Mechanical Performance of Wood Under Artificial and Natural Weathering Treatments

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Natural and artificial weathering treatments were studied to determine the change of wood properties as a function of exposure time. This paper aimed to provide general information about the mechanical performance of wood under natural and artificial weathering treatments and define a relationship between them. The eight strength classes of ABNT NBR 7190 (1997) were considered, in addition to a paired sampling approach. The modulus of elasticity and conventional strength value in static bending, strength in compression parallel to the grain, hardness perpendicular to the grain, and the elastic limit in the static bending test were investigated. Linear regression models for mechanical performances under artificial and natural aging treatments of the exposure time were made and tested using an analysis of variance. According to the results, 360 days of natural weathering provoked a change in mechanical performance of 15.72% that included a decrease in strength and modulus of elasticity and an increase in elastic limit. Twelve hours of the artificial weathering treatment provided the effect of 6.22 days of natural weathering exposure.

Keywords: Artificial weathering; Mechanical performance; Natural weathering; Timber structures; Wood

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INTRODUCTION

The civil construction industry is one of the most important sectors of wood utilization (Calil, Jr. *et al.* 2003; Almeida *et al.* 2017). Wood can be used as a structural material or as non-structural pieces (building elements such as doors, floors, *etc.*) in civil constructions (Almeida *et al.* 2017b). The Brazilian standard code ABNT NBR 7190 (1997) "Design of timber structures" provides procedures for the structural calculation for wood materials as well as physical-mechanical characterization.

According to this standard, there are three strength classes for softwoods (C20, C25, and C30) and five strength classes for hardwoods (D20, D30, D40, D50, and D60), totaling eight strength classes. The strength classes are determined by the characteristic value of the strength in compression parallel to the grain and are measured using defect-free specimens at a 12% moisture content (Almeida and Dias 2016). According to Almeida *et al.* (2016), strength classes can be used for sampling in wood research and cover a range of wood densities.

It is common to use wood for outdoor structures in above-ground environments (Viitanen *et al.* 2011; Mohebby and Saei 2015; Oberhofnerová *et al.* 2017). In this situation, wood materials are exposed to natural weathering, which pertains to rainfall incidence, dew, air humidity, and ultraviolet (UV) radiation (Rodríguez-Anda and Fuentes-Talavera 2003; Pandey 2005; Rosu *et al.* 2010). The UV light is divided into three wavelength intervals: UVA corresponds to radiations with wavelength values between 315 nm and 400 nm, UVB corresponds to radiations with wavelength between 280 nm and 315 nm, and UVC corresponds to radiations with wavelength between 100 nm and 280 nm. A smaller radiation wavelength results in higher energy and penetration power of this radiation (George *et al.* 2005).

Weathering provokes wood degradation (Ganne-Chédeville *et al.* 2012; Cogulet *et al.* 2016), and accelerated artificial weathering treatments are used for simulating the natural aging process and to investigate its effects on properties of the wood (Fechine *et al.* 2006; Hansmann *et al.* 2006; Miklečić and Jirouł-Rajković 2011; Yildiz *et al.* 2011, 2013; Baysal 2012; Teodorescu *et al.* 2017). The artificial aging of nonmetallic materials was performed according to the standard ASTM G154 (2016).

For the design of timber structures it is important to understand the mechanical properties of the materials being used (Calil, Jr. *et al.* 2003; Almeida *et al.* 2016). The mechanical performance of wood under natural weathering treatments as well as mechanical performance changes under artificial weathering treatments must be investigated to understand the natural aging treatment and provide background for future research in this field.

This paper aims to investigate mechanical performance changes of wood under natural and artificial weathering treatments, covering all strength classes of the Brazilian standard code, to provide more general and useful information about the mechanical performance of aged wood. In addition, a relationship between the artificial and natural weathering treatments based on the mechanical properties of wood was determined.

