Correlation between natural and artificial aging in particleboards

Correlação entre envelhecimento natural e artificial em painéis de partículas

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Abstract

The main objective of this work was to establish a correlation between natural aging with artificial aging in medium density particleboards produced with polyurethane resin of castor oil and *Pinus* sp. For such correlation, climatological parameters at São Carlos city, São Paulo state Brazil were used. The established correlation was that 20 cycles would be proportional to the same degradation of two months of exposure under natural aging. The relation between physical and mechanical properties with the effects provided by number of months (M) on the natural aging with number of cycles (Nc) on the artificial aging was obtained with cubical polynomial regression models. In general, for physical properties, 20 Nc represents 7 to 8 months and for mechanical properties, 11 to 12 months, with exception to internal bonding, with 8 months of natural aging. The equations which best represent the relation between Nc and M were thickness swelling at 2h and water absorption at 2 h and 24 h, with R above 93%.

Keywords: Natural aging. Artificaial aging. Mathematical models. Particleboards. Weathering.

Resumo

O principal objetivo deste trabalho foi estabelecer uma correlação entre o envelhecimento natural com o envelhecimento artificial em painéis aglomerados de média densidade produzidos com resina de poliuretano de mamona e Pinus sp. Para tal correlação, foram utilizados os parâmetros climatológicos da cidade de São Carlos, estado de São Paulo, Brasil. A correlação estabelecida foi que 20 ciclos seriam proporcionais à mesma degradação de dois meses de exposição ao envelhecimento natural. A relação entre as propriedades físicas e mecânicas com os efeitos proporcionados pelo número de meses (M) sobre o envelhecimento natural com número de ciclos (Nc) sobre o envelhecimento artificial foi obtida com modelos de regressão polinomial cúbica. Em geral, para propriedades físicas, 20 Nc representa de 7 a 8 meses e para propriedades mecânicas, de 11 a 12 meses, com exceção da tração perpendicular, de 8 meses de envelhecimento natural. As equações que melhor representam a relação entre Nc e M foram o inchamento em espessura às 2h e a absorção de água às 2h e 24h, com R^2 *acima de 93%.*

Palavras-chave*: Envelhecimento natural. Envelhecimento artificial. Modelos matemáticos. Painéis de partículas. Intemperismo.*

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Introduction

Wood panels, when exposed to weathering, undergo changes on physical and mechanical properties due to their production and exposure conditions. It is possible to submit particleboards to natural and artificial weathering. For artificial weathering, UV light, which causes chemical changes on wood, is controlled in laboratory, as well as temperature and moisture content, leading to a well-controlled process. Otherwise, for natural weathering, sunlight, temperature and humidity follows the local climate where the panels are located. The variations on particleboards are caused by combinations of several effects like moisture, sunlight, oxygen, atmosphere pollutants and microorganisms. When the sunlight and oxygen reach the wood, it leads to hemicellulose and lignin oxidation and cellulose depolymerisation (LIONETTO *et al.*, 2012).

For wood panels use under outdoor exposure, long-term performance and durability information are necessary. Also, performance under environmental conditions is needed. To obtain outdoor exposure data, long time experiments are mandatory, being difficult to perform such tests and the information reached by them represents the conditions for determining climate. On the other hand, artificial tests can cause changes in the mechanical and physical properties, and such tests are superior to short-term outdoor exposure tests. Besides, it may determinate the durability of wood-based panels (KOJIMA; SUZUKI, 2011a).

On the literature, some researches evaluated natural conditions and their effects on particleboards under outdoor exposure. Also, which is the correlation between natural exposure and artificial weathering.

Kojima and Suzuki (2011a) evaluated the effects of accelerated aging treatments on the bending properties of structural panels. Four groups of panels were used, being particleboard (PB), plywood (PW), MDF and OSB, in which each group had two types of differing specifications for a total of eight panels with difference between thickness, wood and binder (MDI or PF). The accelerated aging was performed in five ways: cyclic JIS-B, Cyclic APA D-1, V313, ASTM six-cycle and vacuum pressure soaking and drying (VSPD), and the treatment has been carried out one, three and six times. Also, the panels were exposed for 5 years of outdoor exposure in Japan. For each accelerated aging treatment, the bending properties decreased exponentially with increasing of cycles. In the outdoor exposure after 5 years the bending properties of OSB (pine), PB (PF) and OSB (aspen) were less than 40%, 30% and 10%, respectively. In contrast with the MDI-bonded boards, which maintained high bending properties in the same period than the PF-bonded panels. Authors performed the correlations between accelerated aging treatments and outdoor exposure for five years using bending properties. The results showed good correlation (R between 0.82 and 0.95). The bending properties after six cycles of the JIS-B, APA D-1 and ASTM treatments showed a nearly one-to-one correspondence. The authors concluded the six repetitions of the ASTM treatment can be correlated to 5 years of outdoor exposure.

