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Improvement of the properties of hardboard with heat treatment application

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ABSTRACT

The attempt to face the limitations of wood-based materials, especially concerning the relationship with water, is still a considerable gap in research on this subject. The present work proposes the accomplishment of thermal treatment in fiberboard-type hardboard, using different temperatures and times, to evaluate the effect on the physical-mechanical properties. The parameters of the heat treatment were temperatures of 120 and 160 °C and times of 20 and 40 min. The hardboards were individually heat treated in a kiln. The characterization was performed from physical tests such as bulk density, moisture content, water absorption (2 and 24 h), thickness swelling (2 and 24 h); and mechanical properties of flexural strength. The treatment with a temperature of 160 °C for 40 min showed the lowest values of water absorption in 24 h (34%). Thickness swelling was lower compared to control, for all the treatments applied. Regarding flexural strength, the treatment that adopted the 160 °C for 20 min showed the highest MOR value (26.3 MPa). In general, the performance of heat treatments positively influenced the physical and mechanical properties of the hardboards, being an interesting alternative in the development of products for applications in internal environments.

Keywords: Fiberboards; Material characterization; Durability; Wood performance.

1. INTRODUCTION

The demand for materials made from wood has been increasing rapidly to meet society's needs in the development of technologies [1]. These materials are widely used in the production of furniture and laminate floors, as they have good strength and rigidity properties, in addition to being an easy-to-process material [2]. According to MAGALHÃES *et al.* [3], fiberboard can also be used in civil construction as an ecological alternative to replacing solid wood due to the good combination of thermal and mechanical properties and a competitive price.

The fiberboards contain unique and advantageous properties compared to solid wood products, as they have better dimensional stability, good machinability, and resistance to temperature changes, besides being versatile and without cracks [4]. On the other hand, as a material from wood, it presents dimensional changes when subjected to environments with variations in humidity [5]. Dimensional instability is a response to both loss and water absorption, one of the main disadvantages that limit wood for use as a construction material [6]. According to MELO *et al.* [7], both water loss and absorption are a phenomenon performed by wood and its components to maintain balance with the environment. These factors are directly linked to its porous structure and capillarity.

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The improvement of physical-mechanical properties, and consequently the quality and durability of wood panels for applications in dry and humid environments, has motivated the development of research aiming at improving the properties of materials from the performance of heat treatments. Heat treatment is considered one of the most ecological and economically viable methods for improving durability properties, resistance to deterioration by fungi, resistance to degradation by ultraviolet radiation (UV), reduction of hygroscopicity, better dimensional stability, and resistance to surface hardness in wood materials [8].

The heat treatment provides a modification in the wood characteristics, resulting in an improvement of resistance to deterioration and dimensional stability [9]. The development of research in the performance of heat treatments in oriental beech wood (*Fagus orientalis*) and oriental fir (*Picea orientalis*) at a temperature of 190 °C, and wild pine (*Pinus sylvestris*) at a temperature of 212 °C, showed the degradation of hemicelluloses and consequently the decrease of free hydroxyl groups responsible for the high moisture absorption of wood [10]. VAN NGUYEN *et al.* [11] report that research performing heat treatments with larch (*Larix gmelinii*) and poplar (*Populus alba*) showed an increase in hardness in the cross and longitudinal sections of these woods when subjected to treatments at temperatures of 170 and 180 °C. Similarly, ALI *et al.* [12] performed heat treatment on hardboards made with kenaf, at temperatures of 200 °C for 90 min and 225 °C for 30 min, both under conditions of 85% humidity, providing a significant reduction of 25 to 30% in thickness swelling. The heat promoted the degradation of hemicelluloses, improvements in dimensional properties, and residual stress relief.

The literature presented above shows the effect of heat to minimize the negative effects caused by moisture on the physical-mechanical properties of wood and its derivatives. Nevertheless, treatments concerning the improvements of hardboard properties are still lacking in the scientific field, since they are industrial products and little studied in laboratories. The development of this research will bring important contributions to the furniture and related industries, as it will present the best parameters of temperature and time for the application of an efficient treatment, as well as the diffusion of this improved material to the market with suitable quality and able of withstanding different types of environments. In this context, the present work aimed to perform heat treatment of these boards using different temperatures and times.

