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Influence of the temperature on the compression strength parallel to grain of paricá

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ABSTRACT

The aim of this work is to determine the influence of the temperature, in a range from 20 °C to 230 °C, on the compression strength parallel to grain of paricá (*Schizolobium amazonicum*) from cultivated forests. The sample was formed by 105 small clear specimens assembled in 15 groups of seven elements. The specimens of each group were heated at a constant temperature, during 180 min, before the mechanical test was performed in a temperature-controlled chamber. The results obtained have shown that the temperature increase leads to a nonmonotonic decrease of the compression strength, reaching 35% of compression strength at room temperature. This decrease can be associated to the influence of the temperature on the wood polymers and the moisture content of the specimens.

1. Introduction

Wood is a truly sustainable resource because forests are able to regenerate themselves or be cultivated within our lifetime. The wood from cultivated forests can be a solution to supply the construction market, avoiding the increasing deforestation of the native tropical rainforests. In the Brazilian Amazon, there are plantations of *Schizolobium amazonicum*, a hardwood tree (angiosperm) locally known as "paricá". This native tropical rainforest species stands out for presenting fast growth, straight trunk with branches stemming above seven meters, and lumber with high quotation in the market. Currently, "paricá" is used almost exclusively in the production of plywood and lumber core plywood, being also applied for packing and pallets. Some researchers have shown that the "paricá" lumber presents mechanical properties that make it suited for glue-laminated timber [1].

Among the conditions under which the wood can be submitted as a construction material, a fire is a very particular situation in which its properties reveal their antinomy. Wood is an isolating material but it is also combustible. The fire performance of hardwood lumber from cultivated forests is well known and the experience has shown that it keeps satisfactorily several of its mechanical properties despite its heating.

Wood is a cellular inhomogeneous composite from botanical origin. Its cell walls are constituted grossly by cellulose, hemicelluloses and lignin. Cellulose is the most abundant component in wood, consisting of a long and linear chain of carbon that plays a major role in wood strength. Hemicelluloses are branched amorphous polymers consisting of pentoses and hexoses. They are considered the interface between cellulose and lignin in the wood material structure. Lignin is an amorphous polymer with wide variation in configuration based on phenyl propane units. It is considered to be the glue of wood structure [2,3,15].

At room temperature, the wood properties depend on their complex internal porous structures that vary according to tree species and age, environmental factors as climate and water supply, moisture content and localized defects as knots and wood reactions. The pore structure takes different forms according to species and its functional cell types: tracheids, vassels and parenchyma cells. The arrangement of cells in growth zones and the transition from one zone to the next has significant influence in mechanical properties in transverse direction. A detailed explanation of these parameters is presented in [2,3]. At high temperatures, the wood properties depend also on the thermal degradation of wood polymers and on the internal drying stresses that cause checks during the fire. Several works have been published on the influence of the temperature and the moisture content on the mechanical properties of wood [2–12] as well as on the influence of the chemistry of wood [12–14]. Many works show that the mechanical strength is reduced with the increase of the moisture content and temperature [2–12].

The temperature can affect the wood and their polymers by decomposition, by changes in the crystallinity chains or glass transition. The polymers decomposition depends also on the moisture content, the temperature level and the exposition period. The dry cellulose degradation occurs at temperatures above 300 °C, while that of hemicellulose occurs at temperatures between 150 and 200 °C. For lignin, the temperature range in which the corresponding degradation takes place is between 220 and 250 °C [14,16].

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According to Schniewind [13], the dehydration of lignin occurs around 200 °C. Irvine [23] determined that the temperature and humidity influence the glass transition of wood and its polymers. The glass transition of dry cellulose of various wood species is situated between 200 and 250 °C [22]. For isolated dry hemicellulose, the glass transition has been observed in a range of 190–220 °C and for dry lignin in a range of 124–193 °C [25]. For cellulose with different degrees of crystallinity and moisture content in a range from 4% to 20%, the glass transition temperature is situated between 0 and 75 °C. For hemicellulose with moisture content of 20%, the glass transition temperature of 54 °C was found [25,26]. For lignin, the glass transition temperature of 174 °C at dry conditions changes to 115 °C at 5% moisture content [25,26].