Bertolini *et al.* (2013) worked with particleboards from *Pinus* sp. impregnated with CCB and castor oil resin under accelerated artificial aging. The panels were produced with different particle mass, resin content and pressing time, resulting in eight treatments. After physical and mechanical properties characterization, B and G treatments were chosen to undergo artificial accelerated aging. Such treatments were taken because their results met normative requirements with lowest (B) and highest (G) resin consumption in their production, respectively. The tests were carried out following the American standard G154 (AMERICAN..., 2006) on Atlas Weather-Ometer Equipment, model XW 65-WR1, working with xenon lamp at 6,500 W. The cycle was 55 days (1,200 h) in the equipment, time equivalent to one-year age, according to manufacture information. The results obtained by statistical analysis (ANOVA) showed no difference on MOR for both panels compared with non-aged panels, opposite to MOE, in which the results were different. But the results for B and G panels showed the better performance for MOR and MOE after aging. The results in the non-age and aging panels for MOR and MOE in the B panels were 23 and 26 MPa, and 2,297 and 3,185 MPa, respectively; and for G panels were 29 and 30 MPa, and 2,963 and 3,456 MPa, respectively.

Not all of the factors of weathering can be recreated in an accelerated chamber. However, there is a large number of other variables that may cause an incorrect result, and therefore lead to a wrong conclusion. Number of cycle times and the effect on the exposed specimens are different between the outdoors and on chamber. Over-exaggerated test conditions may also cause the wrong failure type (CREWDSON, 2017).

Also, considering the major use of medium density particleboards on civil construction, with possibility for use on structural purpose and non-structural purpose (BUZO *et al.*, 2020; MACEDO *et al.*, 2019; POLETO *et al.*, 2020; SILVA *et al.*, 2021; YANO *et al.*, 2020), it is important to evaluate the behavior of medium density particleboards under weathering and its performance along their lifespan.

Considering the literature review, there are several test methodologies. Also, there is no work on the literature which correlates natural weathering and artificial weathering for the Equilam Machine by calculation for a specific place. The other important factor is that the cost of maintenance of an Equilam Machine is lower than the Weather-Ometer.

In this line, the main objective on this research is to establish a correlation between artificial aging in an Equilam Machine (EQUV-RC) and natural weathering based on the climatological parameters at São Carlos city, São Paulo state, Brazil. Also, based on the physical and mechanical properties after almost 2 years in the natural aging, establishes a correlation between the number of cycles in the artificial aging and time on natural weathering.

Materials and methods

Particleboard production and natural and artificial aging tests were performed at Laboratory of Wood and Structures in wood (LaMEM), Department of Civil Engineering, at the University of São Paulo, in São Carlos city, Brazil.

The particleboard was manufactured with *Pinus* sp. Residue, using nominal density of 0.75 $g.cm^{-3}$, with thickness of 10 mm and bicomponent polyurethane (PU) resin was used as matrix phase. The resin was obtained by company Plural Chemistry, at São Carlos, and it is composed by castor oil and 4,4′-diphenylmethane di-isocyanate oil (MDI). The use of castor oil based bicomponent polyurethane resin lies on the improved performance of physical and mechanical properties when compared with formaldehyde based resins (BUZO *et al*., 2020; POLETO *et al*., 2020; SILVA *et al*., 2021; YANO *et al*., 2020). Initially, the particles were crushed to reach waste homogeneity on a knife mills, produced by Lafrance Company, SG 230F model with a 10 mm sieve. The granulometry of wood particles ranged between 2 mm to 6 mm. After this step, the particles were glued with 12% of PU resin in relation to the wood mass. The gluing process was carried out with an electric mixer model BP 38-C, produced by G-Paniz Company for ten minutes. For adequate distribution of resin in the wood particles the polyurethane resin was added slowly on the mixture. The next step was forming a mattress in a small hydraulic press with 0.01 MPa of pressure, with particleboards distributed in multi layers, in order to simulate commercial particleboards. After, the mattress was pressed in a semi-automatic press with hot plates, MA 098/50 model, produced by Marconi Company, with 4 MPa of pressure, at 100ºC, for ten minutes. Then, the panels were unfolded after 72h of curing time.

Physical and mechanical properties were obtained in accordance with the Brazilian Standard NBR 14810-2 (ABNT, 2018). The size of samples for the thickness swelling (TS), water absorption (WA), internal bonding (IB) and for bulk density (ρ) were 5 cm x 5 cm x 1 cm. For strength (MOR) and stiffness (MOE) properties in bending the size of samples were 25 cm x 5 cm x 1 cm.

On natural weathering (Figure 1), the samples were cut and put on a grid at 45º of inclination, in Ecuador direction, following the prescription of Battistelle *et al*. (2005). The climatological parameters of solar radiation, annual precipitation, temperature and relative humidity were obtained by site Embrapa Southeast Livestock (EMPRESA..., 2017).

Figure 1 – **Samples under natural weathering**

The artificial weathering was carried out following the G154 (AMERICAN..., 2006) and researches of Nascimento (2003, 2014), Bertolini (2011), Varanda (2012), and Silva (2014). The machine utilized for aging chamber – UV, Equilam Machine (EQUV-RC) with the following characters in accordance of manufacturer:

(a) accelerated deterioration;

(b) loss of brightness;

(c) embrittlement of materials through the UVA – UVB irradiation;

(d) condensation;

(e) thermal sock;

(f) meeting standards ASTM;

(g) DIN;

(h) EN;

(i) ISO;

(j) ABNT; and

(k) others.

The irradiation parameters and others are controlled automatically after programming.

In this work, one of the purposes was to define correlation between the artificial weathering cycle and natural aging data. To perform such correlation, one artificial weathering cycle was defined based on "Weathering Testing Guidebook", found at Atlas Electric Devices Company (2001), G154 (AMERICAN..., 2006) and the climatological parameters by Embrapa Southeast Livestock (2017).