2. MATERIAL AND METHODS

2.1. Getting the panels, heat treatment, and making the samples

The commercial hardboards were obtained from a regional company in dimensions of 400 × 400 × 4 mm (width × length × thickness), manufactured from wood retained from clones of eucalyptus spp. and urea-formaldehyde adhesive. They were randomly selected into five groups to perform the different heat treatments. Subsequently, each group was added individually to an oven with forced air circulation. The treatments were carried out at temperatures of 120 and 160 °C (±2 °C) for 20 and 40 min (Table 1). To evaluate the performance and effectiveness of the heat treatment on the material, control samples were produced from a hardboard without treatment.

The physical tests: bulk density, moisture content, water absorption, thickness swelling, and non-return rate in thickness, were carried out following the dimensional parameters of 40 × 40 × 4 mm established by the Brazilian Standard NBR 14810-2 [13] (Figure 1A). To ensure better use of the panels purchased and a greater number of samples for carrying out the physical tests. An adaptation of the standard was carried out, reducing the dimensions of the samples to 40 mm × 40 mm (length × width). For the mechanical test of flexural strength in three points, the samples followed the dimensional parameters of 300 × 40 × 4 mm (length × width × thickness) with a useful length of 96 mm (equivalent to 24 times the thickness of the specimen) established by the American Standard ASTM D1037-12 [14] (Figure 1B). As the commercial panels obtained had a thickness dimension of 4 mm, an adaptation of the norms for the manufacture of three-point bending samples was carried out.

Table 1: Parameters of the treatments performed for the hardboards.

TRATAMENTS	TIME (MIN)	TEMPERATURE (°C)
Control	0	25
20–120	20	120
40–120	40	120
20–160	20	160
40–160	40	160

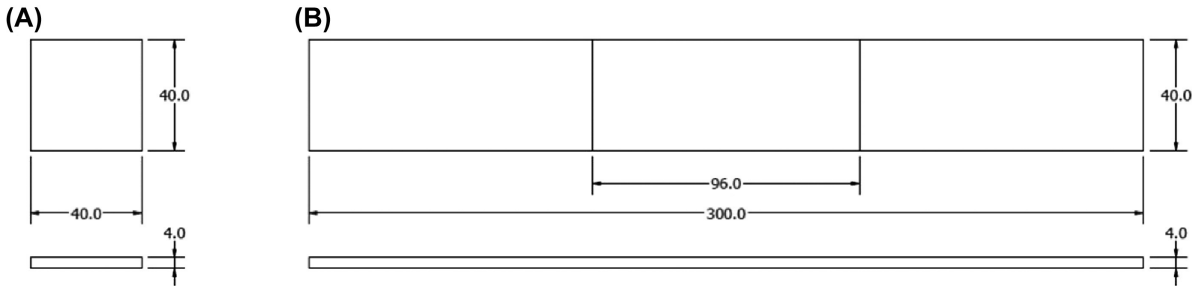

Figure 1: Samples for physical and mechanical tests (dimensions in mm); (A) physical tests: bulk density, moisture content, water absorption, thickness swelling, and non-return rate in thickness; (B) flexural strength (three points).

2.2. Characterization of the boards

2.2.1. Bulk density, moisture content, water absorption, and thickness swelling

The bulk density was determined following the Brazilian Standard NBR 14810-2 [13], with eight repetitions for each treatment. The boards were dried in an oven with forced air circulation, where they remained for 24 h at a temperature of 105 ± 2 °C. The samples were weighed using an analytical balance (±0.01 g). The length, width, and thickness dimensions were measured using a digital caliper (0.01 mm). Data were collected and subsidized the results for bulk density from the division of the mass by the volume of the samples.

The moisture content was performed following the Brazilian Standard NBR 14810-2 [13] standard, with eight repetitions for each treatment. Initially, the samples were weighed on an analytical balance to obtain the wet mass. Then they were dried in an oven with forced air circulation, where they remained for 24 h at a temperature of 105 ± 2 °C. Subsequently, the samples were weighed to obtain the dry mass. Before both tests, the samples were kept in an air-conditioned room at 21 ± 2 °C and 65 ± 2% of relative humidity for 10 days.

