

CHARACTERIZATION OF THE FIRE BEHAVIOUR OF TROPICAL WOOD SPECIES FOR USE IN THE CONSTRUCTION INDUSTRY

María Pilar Giraldo¹, Laia Haurie², Javier Sotomayor³, Ana M. Lacasta², Joaquín Montón², Mariana Palumbo² Antonia Navarro².

ABSTRACT: It is widely acknowledged that wood is a combustible and flammable material. However, not all woods have the same fire behaviour; this can change significantly depending on the type and species of wood. Usually, hardwoods have better fire behaviour in comparison with softwoods. This is often due to their physical structure (morphology), their density and hardness and also their moisture content. However, in some cases the main cause is their chemical composition. Some tropical woods with relatively low density present better fire behaviour than other with high density. This indicates that other aspects such as the content of extracts, exudates (oils, waxes, mucilage, tannins etc.) and minerals can greatly influence their fire performance. In this study, seven Mexican tropical wood were characterized in order to determine their fire behaviour. For this purpose, an extensive series of laboratory tests were conducted. The results show a different behaviour in all the species studied, in some cases, with very significant differences. It is observed that although there is some correlation between high density and hardness of the species and their good fire behaviour, these factors are not always determinant. In some species, other factors as anatomy and composition of wood are more relevant to achieve a better fire behaviour.

KEYWORDS: tropical wood species, fire behaviour of wood, ignitability and flammability, fire reaction, extracts and exudates of wood.

1 INTRODUCTION

Wood is one of the most applicable materials in industrial activities due to its versatility, its remarkable mechanical properties and its excellent strength/density relation. Tropical wood species are particularly attractive to different industries (e.g. furniture, timber, plywood outdoor applications etc.) due to their wide diameters, varied textures and their high durability and decay resistance.

In many developed countries such as Canada, EEUU, New Zealand, Germany, Switzerland and some Scandinavian countries, wood is used extensively for structural and room separating elements in building applications. In México, despite having a forest sector with a huge potential, most of wooden panels and some

structural elements used in local construction industry are imported.

According to a FAO report [1], in Mexico the volume of forest with commercial potential is approximately 2,800 million m³, of which 1,000 million are in tropical areas. However, it is estimated that only between 15 and 22% is exploited as commercial timber. Mexico has around 190 species of tropical wood documented, however only a small part has been characterized in terms of mechanical properties and there is a significant lack of information about their fire behaviour. It is known, that the fire behaviour is one of the main obstacles to use more widely wood in the construction sector.

The thermo chemical processes that occur in wood in fire conditions are very complex, involve factors like heat transfer, drying, pyrolysis, charring, mass loss and smouldering [2–3]. These processes ultimately determine the evolution of the char layer, which is important in terms of fire resistance, and the different parameters related to reaction to fire of wood such as the ignitability, the burning rate and the flammability. They are all closely linked of both physical structure (morphology) and specificity of chemical structure of the wood species [4]. An agreement of many researches regarding different wood species is that the charring rate is strongly affected by the wood anatomy. In consequence, the response of wood species to fire temperatures is strongly affected by the intrinsic course of thermo-physical and thermo-chemical processes on

¹María Pilar Giraldo, Incafast- Catalan Institute of Wood, Forest Sciences Center of Catalonia CTFC, Spain, pilar.giraldo@incfast.cat

²Laia Haurie, Universitat Politècnica de Catalunya UPC, Spain, laia.haurie@upc.edu.

³Javier Sotomayor, Universidad Michoacana de San Nicolás de Hidalgo. Mexico, mader999@yahoo.com.

²Ana M. Lacasta, Universitat Politècnica de Catalunya UPC, Spain, ana.maria.lacasta@upc.edu.

²Joaquín Montón, Universitat Politècnica de Catalunya UPC, Spain, joaquin.monton@upc.edu.

²Mariana Palumbo, Universitat Politècnica de Catalunya UPC, Spain, mariana.palumbo@upc.edu.

²Antonia Navarro, Universitat Politècnica de Catalunya UPC, Spain, antonia.navarro@upc.edu.

micro scale. This is especially important in tropical wood species because its anatomy and composition is rich and complex.

In this study the influence of these aspects in the parameters that define the fire behaviour of some tropical woods is observed through the different test carried out.

