Time of Exposure at 60 °C Service Temperature: Influence on Strength and Modulus of Elasticity in Compression Parallel to the Grain of Hardwood Species

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The aim of this research was to determine the influence of exposure time at 60 °C in the compression strength parallel to the grain (f_{c0}) and modulus of elasticity in compression parallel to the grain (E_{c0}) for cupiúba (*Goupia glabra*), eucalypt (*Eucalyptus saligna*), garapeira (*Apuleia leiocarpa*) and jatobá tamarindo (*Hymeneae* sp.) wood species. The factor investigated in this research was the residence time in kiln (exposure at controlled temperature 60 °C) of specimens: 0 (wood tested at room temperature and moisture content around to 12%), 168, 456, 720, and 2160 hours, simulating the reaction of the material in confined roof structures. Compression parallel to the grain tests were conducted according to the methods of the Brazilian Standard Code ABNT NBR 7190 (1997). ANOVA results indicated that the temperature (60 °C) had a significant influence in the five exposure times. All studied wood species showed an increase in the f_{c0} value with increasing time of exposure at 60 °C. For E_{c0}, this phenomenon occurred only for the jatobá tamarindo and cupiúba wood species.

Keywords: Amazon forest; Mechanical properties; Planted forest; Tropical wood; Wood

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INTRODUCTION

Wood is one of the main raw materials used in the world, from small artifacts with little technology, for example, a teaching kit for children apprentices (Vieira *et al.* 2010), to research for their use in aggregates for higher value purposes (Song *et al.* 2018). Wood used in industry may come from native forests (Ter Steege *et al.* 2016; Barbosa *et al.* 2017) or planted forests (Bäcklund *et al.* 2017; De Araújo *et al.* 2017).

Brazil has within its territory different biomes with numerous species of native trees that can supply quality raw material for several industrial sectors. One such biome is the Amazon Forest (Almeida *et al.* 2017).

According to Ter Steege *et al.* (2016) and Cardoso *et al*. (2017), it is estimated that only in the Brazilian territory, the Amazon Forest presents around 12,000 tree species that have yet to be catalogued. Therefore, the study of the properties of the wood is important for its rational use (Top *et al.* 2018) and forest sustainability (Ilha *et al.* 2018; Metcalfe *et al.* 2018).

As pointed out by De Araújo *et al.* (2016) and Sotsek and Santos (2018), wood is used as a structural member in bridges (Cheung *et al.* 2017), footbridges (Robbers *et al.* 2018), and other civil construction projects (Chen and Guo 2016).

For the use of wood as a structural member, its physical and mechanical properties should be determined according to standardized laboratory procedures (Kloiber *et al.* 2015; Mahmud *et al.* 2017).

Strength in compression parallel to the grain (f_{c0}) and the modulus of elasticity in compression parallel to the grain (E_{c0}) are the main mechanical properties to classify some wood species for the construction of structures according to the Brazilian Standard Code ABNT NBR 7190 (1997) "Design of Wooden Structures" (Almeida *et al.* 2013; Christoforo *et al.* 2017; Lahr *et al.* 2017).

Wood varies in its properties according to the place of origin (Csordós *et al.* 2014; Silva *et al.* 2018), tree species (Matos and Molina 2016), moisture content (Stolf *et al.* 2014), age (Lourençon *et al.* 2014), and other edaphoclimatic factors (Vásquez-Cuecuecha *et al.* 2015). However, the use of wood in structures is influenced by weather conditions (Guo *et al.* 2018; Herrera *et al.* 2018; Reinprecht *et al.* 2018), even when previously chemically treated against the attack of decay organisms (Pigozzo *et al.* 2017).