Water absorption and thickness swelling were performed following the parameters established by Brazilian Standard NBR 14810-2 [13], with eight replications for each treatment. The samples were placed in a drying and sterilization oven with forced air circulation for 24 h at a temperature of 105 ± 2 °C for drying and then placed in a desiccator for 30 min to reach room temperature. Subsequently, the samples were weighed with an analytical balance, and the dry mass values were collected. The initial measurements were made using a digital caliper for the thickness of the samples, being posteriorly immersed in a rectangular polypropylene com dimensões de 430 × 295 × 70 mm (length × width × thickness) tray with distilled water at 30 ± 2 °C.

After 2 h of immersion, the excess water was removed using absorbent paper towels, obtaining the wet mass and the thickness of the hardboards. Then the samples were again placed in the water, and the procedure was repeated after 24 h of immersion. To obtain the non-return rate in thickness, the samples were placed in trays and left at room temperature for 8 days and their thickness was measured. Data were collected and subsidized the results for water absorption, thickness swelling, and non-return rate in thickness from the equations provided by the Brazilian Standard [13].

2.2.2. Flexural strength in three points

American Standard ASTM D1037-12 [14] established the test parameters for the mechanical evaluation, with five repetitions for each treatment in an ADL-10000 universal testing machine (EMIC) with a 100 kN load cell. Initially, the specimen was positioned individually with a horizontal orientation at a distance of 24 times the thickness (4 mm). A speed of 6 mm.min^{-1} was established for the test. The test started with a load application knife with a radius of 3.5 mm, lightly touching the material, and finished after the fracture (Figure 2).

The data provided by the universal machine were organized in software and supported the results of the maximum tensile strength (MOR) and modulus of elasticity (MOE), based on Equations (1) and (2) provided by the American Standard ASTM D1037- 12 [14].

$$Rb = \frac{3\,Pmáx \cdot L}{2 \cdot b \cdot d^2} \tag{1}$$

$$E = \frac{m \cdot L^3}{4 \cdot b \cdot d^3} \tag{2}$$

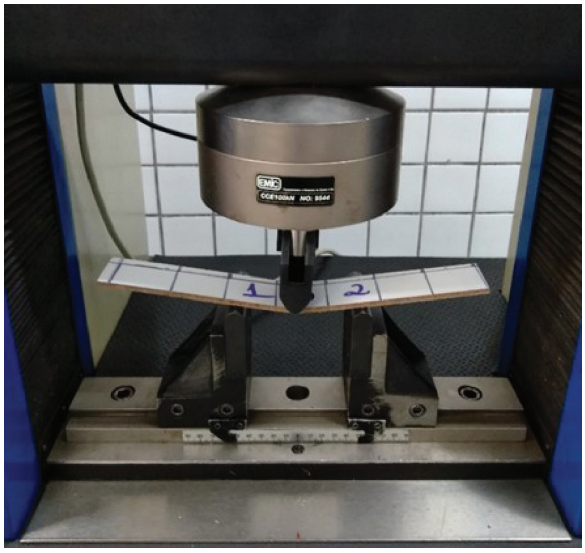

Figure 2: Flexural strength test in three points.

Where: Rb = module of rupture (MPa); Pmax = maximum load (N); L = span length (mm); b = width of the specimen measured in the dry state; d = sample thickness measured in the dry state; E = modulus of elasticity (MPa); m = slope of the force × deflection curve.

2.3. Experimental design

The information obtained by the physical and mechanical tests was analyzed following a completely randomized design. Subsequently, the Shapiro-Wilk test was performed to verify normality and the Levene test to verify the homogeneity of variance. Thereafter, there was an analysis of variance (ANOVA) was performed and, in case of statistical differences, the Tukey test was performed at 95% of significance (p-value < 0.05) (Sisvar software) for comparison of the averages.