In order to establish a relation between artificial weathering cycles and natural aging, Atlas report (ATLAS..., 2001) illustrate a case in south Florida, USA, considering an annual mean UV radiant exposure (295-385 nm) equal to 280MJ/m^2. On an artificial aging machine, irradiance is controlled at a narrow wavelength range on an artificial aging test machine. In this case, the test was conducted at 0.35W/m^2 at 340 nm. Radiant exposure is irradiance integrated over time, following equation: W/m^2 x time (s) = J/m^2. On an artificial aging test machine, radiant exposure is normally measured in kJ/m^2, so joules (J) must be converted to kilojoules (kJ): 1 J/m^2 = 0.001 kJ/m^2. Artificial weathering tests are in h: 3600 s = 1 h. Now, with all conversions performed, it is possible to obtain the following equation: kJ/m^2 = W/m^2 x 3.6 x h. Considering that irradiance is controlled on an artificial aging test machine at 340 nm wavelength band, radiant exposure at this wavelength band must be converted to that UV range measured at outdoor exposure sites. For general purposes, the energy contained in the 340 nm wavelength range is approximately one percent of this UV range. Knowing this, the following conversion can be made: 10 kJ/m^2 (340 nm) = 1 MJ/m^2 (295 – 385 nm).

With these considerations made, the information from UV radiant exposure from south Florida are now inserted into the equation shown above to get a general idea about radiant exposure levels at specific irradiance set point: 2,800 kJ/m^2 (340 nm) = 0.35 W/m^2 (340 nm) x 3.6 x h.

After calculation, the number of light hours h equals to 2222. The conclusion of this methodology is that 2222 h on an artificial aging test machine, with radiation of 0.35 w/m^2, at 340 nm, is equivalent to the degradation of one-year natural exposure in south Florida, USA.

For both particleboards' samples under natural and artificial weathering, no coating was provided during weathering process, such as varnish or plastic layer, aiming to submit the particleboards to the most severe conditions on weathering.

Statistical analysis was conducted using the software Minitab 16. After physical and mechanical properties characterization, the results were compared between the different cycles of artificial aging using analysis of variance (ANOVA) and the Tukey test at 95% confidence interval.

After natural and artificial aging results were obtained, the correlation between natural and artificial were made using a mathematical model which could predict the number of artificial aging cycles in function of number of months under natural aging.

The period of natural exposure was 22 months. Each two months, 8 samples were removed to evaluating. In this line, twelve batches were analysed, including reference batch. The properties of bulk density (ρ), thickness swelling (TS) for 2 and 24 h, water absorption (WA) for 2 and 24h, internal bonding (IB), bending strength (MOR) and bending stiffness (MOE) were performed. Thus, 768 experimental determination with natural aging were performed. For artificial aging, 20 cycles were carried out. On each two cycles, samples were removed for evaluation, totalizing ten treatments for artificial aging. For each treatment, there were 6 samples. In this manner, there were 480 experimental determinations.

With the results in three conditions (natural aging, artificial aging and reference), cubic polynomials regression models (Equations 1 and 2) were initially utilized to relate the physical and mechanical properties with the effect provided by number of natural aging months and by number of cycles of artificial aging, also considering results of the references.

$$Y_{Nat} = a_{Nat} + b_{Nat} \cdot M + c_{Nat} \cdot M^2 + d_{Nat} \cdot M^3 \quad \text{Eq. 1}$$

$$Y_{Art} = a_{Art} + b_{Art} \cdot Nc + c_{Art} \cdot Nc^2 + d_{Art} \cdot Nc^3 \quad \text{Eq. 2}$$

In the Equation 1, Y_{Na}t represent the physical or mechanical properties estimate in function of natural aging (Nat); aNat, bNat, cNat e dNat are coefficients obtained by least squares method and M is the number of months that samples were exposed to natural aging. The meaning of terms of Equation 1 extended to Equation 2, in which the physical or mechanical properties (Y_{Art}) are related by effect number of cycles (Nc) in the artificial aging (Art). Beyond regression models, the quality of adjustment was evaluated by R square (R^2). It should be noted that linear, quadratic, cubic, exponential, logarithmic and geometric polynomial models were tested; however, the cubic polynomial models showed the best result to correlation between Nc and M.

The equality between Equations 1 and 2 correlates number of months in natural aging (M) with the number of cycles in artificial aging (Nc) and the Equation 3 is obtained:

$$a_{Nat} + b_{Nat} \cdot M + c_{Nat} \cdot M^2 + d_{Nat} \cdot M^3 = a_{Art} + b_{Art} \cdot Nc + c_{Art} \cdot Nc^2 + d_{Art} \cdot Nc^3 \quad \text{Eq. 3}$$

Once the adjustment coefficients for physical and mechanical properties are known, the values of cycles number in artificial aging (Nc) are replaced in Equation 3 resulting cubic equations with variable M (number of months), whose roots allow to relate the number of cycles with the number of months by physical or mechanical property investigated. The solution chosen between the three roots real in the cubic equation was performed based on the standard of evolution of M with number of cycles. Being excluded roots complex and the real negative, and with ten relations between Nc and M for each property, the best adjustments between the model tested (linear, quadratic, cubic, exponential, logarithmic) for each property were utilized to estimate the relation between Nc and M for any values of these variables of 0 until 20 cycles of artificial aging.