2 BACKGROUND

Wood is a complex composite material with an excellent weight-to-strength ratio. It has a set of specialized cells that provide mechanical strength to the tree, perform the function of liquid transport and storage of reserve nutrients supplies. Wood is mainly composed of cellulose, hemicellulose, lignin, extractives and exudates. Also it contains different minerals which make an important contribution in the tree metabolism. Most minerals are absorbed from soil through its root system; others can be absorbed from air through leaves. Trees growing in tropical regions are often rich in several substances.

Generally, hardwoods are richer in nutrients than softwoods. Some studies have identified 17 essential inorganic elements, which means that plant needs them to complete its reproductive stage of life cycle. These are: carbon (C), oxygen (O), hydrogen (H), potassium (K), calcium (Ca) and magnesium (Mg) as well as nitrogen (N), phosphorus (P), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), nickel (Ni) and chlorine (Cl). N, P, K, Ca, Mg and S are in a greater proportion, because they are required in large quantities, while Fe, Zn, Mn, Cu, B, Mo, Cl and Ni are required in minor quantities [5]. Total inorganics in wood can be evaluated by determination of ash content after combustion of the material. Woods typically contain from 0.1 to 1.5 % of ash, however in some tropical species these values may be exceeded. The ash is predominantly composed of different metal oxides, silicates, carbonates and other salts [6].

In general, extractives and exudates contained in woods are responsible of essential characteristics such as: the variety of color, smell, density, dimensional stability, durability, resistance to attack by fungi and insects, the specific heat value and inflammability [7].

A more in-depth analysis of all these aspects and its correlations can provide a better understanding of why some species of wood have a better fire behavior irrespective of their density and hardness.

3 OBJECTIVES








In this study were characterized seven tropical wood species from Mexico, in order to evaluate their fire behavior and determine the influence of their physical and chemical characteristics in pyrolysis and combustion processes. This study is part of a more extensive research

devoted to identify the factors that contribute to a better fire performance of some tropical woods. In the first phase of this study, described in this document, several laboratory tests were performed to compare: the fire reaction, the morphology and the content of minerals. In a second phase, a series of laboratory tests will be conducted in order to obtain and analyze the content of extractives and exudates.

4 MATERIALS

Table 1 summarizes the seven different tropical woods originated from Mexico studied in this research. Remarkable differences in their densities can be observed, as well as, in colour and superficial aspect.

Table 1: Characteristics of different wood species

Code	Scientific name	Surface	Density Kg/m ³
TD	<i>Tabebuia donnell-smithii</i>		448
EC	<i>Enterolobium cyclocarpum</i>		504
TR	<i>Tabebuia rosea</i>		604
SH	<i>Swietenia humilis</i>		655
LA	<i>Lysiloma acapulcensis</i>		685
CA	<i>Cordia elaeagnoides</i>		1130
TC	<i>Tabebuia chrysantha</i>		1234

5 METHODS

5.1 TESTINGS

In order to evaluate the influence of the physical and chemical characteristics of the wood samples in their fire performance different fire and materials characterization tests were carried out: flammability tests, limiting oxygen index test (LOI), scanning electron microscopy (SEM), and thermogravimetric analysis (TG). The most relevant procedures are described below.

5.1.1 Flammability test

Wood samples of 70 mm x 70 mm x 10 mm were tested using 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 (Fig.1). Four samples of each wood species were tested and the parameters determined were the time at which the initial ignition occurs, the number of ignitions and the average time of flame persistence during the first 5 minutes of testing.