3. RESULTS

3.1. Bulk density and moisture content

The results obtained from the bulk density determination showed that the heat treatment did not significantly influence this property (Figure 3). The low influence of the heat treatment in reducing the density of the samples may be due to the treatment time and the low mass loss at the temperatures used in the process.

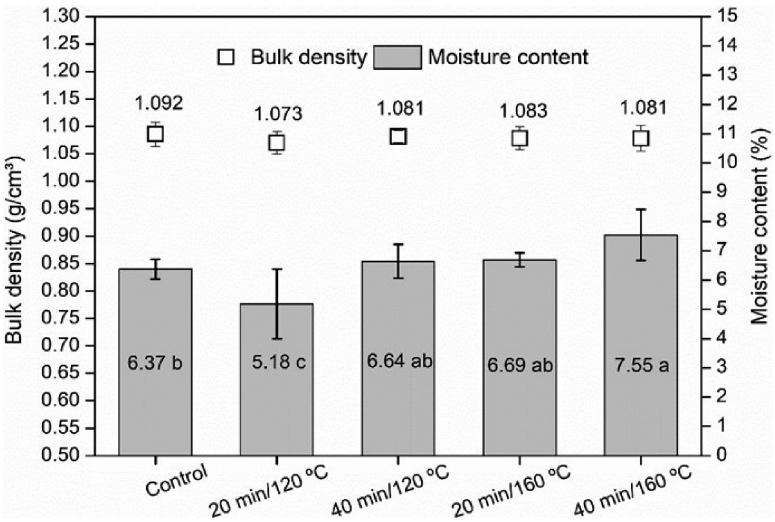

Figure 3: Bulk density and moisture content of the treatments evaluated; averages followed by the same uppercase or lowercase letter do not differ (Tukey test, p > 0.05).

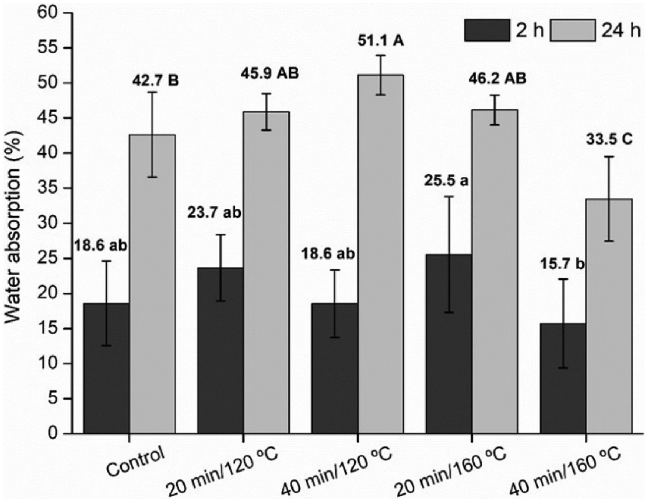

Figure 4: Water absorption after 2 and 24 h of immersion; averages followed by the same uppercase or lowercase letter do not differ (Tukey test, $p > 0.05$).

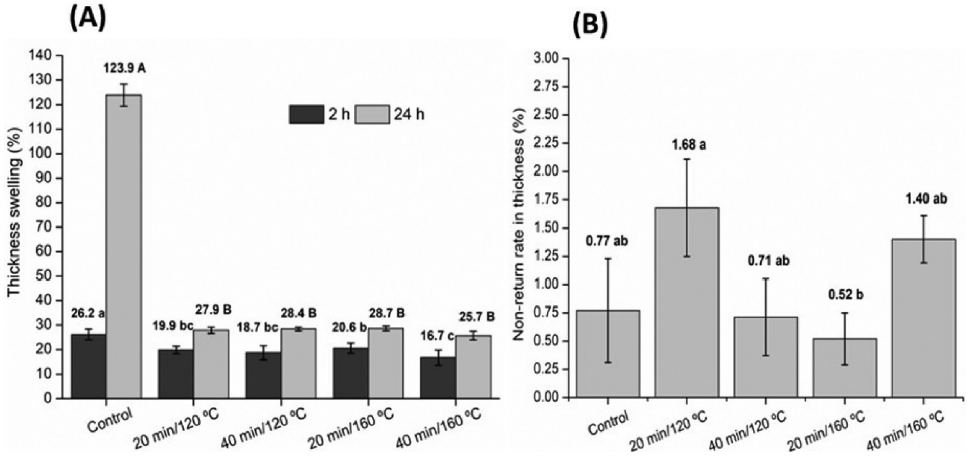

Figure 5: (A) Thickness swelling at 2 and 24 h; and (B) non-return rate in thickness; averages followed by the same uppercase or lowercase letter do not differ Water absorption after 2 and 24 h of immersion; averages followed by the same uppercase or lowercase letter do not differ (Tukey test, $p > 0.05$).