There is evidence that the change of crystallinity of cellulose with temperature influences the rigidity, the dimensional stability and other physical properties of wood. Higher crystallinity was observed in the cellulose of wood pulp than pure cellulose [19].

The assessment of fire performance of real-sized wooden structures is a difficult task due to the complexity and cost of the required tests. However, it can be done by thermo-mechanical analysis that includes models of fire, wood combustion, mass and heat transfer, the isolating effect of charring over the heat affected zone and the influence of temperature on the wood mechanical properties. The knowledge of the behavior of wood at high temperatures is required to assess the safety of structures during a fire, allowing the determination of the time of fire resistance of the building structural elements. The mechanical properties at high temperatures are one of the important parameters to consider in structural elements analysis.

The aim of this work is to determine the effect of the temperature on the compression strength parallel to grain of *S. amazonicum* from cultivated forests. The results may help to assess the behavior of wood structures during a fire.

2. Materials and methods

The tests were carried out on samples of "paricá" (*S. amazonicum*) from cultivated forests, where the volumetric mass was in the range from 296.6 to 464.3 kg/m^3.

2.1. Sample and specimen

The influence of 15 temperature levels, in the range from 20 to 230 °C, on the compression strength parallel to grain was studied using a sample of 105 specimens with average mass density of 379.3 and standard deviation of 37.9 kg/m^3 and average moisture content of 11.7% at 20 °C (Table 1).

Table 1
Average mass density of specimen groups.

Temperature (°C)	Specimens	Mass density at 20 °C (kg/m^3)	Standard deviation
20	7	368.18	41.90
40	7	370.67	40.59
50	7	371.71	40.63
60	7	372.65	40.51
70	7	374.07	39.52
80	7	376.25	39.07
90	7	378.80	38.00
100	7	379.60	37.43
110	7	380.76	37.83
130	7	382.09	39.09
150	7	383.62	40.36
170	7	384.74	39.46
190	7	387.19	41.56
210	7	388.75	42.59
230	7	389.74	42.35
Total	105		

The specimens were prepared with timber classified visually according to the specifications of the Brazilian standard [27]. They were clear, straight-grained material cut from regions distant 30 cm of the tip. The sample was divided in sets of seven specimens so as to constitute groups with densities statistically homogeneous. The homogeneity was verified by variance analysis, using statistically significant differences. The method used to compare the means was Fisher's least significant difference (LSD) procedure, with a confidence level of 95% [28].

The specimen dimensions are those defined in the Brazilian standard [27], 50 × 50 × 150 mm. Cross-section dimensions and length were measured with accuracy of 0.01 mm. Special care was taken in preparing the specimen to ensure that the end surfaces are parallel and that both are aligned perpendicular to the longitudinal axis.

2.2. Mechanical tests

The mechanical tests were realized with a Kratos universal test machine with a Jung-J200 temperature-controlled chamber, with internal dimensions of 37 × 50 × 52 cm. The experimental device was placed inside the chamber. A spherical loading base is used for improving the alignment of the specimen. The test was considered completed when the specimen failed. The displacement was applied with a speed of 2.0 mm min^{-1}, during a period of 5–10 min.

2.3. Specimens heating

The specimens were previously heated, during 180 min, in a Quimis electric drying oven with automatic temperature control and internal dimension of 90 × 100 × 66 cm. After this conditioning period, the specimens were transferred to the temperature-controlled chamber of the universal test machine.

The heating period was determined from preliminary tests, in which the specimens were introduced in the preheated oven at 200 °C. Each specimen had a lateral perforation of 2 mm of diameter in which a thermocouple of type *K* was placed in order to measure the temperature at its geometrical centre. This allowed the determination of the required time for the temperature in the interior of the specimen to reach the temperature of the oven, guaranteeing the homogenization of the temperature of all the heated material.

