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EXPERIMENTAL STUDY OF THE EFFECTS OF ACCELERATED AGING CYCLES ON THE FIRE REACTION PERFORMANCE OF FIVE WOOD SPECIES

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ABSTRACT: The objective of this study is to evaluate the influence of the degradation caused by atmospheric agents' exposure over time (weathering) on the fire behaviour of five species of wood with different natural durability, according to known durability classes (UNE-EN 350:2016). Two laboratory tests were carried out for assessing the wood of Chestnut (Castanea sativa), European larch (Larix decidua), Black pine (Pinus uncinata), Paulownia (Paulownia tomentosa) and Scots pine (Pinus sylvestris), the later with and without durability impregnation-treatment by autoclave. Laboratory tests involved two processes of accelerated aging cycles (without and with spray) for four weeks following the protocols based on the ASTM G154:2016 and UNE-EN 927-6:2019 standards, in order to make reference to the use classes of exposure to humidity 3.1 and 3.2 defined in the UNE-EN 335:2013 standard. Analysis of the variation of the colour and the appearance of deformations and splitting after accelerated aging were performed. Flammability tests were also carried out to analyse the fire reaction performance of the samples in each stage of the aging test. Differences in colour changes were observed depending on the spraying presence in the aging processes. The results indicated that weathering significantly influences the fire reaction on a wooden surface, especially in softwoods with a medium and low degree of natural durability. Surface roughness and splitting hinder the ability to extinguish the flame. On the other hand, larch proved to have both a good resistance to degradation and good fire behaviour.

KEYWORDS: Natural durability of wood, weathering degradation, fire performance of wood, aging cycles.

1 INTRODUCTION

Natural wood durability is generally associated with hardwoods and tropical woods. Their density, hardness, and composition (extractive compounds) make them highly resistant to degradation by abiotic agents (weathering) and attack by organisms such as fungi and insects.

However, some resinous softwood species, such as larch (Larix decidua) (*L in this study)*, offer better-than-average natural degradation resistance, so it is widely used for facade claddings.

Durability varies, not only between different wood species but also within each species. In most wood species, the heartwood, which is the inner part of a log, is naturally more durable than the sapwood, the outer layers of the log [1].

When wood is exposed to outdoor conditions, a complex combination of chemical, mechanical, and light energy factors contribute to natural weathering [2].

The three primary sources of wood degradation are fungi (decay or rot), insects, and weathering. So, we can distinguish between wood decay and wood degradation. The repeated actions of wet (rain) and dry, the changing exposure to high and low temperatures and sunlight results in physical and chemical degradation of the wood over time. Physical deterioration consists of surface roughening, checking, splitting, and wood cell erosion [2,3]. Chemical deterioration involves a complex sequence of free-radical reactions. The degradation of wood by any biotic or abiotic agent modifies some of the organic components of wood [2]. These components are primarily polysaccharides (cellulose, hemicelluloses) and polyphenols (lignin).

One of the most relevant weathering factors responsible for changes in the wood surface is moisture in all its varieties: dew, rain, snow, and humidity. The classes of use described in the UNE-EN 335:2013 standard consider the risks to which a wooden building element may be subjected depending on its exposure to ambient moisture. A facade cladding is subject to use classes 3.1 and 3.2,

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which consider outdoor exposure without contact with the ground. Class 3.1 refers to limited wetting conditions with wood temporarily above 20% of moisture content (MC), while class 3.2 refers to prolonged wetting conditions with wood frequently above 20% MC (Fig. 1). Accordingly, the design of appropriate construction details facilitates fast and constant water removal and quick wood drying.

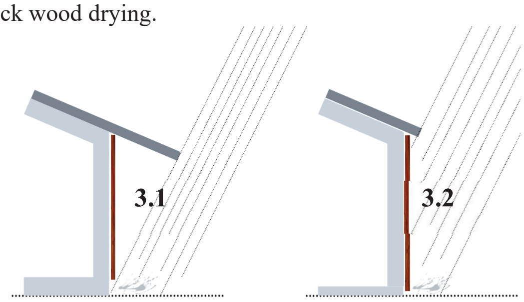

Figure 1. The use classes of facade cladding are 3.1 or 3.2, depending on ambient moisture exposition. Building details are essential to avoid moisture excess and prevent water sorption by capillarity from taking place causing decay effects.