EXPERIMENTAL

Materials

To perform this investigation, softwoods and hardwoods from the eight strength classes designated by the standard code ABNT NBR 7190 (1997) were considered. The softwoods chosen were *Pinus sp.* (divided into three strength classes – C20, C25, and C30). For hardwoods, five tropical Brazilian wood species were considered: *Simarouba amara* (D20), *Anacardium giganteum* (D30), *Erisma uncinatum* (D40), *Bagassa guianensis* (D50), and *Peltogyne lecointei* (D60). Each wood species representing a Brazilian standard code strength class came from certified forests in the northern region of Brazil.

All wood samples were at a 12% moisture content. For the aging procedures, these samples were made with dimensions of 20 mm × 20 mm × 320 mm (the largest dimension was in the grain direction) according to the standard code ABNT NBR 7190 (1997). There were three treatments completed: artificial weathering (artificially accelerated aging) was completed in three levels, natural weathering (natural aging) was completed in three levels, and the control was completed without any treatments. Six samples were tested for each wood species for each aging treatment in each level for a total of 288 samples.

Methods

For better comparisons, each prepared aged sample had a control sample extracted from the same wood piece, which led to a paired sampling. The aged sample performance was compared to the control sample performance to minimize wood variability of the samples.

An artificial weathering chamber (Fig. 1a) was used to simulate the aging conditions for the material testing. The equipment (Artificial weathering chamber; Equilam, São Paulo, Brazil) reproduced UVA/UVB irradiation atmospheres with condensation/thermal shock, which simulated the effects of sunlight, rain, and dew exposure. The radiation sources were eight fluorescent lamps (40 W each) with wavelengths of 340 nm and 313 nm (UVA or UVB lamps, respectively), and an irradiation power of 0.47 to 1.60 W/m²/nm. Figure 1b illustrates the sample arrangement for the natural aging treatment in an outdoor environment.

(a) (b)

Fig. 1. Arrangement of samples for (a) artificial and (b) natural aging

Cycle 7 of the ASTM G154 (2016) was used with conditions of 8 h of UV irradiation at 60 °C, 15 min of water spray, and 3 h and 45 min at 50 °C of condensation, which totaled 12 h/cycle. The average irradiation was 1.55 W/m^2/nm using UVB lamps. There were 8, 16, and 32 cycles performed for the three levels of artificial weathering based on the observed visual effect of the aged samples (96, 192, and 384 h, respectively, of artificial weathering exposure).

Weather conditions for the natural aging treatment were collected based on the data of Empresa Brasileira de Pesquisa Agropecuária- Embrapa [Brazilian Agricultural Research Corporation]. The Embrapa Station is located in São Carlos, São Paulo State, Brazil. The geographic coordinates of the weather station are 21° 57' 42" (S) latitude and 47° 50' 28" (W) longitude with an altitude of 860 m. For artificial and natural aging, the wood samples did not receive any coating. To cover all four seasons of the year, 90, 180, and 360 days of natural weathering exposure were considered.

Mechanical tests were performed according to the annex B of the Brazilian standard code ABNT NBR 7190 (1997) that describes the procedures for physical-mechanical properties determination. The standard’s items B.8, B.14, and B.15 are concerned with compression parallel to the grain, static bending, and hardness tests, respectively. The compression parallel to the grain tests were performed for strength in compression parallel to the grain (f_{c0}) determinations. The static bending tests were performed for the longitudinal modulus of elasticity (E), conventional strength value (f_m), and elastic limit (L_E) determinations. The hardness tests were performed in a perpendicular direction to the grain (f_{h90}) for Janka hardness determination.

Figure 2 shows the universal testing machines that were used for mechanical characterization. Figure 2a presents the EMIC (EMIC, São Paulo, Brazil) with a 30 kN capacity that was used for the static bending tests. Figure 2b shows the AMSLER (Alfred J Amsler Company, Schaffhausen, Switzerland) with a 25-ton capacity that was used for the compression parallel to the grain and hardness tests.

Figure 3 illustrates the mechanical tests performed. Figure 3a represents the static bending test, Fig. 3b illustrates the compression parallel to the grain test, and Fig. 3c shows the hardness test performed.

The modulus of elasticity for the aged samples was determined in two directions: the most aged surface in tension (E_T) and the most aged surface compression (E_C).