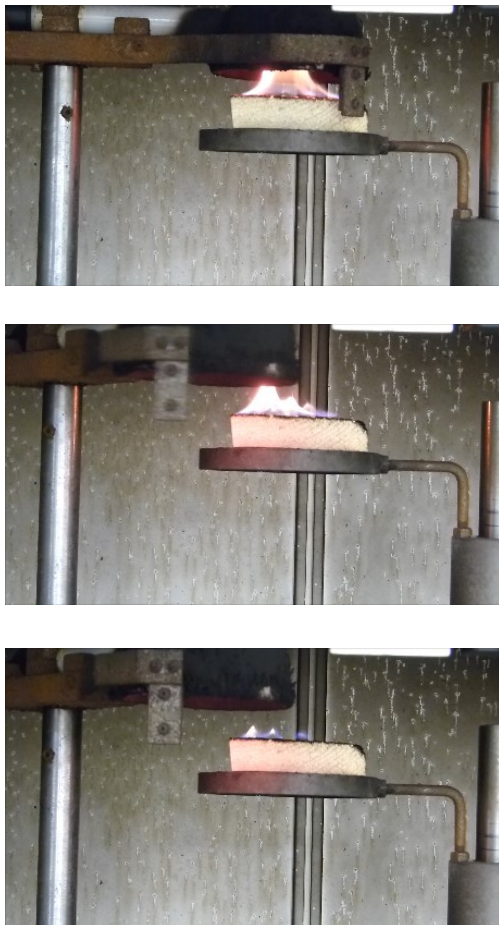


Figure 1: Flammability test images. (top) Heat source on the sample once ignition started (middle) while the heat source is removed (bottom) once heat source is removed.

5.1.2 Limiting oxygen index test

The limiting oxygen index (LOI) corresponds to the minimum concentration of oxygen needed to sustain the combustion of a sample in accordance with ISO 4589. The tests were performed on wood samples of 80 mm x 10 mm (Fig.2). The concentration of oxygen in a mixture of oxygen and nitrogen was varied until it has reached the minimum concentration at which the sample burned for a length of 50 mm or for a period of 3 min.

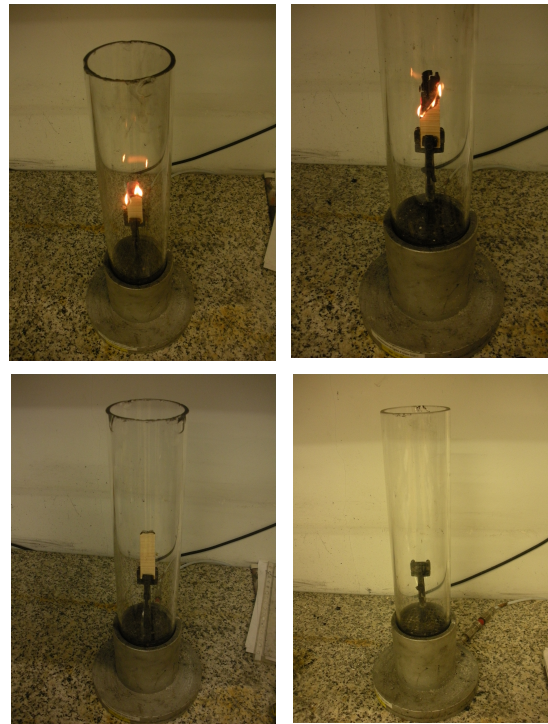


Figure 2: Limiting oxygen index test. Sample with different concentration of oxygen.

5.1.3 Scanning electron microscopy (SEM)

The morphology of the samples was studied by scanning electron microscopy using an Environmental microscope, ESEM Quanta 200 FEI. Elemental analysis using energy dispersive X-ray spectroscopy (EDS) was also performed to identify the elements present in the mineral crystals observed inside the wood cells.

In order to obtain more information about the amount and nature of the inorganic phases, the different wood samples were calcined at 800°C during 1h to obtain the residue. This residue was also observed and analyzed by SEM and EDS respectively.

5.1.4. Thermal analysis

Thermogravimetric analyses (TGA) were performed using a furnace coupled with a precision scale. This device allowed testing larger samples than the conventional TG equipment, which is interesting for heterogeneous samples. The samples were heated from 25°C until 1000°C in 4 hours under air atmosphere.

6 RESULTS

All the wood samples studied exhibit differences in their fire behaviour. The main results of flammability and LOI test are summarized in table 2. The initial ignition time increases with the density of the wood. However, this trend is not observed for the flame persistence of each of the ignitions. In this case shorter times indicate more ability of the wood sample to extinguish the flame once the heating source is removed, as is the case of LA sample. A similar behaviour was found in the LOI test.

Sample LA exhibited the highest LOI value and low density EC sample had the same LOI value, 24, as the dense TC sample. On the other hand, the TD sample with lowest density obtained the worst results regarding fire performance. These results show that despite wood density has an influence on the fire performance of wood it cannot be taken as the only affecting factor. During flammability test, high density samples lost less mass in comparison with other samples. LA was the sample with highest percentage of mass loss. This is due to LA had a large number of ignitions (Table 3) (Fig 3).