2.4. Determination of compression strength and strain parallel to grain

The compression strength parallel to grain ($f_{c0,T}$) and the strain (ε) were determined from the maximum compression force (F_{max}) and displacement (u) of the crosshead of the universal test machine corresponding to the maximum force, respectively (Fig. 1). All these values were obtained from tests of parallel compression to grain for different levels of temperatures according to Eqs. (1) and (2).

$$f_{c0,T} = \frac{F_{max}}{A_t} \quad (1)$$

$$\varepsilon = \frac{u}{l_0} \quad (2)$$

where F_{max} is the maximum compression force applied to the specimens during the test, in *N*, for a level of temperature *T*; A_t is the cross-section area of the heated specimen, in mm^2; u is the displacement corresponding to the maximum force, in mm; l_0 is the specimen initial length, in mm.

2.5. Determination of the moisture content

The determination of the specimen moisture content during the mechanical test was carried out using the same specimen. After rupture, the specimen was weighted for the determination of the final mass (m_f), and then submitted to drying at a maximum temperature of 103 ± 2 °C, as required by the Brazilian standard [27],

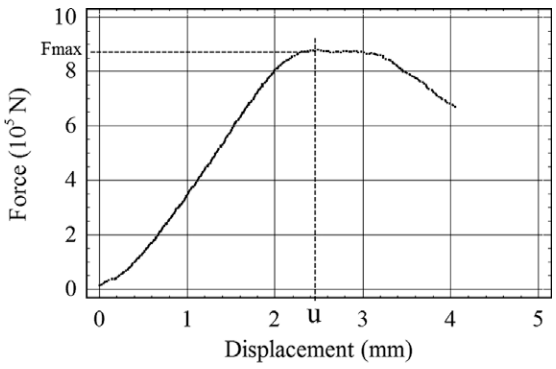

Fig. 1. Force *x* displacement curve.

until the difference between two consecutive measures was less or equal 0.5% of the last measured mass. In this condition, the measured mass is considered to be the dry mass (m_d). The moisture content (mc) was determined by Eq. (3)

$$mc = \frac{m_f - m_d}{m_d} \cdot 100 \quad (3)$$

3. Results and discussions

In this section, the test results concerning the influence of temperature on the moisture content, colour, strain and compression strength parallel to grain of *S. amazonicum* are presented. All mechanical data concerning the strain and compression strength were statistically treated. Variance analysis [28] was carried out in order to verify statistically significant differences, with 95% reliability, between the average mechanical values at a given temperature and those at room temperature.

3.1. Moisture content at the end of the test

The moisture content of the sample, after a heating period of 180 min in the oven and 5 min mechanical test is shown in Fig. 2. It decreases linearly with the increase of the temperature. It was observed that the specimens were completely dry at about 150 °C.

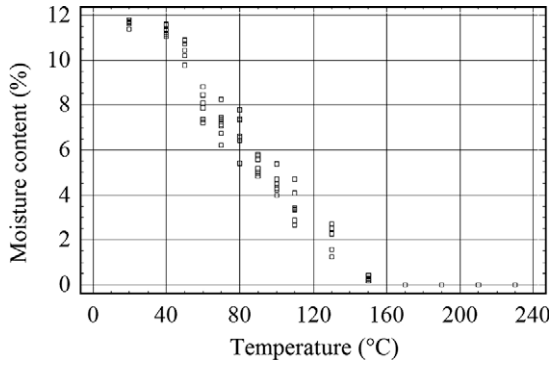

Fig. 2. Moisture content.

3.2. Colour changes and shrinkage of specimens

During the heating period of the specimens, in the temperature range from 20 to 230 °C, changes in wood colour occurred in the inner and external parts of the specimens (Fig. 3a–c) and were visually detected. These changes were more apparent at higher temperatures, above 150 °C. At 230 °C, the changes of wood colour were more intense (Fig. 3c) and it was observed the beginning of wood combustion and checking at the specimens end (Fig. 4). In these regions, the release of gas resulting from the thermal degradation of wood chemical components occurred easily because of the grain orientation.