As a means to minimize wood variability and make a more general approach (regardless of the wood species), the relative mechanical performance of the wood samples was considered (ratio between mechanical performance of aged and control samples), which made it possible to evaluate only the aging effects.

To investigate any of the mechanical performance changes with the exposure time to the aging treatments, linear regression models were performed using the ordinary least squares method and tested using an analysis of variance (ANOVA) at a 5% significance level. The null hypothesis was the non-representativeness of the model (p-value > 0.05), and the otherwise, as an alternative hypothesis, the proven representativeness of the model (p-value < 0.05). For the statistical analysis the software R version 3.5.2 was used (R Foundation for Statistical Computing, version 3.5.2, Vienna, Austria).

(a) (b)

Fig. 2. Universal testing machines: (a) EMIC and (b) AMSLER

Linear regression models for the modulus of elasticities in static bending ($E_{T`}$ and $E_{C`}$), conventional strength value in static bending ($f_{m`}$), strength in compression parallel to the grain ($f_{c0`}$), hardness perpendicular to the grain ($f_{h90`}$), and the elastic limit in the static bending test (L_E) were performed for the natural and artificial aging treatments using relative values (ratio between control and aged sample performances - paired sampling).

For a better comparison of the natural and artificial weathering effects on the mechanical properties of the wood, boxplots of the relative values were made, as well as comparisons between the most aged relative mechanical performances (levels 3 – 384 hours of artificial weathering and 360 days of natural weathering) with the unitary populational average. This average comparison was made with Wilcoxon's test at the same significance level, in which a p-value greater than 5% implied the average equivalence, and non-equivalence otherwise (p-value less than 5%).

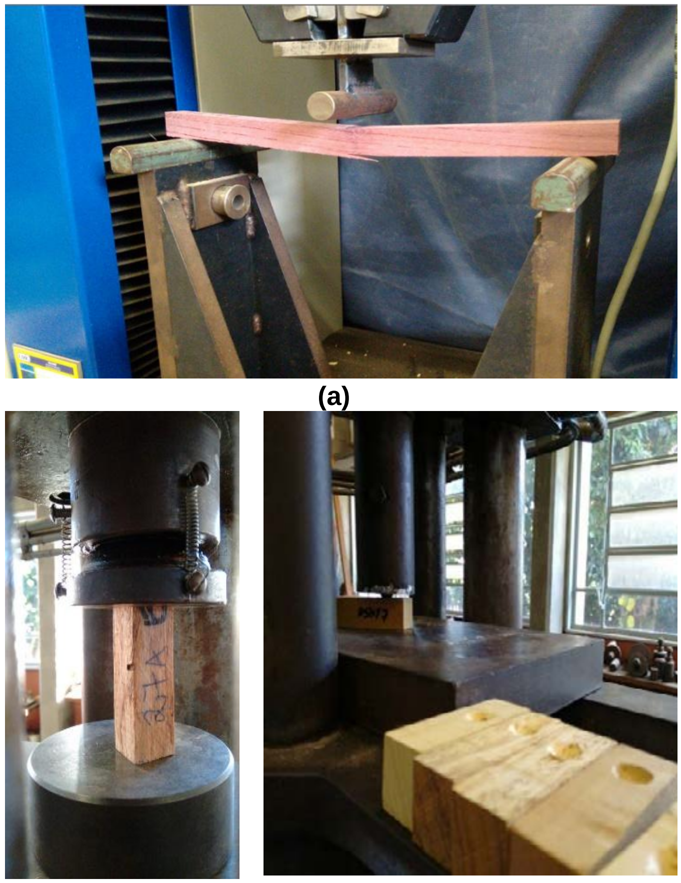
(a) (b) (c)

Fig. 3. Illustration of mechanical tests: (a) static bending, (b) compression parallel to the grain, and (c) hardness perpendicular to the grain

The decrease in relative mechanical performances as an effect of the aging treatments for the most aged wood samples (384 h of artificial aging and/or 360 days of natural aging) was determined using the confidence intervals of the adjusted linear models. Using these values helped to compare both weathering treatments based on the decrease in the mechanical performance that each treatment provided, and to calculate how many days of the natural aging treatment (at the same conditions) corresponded to one cycle of the artificial aging treatment (12 h).