Table 2: Summary of results of flammability and LOI testing.

Code	Initial ignition (s)	Number of ignitions	Avg. flame persistence (s)	LOI (%)
TD	17	8	29	21,1
EC	17	12	16	24
TR	24	8	29	21,5
SH	28	14	16	23,1
LA	31	16	9	26,5
CA	37	9	26	25,1
TC	49	13	20	24

In order to further investigate the causes of the differences in fire behaviour, the morphology of the different wood samples was examined with SEM, (Fig. 4-6) besides the differences in the wood microstructure, SEM images also showed differences in the amount and nature of the minerals present in each wood sample (Fig.4-6). It was observed that LA, CA and TC have a more compact morphology compared with the other samples. This is not surprising in woods species with high density as CA and TC; however, it is remarkable in a medium density wood as LA. Tangential section of LA shows mostly uniseriate and biseriate rays and seldom triseriate rays. Many cells in uniseriate rays are saturated with minerals and also some saturated tracheids can be found. This saturation may influence the oxygen and gases flow during the combustion.

Regarding the minerals, from the crystal habit it can be deduced that samples EC, SH, CA contain whewellite, a monohydrated calcium oxalate. This is in good agreement with the formation of calcium oxide in the calcination of the wood, which is subsequently transformed to calcium hydroxide or calcium carbonate.

Table 3: Results of flammability test: mass loss rate.

Code	Initial mass. (g)	Final mass (g)	Mass loss percentage (%)
LA	33,55	26,58	20,8
EC	24,55	19,95	18,68
TD	23,83	20,08	15,87
SH	32,00	27,23	14,93
TR	28,53	25,13	10,40
TC	54,63	52,35	7,80
CA	61,45	56,68	4,15

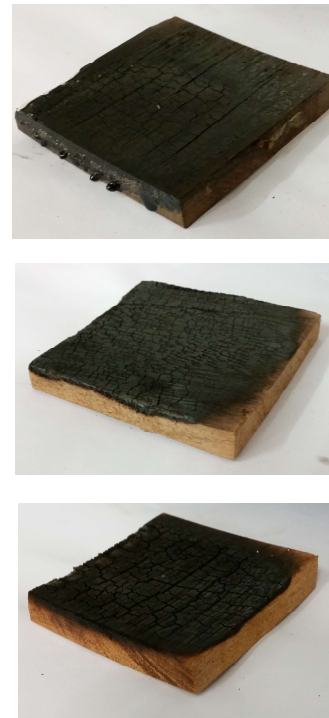


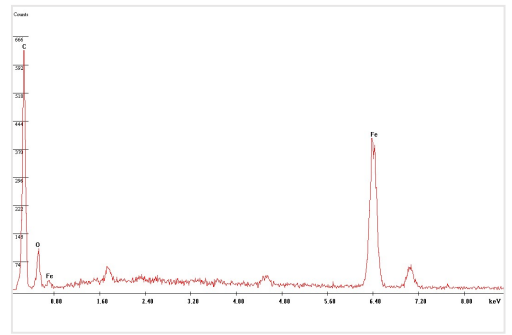
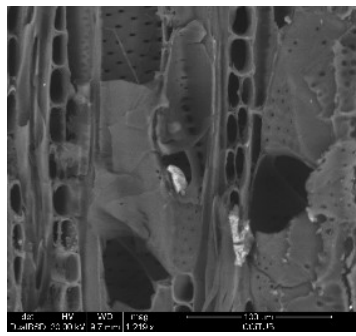
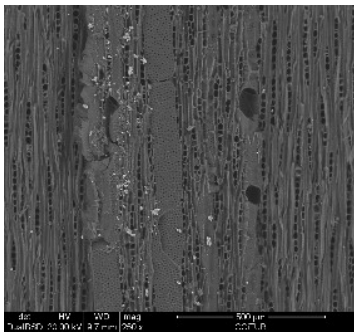
Figure 3: Burned samples CA (top) SH (middle) LA (bottom) after flammability test.