For moisture content, the treatment of 40 min/160 °C presented the highest value, 7.55%. The lowest value was 5.18%, indicated by the treatment of 20 min/120 °C. It was found that the heat treatment carried out at 120 °C/20 min showed greater efficiency in reducing the ability of the panels to absorb moisture.

3.2. Water absorption and thickness swelling

The results for water absorption showed that after 2 h of immersion, the treatment of 20 min/160 °C presented the highest absorption value (25.5%). The lowest absorption value was 15.7%, presented by the treatment of 40 min/160 °C (Figure 4). Regarding the water absorption after 24 h, the highest value was 51.1%, presented by the treatment of 40 min/120 °C, and the lowest value was 33.5%, indicated by the treatment of 40 min/160 °C (Figure 4). The application of heat treatment of 40 min/160 °C provided greater efficiency in reducing the water absorption of the boards, showing that the application of temperature directly reduces the hygroscopicity of wood materials.

After 2 h of immersion, the control treatment showed the highest value for thickness swelling (26.2%). The lowest value was 16.7%, indicated by the treatment of 40 min/160 °C, which was the most efficient (Figure 5A). After 24 h of immersion, the highest value was 123.9% presented by the control, and the lowest was 25.7% indicated by the treatment of 40 min/160 °C, not differing statistically from the values shown by the treatments 20 min/120 °C, 40 min/120 °C, and 20 min/160 °C. All the thermally treated materials showed promising results when compared to the control. Therefore, the thickness swelling results show that the increase in temperature and time positively influence the dimensional stability of the hardboards. Evaluating the results presented for the non-return rate in thickness, the highest value found for the treatment of 20 min/120 °C was (1.68%). The lowest value was 0.52%, indicated by the treatment of 20 min/160 °C (Figure 5B).

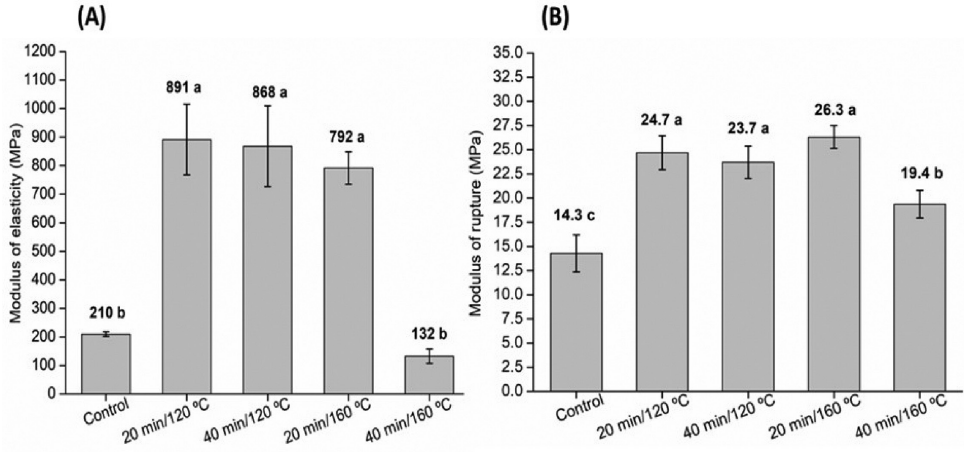

Figure 6: (A) Modulus of elasticity (MOE); and (B) modulus of rupture of the hardboards subjected to flexural strength (Tukey test, $p > 0.05$).