RESULTS AND DISCUSSION

Meteorological data related to the temperature, relative air humidity, rainfall incidence, and solar irradiation at the natural weathering treatment location during 360 days of exposure were collected. Table 1 presents these results.

Table 1. Summary of Meteorological Data

Statistics	Average	CV (%)	Min	Max	Sum	Count
Temperature (°C)	18.26	14.89	11.20	23.70	-	90.00 (N1)
Relative air humidity (%)	72.17	21.32	43.50	100.00	-	
Rainfall incidence (mm)	2.87	258.58	0.00	34.30	258.40	
Solar irradiance (MJ/m²)	14.26	31.67	2.97	19.75	1283.55	
Temperature (°C)	19.51	15.97	11.20	28.30	-	180.00 (N2)
Relative air humidity (%)	68.81	21.55	36.80	100.00	-	
Rainfall incidence (mm)	2.25	277.82	0.00	34.30	405.60	
Solar irradiance (MJ/m²)	16.76	33.15	2.97	27.60	3016.65	
Temperature (°C)	21.06	14.24	11.20	28.30	-	360.00 (N3)
Relative air humidity (%)	73.14	18.10	36.80	100.00	-	
Rainfall incidence (mm)	4.03	221.28	0.00	48.80	1449.30	
Solar irradiance (MJ/m²)	18.87	31.73	2.97	31.46	6792.39	

In the southeast region of Brazil, there is high solar irradiation, high relative air humidity, and little variation in daily temperature. A total of 6792.39 MJ/m^2 in solar irradiation (approximately 437 J/s/m^2 for 12 h of radiation per day) covered the full range of wavelengths. For the artificial weathering treatment, the radiation used was concentrated only on UVB rays, which irradiated approximately 485 J/s/m^2 with lamps of 313 nm wavelength.

The relative values of the mechanical properties were calculated after performing mechanical characterization that determined the modulus of elasticities (E_T and E_C), conventional strength value in static bending (f_m), strength in compression parallel to the grain (f_{c0}), hardness perpendicular to the grain (f_{h90}), and the elastic limit in the static bending test (L_E), for the aged and control samples.

These relative values ($E_{T'}$, $E_{C'}$, $f_{m'}$, $f_{c0'}$, $f_{h90'}$, and $L_{E'}$) were used for linear regression model development of the mechanical performance of the wood by the exposure time to artificial or natural weathering treatments. Table 2 presents these linear regression models, where the “a”, “b”, R^2, and P-value represent the intercept, slope coefficient, coefficient of determination, and P-value of the ANOVA tests, respectively. In Table 2, the significant models have underlined P-values.

Table 2. Linear Regression Models Adjusted

Property	Weathering	a	b	R^2	P-value
$E_{T'}$	Artificial	0.9942	-0.0002	0.0406	<u>0.0003</u>
$E_{C'}$	Artificial	0.9942	-0.0002	0.0533	<u>0.0000</u>
$f_{m'}$	Artificial	0.9967	-0.0002	0.0136	<u>0.0269</u>
$f_{c0'}$	Artificial	0.9994	-0.0001	0.0040	0.1437
$f_{h90'}$	Artificial	1.0060	0.0001	0.0020	0.4520
$L_{E'}$	Artificial	1.0247	0.0004	<u>0.1083</u>	<u>0.0000</u>
$E_{T'}$	Natural	0.9875	-0.0003	0.0804	<u>0.0000</u>
$E_{C'}$	Natural	0.9875	-0.0003	0.0746	<u>0.0000</u>
$f_{m'}$	Natural	0.9743	-0.0004	0.0810	<u>0.0000</u>
$f_{c0'}$	Natural	0.9898	-0.0003	0.0473	<u>0.0001</u>
$f_{h90'}$	Natural	1.0050	-0.0001	0.0053	0.1126
$L_{E'}$	Natural	1.0310	0.0004	<u>0.1448</u>	<u>0.0000</u>

As shown in Table 2, only the $E_{T'}$, $E_{C'}$, $f_{m'}$, and $L_{E'}$ linear regression models were significant for the artificial weathering treatment (P-value < 0.05), which meant that the artificial aging influenced the mechanical properties of the wood. For natural weathering, the only model not influenced by the aging treatment was $f_{h90'}$ (p-value > 0.05), but it was significant for all other linear regression models.