Table 4: Summary of results of calcined residue analysis

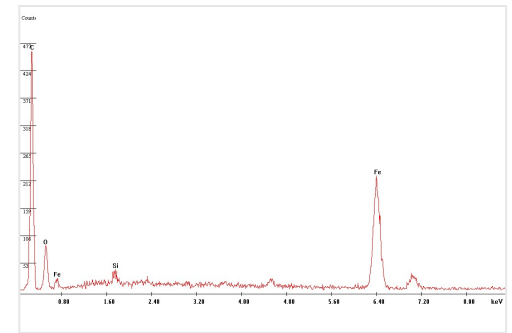
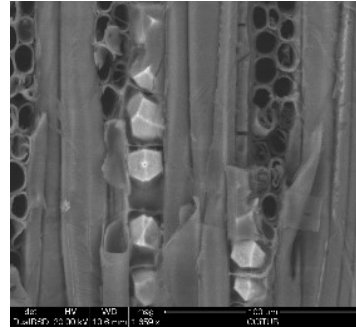
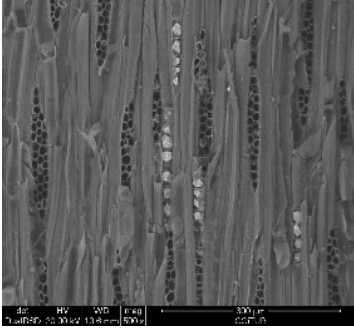
Code	Calcined Residue (%)	Main elements
TD	0.6	P, Ca, K
EC	0.5	Ca, K
TR	0.5	Ca
SH	0.4	Ca
LA	1.3	K, S, Ca
CA	1.5	Ca
TC	2.8	Ca

In sample LA the presence of two types of inorganic compounds was observed. One rich in sulphur and potassium, probably a form of potassium sulphate, and the other containing calcium as the main element. Table 4 shows the amount of solid residue contained in each sample after calcination.

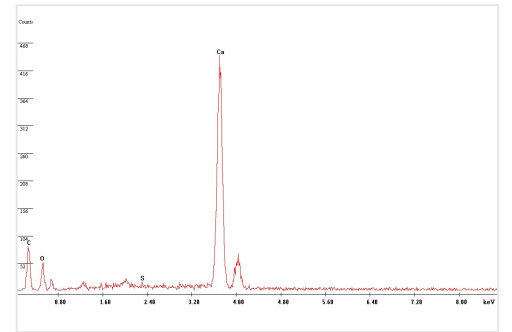
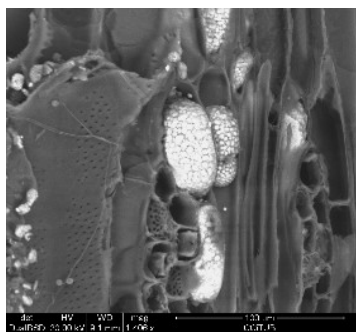
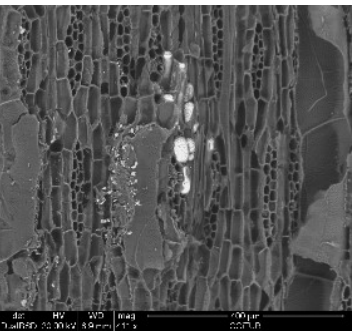
The elements listed in Table 4 correspond with the main chemical elements detected by EDS during the SEM observation of the calcined residues. Several authors reported the influence of the inorganic compounds in the modification of the thermal decomposition and pyrolysis of lignocellulosic products.



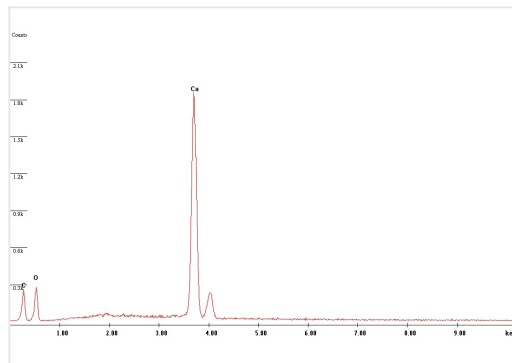
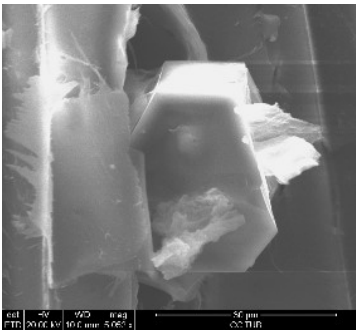
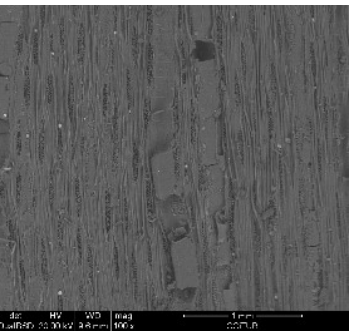
TD-1