At low temperatures, the colours changes are weak because the extent of the chemical changes depends on the temperature level [17] and, in the temperature range from 40 °C to 90 °C, the physical changes are emission of water and volatile extractives [29]. According to Rapp and Sailer [30], the heat treatment darkens the colour of the wood, as observed, and reduces its shrinkage and swelling and improves the equilibrium moisture content of wood permanently.

It was also observed the increase of cross-section shrinkage with the increase of the test temperature, in agreement with reference [7].

3.3. Specimens failure

The examination of specimens after testing revealed several patterns of failure, which varied with the temperature (Fig. 5a–c). In a range from 20 to 110 °C (Fig. 5a), the failure plane occurred at the middle of specimens with an angle between 55° and 65°. In a range from 130 to 170 °C (Fig. 5b), the failure plane occurred between the middle and the end of the specimens with an angle

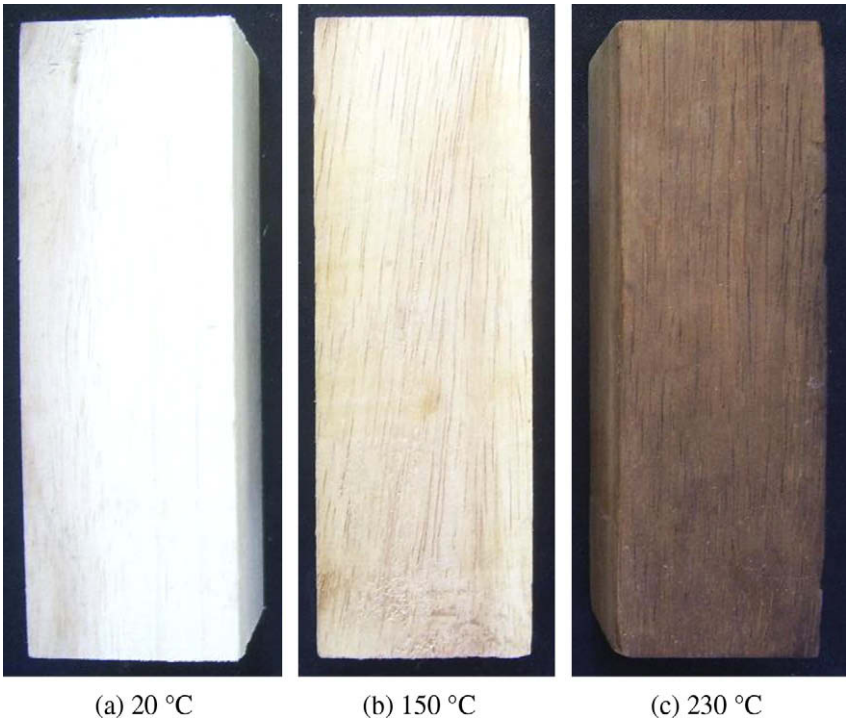

Fig. 3. Color changes.

