

Because of its amorphous and branched structure, hemicelluloses are more susceptible to thermal degradation. Windeisen et al. [9] noted that for the temperature of 200 °C there was a reduction of 1/3 of the xylan content and a 60% reduction of the aliphatic hydroxyl

groups of beechwood. This promoting an increase in wood durability. Guo et al. [10] also noticed the degradation of xylan, glucomannan and lignin during the heat treatment. The cell walls of the fibers, the rays and the spikes of the wood also undergo degradation during the heat treatment, as noted by Awoyemi and Jones too [11].

In this type of treatment, the higher the temperature, the less the subsequent attack of the wood by xylophagous fungi, especially in temperatures close to 200 °C [12,13]. The temperature used for the modification of wood may vary between 180 °C and 260 °C; below 140 °C, the changes occurring are irrelevant and, above 260 °C, the treatment compromises the integrity of the samples [14]. In the literature, Ferreira et al. [2] observed no loss in resistance and stiffness in static bending of heat-treated plywood at 160 °C, 180 °C and 200 °C. Luo et al. [15] verified the improvement of the mechanical properties of the thermally treated plywood with the use of an alternative adhesive.

It is well known that plywood heat treatment brings great improvements (increased rigidity and durability) to the material. Besides, the treatment is only done in the final product (plywood), not being done on the wood veneers used. According to Safin et al. [16], heat treatment of veneers improved water repellent properties without increasing their toxicity. Fang et al. [17] analyzed those higher temperatures increase the densification of the material and reduces its mechanical performance, however, the densification was deliberately applied by mechanical-thermo treatment (compression) of veneers. On the other hand, Ferreira et al. [18] verified that the bonding quality of plywood was reduced by the heat treatment of the veneers. The reduction of the resistance in the glue line can be an indicator of a possible reduction of the mechanical performance in the static bending. Finally, Kamperidou et al. [19] evaluated the mechanical properties of *Pinus sylvestris* L. when subjected to heat treatment. In the end, it can be seen that the mechanical properties of the material increased, but there was a reduction in MOE (modulus of elasticity), MOR (modulus of rupture), impact bending strength and hardness.

As can be seen, heat treatment is done to improve the durability of wood, but it ends up reducing some material properties. However, performing this type of treatment on plywood veneers has not been verified yet. Thus, this paper aims to study whether performing the heat treatment on the veneers reduces or maintains the properties of the final product (plywood). For this, the physical and mechanical properties of the manufactured plywood were tested (produced with *Pinus taeda* veneers). Through statistical methodology (i.e., Tukey's test), it was possible to analyze if there were differences in the plywood properties with (at 160 °C, 180 °C, and 200 °C) or without thermal treatment of the veneers. Through the result obtained, it will be possible to determine a new way of heat treatment, without decreasing the material properties (plywood) and increasing its durability.

2. Materials and Methods

2.1. Materials

We used veneers of *Pinus taeda* (density of 0.45 g/cm^3) with a thickness of 2.3 mm laminated from 20 year old trees from the region of Imbituva—PR in Brazil. The adhesive used was composed of phenol-formaldehyde (specific gravity 1.14; viscosity 123 cps; pH 8.5; free Phenol 8.05%), wheat flour and water in the ratio of 10:1:1, respectively, as recommended by Iwakiri [20].

The wood veneers were cut in the dimensions of 0.45 m × 0.45 m and then were visually classified according to ABNT NBR ISO 2426-3 [21], where the class veneers used in this study were "E", "I", "II" and "III", due to their lower number of natural defects.

2.2. Heat Treatment

The heat treatment took place in a forced-air laboratory oven, where the veneers were stacked on top of each other using wooden separators (Figure 1a), so that heated air could pass on both veneer surfaces.



(**a**) (**b**)

Figure 1. Heat treatment of the veneers. (**a**) Veneers stacking. (**b**) Heat-treated veneers: (i) no treatment, (ii) 160 °C, (iii) 180 °C and (iv) 200 °C.

Four treatments were carried out, the control and three heat treatments with maximum temperatures of 160 °C, 180 °C and 200 °C, respectively. Figure 1b shows the veneers appearance after the heat treatment.