Colour is one of the main attributes of wood from an aesthetic point of view, and it is therefore important to analyse its stability against weathering [4]. One of the most important causes of photodegradation in wood is ultraviolet (UV) (visible, and infrared light), light, which induces chemical reactions between its main constituents. Colour differences can be determined according to the CIE-L*a*b* (CIELAB) standard from the International Commission on Illumination CIE. The determination of the colour coordinates according to this standard, before and after aging, allows the quantification of their variations. Research on different wood species reveals an important darkening effect depending on the time and type of aging (natural or accelerated) [5,6].

Wood is a combustible material that exhibits smouldering due to the char layer generated during its burning process. Many research papers focusing on the reaction to fire of wood define the most important factors influencing the fire characteristics of wood are mainly density, orientation concerning the heat source, moisture content, and quality of wood surface treatment [7,8]. In some wood species, particularly rich in extractive substances and exudates, the composition may have more influence on fire behaviour than the density [9]. Weathering factors, especially rain moisture cause leaching which degrades lignin the most thermally stable component of wood as well as the least thermally stable hemicelluloses and extractive substances [10]. As a result, the cellulose in the fibres becomes more apparent and can protrude and produce a fibrous surface and roughness [1]. Defects of wood and cracks influence the persistence of flames on the surface [11].

This study intends to focus on the long-term degradation of wood and how this affects its fire behaviour. This issue is especially important in façade claddings, given the increasing use of this material in both private and public building construction. In some countries, such as Spain, the height limit for timber cladding (D, S2,d0 reaction to fire classification) is 10 m, and the use of flame retardants to improve the fire performance of wood is not an option, because guaranteeing the durability of these products against weathering remains a challenge.

2 MATERIALS

Five wood species were studied. Two hardwoods: chestnut (C) and Paulownia (P) and three softwoods: European Larch (L) Black Pine (PN) and Scots pine, the latest with (PRN) and without treatment (PRT). The natural durability of the heartwood in each of them according to UNE-EN 350:2016 standard is shown in table 1.

Table 1*: Natural durability of studied species*

Code	Density Kg/m^3	wood-decay attack	Insects attack	
C	520	2 (1)	DC2	(D) Durable
L	584	3 - 4	DC2	(D) Durable
*PN	517	-	-	(P) Not very durable
PRN	516	3 - 4	DC2	(D) Durable
P	266	5	DC5	(ND) Not durable

Wood-decay from better to worst 1 → 5. *Data from [12]

Scots pine (*Pinus sylvestris*) has an excellent impregnation capacity (Class 1), a natural (PRN) and treated (PRT) sample was tested. The treatment preventive and curative were impregnated by autoclave with a penetration level of NP5 (UNE-EN 351).

3 METHODS

3.1 TESTINGS

In order to carry out the accelerated aging processes on the wood samples and the subsequent analysis of the colour degradation and the fire behaviour analysis the tests described below were performed.

3.1.1 Accelerating aging tests

Two different exposure conditions (A1 and A2) have been tested for four weeks through an equipment QUV/spray accelerated weathering tester. The A1 process (no sprayed) was conducted according to the protocol of ASTM G154:2016 cycle 1, consisting of 56 alternating cycles of an 8-hour UV-A 340 radiation period and 4 hours of condensation. The A2 process was carried out following the protocol of the standard UNE-EN 927-6:2019. In this process, a one-week exposure cycle begins with 24 hours of condensation, followed by 48 cycles of 3 hours that combine a 2.5-hour UV-A 340 radiation period and a water spray period of 0.5 h. Table 2 shows the total time for each period. The A1 and A2 aging conditions represent the use class 3.1 and 3.2 respectively according to UNE-EN 335:2013 standard.

Wood specimens of 300 x 100 x 15 mm were previously stabilized in a climatic chamber for one week under controlled conditions of 20 ± 2 ° C temperature and 65 ± 5% relative humidity.