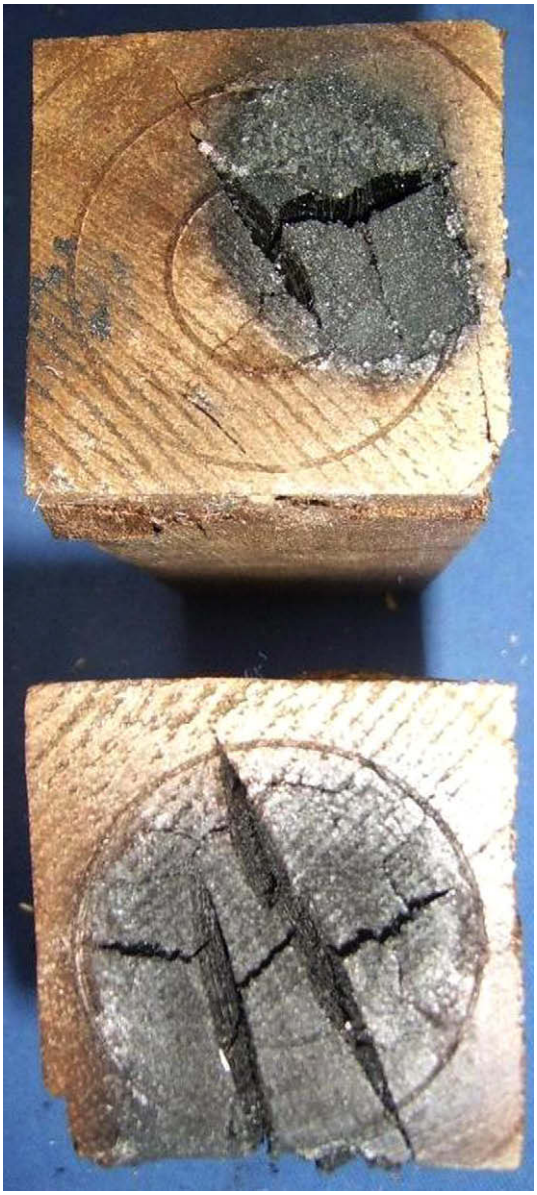

Fig. 4. End checking of specimens.

between 45° and 55°. Finally, at 230 °C (Fig. 5c), the failure plane occurred near the end of specimens, with an angle near to 30°.

3.4. Compression strength parallel to grain

The results of compression strength parallel to grain are presented in Fig. 6. They show that the compression strength is influenced by the temperature increase. The tests performed at 20 °C presented average strength of 32 MPa and standard deviation of 4 MPa. The variance analysis has shown that there are statistically significant differences, with 95% of reliability, between the compression strength at 20 °C and at other temperature levels, with the exception of the results obtained at 150 °C.

The compression strength was nonmonotonically reduced. The averages were 25 MPa, 29 MPa and 11 MPa at 80, 150 and 230 °C, respectively. These values represent 77%, 90% and 35% of the average compression strength at room temperature, respectively. Moraes et al. [11] obtained similar results for embedding strength of *Pinus sylvestris*.

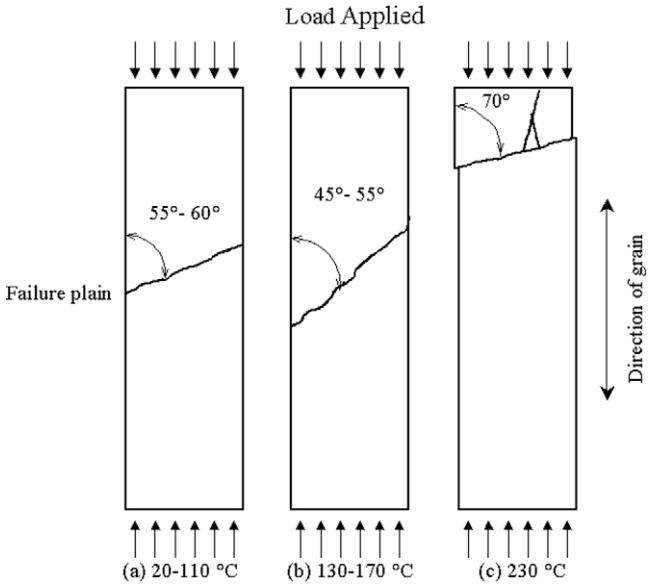

Fig. 5. Pattern of rupture.

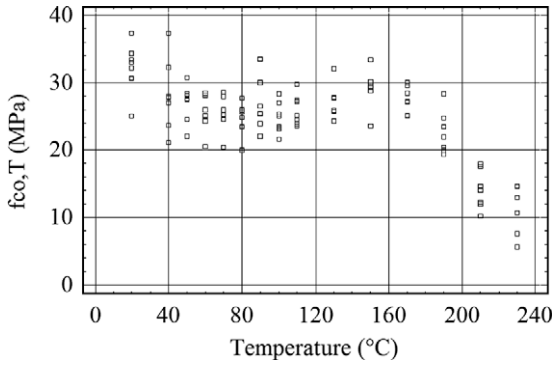

Fig. 6. Compression strength parallel to grain.