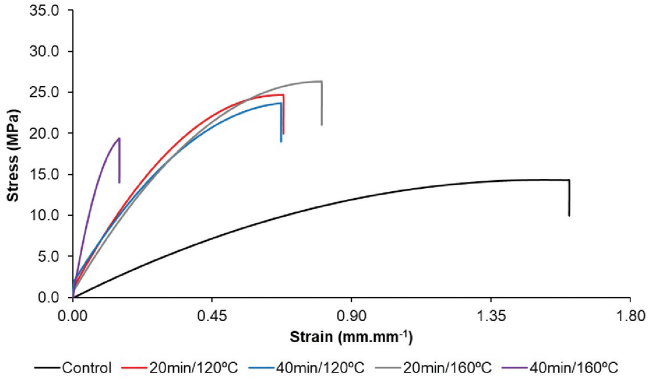

Figure 7: Stress × strain curves for the bending test of the different evaluated treatments.

3.3. Flexural strength in three points

The flexural strength test showed that the treatment of 20 min/160 °C presented the highest value for modulus of rupture (MOR), 26.3 MPa. However, this treatment did not differ statistically from the values shown by the specimens treated at 120 °C for 20 and 40 min. The control treatment obtained the lowest value, 14.3 MPa (Figure 6). From the results obtained, it was observed that the treatment of 20 min/160 °C provided greater strength to the hardboards. On the other hand, the increase in the treatment time to 40 min promoted a significant decrease in flexural strength. From the analysis of the stress × strain curves, it is verified that the treatments at 20 min/120 °C, 40 min/120 °C, and 20 min/160 °C showed significantly higher flexural strength when compared to the control, showing the heat treatment efficiency (Figure 7).

For the modulus of elasticity (MOE), the highest value was indicated by the treatment of 20 min/120 °C (891 MPa). However, this value did not differ statistically from the results shown by the treatments at 40 min/120 °C and 20 min/160 °C. The lowest value was 132 MPa, indicated by the heat treatment performed at 160 °C for 40 min, which was not statistically different from the control (Figure 6B). The heat treatment carried out at 20 min/120 °C provided greater rigidity to the panels. However, when the heat treatment was carried out at 40 min/160 °C, the MOE value showed a significant decrease in the rigidity of the boards. Given this, it was possible to verify that the increase in the treatment time performed at 160 °C, negatively leads to a reduction in the stiffness of the samples.

4. DISCUSSION

4.1. Bulk density and moisture content

The bulk density values of the heat-treated samples did not show a significant difference compared to the control. CHAOUCH *et al.* [15] performed heat treatments on beech, poplar, ash wood, pine, and spruce species and found that at temperatures up to 160 °C, there was a slight mass loss, which corresponds only to the vaporiza-

tion of volatile extractives and water absorbed by the wood structure. TODARO *et al.* [16] showed that during wood heating, chemical changes occur directly depending on the time and temperature used. When carried out at temperatures up to 150 °C, causes the loss of free water, followed by the water bound to the cell wall.

Mass loss is a factor that depends on the density and nature of the wood species, with lower-density species showing better stability in thermodegradation compared to higher-density species. These characteristics are associated with the thermal properties of each wood [15]. KUBOVSKÝ *et al.* [17] state that the chemical changes in the wood resulting from heat treatment are influenced by external conditions such as temperature, heating time, and the type and composition of the atmosphere during the treatment. During the heat treatment, a series of reactions occur simultaneously, that significantly influence the process, being one of the factors responsible for the different results found by other researchers when studying the heat treatment of wood.

The results showed that the heat treatment provides efficiency in the reduction of moisture. This was assumed to be due to the removal of hemicellulose, the depolymerization of hydrocarbons and lignin, or the increase in the degree of crystallinity of the amorphous cellulose [18]. While conducting research with Indian teak boards, BUDHE *et al.* [19] found that the heat treatment decreased the wood surface wettability. In research with *Pinus caribaea*, SANTOS and SILVA [20] observed that the process of thermal modification influenced the wood's physical properties, promoting a reduction in the equilibrium moisture, a lower hygroscopicity, and greater dimensional stability, in addition to evidencing the notoriety of the material subjected to a higher temperature. Wood constituent elements such as cellulose, hemicellulose, and lignin, during heat treatment, decompose at different temperatures and consequently have their chemical properties modified and their tendency to reduce water absorption with increasing the treatment temperature [21]. According to ESTEVES *et al.* [22], performing heat treatments with high temperatures and long periods can cause an increase in the dimensional stability of wood.