Temperature is another factor that can influence the wood properties. Some thermal treatments change the surface wood coloration to increase its value added to the market (Lopes *et al.* 2014; Santos *et al.* 2014; Zanuncio *et al.* 2015; Yang *et al.* 2015). The mechanical properties of wood can be improved with heat-thermal treatments (Cademartori *et al.* 2015; Anjos and Sousa 2015; Zhang *et al.* 2015; Holocek *et al.* 2017). Timber members exposed to fire conditions are also research topics that will increase the knowledge of the behavior of the wood in this situation (Moreno Junior and Molina 2012; Moreno Junior *et al.* 2013).

According to Coelho *et al.* (2017), asbestos-free fiber cement roof tiles with a high rate of solar radiation can reach 60 ºC. In service, the wood used in the roof structures is exposed to this temperature of service.

The aim of this research was to determine the influence of time of exposure to the service temperature on the compression parallel to the grain strength and modulus of elasticity in compression parallel to the grain for cupiúba (*Goupia glabra*), eucalypt (*Eucalyptus saligna*), garapeira (*Apuleia leiocarpa*), and jatobá tamarindo (*Hymeneae* sp.) wood species.

EXPERIMENTAL

Three homogeneous batches of cupiúba (*Goupia glabra*), garapeira (*Apuleia leiocarpa*), and jatobá tamarindo (*Hymeneae* sp.) from different extraction sites in the Amazon Forest (certified areas on North of Brazil) and one homogeneous batch of eucalypt (*Eucalyptus saligna*) from a planted forest area in the state of São Paulo, Brazil, were used. In this research, hardwood types were studied because they are more often used in roof structures in Brazil. All wood batches were dried at room temperature until they reached a moisture content of 12%, as designated for manufacturing specimens in the ABNT NBR 7190 (1997) standard. All specimens had a length in the grain direction of 15 cm and a square cross section with an edge of 5 cm.

Compression parallel to the grain tests were carried out in an AMSLER universal testing machine (Schaffhausen, Switzerland) at 250 kN capacity. f_{c0} and E_{c0} values were obtained according to ABNT NBR 7190 (1997).

The factor investigated in this research was the time inside the kiln (Marconi, Piracicaba, Brazil), with an exposure at controlled temperature 60 ºC of specimens: 0 (wood tested at room temperature and moisture content close to 12%), 168 (7 days), 456 (19 days), 720 (30 days), and 2160 h (90 days), simulating the reaction of the material in confined roof structures (according to Coelho *et al.* 2017).

For mechanical properties of wood species, 24 values were determined for specimens at room temperature and 12% moisture content and six values determined for the four other exposure times evaluated (168, 456, 720, and 2160 h), resulting in a total of 384 values. It is noteworthy that specimens for each experimental condition were made in pairs, implying that possible differences in results are explained mainly by wood exposure time, at 60 °C, decreasing intrinsic variability of wood.

To investigate the effect of exposure time (0, 168, 456, 720, and 2106 h) of specimens in the kiln in the f_{c0} and E_{c0} values, the analysis of variance (ANOVA) was applied, using the software Minitab®14 (Minitab, State College, PA, USA), considering a 5% significance level (α). The null-hypothesis consisted of means equivalence (H_0) and their non-equivalence (at least two) as an alternative hypothesis (H_1). By hypotheses formulation, a P-value greater than the significance level implies accepting H_0 (means of the investigated treatments are equivalent), and lower values (P-value < 0.05) refute H_0 (at least one the means differs significantly).

For ANOVA's validation, normal distributions of f_{c0} and E_{c0} values and variance homogeneity of treatment using Anderson-Darling (*AD*) and Bartlett (*Bt*) tests, respectively, were investigated, both at 5% significance. To test formulation, a P-value exceeding 5% means that answers that present a normal distribution and variance of treatments are equivalent, thus validating ANOVA model. If considered significant, the influence of exposure time at 60 ºC, by ANOVA, graphs of main effects (visual inspection), and, subsequently, the multiple comparison Tukey test (contrast test) to group the levels of factor investigated were applied. In the Tukey test, means in descending order are labeled A and B, with A being the highest average. It is noteworthy that factor levels investigated with the same letters show statistically similar means.

