Fire Behavior of Bamboo, *Guadua angustifolia*

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Abstract. Bamboo is a promising building material because it is a renewable resource and it grows extremely fast. Bamboo has been widely used in the traditional architecture of some countries, but now the development of different bamboo products can expand its applications. As in the case of timber products, one of the main concerns about bamboo is the fire behavior. Therefore, in this work we have studied the fire behavior of the *Guadua angustifolia* depending on various parameters. We have evaluated the effect of moisture and also the influence of the microstructure on the flammability of bamboo. The results show a clear influence of the level of moisture on the fire behavior and some differences depending on the microstructure of bamboo. The internal part, which is rich in vascular cells and parenchyma tissue, has less ability to form a charred residue than the external layer rich in silicon.

Another part of this work consisted on evaluating the performance of different flame retardants added into bamboo trough impregnation. We have used different combinations of flame retardants, based on boron and phosphorous salts. We have found promising results that could allow the improvement of the fire reaction classification of some bamboo products.

Keywords: Bamboo · Fire reaction · Flame retardant · Impregnation

1 Introduction

Bamboo is the common name that woody grasses that belong to the *Bambusoideae* subfamily receive. The *Bambusoideae* are divided into three tribes, the *Olyreae* that contains herbaceous species, and the *Arundinarieae* and *Bambuseae* tribes that are formed by woody species. On all continents, with the exception of Europe and Antarctica, there are endemic bamboo species [1]. Bamboo is a material with excellent mechanical performance widely used in the vernacular architecture of many Asian, African and Latin American countries [2, 3]. The rapid growth of bamboo, whose cultivation can yield from 5–6 years, and the adaption of its cultivation to a wide variety of climates make bamboo an excellent candidate to consider in sustainable architecture [4]. The development of gluing techniques opens the door to bamboo products, both structural and cladding [5, 6].

One of the aspects to take into account when designing with bamboo is its fire behavior. This work aims to deepen the knowledge of the fire behavior of the *Guadua angustifolia* species taking into account variables such as the humidity of the piece or

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the influence of the microstructure of the bamboo cane. In order to evaluate the best strategy to improve the fire reaction of bamboo, the behavior of pieces impregnated with a flame retardant based on boron and another based on phosphorous has been characterized [7, 8]. On one hand, it has been selected a boron salt, sodium octaborate tetrahydrate, of greater solubility than boric acid and borax, usually used in the treatment of bamboo [9]; and on the other hand, a commercial flame retardant based on ammonium polyphosphate.

2 Materials and Methodology

The *Guadua angustifolia* used for the tests was supplied by Bamboo Import Europe. Pieces of different dimensions and sections were cut (Fig. 1), depending on the type of test. A set of pieces was conditioned in a climatic chamber for a minimum of 24 h, at a temperature of 23 °C and with a relative humidity of 50%. Equilibrium moisture content of bamboo samples after conditioning in the climatic chamber was around 8% for all the cases. The other set was allowed to dry in the oven at 50 °C until the time of testing.

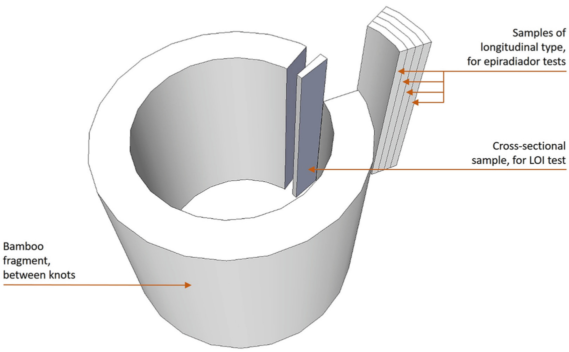


Fig. 1. Diagram with the types of bamboo samples used.

Of this second set, a third part of the pieces were impregnated in an autoclave with a solution of sodium borate ($Na_2B_8O_{13}{\cdot}4H_2O$ tetrahydrated sodium octaborate (DOT), Solubor®), dissolved in distilled water and with a concentration of 20%, achieving a 5% absorption. Another third part of the pieces was also impregnated in an autoclave but this time with the phosphate flame retardant.