An accelerated aging process of 4 weeks resulted in a significant deterioration of the samples. Some studies indicate that 4 weeks under accelerated aging may be equivalent to 2 years of natural aging [13]. Table 2 shows details on the total hours of each cycle.

***Table 2**: Protocols followed for accelerated aging processes A1 and A2.*

Standard	Tests	Exposure periods throughout the trial (h)			
		Condensation	UV-A	Water spray	Total test time
ASTM G154:2016 C.1	A1	224	448	No	672
UNE-EN 927-6:2019	A2	96	480	96	672

3.1.2 Colour measurements

A PCE-TCR 200 colorimeter has been used to measure the CIELAB colour coordinates L^*, a^* and b^*. L^* is the lightness, going from 0 (black) to 100 (white) whereas a^* and b^* are the colour coordinates, from green (negative) to red (positive) and from blue (negative) to yellow (positive) respectively. The total colour differences ΔE_{ab}^* can be calculated as:

$$\Delta E^*_{ab} = \sqrt{(L^* - L^*_0)^2 + (a^* - a^*_0)^2 + (b^* - b^*_0)^2}$$

where L^*, a^* and b^* are the measured values after aging and L_0^*, a_0^* and b_0^* are the corresponding reference values from non-aged samples. Each colour data corresponds to the average of measurements taken from four different points.

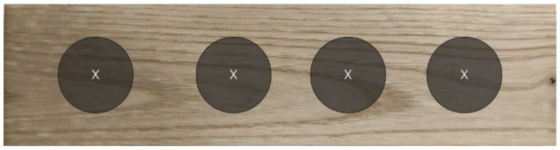

***Figure 2.** Points on the sample for colour analysis*

3.1.3 Epiradiator test

Wood samples of 100 x 100 x 15 mm were tested with the device described in the Spanish standard UNE 23727-90. The samples were placed on a metallic grid 3 cm below a heat source of 500 W. The heating source was removed and put back after each ignition and extinction. The parameters determined were the time to ignition, the number of ignitions, and the average time of flame persistence during the first 5 minutes of testing. The results obtained are detailed in section 4.3.

4 RESULTS AND DISCUSSION

4.1 VISUAL OBSERVATIONS

Overall, the degradation of all samples during the four weeks is significant. Remarkable differences are observed between the specimens exposed to the aging cycles without spray (A1) and with spray (A2). Samples tested under A2 testing showed greater surface degradation consisting of cracks and fissures.

The Scots pine (PRN and PRT) and Black pine (PN) samples showed the most significant degradation. These samples developed different sizes of checking and cracking, some of them deep, especially in PRN. Additionally, some of the PRN specimens were curved (Fig. 3).

However, no cracks or texture changes were observed on the surface of the Paulownia (P) samples. Paulownia pieces exhibited exceptional dimensional stability and smooth surface without roughness or cracks, even for the specimens of week 4. Larch (L) also showed a good appearance and dimensional integrity during the 4 weeks, with some small cracks.

***Figure 3.** Photographs of three of the samples studied in three different views: (left) lateral side, (middle) frontal, and (right) fontal after the flammability test. All of them aged with the A2 process (with sprayed). (a) Scots pine (PRN) after 2 weeks of aging. The specimen exhibits several cracks and curved deformation. (b) Paulownia (P) after 4 weeks of aging. The sample remains smooth, with a good appearance, without deformations and no cracks are visible to the naked eye. (c) Larch (L) after 4 weeks of aging. The specimen remains with a good appearance without deformations, with small cracks little perceptible.*

Figure 4 shows a series of photographs, comparing non-aged samples (NA) with those subjected to accelerated aging according to the two procedures summarized in table 2, for 1, 2, 3 and 4 weeks. Samples exposed to the test without spraying (A1) show a progressive darkening and a colour change towards reddish tones. On the other hand, after the A2 test, the samples show less noticeable colour changes. The general trend is towards darkening, except in the case of paulownia (P) which becomes progressively lighter. The tonalities after A2 exposure are bluish.