RESULTS AND DISCUSSION

Table 1 presents the f_{c0} and E_{c0} values and coefficient of variation (*CV*) for four wood species in the five conditions of exposure at a controlled temperature of 60 ºC. Silva *et al.* (2018) found that for cupiúba wood from different provenances and ages in Brazil, average f_{c0} values were equal to 62.07 (Caracaraí, state of Roraima), 47.73 (Bonfim do Sul, state of Roraima), and 57.42 MPa (Claúdia, state of Mato Grosso). All these values were lower in comparison with the present research. The E_{c0} value of cupiúba from Caracaraí was equal to 15,976 MPa, higher that the E_{c0} determined in this research in the same condition, without time exposure at 60 ºC.

Table 1. The f_{c0} and E_{c0} Values for Hardwoods at Different Exposures to 60 ºC

Wood Species	Properties	Exposure Time at 60 ºC (h)				
		0	168	456	720	2160
Cupiúba	E_{c0} (MPa)	13,117	20,720	15,295	17,350	15,977
	CV (%)	17.30	19.70	15.60	22.60	23.80
	f_{c0} (MPa)	70.79	98.21	89.40	82.28	76.99
	CV (%)	10.00	10.50	5.70	14.00	22.30
Eucalypt	E_{c0} (MPa)	14,137	14,351	13,745	17,047	12,728
	CV (%)	16.20	8.50	13.10	15.30	15.60
	f_{c0} (MPa)	50.43	62.58	54.59	68.31	61.96
	CV (%)	13.40	23.00	13.50	18.10	16.70
Garapeira	E_{c0} (MPa)	11,284	11,488	15,124	10,799	11,513
	CV (%)	14.50	10.90	46.10	6.48	8.30
	f_{c0} (MPa)	62.49	72.53	72.67	72.06	77.02
	CV (%)	9.80	6.00	6.70	6.70	9.90
Jatobá Tamarindo	E_{c0} (MPa)	17,253	19,484	20,038	19,104	20,590
	CV (%)	8.00	11.40	8.90	7.70	16.30
	f_{c0} (MPa)	97.10	96.52	98.78	119.01	119.22
	CV (%)	10.00	23.50	13.80	15.70	14.80

Moreira *et al.* (2017) determined f_{c0} and E_{c0} values equal to 57 and 12,970 MPa for cupiúba, both values being lower than this research. Almeida and Dias (2016) found cupiúba wood f_{c0} and E_{c0} values equal to 44.50 and 11,114 MPa, for wood at 12% of moisture content. The E_{c0} value determined by Almeida and Dias (2016) was close to the determined value in this research, but the f_{c0} value was much lower. Jesus *et al.* (2015) determined the value of the modulus of elasticity in compression parallel to the grain (E_{c0}) equal to 13,900 MPa. Ferro *et al.* (2015) found E_{c0} values of 14,600 and 17,800 MPa for cupiúba wood. Cupiúba wood studied in this research at first condition of exposure presents a lower E_{c0} value compared to values determined by Ferro *et al.* (2015). Dias and Lahr (2004) classified Cupíuba wood in C30 strength class for Brazilian native hardwood according ABNT NBR 7190 (1997), with f_{c0} and E_{c0} values equal to 54 and 14,125 MPa.

ABNT NBR 7190 (1997) showed for garapeira (*Apuleia leiocarpa*) f_{c0} and E_{c0} values equal to 78.40 and 18,359 MPa. The values determined in this research were lower. Dias and Lahr (2004) classified garapa wood (*Apuleia leiocarpa*) in the C60 strength class for Brazilian native hardwood according to ABNT NBR 7190 (1997), with f_{c0} and E_{c0} average values equal to 73 and 17,718 MPa.