Results and discussions

With the results of the climatological parameters of solar radiation, annual precipitation, temperature and relative humidity obtained by site Embrapa Southeast Livestock (EMPRESA..., 2017) in the period between of June 1st, 2015 to May 31st, 2017, at São Carlos, São Paulo state, Brazil, the cycles of artificial aging were defined, thus establishing correlation between natural and artificial aging.

Initially, the solar radiation of the year in study of outdoor exposure was 6,024.33 MJ/m^2. Of the total energy of the solar spectrum calculated from one year, approximately 4% is derived from ultraviolet radiation, as described on Atlas (ATLAS..., 2001) and Silva (2008). Thus, the energy accumulated of the ultraviolet radiation in one year of exposition was 241 MJ/m^2. To calculate the equivalence between artificial aging and natural aging was following the methodology described in the Weathering Testing Guidebook (EMPRESA..., 2017). The results found were 956.35 h. This means that this would be the time required for the specimens to be exposed to the artificial radiation in order to have the degradation similar to one year of natural aging. However, the samples were retired of the natural aging each two month, for this reason this value was divided by six to have the number of h each two month, and this value was 155.65 h. Thus, the solar degradation in the natural aging for two months is similar to the degradation in the artificial aging by 6.64 days.

The time of the cycle in the artificial aging in the G154 (AMERICAN..., 2006) standard is eight h to radiation in UVB lamps. For this reason, it was adopted in this work the same time for radiation in one cycle. Thus, it was divided the number of h similar two months of outdoor exposition by eight, and the result was 19.92 cycles, approximately 20 cycles.

For definition, the water spray time was calculated by the volume of spray water in the machine Equilam in square meters by one minute. The result was 14.62 L/m^2.min. Considering this value, it was possible to stabilize correlation with annual precipitation. The precipitation in the period considered was 1,813 L/m^2. Thus, the precipitation at two months was 302.17 L/m^2, and this value was divided by 20 cycles for two months of radiation solar, in which the result was 15.11 L/m^2. This value was divided by volume of spray water the machine Equilam in square meters by one minute and the results was 1.03 min by cycles. In this line, the time of spray was defined in 1 min, or 0.02h.

To relative humidity, in condensation phase, the Equilam machine works with a humidity minimum of 95% like described by manufacturer. For this reason, it was the moisture adopted in this work, because there was no possibility of change. It is important to know that the humidity average in the period considered for natural aging was 77.94%.

The time of condensation and spray in the G154 (AMERICAN..., 2006) standard is 3.75 h and 0.25 h, respectively. Considering the results obtained in this work, it was defined that the time of condensation was 3.98 h, and the time of spray was 0.02 h.

The average temperature in the period considered was 21.63 ºC. The Equilam machine was programmed to work in this temperature, but it was impossible because the heat of the UVB lamps increased the internal temperature of camera, and for this reason the machine triggered a written alarm “Camera does not heat in UV mode” and the machine stopped working. To solve this problem working in larger temperature was necessary. For this, the lowest temperature that was possible to work was at 42 ºC. For this reason, this temperature was adopted in this work.

Summarizing, one cycle in the artificial aging in the Equilam machine had 12 h, following this manner:

(a) 8 h in UVB lamps, with irradiance of 0.70 W/m^2 (313 nm) at temperature 42 ºC;

(b) 0.02 h of spray; and

(c) 3.98 h of the condensation at temperature 42 ºC.

With parameters for one cycle defined, it was decided that the samples underwent 20 cycles in the aging artificial, equal to two-month outdoor exposure. Also, each two cycles the samples were analysed. Thus, 2Mart and 4Mart means that these samples suffered two and four cycles in the artificial aging, respectively. This decision was made considering researches on the literature (NASCIMENTO, 2003, 2014; BERTOLINI, 2011; VARANDA, 2012; SILVA, 2014).

Considering the mean values of bulk density, the reference value was classified as “medium density” according to the American standard [A 208.1(AMERICAN..., 2009)] (0.8 g.cm^{-3}). This classification is important because, according to Bertolini (2011), panels properties are related to density. In general, the density was decreasing over time. Such behavior may have occurred by the loss of raw material in the outer layers, where there was no coating protection and sample expansion. The results of statistical analysis showed that only after 12 months (batch 6M), the density presented significant changes in natural aging. The same did not happen with artificial aging, with all treatments were statically equals to reference.

Observing water absorption results for natural aging on Table 1, there was a reduction only in the treatments 1M and 2M after 24h. The results for other batches were larger in relation to reference.

Observing the results of thickness swelling on natural aging, Tukey test illustrate that batches 1M, 2M, 3M, 10M e 11M are similar to reference value after 2h, and the batches 2M, 3M, 4M, 5M, 6M, 7M, 8M and 9M are similar to the reference after 24h.

According to Table 1, water absorption results demonstrate that treatments 1M and 2M are similar to the reference value after 2h. After 24h, the treatments similar to the reference are 1M, 2M, 3M, 5M and 11M.

Such behavior may be explained by wetting and drying cycles on particleboard, leading to a permanent swelling on panel. Drying process occurs without the external pressure and temperature initially used on panel manufacturing and covalents bonds are broken due to swelling stress and are not reformed (BACK; SANDSTROM, 1982). Also, ultraviolet radiation (UV) starts chemical decomposition on wood, forming free radicals which mainly attack wood components such lignin, hemicellulose and extractives (PASTORE *et al.*, 2008).

Considering the results presented on Table 2, most treatments presented statistically equivalent results to reference value for all physical properties.