4.2 COLORIMETRY RESULTS

The colour changes observed visually and discussed in the previous section can be quantified by the CIELAB colour parameters in Figure 5, the lightness L* is shown for both accelerated aging processes A1 (top) and A2 (bottom). In the non-spraying case (A1), for all the wood species, there is a significant decrease in L*, i.e. a darkening of the surface, in the first week of exposure. Over the following weeks, the samples continue to darken, although at a slower rate. The behaviour is similar for all species, being more remarkable for paulownia (P), where L* is reduced by about 45%. The Scots pine samples darken the least, showing no significant differences between natural (PRN) and treated (PRT) Scots pine. In the case of the A2 aging process, which introduces periods of water spraying but has a shorter condensation time, the samples hardly darken at all. Indeed, in the case of paulownia, some lightning is observed.

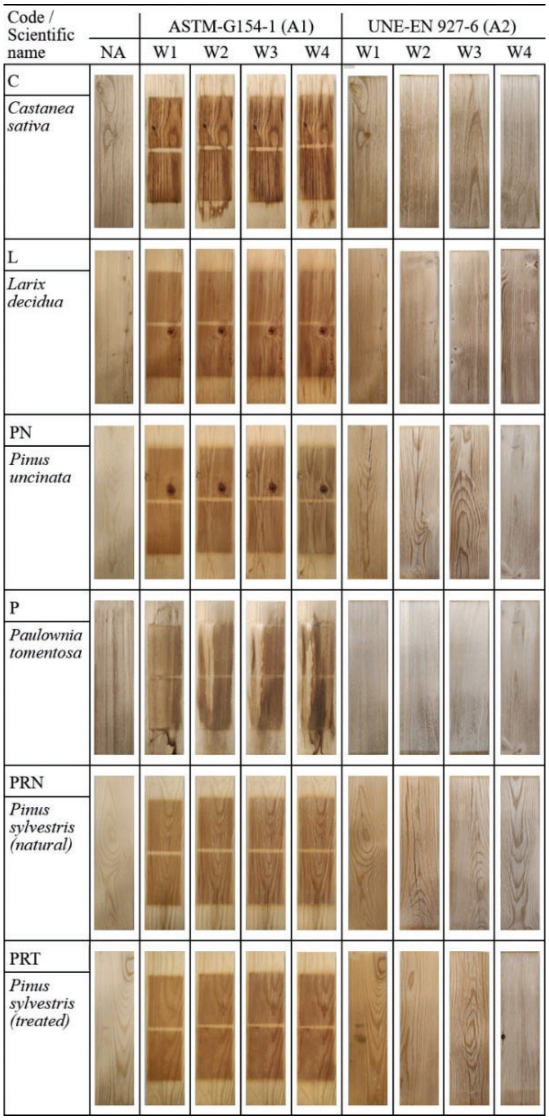

Figure 4. *Four-week aging test. For each specie, photographs of a non-aging (NA) sample and for each week under aging procedures A1 and A2 are present.*

The differences between the two types of aging can be seen more clearly in Figures 6-7, where only the results of week 4 (W4) are compared. Figure 6-top represents the L* values corresponding to no-aging (NA), aging type A1 and aging type A2. Figure 6 (bottom) plots the difference in colour coordinates a* and b* from the initial condition to the situation after 4 weeks of exposure. The arrows show the direction of change for each wood specie, both for A1 (left) and A2 (right) aging. The results obtained in both cases concerning the colour coordinates are quite different. While the unsprayed aging process (A1) increases the values of a* (red) and b* (yellow), the sprayed process (A2) decreases both coordinates. These results are in good agreement with the tonalities towards red in the case of procedure A1 and blue in the case of procedure A2 that were observed in Figure 4.

Finally, as an indicator of the total colour differences, figure 7 shows the ΔE_{ab}^*parameter. As expected, the overall changes are more significant for the A1 procedure than for A2 for all species, with Paulownia showing the most significant differences.