The treatments were divided into four stages, following the methodology of Ferreira et al. [2]: (1) 24 h drying at 80 °C; (2) heating the air inside the oven from 80 °C—drying temperature—to the maximum temperature, with the rate of 2.6 °C.min^{-1}; (3) maintenance of the maximum temperature for a period of one hour; (4) turning off the heating and removing the veneers after 30 min. Then they were placed in an air-conditioned environment with 25 °C and 60% relative moisture content.

2.3. Plywood Production

First, the veneers were dried in the forced-air laboratory oven at 80 ± 2 °C until they reached 3% moisture content for the panels production, to prevent the appearance of water vapor bubbles between them. This moisture content was obtained from the sample weight (knowing the dry weight, it was possible to determine the weight with 3% moisture content).

Each board was produced with seven layers, where the two outermost layers were class "E" and "I" and the three internal layers were class "II" and "III" based on ABNT NBR ISO 2426-3 [21].

The adhesive was prepared with phenol-formaldehyde resin, wheat flour and water, in proportions of 100:10:10, respectively. The weight used was 0.4 kg·m^{-2} and the veneer's dimensions were 0.45 × 0.45 m, so there were 81 g of adhesive per glue line. The adhesive application was performed manually with a silicone spatula on one side of the veneer (Figure 2a), following the methodology of Ferreira et al. [2]. The seven layers were disposed orthogonally to each other (Figure 2b) and cold pressed in a pneumatic press Hidral-Mac (HIDRALMAC Group, Araraquara, Brazil) for 20 min at 9.8 × 10^4 Pa (Figure 2c). Then the hot pressing was made in a heated hydraulic press with a maximum pressure of 5.9 × 10^5 Pa, temperature of 180 °C in three cycles of 180 s with two 30 s pressure reliefs.

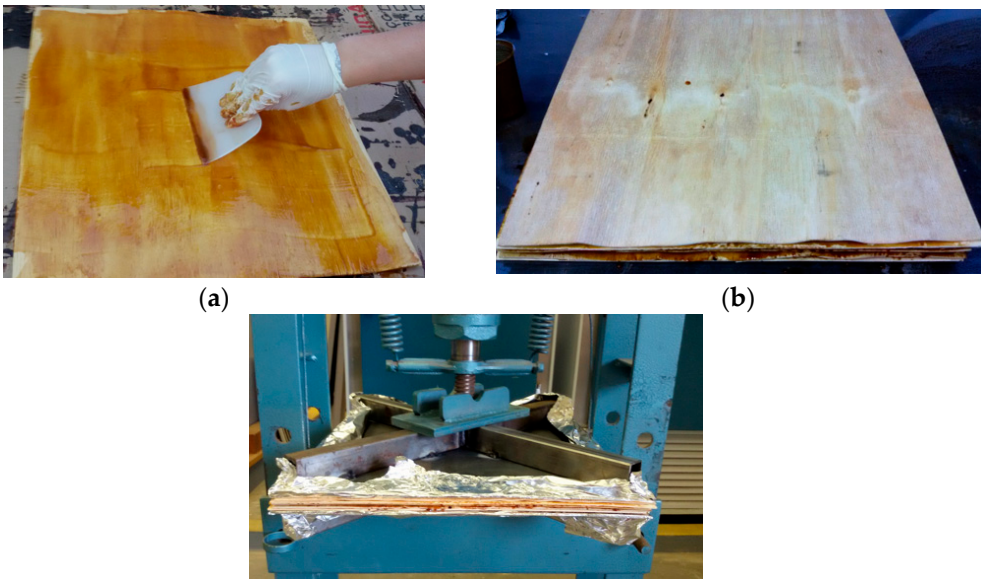


Figure 2. Plywood production. (**a**) Adhesive application, (**b**) seven veneers arrangement and (**c**) cold pressing.

After pressing, the boards were climatized in an air-conditioned environment (25 °C and 60% relative moisture content) for 72 h before being cut into specimens according to the normative specification described below. Four panels were produced for each treatment performed. The entire methodology used in the production of the panel was in accordance with Ferreira et al. [2].

2.4. Plywood Characterization

The veneers were characterized by their extractives content according to TAPPI T204 cm-97 [22], and by their superficial appearance with a Scanning Electron Microscope (SEM) ZEISS, model EVO LS 15.