Lahr *et al.* (2016) investigated jatobá wood from different provenances in Brazil, finding average f_{c0} values equal to 93.91 (Caracaraí, state of Roraima), 93.42 (Bonfim do Sul, state of Roraima), and 94.38 (Alta Floresta, state of Mato Grosso), all values being lower than in this research. For the E_{c0}, Lahr *et al.* (2016) found the following values for jatobá wood: 22,482 (Caracaraí, state of Roraima), 21,403 (Bonfim do Sul, state of Roraima), and 21,759 MPa (Alta Floresta, state of Mato Grosso), and all values were higher than in this research.

Dias and Lahr (2004) classified jatobá wood in the C60 strength class for Brazilian native hardwood according to ABNT NBR 7190 (1997), with f_{c0} and E_{c0} values equal to 91 and 22,967 MPa. The f_{c0} and E_{c0} values determined that the Brazilian native hardwood species studied in this research show the variability in both mechanical properties. There are few other reports on the properties of cupiúba, garapeira, and jatobá tamarindo wood, reinforcing the need for more research on the physical and mechanical properties of wood from Amazonian forest trees (Ter Steege *et al.* 2016; Cardoso *et al.* 2017).

Serpa *et al.* (2003) found the *Eucalyptus saligna* wood value for f_{c0} equal to 60 MPa, which is above that determined in this reseach; however, the value determined in this research was higher than the f_{c0} determined for *Eucalyptus grandis*, also by Serpa *et al.* (2003). ABNT NBR 7190 (1997) shows f_{c0} and E_{c0} values to *Eucalyptus saligna* equal to 46.80 and 14,933 MPa, respectively, which is close to the results determined in this research.

Nogueira *et al.* (2018a,b) studied the mechanical properties of *Eucalyptus umbra* and *Eucalyptus camaldulensis*, respectively. *Eucalyptus umbra* presents f_{c0} and E_{c0} values equal to 42.70 and 14,579 MPa; for *Eucalyptus camaldulensis*, the f_{c0} and E_{c0} average values were equal to 48 and 13,286 Mpa, respectively. Lahr *et al.* (2017) determined f_{c0} and E_{c0} for *Eucalyptus urophylla* equal to 46 and 13,391 MPa, respectively, and both values are lower compared to values determined in this research for *Eucalyptus saligna*. The f_{c0} and E_{c0} values of *Eucalyptus saligna* wood reported here were lower than that of *Eucalyptus benthamii* wood as determined by Müller *et al.* (2014). Lima *et al*. (2014) reported the f_{c0} value of *Eucalyptus resinifera* wood equal to 55.87 MPa, which was higher than that determined for *Eucalyptus saligna* wood in this research. Almeida and Dias (2016) determined the f_{c0} and E_{c0} for *Lyptus* wood (*Eucalyptus* hybrid) equal to 53.6 and 22,559 MPa, respectively. *Lyptus* wood presented a higher f_{c0} value than the batch of *Eucalyptus saligna*.

Table 2 presents ANOVA and test validations (*AD* and *Bt*) for the evaluated mechanical properties. The distributions by property and for all wood species were normal and the variances between the treatments were homogeneous, validating the ANOVA model (P-value > 0.05). The P-values of ANOVA for both properties and wood species were lower than the significance level considered (0.05), implying the influence of the exposure time at 60 ºC.