Several authors point out that the moisture content and temperature are important factors in the mechanical strength of wood [2–11]. According to them, the moisture content decrease causes the increase of mechanical properties while the increase of the temperature produces a decrease in those properties. The decrease of compression strength of paricá can also be associated to the glass transition of wood polymers at wet and dry conditions [20–24], considering that, near 80 °C, the specimens presented moisture content (Fig. 2) near to the values found by Irvine [23] for the glass transition.

Young and Clancy [9] report that the cellulose chains in the interior of fibers are responsible for the compression strength parallel to grain. According to Schaffer [4], the compression strength depends strongly on the lignin, located at the exterior of wood fibers, which softens at about 100 °C and hardens at higher temperatures. This author reports that, from 55 °C onwards, the lignin structure is modified and the hemicelluloses start to soften. From 140 °C onwards, the bound water in the wood starts to be released and polymers start to degrade [4,9]. Above 100 °C, the temperature effects are irreversible. This is caused by the degradation of some elements that form the wood. This degradation results in mass loss and reduction of mechanical strength [6,7,12].

The pronounced decrease of compression strength, above 150 °C, can also be explained by the glass transition [23] and the thermal degradation of dry wood polymers, as discussed in the Introduction.

3.5. Deformation at the maximum force

In Fig. 7, the total deformation of specimens, including the deformation by crushing on the specimens ends, is presented. It was observed that the total deformation decreases with the increase of the temperature until 50 °C. After that, the deformation rate remains constant up to 170 °C, as shown by the plateau in Fig. 7. From 170 °C onwards, the deformation decreases again. It is important to remark that the specimens had 0% of moisture content from 150 °C onwards (Fig. 7). By variance analysis [28], it was verified that there are statistically significant differences, with 95% of reliability, between the strain at a given temperature and those at room temperature.

The reduction of the total deformation can be associated with the variation of moisture content of the specimens and the behaviour of wood polymers at high temperatures (Fig. 2). The heat treatment can reduce the hygroscopicity by thermal degradation of the hemicellulose component of the cell wall. Its degradation products polymerize under heat to produce a water insoluble polymer [31], which result in a reduction in the tendency of wood to take on water, reducing the tendency to swell. According to Winandy and Rowell [12], the cellulose is a polymer that contributes most to the strength of wood. The chains of cellulose are highly resistant to tension and compression efforts due to hydrogen bonds that link the chains and give it rigidity [14,15]. The decrease in moisture content causes the approximation of the cellulose molecules, which are linked by hydrogen bonds. Several authors found that the cellulose crystallinity increases at high temperatures in the range between 120 and 230 °C, although there is degradation of the polymer for higher temperatures [18] cited in [14,19,20]. Finally, the decrease in moisture content and increasing temperature increases the crystallinity of cellulose, improving the dimensional stability and stiffness in the same degree [14,15,19,20].

3.6. Relative compression strength

In Fig. 8, the average values of the compression strength, normalized by those at room temperature and those obtained by Knudson and Schniewind [5] and by Schaffer [4] are presented. These authors studied the mechanical resistance of *Pseudotsuga menziesii* e Douglas-fir, respectively. In the same figure, the relative embedding strength of *P. sylvestris,* obtained by Moraes et al. [11], is also presented.