The Brazilian Standard NBR 14810 (ABNT, 2018) recommends not more than 8% in the thickness swelling results after 2h. All the results in natural and artificial aging obtained after 2h were lower that recommendation by Brazilian Standard.

Nascimento (2003) reached thickness swelling results of 21% for *Eucalyptus* particleboards. Dias (2005) analyzed particleboards produced with *Eucalyptus urophilla* and *Eucalyptus grandis* and found results of thickness swelling between 19 and 23%. The results obtained by Zau *et al*. (2014) for Cumaru particleboards produced with castor oil polyurethane resin were 0.58 and 0.77% for 2h, between 2.11 and 4.75% for 24h, with density between 0.82 and 1.0 g.cm-3. In general, the results found in this research were similar to the literature.

Table 3 and 4 presents the mean values and Tukey test results for strength (MOR) and stiffness (MOE) properties on static bending and internal bonding (IB), for natural aging and artificial aging, respectively.

The Brazilian Standard NBR 14810 (ABNT, 2018) and American standard A 208.1 (AMERICAN..., 2009) establish static bending strength (MOR) and stiffness (MOE) equal to 11 MPa and 1800 MPa, respectively. Considering this, the results on Table 3 are satisfactory.

Table 1 – **Physical properties for samples under natural aging**

Bulk density			Thickness swelling				Water absorption			
Batch	**ρ ($g.cm^{-3}$)[1]**	**Tukey[2]**	**2 h Mean (%)[1]**	**Tukey[2]**	**24 h Mean (%)[1]**	**Tukey[2]**	**2 h Mean (%)[1]**	**Tukey[2]**	**24 h Mean (%)[1]**	**Tukey[2]**
Test	0,80 ± 0,04	A	3,1 ± 1,4	DEF	6,5 ± 1,9	ABC	5,3 ± 3,2	E	24,1 ± 13,7	CD
1M	0,79 ± 0,03	AB	2,3 ± 0,8	EF	3,8 ± 1,0	DE	5,8 ± 1,5	E	13,8 ± 2,5	D
2M	0,80 ± 0,03	AB	4,3 ± 1,9	CDE	4,8 ± 2,0	CD	13,0 ± 10,4	DE	23,5 ± 14,4	CD
3M	0,77 ± 0,05	ABC	4,9 ± 1,6	BCD	4,5 ± 1,3	CD	23,9 ± 15,8	CD	31,3 ± 13,6	BC
4M	0,77 ±0,03	ABC	5,4 ± 1,2	ABC	6,4 ± 0,7	ABC	39,4 ± 8,4	AB	44,8 ± 8,3	AB
5M	0,79 ± 0,04	AB	4,4 ± 1,9	CD	5,2 ± 0,8	CD	23,7 ± 9,7	CD	32,8 ± 7,9	BC
6M	0,73 ± 0,05	C	7,5 ± 0,9	A	8,3 ± 0,8	A	45,6 ± 10,1	AB	49,5 ± 8,7	A
7M	0,72 ± 0,02	C	7,0 ± 0,9	AB	7,9 ± 0,6	AB	44,4 ± 12,1	AB	49,7 ± 9,5	A
8M	0,74 ± 0,03	BC	6,6 ± 1,4	AB	7,7 ± 1,3	AB	48,5 ± 3,3	A	53,2 ± 3,0	A
9M	0,76 ± 0,03	ABC	5,4 ± 0,7	ABC	6,0 ± 1,4	BC	40,8 ± 5,8	AB	45,7 ± 4,4	AB
10M	0,73 ± 0,04	C	1,0 ± 0,8	F	1,6 ± 1,2	F	41,5 ± 6,3	AB	45,7 ± 5,6	AB
11M	0,77 ± 0,03	ABC	1,4 ± 1,0	F	2,1 ± 1,2	EF	32,7 ± 10,2	BC	37,8 ± 8,6	ABC

Note: [1]Values are mean ± standard deviation (SD); and [2]Means followed by the same letter are not significant (Tukey α = 5%).

Table 2 – **Physical properties of samples under artificial aging**

Bulk density			Thickness swelling				Water absorption			
Batch	**ρ ($g.cm^{-3}$)[1]**	**Tukey[2]**	**2 h Mean (%)[1]**	**Tukey[2]**	**24 h Mean (%)[1]**	**Tukey[2]**	**2 h Mean (%)[1]**	**Tukey[2]**	**24 h Mean (%)[1]**	**Tukey[2]**
Test	0,80 ± 0,08	A	3,1 ± 1,4	A	6,5 ± 1,9	AB	5,3 ± 3,2	B	24,1 ± 13,7	B
2Mart	0,79 ± 0,03	A	3,2 ± 1,9	A	7,4 ± 2,0	AB	9,6 ± 6,4	B	27,2 ± 13,1	B
4Mart	0,84 ± 0,08	A	4,8 ± 2,4	A	7,0 ± 4,0	AB	13,1 ± 11,5	B	24,5 ± 15,8	B
6Mart	0,78 ± 0,05	A	1,7 ± 2,5	A	3,5 ± 2,3	B	24,0 ± 11,4	B	34,0 ± 8,6	B
8Mart	0,77 ±0,04	A	3,2 ± 1,6	A	6,5 ± 2,5	AB	22,0 ± 10,2	B	39,0 ± 7,4	B
10Mart	0,83 ± 0,08	A	4,5 ± 3,0	A	8,6 ± 1,8	A	19,6 ± 17,8	B	35,7 ± 18,0	B
12Mart	0,76 ± 0,06	A	5,5 ± 3,3	A	7,5 ± 1,2	AB	51,8 ± 19,0	AB	67,3 ± 14,0	AB
14Mart	0,84 ± 0,05	A	3,9 ± 1,6	A	6,7 ± 1,6	AB	13,8 ± 11,7	B	25,6 ± 10,9	B
16Mart	0,77 ± 0,04	A	3,7 ± 1,8	A	6,4 ± 1,1	AB	17,9 ± 4,5	B	35,8 ± 10,5	B
18Mart	0,84 ± 0,03	A	3,8 ± 1,0	A	7,3 ± 2,1	AB	13,1 ± 5,4	B	27,4 ± 8,8	B
20Mart	0,77 ± 0,09	A	5,4 ± 2,5	A	6,6 ± 2,2	AB	27,2 ±15,2	B	40,7 ± 15,2	B