The plywood was physically characterized according to the Brazilian standards as follows: ABNT NBR 9485 [23] for determination of the specific gravity, ABNT NBR 9484 [24] for determination of moisture content and ABNT NBR 9535 [25] for determination of swelling in thickness. The characterization was performed with ten samples for each test. They were also mechanically characterized for determination of MOE and MOR in static bending in minor and major axis according to ABNT NBR 9533 [26], with four samples for each test.

2.5. Statistical Analysis

An ANOVA was performed using the obtained results through a Tukey test with 5% significance. Additionally, linear regressions were performed correlating the properties in function of the temperatures of the heat treatments. All statistical tests were performed using the R software version 3.4.2 [27].

3. Results and Discussion

The Scanning Electron Microscopy (SEM) images of the veneers for each treatment are shown in the figures below (Figures 3–6).

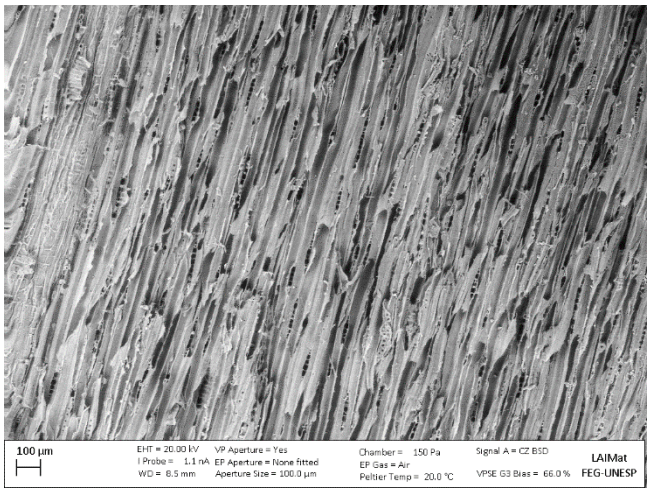


Figure 3. SEM image of veneer surface from control treatment.

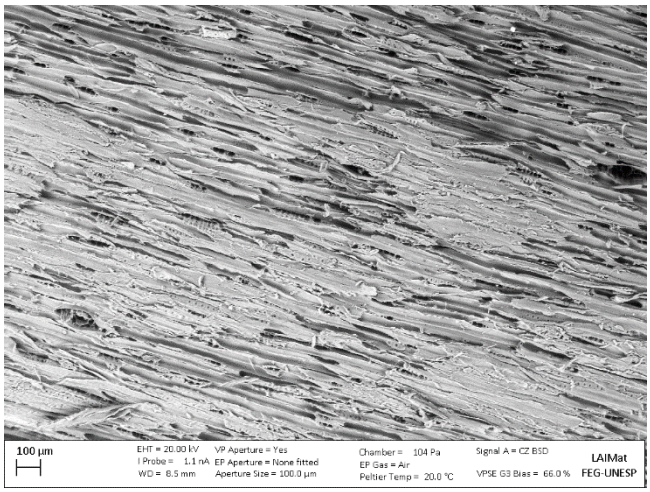


Figure 4. SEM image of veneer surface treated at 160 °C.

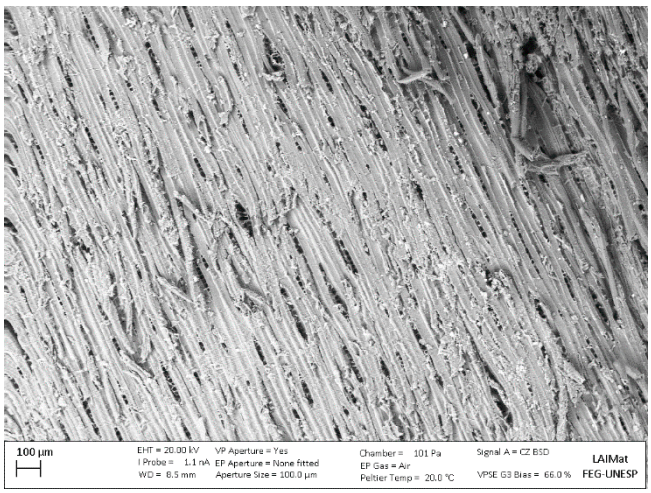


Figure 5. SEM image of veneer surface treated at 180 °C.