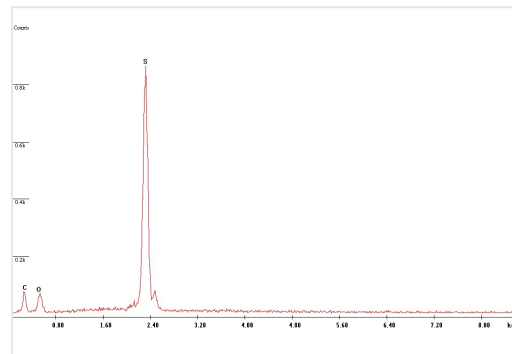
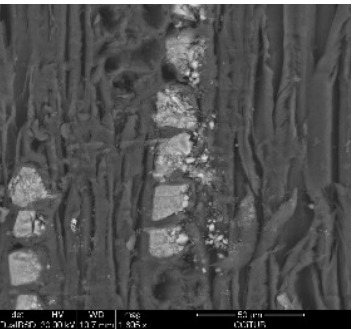
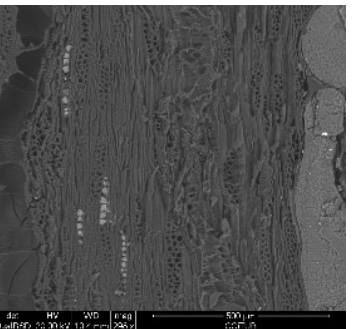
EC-1



TR-1

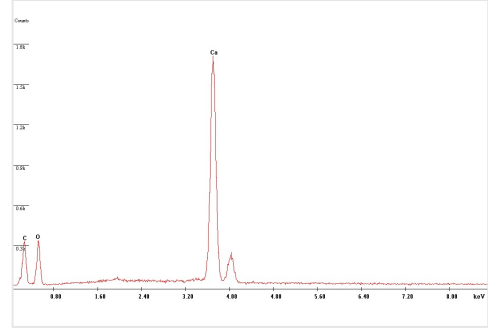
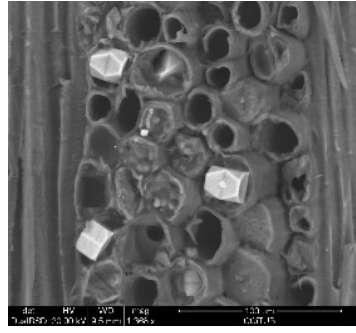
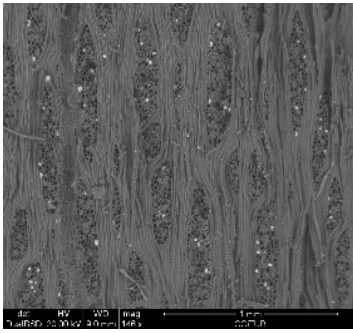


SH-1

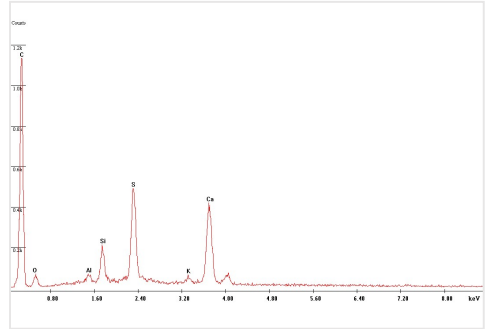
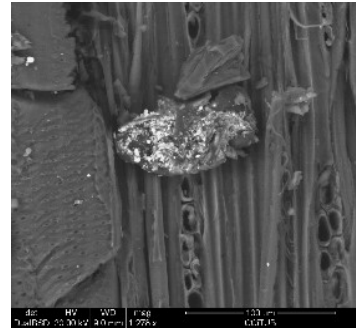
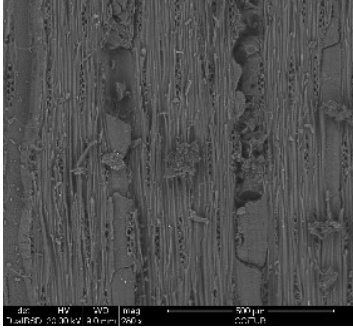