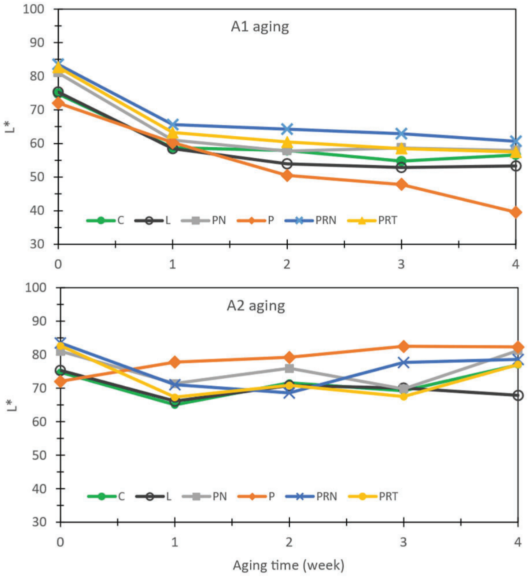

Figure 5. *Lightness L*, as a function of the aging weeks, for the different species analysed. The figures correspond to the accelerated aging processes A1 (top) and A2 (bottom).*

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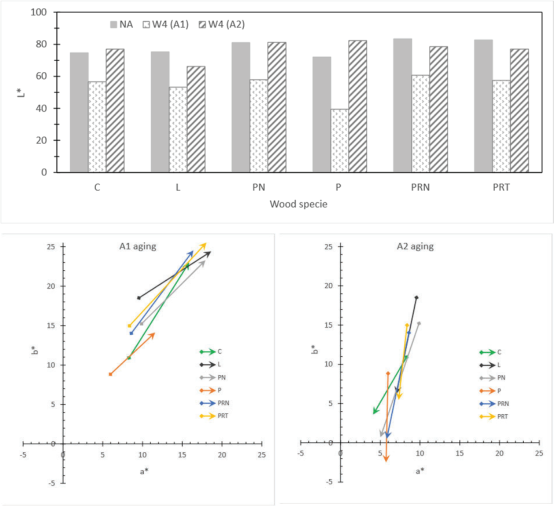

Figure 6. CIELAB colour parameters for the different species. Top panel: lightness L corresponding to non-aging (NA) and 4 weeks of exposure according to procedures A1 and A2. Bottom panels: colour coordinates a* and b* showing the difference from the initial measurements (NA) to those determined after 4 weeks of exposure type A1 (left) and A2 (right). The arrows indicate the direction of the change, from the initial to the final situation.*

Figure 7. *Total colour differences after 4 weeks of exposure according to aging procedures A1 and A2*

4.3 FIRE BEHAVIOUR

Fire behaviour of the different wood species without aging and after A1 and A2 accelerated aging programs have been evaluated with the epiradiator test. In the case of the non-sprayed aging procedure (A1), samples of each species were tested after 4 weeks of aging, while for the sprayed aging procedure (A2) the fire tests were performed after each week of aging up to 4 weeks.

Figure 8 shows the time at which the first ignition occurs for non-aged, and samples aged under A2 spray conditions. It can be observed that Paulownia has a significantly lower initial ignition time. This hardwood has a low density, 266 kg/m^3, and therefore a highly porous structure that facilitates the release of flammable gases. Larch and Scots pine exhibit higher initial ignition times for non-aged samples with a density of 584 and 516 kg/m^3 respectively.

The time of the first ignition tends to increase with aging which can be explained by the leaching of low thermal stable constituents of wood such as extractives and low molecular weight polysaccharides from hemicellulose [10,14]. The self-extinguish ability of wood samples is related to the average value of flame duration depicted in figure 8 (bottom). Larch exhibits the best behaviour both for non-aged and aged samples. Its good durability and the absence of remarkable cracks are responsible for its good fire behaviour. On the other hand, the porous structure of Paulownia contributes to increasing the duration of the combustions and the propagation rate.

Although there exists some variability, the general trend is a worsening of the fire behaviour with A2 aging, observed through an increase in the persistence of the flames. Several factors can explain this behaviour, one of them is the reduction of the charring ability of wood samples due to the loss and photodegradation of hemicellulose and lignin [10,14]. Hemicellulose and lignin play an important role in wood charring, which is one of the main mechanisms for wood protection in case of fire [15,16]. Another effect is the occurrence of splitting after the dry and wet cycles of aging, as can be observed in figure 3. The presence of cracks favours the release of flammable gases and the persistence of the flames. Black pine and Scots pine are the species that show a higher level of splitting with aging.