Note: [1]Values are mean ± standard deviation (SD); and [2]Means followed by the same letter are not significant (Tukey α = 5%).

Table 3 – **Mechanical properties of samples under natural aging**

Batch	MOR (MPa)[1]	Tukey[2]	MOE (MPa)[1]	Tukey[2]	IB (MPa)[1]	Tukey[2]
Test	20,6 ± 2,1	A	2050 ± 233	B	3,3 ± 0,2	A
1M	20,2 ± 1,9	A	1697 ± 172	BC	2,7 ± 0,6	AB
2M	18,8 ± 2,5	A	1477 ± 138	CD	2,4 ± 0,2	BC
3M	22,7 ± 4,6	A	2650 ± 571	A	2,1 ± 0,6	BC
4M	14,1 ± 2,3	B	1141 ± 165	DE	2,0 ± 0,5	BC
5M	12,0 ± 1,4	BC	955 ± 159	EF	1,3 ± 0,5	DE
6M	12,5 ± 3,0	BC	1102 ± 297	DEF	1,3 ± 0,1	DE
7M	11,7 ± 2,6	BC	882 ± 255	EFG	1,7 ± 0,7	CD
8M	11,5 ± 1,8	BC	861 ± 159	EFG	1,3 ± 0,3	DE
9M	9,4 ± 2,1	CD	727 ± 131	FGH	0,9 ± 0,2	E
10M	5,3 ± 0,6	E	405 ± 41	H	0,8 ± 0,1	E
11M	7,0 ± 1,0	DE	493 ± 73	GH	1,0 ± 0,4	E

Note: [1]Values are mean ± standard deviation (SD); and [2]Means followed by the same letter are not significant (Tukey α = 5%).

Table 4 - **Mechanical properties of samples under artificial aging**

Batch	MOR (MPa)[1]	Tukey[2]	MOE (MPa)[1]	Tukey[2]	IB (MPa)[1]	Tukey[2]
Test	20,6 ± 2,1	A	2050 ± 233	A	3,3 ± 0,2	A
2Mart	14,2 ± 6,5	B	1319 ± 626	B	1,6 ± 0,8	BC
4Mart	11,9 ± 2,4	B	1111 ± 206	B	0,7 ± 0,5	C
6Mart	10,9 ± 2,1	B	1013 ± 232	B	0,8 ± 0,6	C
8Mart	13,8 ± 3,4	B	1261 ± 223	B	1,6 ± 0,7	BC
10Mart	12,4 ± 1,9	B	1089 ± 152	B	1,5 ± 0,4	BC
12Mart	9,1 ± 2,8	B	799 ± 270	B	1,2 ± 0,5	C
14Mart	13,0 ± 2,1	B	1100 ± 146	B	1,7 ± 0,4	BC
16Mart	12,7 ± 3,5	B	991 ± 249	B	2,4 ± 0,5	AB
18Mart	13,4 ± 1,2	B	1164 ± 152	B	2,4 ± 0,5	AB
20Mart	11,4 ± 3,6	B	1038 ± 338	B	1,7 ± 0,6	BC

Note: [1]Values are mean ± standard deviation (SD); and [2]Means followed by the same letter are not significant (Tukey α = 5%).

Besides, the results obtained in the mechanical properties have been modified in the natural and artificial aging. In the MOR and MOE, the modifications were more pronounced in the natural aging, in which, in general, there was a larger reduction in the results. Statistical analyses showed that, in the MOR, groups 1M, 2M and 3M were statistically similar with a reference in the natural aging. Only the batch 1M was statically similar to reference in the stiffness property (MOE) on static bending for natural aging, whose variability in the statistical analyses was greater than MOR.

In the artificial aging, there was no group statistically similar to the reference, but all the groups under artificial aging were statistically similar, thus, showed stability in the results along the time in the MOR and MOE.

The results in 3M batch under natural aging were larger than other batches, including reference value for MOR and MOE. It may be explained by a strengthening on first aging phase. Radiation, especially U.V. rays, has a catalytic effect on chemical reactions, especially autoxidation and free radicals formation (BACK; SANDSTROM, 1982). Radiation acts mainly in the surface layer of panel on outdoor exposure. Due to these reactions, generally the strength properties may improve and later strength properties slowly reduce by covalent bond breaking in wood and resin components.