The results obtained by Knudson and Schiewind [5], for samples with 12% moisture content, were similar to those found in this work. The disparity found in a range from 110 to 190 °C can be associated to the way the specimens were heated. In the present work, the specimens were homogeneously heated, ensuring that all their parts were at the same temperature with moisture content

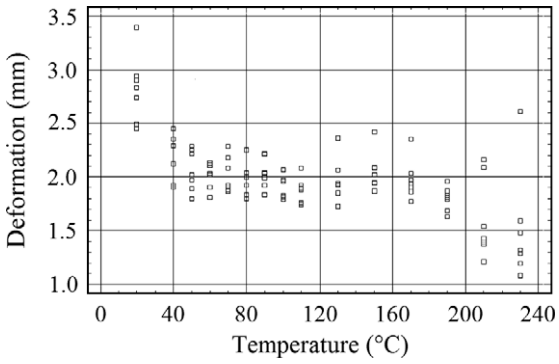

Fig. 7. Total deformation at maximum compression force.

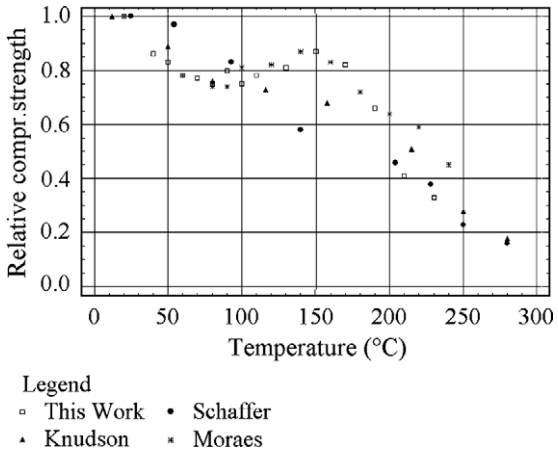

Fig. 8. Normalized compression strength.

in the range of 4%–0%. The results obtained by Schaffer [4] present values higher than those obtained in this work in a range from 25 to 50 °C. This disagreement can be attributed to the moisture content of 0% of Douglas-fir and of 12% of the *S. amazonicum* at room temperature.

The relative values of embedding strength found by Moraes et al. [11] present the same behaviour as the relative compression strength obtained in this work, in the range from 60 to 200 °C. Although the mechanical properties are different, both are compression effort. In the ranges from 90 to 110 °C and 200–250 °C, the results obtained in this work are similar to those of Knudson and Schniewind [5] and Schaffer [4].

A third order polynomial model, which can help to assess the behavior of the wood structures during a fire, was used to describe the relationship between $\frac{f_{c0,T}}{f_{c0,20^\circ C}}$ and temperature (T). The equation of the fitted model is

$$\frac{f_{c0,T}}{f_{c0,20^\circ C}} = 1.21557 - 0.013432T + 1.33536 \times 10^{-4}T^2 + 4.032 \times 10^{-4}T^3 \quad (4)$$

with a r^2 statistic of 70.7%.

4. Conclusions

The aim of this work is to determine the influence of temperature, in a range from 20 °C to 230 °C, on the compression strength parallel to grain of "paricá" (*S. amazonicum*) from cultivated forests. The sample was formed by 105 small clear specimens assembled in 15 groups of seven elements. The specimens of each group were heated at a constant temperature during 180 min before the mechanical test was performed in a temperature-controlled chamber. The results obtained lead to the following conclusions:

- The average compression strengths parallel to grain of "paricá" are 32 MPa and 11 MPa at 20 and 230 °C, respectively. The value at the highest temperature level corresponds to 35.0% of the compression strength at room temperature.
- There are differences, with statistical significance, between the compression strength at 20 °C and at other temperature levels, with the exception of the results obtained at 150 °C.
- The temperature increase leads to a nonmonotonic decrease of the compression strength. This decrease can be associated to the behaviour of the wood polymers and the moisture content of the specimens.

- The decrease of the strain with the increase of the temperature can be associated to the decrease of the moisture content, the glass transition of the wood polymers and also to the thermal degradation of specimens at different temperatures.
- The exposition of the specimens to high temperatures causes changes in the wood color, internal and externally, which are more pronounced at temperatures above 150 °C.
- Although small clear specimens were used, these results may help to assess the behaviour of wooden structures during the fire by numerical analysis, by providing a mathematical expression to describe the influence of temperature on compression strength of residual heated wood.

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