Aging under spraying conditions (A2) is more aggressive than non-spraying aging (A1) and the variations in the first ignition values and the average flame durations are more pronounced for A2 samples after 4 weeks of aging.

Figure 10 compares the behaviour of non-treated (PRN) and treated (PRT) Scots pine. The presence of an organic protective treatment shows a positive effect on delaying the ignition of non-aged samples. This could be due to the clogging of the cellular structure that hinders the release of flammable gases. PRT sample also exhibits a smaller number of cracks after aging and this can explain the lower flame duration of week 4 samples aged under A2 procedure. However, in order to assess the effect of the treatment on splitting a higher number of samples would be needed.

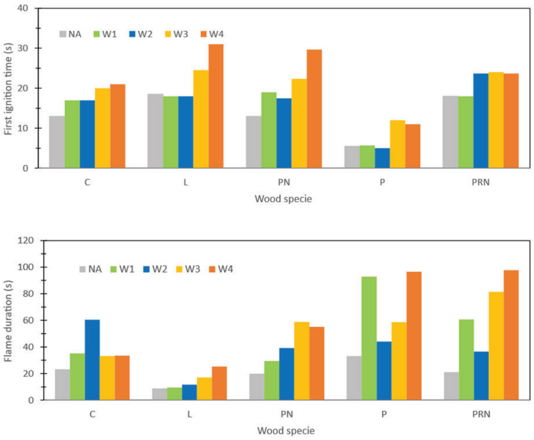

Figure 8. *Comparison of the flammability between species for each week of the A2 accelerated aging procedure. The graphics correspond to the first ignition time (top) and flame duration (bottom).*

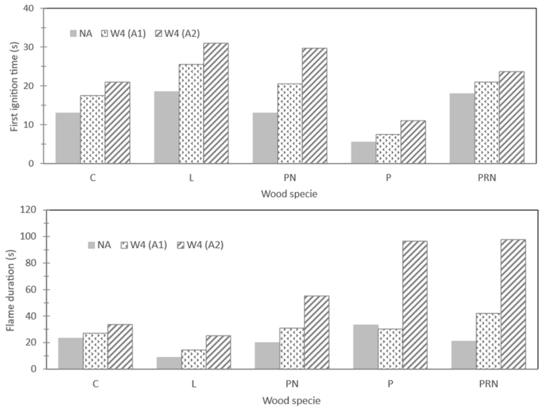

Figure 9. *Comparison between species for no aging (NA) and aged samples in both procedures A1 and A2 at week 4. The graphics show the comparison of first ignition time (top) and flame duration (bottom).*

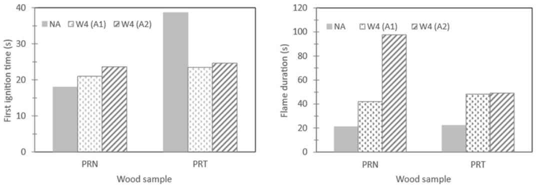

Figure 10. *Comparison between Scots pine non-treated (PRN) and treated (PRT) for no aging (NA) and aged samples in both procedures A1 and A2 at week 4. First ignition (Left) and Flame duration (right).*

5 CONCLUSIONS

Overall, the results show a correlation between weathering degradation and a gradual worsening in the fire behaviour of the samples. Despite the initial ignition time increases for the samples aged with both procedures, the self-extinguish ability worsens leading to a higher flame persistence. Photodegradation and leaching of different components of wood and the appearance of cracks and deformations play a major role in fire behaviour. The good durability of Larch and the absence of remarkable cracks contribute to a good response in fire reaction. On the other hand, although Paulownia does not present cracks and deformations after aging, it exhibits fast propagation of flame and low time of ignition due to its low density and porous structure. Aging causes darkening in most of the samples and changes in colour, being more significant for the non-spraying procedure (A1). The aging process (A2) also produces a progressive darkening of the specimens except for Paulownia, which becomes increasingly lighter. In both cases, Paulownia shows the most relevant differences in its appearance.

6 ACKNOWLEDGMENTS

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