Kojima and Suzuki (2011a) evaluated the effects of accelerated aging treatments on the bending properties of structural panels (particleboard (PB), plywood (PW), MDF and OSB) were exposed for 5 years outdoor exposure in Japan. The accelerated aging was carried out in five methods: cyclic JIS-B, Cyclic APA D-1, V313, ASTM six-cycle and vacuum pressure soaking and drying (VSPD). For each accelerated aging treatment, static bending properties (MOE and MOR) decreased exponentially with increasing of cycles. In the outdoor exposure after 5 years, static bending properties of OSB (pine), PB (PF) and OSB (aspen) were less than 40%, 30% and 10%, respectively, when compared to the reference values.

Varanda (2012) analysed artificial aging in particleboards produced with *Eucalyptus grandis* and oats bark. The weathering was performed following the recommendations of APA PRP 108 (ENGINEERED..., 1994), Cycle APA D-1. After the test, the samples presented cracks and delamination. Also, significant reduction on physical and mechanical properties.

The Brazilian Standard NBR 14810 (ABNT, 2018) and American Standard A 208.1 (AMERICAN..., 2009) establish minimum values of 0,4 MPa e 0,49 MPa for internal bonding (IB), respectively. Thus, all results obtained in this work for natural and artificial aging are satisfactory in all batches and cycles. In the natural aging only the 1M batch was statistically similar to the reference.

Kojima and Suzuki (2011b) evaluated the internal bond strength (IB) after 5 years of outdoor exposure and five different cycles on the artificial aging. On each accelerated aging test, the IB retention of MDI-bonded panels showed high retention compared to other panels. Outdoor exposure in Shizuoka City resulted in an IB retention value for particleboard (PF) and oriented strand board (aspen) of less than 10% after the 5-year exposure period when compared to reference value. Medium-density fiberboards maintained their initial IB strength over the same period. The results of the mean IB retention for all board types allowed to compare the severity of aging between the accelerated test methods and outdoor exposure. The ASTM six-cycle test method was the most severe among the standard treatment cycles applied.

Table 5 shows the regression models results obtained by estimating physical and mechanical properties in function of natural and artificial aging.

For natural aging (Y_{Nat}), the best results were from MOE and internal bonding with results of 91% for R . The results for MOR and water absorption were higher than 84% for R . And for density and thickness swelling were bigger than 73% for R . In the artificial aging (Y_{Art}), the results from internal bonding, thickness swelling after 2 h and water absorption after 24 h were above 80% for R . The results from density and MOE were close to 80% for R and MOR had R^2 at 75%. The dispersion results from thickness swelling and water absorption were too big and for this reason the models were inaccurate.

The equivalence between cycle number (artificial aging, Nc) and month number (natural aging, M) in the mechanical and physical properties are shown in Table 6.

Table 5 – **Regression models results from particleboards**

Properties	$Y_{Nat}=a_{Nat}+b_{Nat}\cdot M+c_{Nat}\cdot M^2+d_{Nat}\cdot M^3$				
	a_{Nat}	b_{Nat}	c_{Nat}	d_{Nat}	R^2(%)
TS 2h	2.759	0.0924	0.05130	-0.002750	77.7
TS 24h	5.802	-0.7328	0.1273	-0.004759	73.5
WA 2h	3.119	2.575	0.1749	-0.01052	88.4
WA 24h	19.50	0.260	0.3324	-0.01404	84.3
ρ	0.7964	0.002110	-0.000907	0.000032	78.2
MOR	21.25	-0.2627	-0.05637	0.001716	85.9
MOE	1,998	-122	4.791	-0.1142	91.1
IB	3.254	-0.2574	0.01139	-0.000210	91.6
Properties	$Y_{Art}=a_{Art}+b_{Art}\cdot Nc+c_{Art}\cdot Nc^2+d_{Art}\cdot Nc^3$				
	a_{Art}	b_{Art}	c_{Art}	d_{Art}	R^2(%)
TS 2h	2.957	0.2490	-0.02201	0.000755	80.2
TS 24h	6.555	0.3164	-0.02665	0.000658	65.9
WA 2h	3.564	4.387	-0.3260	0.008010	68.6
WA 24h	23.41	1.345	0.0481	-0.003560	80.5
ρ	0.7986	-0.002327	-0.000452	0.000030	79.3
MOR	19.98	-2.693	0.2511	-0.006879	75.8
MOE	1,917	-252.2	21.24	-0.5424	79.3
IB	3.089	-0.8145	0.08856	-0.002557	80.3

Table 6 - **Relation between cycle numbers and month numbers in analyzed properties**

Properties	Numeric relations between Nc and M										
TS 2h	Nc	2	4	6	8	10	12	14	16	18	20
	M	2.84	3.66	3.82	4.41	4.59	4.80	5.10	5.59	6.35	7.49
TS 24h	Nc	2	4	6	8	10	12	14	16	18	20
	M	16.25	14.40	-	-	-	-	-	-	-	-
WA 2h	Nc	2	4	6	8	10	12	14	16	18	20
	M	2.68	4.25	5.23	5.80	6.07	6.14	6.13	6.15	6.29	6.70
WA 24h	Nc	2	4	6	8	10	12	14	16	18	20
	M	4.56	5.76	6.88	7.92	8.85	9.64	10.22	10.51	10.43	9.92
ρ	Nc	2	4	6	8	10	12	14	16	18	20
	M	3.99	5.86	7.47	8.82	9.79	10.21	9.85	8.49	5.63	-
MOR	Nc	2	4	6	8	10	12	14	16	18	20
	M	9.03	12.18	13.83	14.30	13.94	13.17	12.38	11.94	12.23	13.65
MOE	Nc	2	4	6	8	10	12	14	16	18	20
	M	5.00	8.86	11.56	12.82	12.89	12.26	11.40	10.76	10.79	11.94
IB	Nc	2	4	6	8	10	12	14	16	18	20
	M	8.20	18.04	22.50	20.91	15.07	9.57	6.33	4.82	5.10	8.44