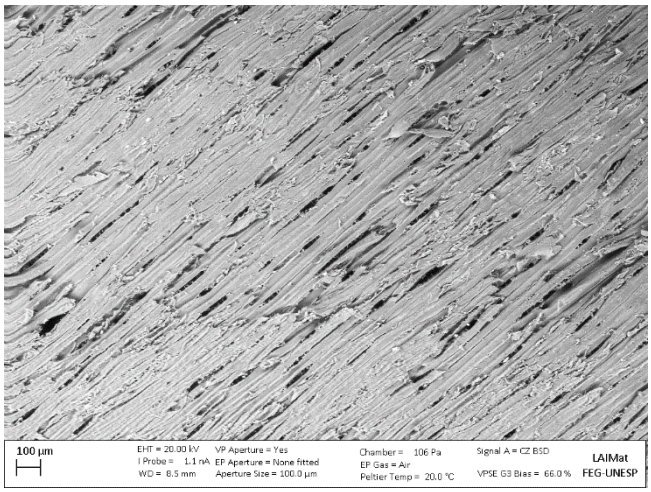


Figure 6. SEM image of veneer surface treated at 200 °C.

The SEM images (Figures 5–8) indicate the surface veneer degradation as the temperature of the heat treatment increased. Kamdem et al. [28] observed similar phenomena in a study of solid wood, as well as Candan et al. [29] that compressed wood veneers at high temperatures.