The tests carried out are detailed below:

- Pyrolysis microcalorimeter (PCFC): The objective of the test is to analyze the heat release rate of bamboo samples based on the cutting section (exterior, center and interior of the piece) and the humidity of the samples. One sample of each of these cases was tested. For this, a Fire Testing Tecnology microcalorimeter was used, which consists of a pyrolysis chamber, where the samples are heated to 750 °C, at 1 °C/s in a nitrogen atmosphere. The gases released ascend to a combustion chamber that contains oxygen and, depending on the oxygen consumption, the heat release rate is determined.

- Epiradiador: The aim of the test is to evaluate the capacity of self-extinguishing of the material, subjected to a radiator configured according to the standard UNE 23725-90 [10] and with a nominal power of 500 W. The bamboo samples are deposited in a metal grid on the sample holder, which is previously placed at a distance of 3 cm under the radiator.

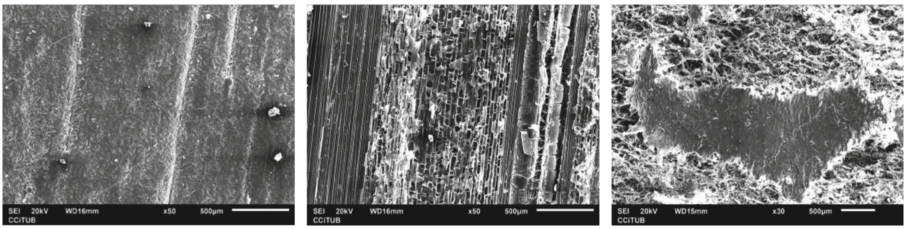
The test lasts 5 min, and from it the time that elapses until the first ignition occurs, the total number of ignitions and the average value of the duration of the ignitions produced during that period of time are obtained. Triplicates were performed for each type of sample.

- Limit oxygen index (LOI): The objective of the test is to determine the minimum oxygen concentration, in a mixture with nitrogen, which allows the combustion of the samples and the indications of ISO UNE-EN 4589-2 are used as reference [11]. The samples are placed vertically in a controlled atmosphere of nitrogen and oxygen. The amount of specimens used for each test corresponds to the number indicated in the standard.

In addition to the fire behavior tests, observations have been made on a Jeol JSM 6510 scanning electron microscope (SEM) coupled to an X-ray dispersive energy detector (EDS) to identify the elements present.

3 Results

Figure 2 shows SEM images of the different areas of the longitudinal direction of bamboo specimens (Fig. 1). In the image corresponding to the central zone, parenchyma cells, vascular cells and tissues of metaxylem and metafloem can be observed [12]. The other two images show the outer bamboo parts: on the one hand, the upper part of the culm that shows a smooth surface and, on the other, the inner part that has a poorly structured morphology with some areas covered by white fragments such as the one seen in Fig. 2c. The elementary analysis carried out by EDS shows that these two zones (Fig. 2a and 2c) are rich in silicon, unlike the central zone (Fig. 2b) in which silicon is much less detected.



a. Exterior b. Center c. Interior

Fig. 2. SEM images of longitudinal cuts of bamboo culm.

Figure 3 shows the heat release rate as a function of temperature and Table 1 shows the main results obtained with the PCFC test: the values of the maximum heat release peak (pHRR), the temperature at which the maximum peak occurs (TpHRR) and the total heat released (THR). Although no large differences are observed between samples, there is a trend related with the moisture of the samples. As expected, the samples conditioned in the climatic chamber, which have an equilibrium humidity greater than those dried in an oven, exhibit a lower value of the total heat released, since part of the sample mass corresponds to the moisture of the sample. For the same reason, the central and internal cuts conditioned in a climatic chamber have a lower value of the heat release peak. In the case of the external cut the moisture content modifies the behavior in the microcalorimeter to a lesser extent.