The equivalence between Nc and M showed that Nc is very different from the M. In this work, It was established that 20 cycles of artificial aging were equivalent to two month of natural aging, which did not occur. For example, in the thickness swelling at 2 h, the results found that 2 cycles and 20 cycles (20 Nc) is the same 2,84 and 7,49 months of natural aging, respectively. This result was different than expected. The same methodology should be also considered in the other properties. Thus, the correlation between 20 Nc and water absorption at 2 h and 24 h, MOR, MOE and internal bonding are 6.7, 9.72, 13.65, 11.94 and 8.44 M, respectively. For density 18 Nc was the same 5.63 months.

There is no correlation between thickness swelling at 24 h from 4Nc due great dispersion that was found in the data.

With the results obtained in the Table 6, 20Nc represents, for physical and mechanical properties, an aging of around 7 and 8 months, and of 11 and 12 months, respectively. Exception to internal bonding, with 8 months.

The equations which assign the number of months in the natural aging with the number of cycles of artificial aging are shown on Table 7.

The equations on Table 7 were created to estimate the relations between weathering with other intermediary values between number cycles and number months, i.e., with the equation it is possible to know the relation between 1 cycle, not utilized in the experiment, with the number of months. For the thickness swelling at 24 h there was no correlation between Nc and M due to the great dispersion in the datas.

In the thickness swelling at 2 h, water absorption at 2 h and 24 h, the values obtained for R^2 were greater than 90%, indicating a good quality on the adjustment, with strong correlation (DANCEY; REIDY, 2006; MONTGOMERY, 2012). On other properties such density, MOR, MOE and IB the R^2 values were 45.03, 32.93, 58.74 and 42.08%, respectively, indicating a weak correlation, with poor quality on the adjustment (DANCEY; REIDY, 2006; MONTGOMERY, 2012). Thus, in general, physical properties were better to establish a relation between Nc and M.

Conclusions

The parameters, being adhesive content and pressure utilized, used for production of the particleboards were satisfactory, in which all the results to reference were in accordance with the normative documents, such Brazilian Standard NBR 14810 (ABNT, 2018).

An important parameter was the definition of the cycles of artificial aging based on the climatological parameters to outdoor exposure, in which was defined through calculation that one cycle of aging artificial had 8 h in UVB lamps, 0.02 h of spray and 3.98 h of the condensation at temperature 42 ºC. And it was calculated that 20 cycles would be proportional to the same degradation of two months of exposure to natural aging.

Table 7 – **Models of the relations between Nc and M in the particleboards**

Properties	Relation between M and Nc	R^2 (%)
TS 2h	$M = 2.852 \cdot e^{0.0454 \cdot Nc}$ [Exponential]	95.80
TS 24h	×	×
WA 2h	$M = 2.0222 + 1.5982 \cdot \ln(Nc)$ [Logarithmic]	93.04
WA 24h	$M = 3.5124 \cdot Nc^{0.3842}$ [Geometric]	95.67
ρ	$M = 3.9661 \cdot Nc^{0.2993}$ [Geometric]	45.03
MOR	$M = 9.9916 \cdot Nc^{0.1042}$ [Geometric]	32.93
MOE	$M = 5.4782 \cdot Nc^{0.2955}$ [Geometric]	58.74
IB	$M = 20.2419 \cdot e^{-0.0616 \cdot Nc}$ [Exponential]	42.08

The results for density showed the particleboards were classified as medium density panels considering in normative documents. For thickness swelling at 2 h all the results in natural and artificial aging obtained after 2h were lower than recommended by Brazilian Standard. The same document did not make any recommendation for testing after 24h, but only one batch and one cycle had results slightly above 8%.

The use of castor oil showed good performance when compared with other results in the literature. The mechanical properties of reference treatment had satisfactory results. In general, along the time, the results obtained for mechanical properties have been modified under natural and artificial aging. For MOR, MOE and internal bonding, the modifications were more pronounced under natural aging with considerable reduction. Statistical analyses showed that the changes on mechanical and physical properties were lower on samples under artificial aging in function of methodology established.

The relation between physical and mechanical properties considering the number of months in the natural aging with the number of cycles in the artificial aging was obtained with cubical polynomial regression models. The expressions that correlate M and Nc were obtained by polynomial equations. Thus, the correlation between 20 Nc under artificial aging for thickness swelling at 2 and 24 h, water absorption at 2 and 24 h, MOR, MOE and internal bonding are 2.84, 7.49, 6.7, 9.72, 13.65, 11.94 and 8.44 M, respectively. For density, 18 Nc represents 5.63 months under aging. In general, for physical properties 20 Nc stands for 7 to 8 months, and for mechanical properties, 11 to 12 months, with exception to internal bonding, with 8 months. The expectation on the calculation was to reach 2 months of outdoor exposure for 20 Nc. Despite all the efforts the results showed that the tests of artificial aging are more aggressive than expected. The equations that best represent relation between Nc and M were thickness swelling at 2h and water absorption at 2 h and 24 h, with R^2 larger 93%, indicating a great quality on the adjustment, with strong correlation.

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