Table 2. ANOVA and Validation Tests Results

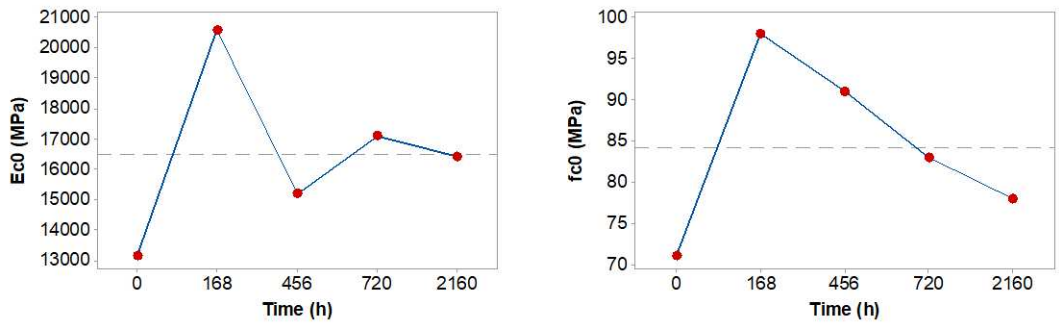
Wood Species	Properties	*FD*	Validation		ANOVA
			AD	*Bt*	
Cupiúba	f_{c0}	47	0.382	0.556	0.000
	E_{c0}	47	0.174	0.321	0.000
Eucalypt	f_{c0}	47	0.430	0.628	0.000
	E_{c0}	47	0.622	0.784	0.000
Garapeira	f_{c0}	47	0.323	0.371	0.000
	E_{c0}	47	0.622	0.544	0.000
Jatobá Tamarindo	f_{c0}	47	0.431	0.683	0.002
	E_{c0}	47	0.694	0.602	0.001

Note: FD, freedom degrees; AD, Anderson-Darling test; Bt, Bartlett test

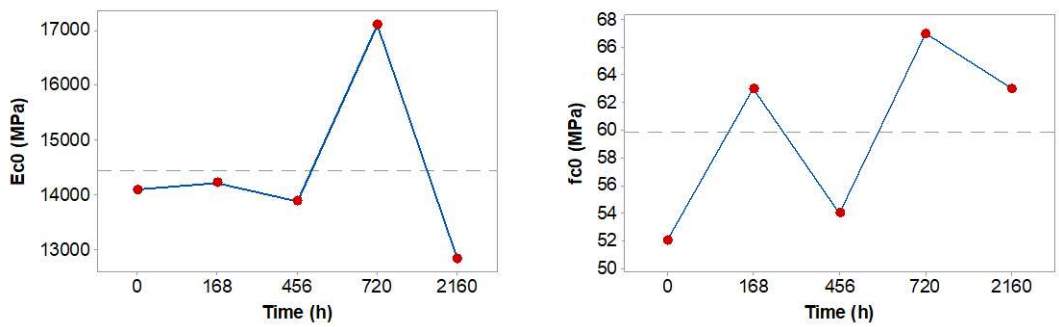
Table 3 presents the results of Tukey's multiple comparison test, and Fig. 1 shows the results of the main effects graphs. For all studied wood species, there was an increase in the value of f_{c0} with the increase of the time of exposure at 60 ºC. For E_{c0} values, this phenomenon occurred only for the species jatobá tamarindo and cupiúba.

Almeida *et al.* (2018) studied the influence of exposure time (0, 168, 456, and 720 h) at 60 ºC in shear parallel to the grain strength (f_{v0}) of softwoods *Pinus taeda* and *Pinus elliottii* from planted forests. Similar to hardwoods studied in this research, times of exposure at temperature service had an influence in the f_{v0} softwoods.

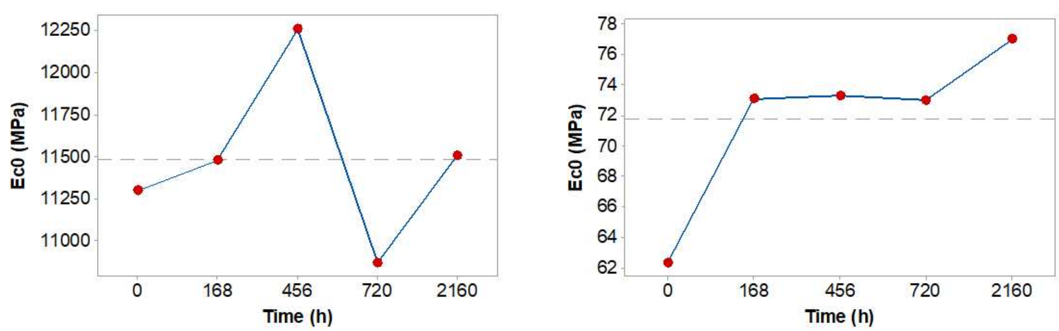
According to Figueroa and Moraes (2009), in heat-treatment between 0 and 200 ºC, wood presents the following phenomena: the process called slow pyrolysis; water vapor and gas release; wood is not ignited; existence of some exothermic oxidative reactions; and color change. From 55 ºC, lignin and hemicellulose is altered, which explains the change in the values of f_{c0} obtained in the present research, but, just after 100 ºC, the wood chemical compounds (lignin, cellulose, and hemicellulose) are negatively affected.