Comparing the results of moisture content obtained in this work with the maximum limits established by NBR 15316-2 [23], it is verified that all treatments studied achieved the criteria of the standard, as they present values below the limit maximum of 11% established. Woods modified from heat treatment may present properties that qualify them for applications in above-ground situations with exposure to weathering [24]. Another critical factor is that heat treatment, besides being efficient, does not require the use of chemical products, being an ecological alternative in replacing traditional chemical treatments [25].

4.2. Water absorption and thickness swelling

Water appears in wood in two fundamental states, which can be bound or free. In the first case, they can be dissolved or absorbed within hygroscopic cell walls and associated with hydrogen bonds. Regarding the free water, they occupy the lumen and cell cavities where they are subject to capillary forces [26]. The moisture present in wood is a factor that affects its durability, stability, and physical properties. The results presented by the heat-treated samples show the thermal process efficiency in reducing the wood hygroscopicity property, considering that the samples showed a reduction in water absorption during 2 and 24 h of immersion. According to SANDBERG *et al.* [27], the performance of heat treatment on wood significantly influences the properties of hygroscopicity, dimensional stability, resistance against fungi and insects, mechanical properties, besides properties such as color, odor, collapsibility, and coating performance.

The decrease in water absorption and thickness swelling in heat-treated wood is a phenomenon resulting from the thermal degradation of hemicelluloses, which show a considerable number of hydroxyl groups (OH) responsible for the wood hygroscopicity [28]. Confirming this explanation, PRIADI *et al.* [29] cited that the reduction in water absorption after heat treatment may come from the reduction of amorphous regions in the wood cell walls. The degradation of elements such as hemicelluloses, the amorphous parts present in cellulose, and the lignin condensation reactions promote the reduction of available hydroxyls, consequently decreasing hygroscopicity and increasing the wood's dimensional stability [25]. According to ZHANG *et al.* [30], heat treatment promotes an improvement of surface hygroscopicity, thus decreasing the water absorption by the wood. This information corroborates the studies by ÖZKAN *et al*. [31] who performed heat treatment on Turkish fir wood (*Abies nordmanniana*) at a temperature of 200 °C for 6 hours in an N2 atmosphere, and found a reduction in water absorption from 54.66 to 18.05%. Already performing a thermal treatment on Jackpine wood (*Pinus banksiana*) at temperatures of 165 and 190 °C for a period of 1 hour, HUANG *et al.* [32] found a reduction of 7.90 and 19.13%, when compared to the control sample.

The results for swelling in thickness after 24 h obtained in this work and compared with the maximum limits established by NBR 15316-2 [23], indicated that all heat-treated hardboards reached the criteria of standards, as they present values below the maximum limit of 40% established. The increase in the dimensional stability after the heat treatment results from the decrease in hygroscopicity caused by the chemical change of

wood subjected to high temperatures. These chemical changes promote greater reactivity of lignin that generates cross-links, responsible for the increased dimensional stability [33].

Excessive swelling in fiberboard is a factor that not impairs the aesthetic appearance but also sharply weakens the board quality, which requires improved dimensional stability for applications with different humidity conditions [34]. The performance of heat treatment is an interesting alternative to improve the properties of these boards, as it provides enhanced dimensional stability. This factor allows their application in environments with considerable humidity, such as bathrooms and kitchens [35].

The values of the non-return rate in thickness showed that both the temperatures and times were factors that influenced the property since the combination of the highest temperature and time presented the lowest rate. According to MENDES *et al.* [36], this characteristic of wood is directly linked to the property of thickness swelling, and the variation presented is a factor resulting from the relief of compressive stresses, which becomes partially unrecoverable. The swelling occurs because of the hygroscopic constituents of the wood, which absorb moisture causing the separation of the particles. As a result, the effect *spring back* occurs, which is stress relief due to the compression used in the pressing of the boards. However, when the board loses moisture, part of the swelling becomes unrecoverable [37].