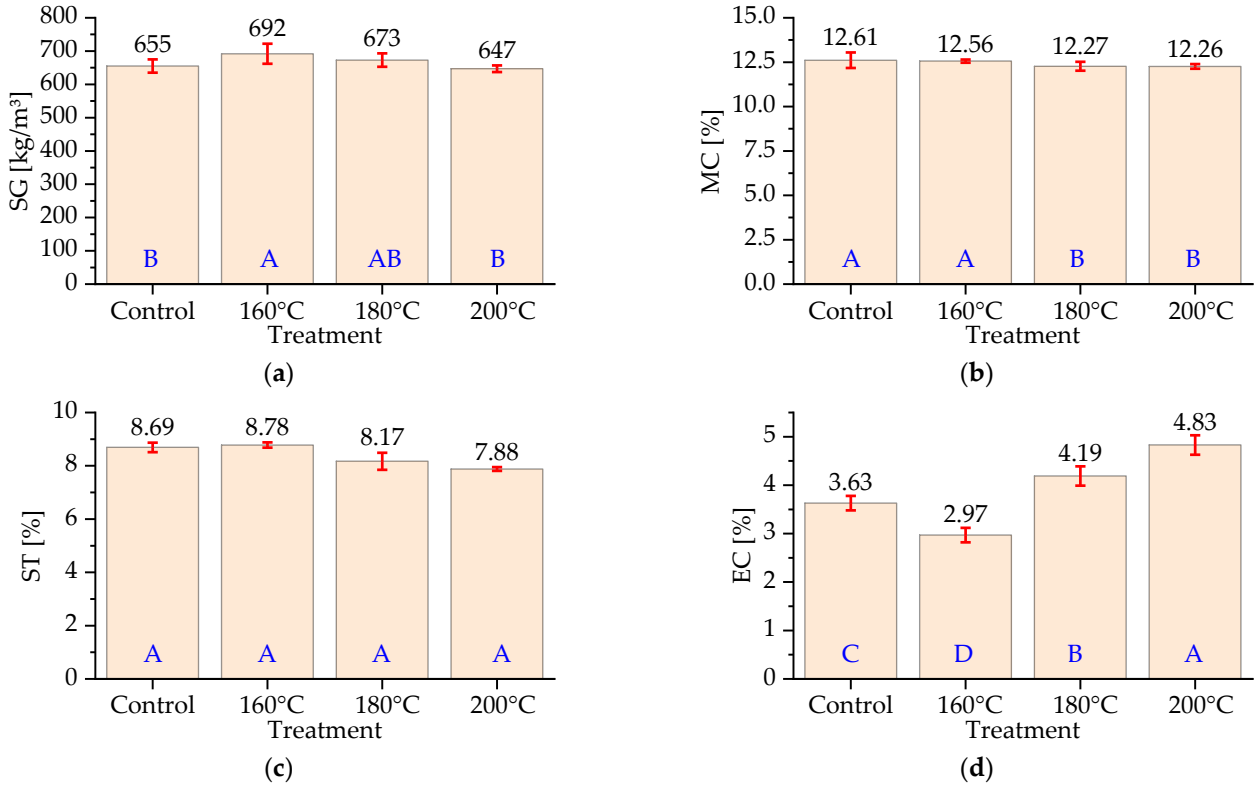


Figure 7. Physical properties of plywood produced with heat treated veneers: specific gravity (**a**), moisture content (**b**), swelling in thickness (**c**) and total extractive content (**d**). Same letters in columns implies that there was no statistical difference with 95% of confidence.

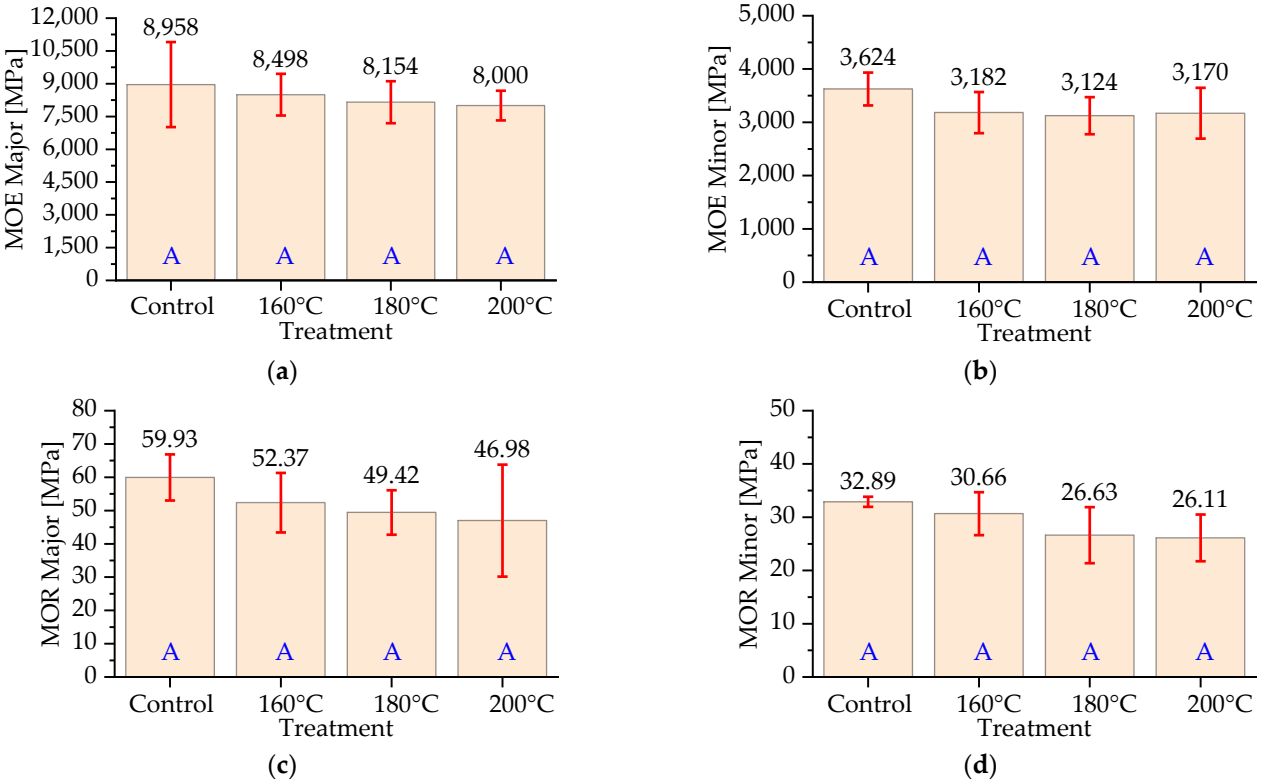


Figure 8. Mechanical properties of plywood produced with heat treated veneers: MOE major (**a**), MOE minor (**b**), MOR major (**c**) and MOR minor (**d**). Same letters in columns implies that there was no statistical difference with 95% of confidence.