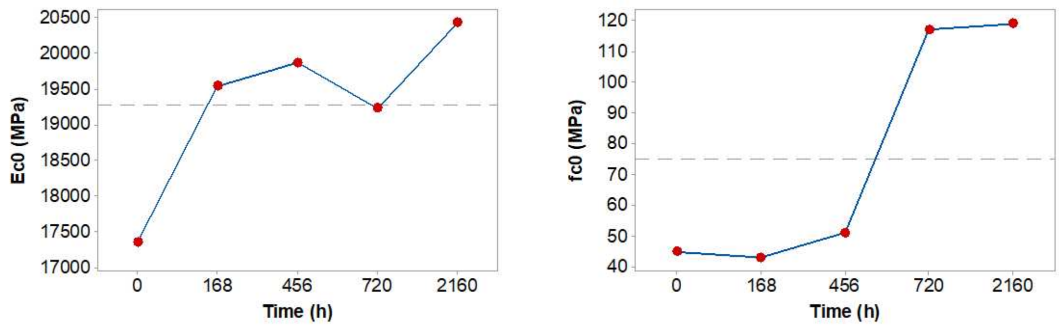
(a)



(b)



(c)



(d)

Fig. 1. Graphs of main effects of exposure time factor on mechanical properties for the four evaluated wood species: (a) cupiúba; (b) eucalypt; (c) garapeira; (d) jatobá tamarindo

Table 3. Tukey Test Results

Wood Species	Properties	Exposure Time at 60 ºC (h)				
		0	168	456	720	2160
Cupiúba	f_{c0}	C	A	AB	BC	BC
	E_{c0}	C	A	BC	AB	ABC
Eucalypt	f_{c0}	B	A	AB	A	AB
	E_{c0}	B	B	B	A	C
Garapeira	f_{c0}	B	A	A	A	A
	E_{c0}	B	B	A	C	B
Jatobá Tamarindo	f_{c0}	B	AB	AB	A	A
	E_{c0}	B	AB	A	AB	A

Jatobá wood (*Hymenaea courbaril*) has a lignin content equal to 21% (Almeida *et al.* 2015); *Eucalyptus saligna*: 21.6% (Foelkel *et al.* 1975); and cupiúba (*Goupia glabra*): 35% (Duarte 2017). The exposure time of wood to 60 ºC might influence the material chemical structure, affecting its mechanical properties.

First, tests were carried out with specimens that exhibited a 12% moisture content and were not treated in the kiln. After a long time in the 60 ºC kiln (in this work, 2160 h), moisture content of specimens decreased, as water vapor was released (Figueroa and Moraes 2009; Phonetip *et al.* 2018), allowing an increase in the f_{c0} and E_{c0} values (Silva *et al.* 2012; Branco *et al.* 2014; Nogueira *et al.* 2018a, b).

CONCLUSIONS

1. Jatobá wood presented the highest f_{c0} and E_{c0} values of the species studied.
2. The f_{c0} and E_{c0} values of all hardwood species (cupíuba, eucalypt, garapeira, and jatobá tamarindo) were influenced by exposure time at 60 ºC.
3. For all wood species, there was an increase in the f_{c0} value with the increase of the time of exposure at 60 ºC. For E_{c0}, this phenomenon occurred only for jatobá tamarindo and Cupiúba.

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