Each adjusted linear regression model had 288 experimental data, among four exposure times (zero, level 1, level 2, and level 3) that negatively influenced the coefficient of determination due to the variability of mechanical performance changes with the aging treatments. The highest R^2 value for the artificial aging linear regression models was 10.83%, and the highest R^2 value for the natural aging linear regression models was 14.48%, which were both relative values from the elastic limit in the static bending tests.

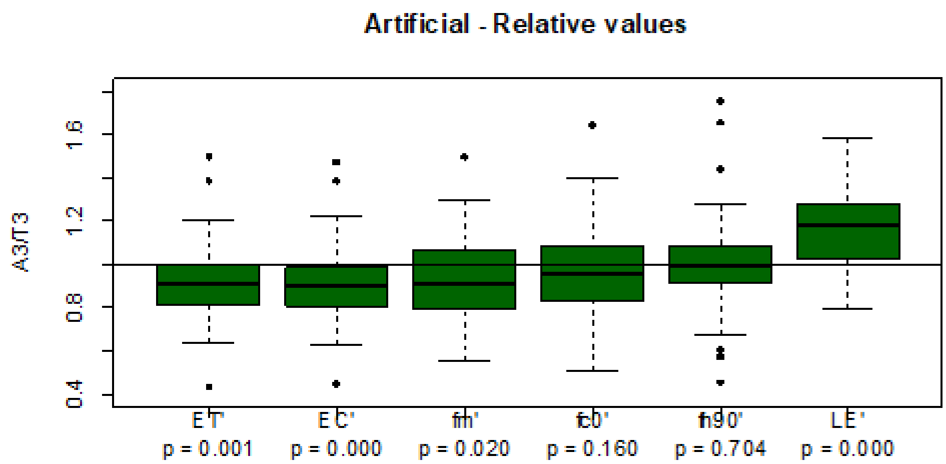

Fig. 4. Boxplots of relative values and Wilcoxon's tests for comparisons with the unitary populational average value for artificial aging

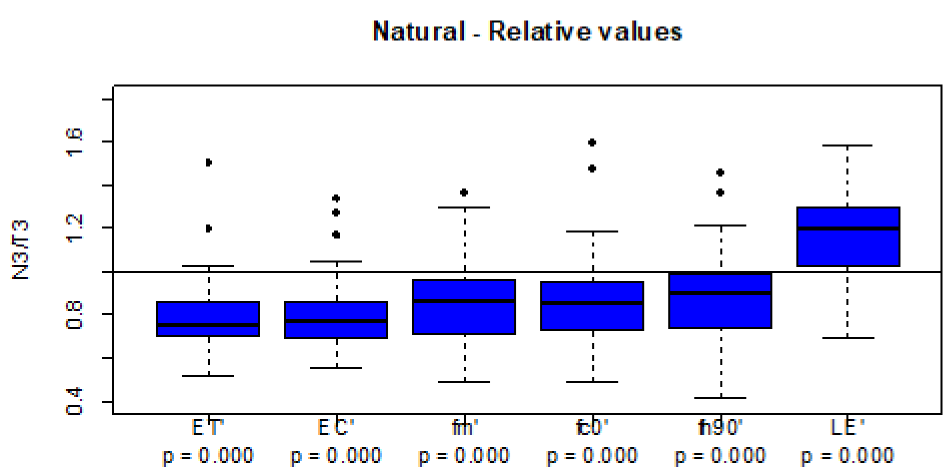

Fig. 5. Boxplots of relative values and Wilcoxon's tests for comparisons with the unitary populational average value for natural aging