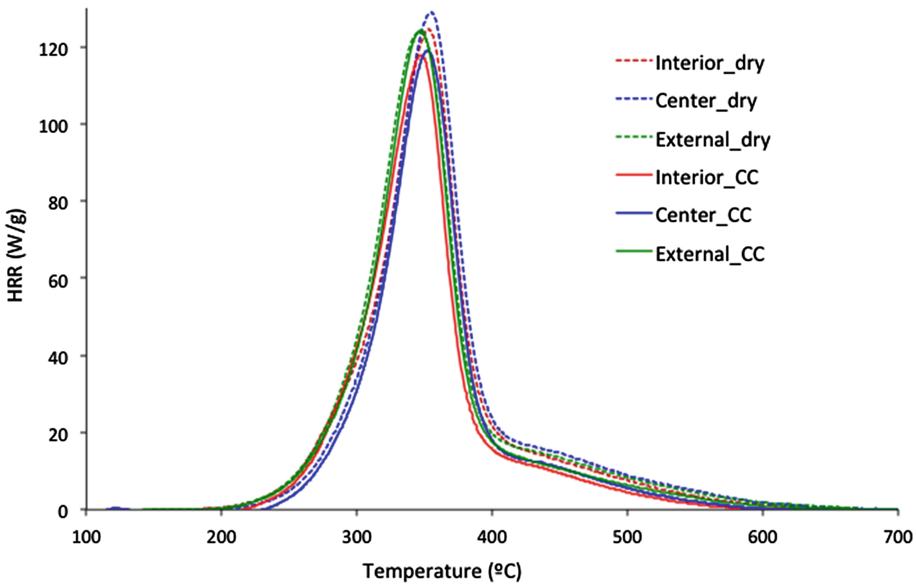


Fig. 3. Release curve of the heat rhythm versus the temperature obtained in the PCFC test.

Table 1. Results obtained with the pyrolysis microcalorimeter.

Source	**Conditioning**	pHRR (W/g)	TpHRR (°C)	THR (kJ/g)
Interior	Oven	124	352	10.3
Center	Oven	129	354	10.3
External	Oven	124	346	10.4
Interior	Climatic chamber	118	347	8.7
Center	Climatic chamber	119	352	8.6
External	Climatic chamber	124	347	9.6

Table 2 shows the results corresponding to the epiradiador tests according to the conditioning of the pieces; the position of the samples; and of the presence of flame retardant.

The LOI test performed in cross-sections for the samples untreated gives a limit oxygen percentage of 29 for the oven dried sample; and 32 for climate chamber conditioning. The samples treated with sodium octaborate tetrahydrate significantly improve the result of LOI and increase up to 47% of oxygen index needed to maintain combustion under test conditions. In case of the samples treated with the phosphate based flame retardant a significant improvement of the oxygen index occurs and it reaches values of 60%.

Table 2. Results of the epiradiador, according to the preparation and the source of the sample.

Preparation	Source	t_0 (s)	No	t_m (s)	% final mass loss
Climatic chamber, no impregnation	Interior	49	6	21	71
	Center	49	4	29	83
	Exterior	100	3	52	46
Oven, no impregnation	Interior	46	2	27	90
	Center	47	3	30	97
	Exterior	57	2	53	68
Oven, impregnation (Boron based FR)	Interior	29	5	6	54
	Center	32	5	7	61
	Exterior	65	7	22	36
Oven, impregnation (Phosporous based FR)	Interior	43	7	7	52
	Center	49	8	5	51
	Exterior	48	11	9	68

4 Conclusions

The fire behavior of several pieces of bamboo, of the species *Guadua angustifolia*, cut transversely and longitudinally, differentiating its origin (exterior, center and interior) has been evaluated. The presence of moisture in the bamboo samples makes more difficult to burn the bamboo samples, but does not significantly change the reaction to fire in bamboo. External areas that are rich in silicon have a higher resistance to combustion, but since the areas are less affected by variations in humidity, their fire behavior is also less affected by the hygroscopic conditions. The addition of 5% sodium octaborate tetrahydrate improves the fire behavior of bamboo; it reduces the duration of combustion in the case of the application of a radiation source and significantly increases the oxygen value necessary to produce combustion in the test of LOI. The use of a phosphate based fire retardant also improves de fire behavior of bamboo; it further reduces the duration of combustion under the radiator compared to samples treated with sodium octaborate tetrahydrate and it requires more oxygen to produce combustion in the test of LOI. The main mechanism of action of boron based flame retardants is the formation of a protective glassy layer that protects the condensed phase, while the phosphorous based flame retardants tend to promote charring during combustion. According to the results obtained both mechanisms lead to a clear improve of the fire reaction of bamboo, and it seems that promotion of charring could be more effective.

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