The changes in the physical properties of plywood (i.e., specific gravity, moisture content and swelling in thickness) after 72 h stocked in air chamber and in total extractive content of the veneers are shown in Figure 7. It is worth noting that if a sample has two letters of the Tukey test, it means that it would be in the transition between the correlated values.

The control treatment showed total extractives content values intermediate to other treatments. Yildiz et al. [30] described that each chemical constituent of wood suffer degradation during wood heating, thus altering its relative values. The increase in extractive content at 200 °C was also observed by Poubel et al. [31] in *Pinus caribaea* wood.

Mendes et al. [32] and Ferreira et al. [2] verified the reduction of the equilibrium moisture content with the increase of the heat treatment temperature of the wood boards, as observed in this study.

The swelling in thickness did not change in any of the treatments performed; although Weiland and Guyonnet [33] and Poubel et al. [31] stated that the heat treatment improves the dimensional stability of wood and therefore reduces swelling values. Thus, it can be concluded that performing the heat treatment on the veneers is better than treating the final product.

The specific gravity of plywood reduced with the increase of the temperature of the heat treatment; however, the control treatment obtained intermediate results, not allowing the observation of some tendency. It was expected that there would be a significant reduction in relation to the control treatment, as reported by Brito et al. [34] and Poubel et al. [31].

The results of the static bending tests in the major axis and in the minor axis of the board are shown in Figure 8.

Kačíková et al. [35] stated that heat treatments above 160 °C significantly reduce the MOE and MOR values of wood. Mendes et al. [36] also verified this situation for structural

boards of wood chips. However, this paper obtained no reduction in this property in the temperature ranges evaluated, proving its effectiveness.

Simple regression analysis results are shown in Table 1, where the functions, the adjusted correlation coefficient and the *p*-value are presented for each of the properties characterized. The linear modeling, which correlates heat treatment temperature with property, with best adjustment was the total extractive content. The other models obtained low coefficient of correlation, especially those of MOE and MOR of the boards.

Table 1. Simple linear regression correlating plywood properties with heat treatment temperature.

Property	Functions	Adjusted R^2	*p*-Value
Specific gravity	$SG = 873 - 1.1 \times T$	0.4460	<5%
Moisture content	$MC = 13.74 - 0.01 \times T$	0.3120	<5%
Thickness swelling	$ST = 12.36 - 0.02 \times T$	0.6157	<5%
Extractive content	$EC = -4.37 + 0.05 \times T$	0.9625	<5%
MOE (major axis)	$MOE_{major} = 10{,}459 - 12 \times T$	−0.0265	>5%
MOE (minor axis)	$MOE_{minor} = 3216 - 0.32 \times T$	−0.0998	>5%
MOR (major axis)	$MOR_{major} = 73.87 - 0.13 \times T$	−0.0499	>5%
MOR (minor axis)	$MOR_{minor} = 48.24 - 0.11 \times T$	0.0895	>5%

Note: "*SG*" is the specific gravity, "*MC*" is the moisture content, "*ST*" is the swelling in thickness, "*EC*" the extractive content, "*MOE*" the modulus of elasticity, "*MOR*" the modulus of rupture and "*T*" is the heat treatment temperature in Celsius.

4. Conclusions

Our research shows that doing the heat treatment on the veneers was extremely positive, mainly because it did not reduce the mechanical properties of the material. Furthermore, it can be concluded that:

i. The veneer heat treatment modified the specific gravity of plywood, reduced the equilibrium moisture content and did not affect swelling values.
ii. There was change in the total extractive content in relation to the control treatment, where the minimum value was reached at the temperature of 160 °C.
iii. The increase of heat treatment temperature caused a reduction of the roughness in the surfaces of the *Pinus taeda* veneers. However, no direct interference was observed in the studied properties.
iv. The MOE and MOR values in both axis of the boards produced with heat treated wood did not present statistical difference with control treatment; also, mechanical properties of all treatments met the requirements for structural use specified by ABIMCI [37].

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