For better comparisons of the aging effects on the mechanical performances of the wood, boxplots of $E_{T'}$, $E_{C'}$, $f_{m'}$, $f_{c0'}$, $f_{h90'}$, and L_E were made. Figures 4 and 5 show these boxplots for the artificial and natural aging treatments (only for level 3 in relation to the controls), respectively. T3 Stands by the control samples performances. Wilcoxon's tests were performed for comparing the average relative values of the mechanical properties with the unitary populational average at a 5% significance level. For Wilcoxon's tests, a p-value greater than 0.05 was the equivalence between the average relative value and the unitary populational average, and the non-equivalence otherwise.

As shown in Fig. 4 for the artificial weathering treatment, only $E_{T'}$, $E_{C'}$, $f_{m'}$, and $L_{E'}$ presented non-equivalent average values compared to the unitary populational average value, which confirmed that the artificial aging did not influence the strength in compression parallel to the grains and the hardness perpendicular to the grain of the considered wood species.

Figure 5 shows that all mechanical properties were influenced by the natural weathering treatment (p-value < 0.05). The properties $E_{C'}$, $E_{T'}$, and $f_{m'}$ decreased with artificial and natural aging, but the property $L_{E'}$ increased with the same treatments, which led to an increase in wood brittleness.

Table 3 presents the confidence intervals of the linear regression models of $E_{C'}$, $E_{T'}$, $f_{m'}$, and $L_{E'}$ for the artificial and natural weathering treatments for the third level (384 h or 360 days, respectively).

Table 3. Confidence Intervals of Linear Regression Models for Affected Wood Properties

Confidence Interval (95% Confidence Level)				
Property	Weathering	Lower Limit	Adjusted	Upper Limit
ET'	Artificial	0.8974	0.9266	0.9559
EC'	Artificial	0.8875	0.9168	0.9461
fm'	Artificial	0.8901	0.9342	0.9783
LE'	Artificial	1.1244	1.1599	1.1953
ET'	Natural	0.8267	0.8645	0.9023
EC'	Natural	0.833	0.8704	0.9078
fm'	Natural	0.7783	0.8243	0.8702
LE'	Natural	1.1529	1.1879	1.2229

Based on the adjusted value of the linear regression model presented in Table 3, it was possible to calculate the percentage change of $E_{C'}$, $E_{T'}$, $f_{m'}$, and $L_{E'}$ for both artificial and natural aging. Table 4 presents these results.

Table 4. Percentage Change of Mechanical Performance with Aging Treatments

Property	Artificial	Natural	Ratio
E_T	7.34%	13.55%	1.85
E_C	8.32%	12.96%	1.56
f_m	6.58%	17.57%	2.67
L_E	15.99%	18.79%	1.18
Average	9.56%	15.72%	1.81

As Table 4 shows, the effects of 360 days of the natural weathering treatment was comparable to the effects of 384 h of the artificial weathering treatment. The average ratio between the effects for E_T, E_C, f_m, and L_E (significant linear regression models) was 1.81. Furthermore, based on this value, 384 h of artificial weathering (32 cycles) provided the effect of approximately 199 days of natural aging and one cycle of artificial weathering (12 h) corresponded to approximately 6.22 days of natural weathering exposure (for the same conditions).

CONCLUSIONS

1. The results from using the entire range of strength classes of ABNT NBR 7190 (1997), a paired sampling approach, and relative values provided an understanding of the weathering effects on the mechanical properties of wood.
2. The statistical analysis performed in this study made it possible to observe mechanical performance changes of the wood with the exposure time to the artificial and natural weathering treatments.
3. The natural weathering was carried out for one year in São Carlos, São Paulo State, Brazil, which covered the four seasons of the year and provided more consistent results to compare with the cycles of the artificial aging treatment.
4. The mechanical performance of the wood decreased 15.7% after 360 days of the natural weathering treatment based on the significant linear regression models.
5. A 12-h cycle of the artificial weathering treatment provided the effects of 6.22 days of natural weathering.

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