Despite the low non-return rate in thickness presented by some heat-treated boards, it is notable that the thermal process promotes a significant reduction in water absorption and an improvement in dimensional stability. Heat treatment is one of the most used methods to improve wood properties, such as water resistance, dimensional stability, and biological durability. Thermally treated wood has been widely used in decks, saunas, doors, windows, wall panels, floors, and garden furniture [38].

4.3. Flexural strength in three points

From the results presented by the flexural strength in three points, it can be observed that the heat treatment efficiently increased the strength of the samples. BORUVKA *et al.* [39] explain that the good performance provided by heat treatment on wood properties is directly related to a limitation in the capacity to absorb bound water, not causing significant chemical changes in the wood. In research with Scots pine, TAGHIYARI *et al.* [40] found that the heat treatment of wood carried out at a temperature of 145 °C caused a low mass loss and consequently a low thermal degradation between lignin and hemicellulose. This low degradation, together with the new connections made by the hemicelluloses and lignin fragments, are factors that improve the physical and mechanical properties. Performing heat treatment in *Fagus orientalis* wood, PERCIN *et al.* [41] found that the treatment at a temperature of 150 °C and a time of 60 min provided an increase of 2.4% in MOR and 1% in MOE during flexural tests. On the other hand, it was found that increasing the temperature to 200 °C and time to 300 min provided a decrease in MOR and MOE.

In the present study, the treatment of 40 min/160 °C promoted a decrease in the wood's mechanical properties. When heat treatment temperatures are high, thermal degradation can increase, which negatively influences physical and mechanical properties [40]. ESTEVES *et al.* [22] confirm these statements citing that performing heat treatments with high temperatures and long periods can increase wood mechanical degradation.

Structural degradation is a factor that directly influences the reduction of the wood's mechanical properties [25]. The mechanical properties of MOR and MOE have notable importance in measuring the strength and elastic behavior of the material subjected to loading. These properties are fundamental for the hardboard's applicability as a structural component of furniture and other products used in construction [2].

Based on the studies, it is noted that research aiming to identify the best temperatures and times for heat treatments will contribute positively to the production of quality products with excellent physical-mechanical properties for application in different environments. According to ARAÚJO *et al.* [42], WANDSCHEER *et al.* [43] and JUIZO *et al.* [44] the performance of heat treatment tends to improve the quality of wood and wood panels, expanding its field of applications in construction and flooring. Furthermore, wood products developed from heat-treated can be used to make furniture, floors, doors, walls, windows, and playground equipment.

5. CONCLUSIONS

The variation in temperature and time directly influenced the properties of the hardboards because when subjected to a temperature of 120 °C for 20 min, the material showed a lower moisture absorption (5.2%). When the temperature was 160 °C, with a time of 40 min, the material showed reduced water absorption and thickness swelling in 24 h, 33.5%, and 25.7%, respectively. As for the mechanical property of flexural strength, all heat treatments positively influenced the increase in hardboard strength. However, the decrease in treatment time at higher temperatures can generate a higher flexural strength in hardboards, considering the highest value (26.3 MPa), obtained for 20 min/160 °C. Therefore, it appears that concerning the physical properties, the research

showed that the heat treatment did not significantly influence the bulk density of the evaluated boards but showed efficiency in reducing the hygroscopicity of the material. As for the mechanical properties of flexural strength, all heat treatments positively influenced the increase in strength.

Because of the developed study, it is noted that heat treatment on fiberboard significantly improved physical and mechanical properties. These factors contribute positively to the quality of products made from these materials, in addition to increasing their applicability in different types of indoor environments. Another essential feature is that heat treatment can be performed without using chemicals, making the process more eco-friendly. The research showed that carrying out the thermal treatment promoted improvements in the physical-mechanical properties of the HDF panels, however, the temperature and the time for carrying out the treatment have a variable effect. Therefore, the work lacks future studies aimed at carrying out heat treatments at higher temperatures and longer periods than those used in this work.

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