LA-1

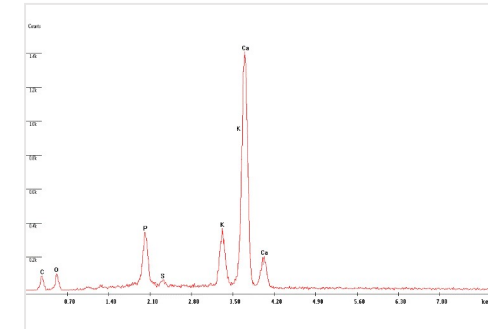
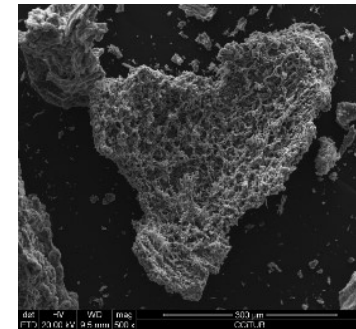
Figure 4: (left) SEM images of the species of wood studied. Tangential section. (right) corresponding EDS spectra of each one.



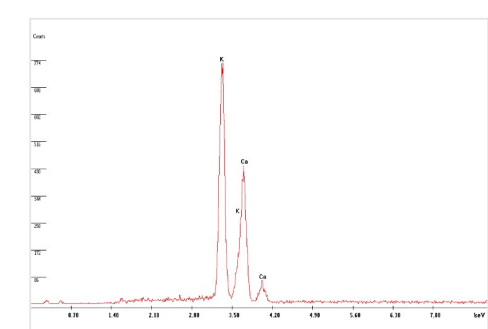
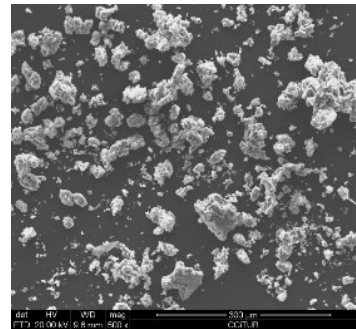
CA-1



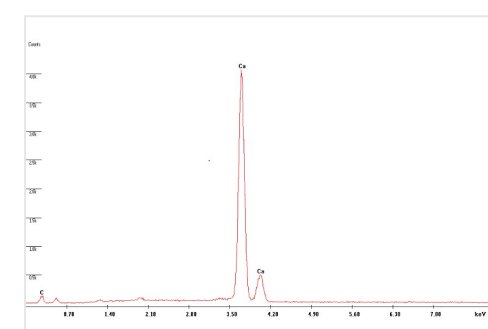
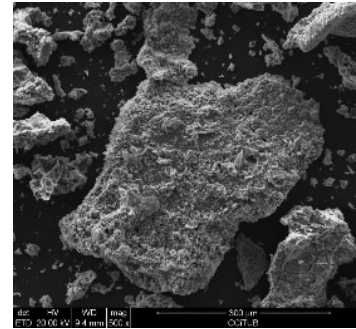
TC-1



TD-2



EC-2

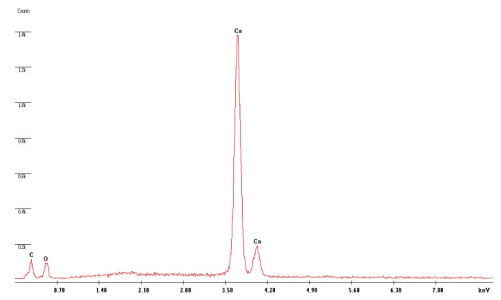
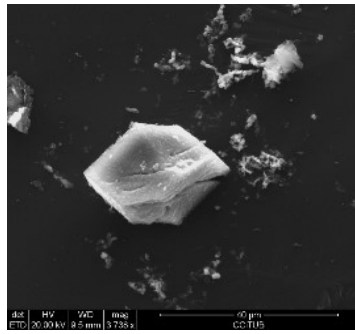


TR-2

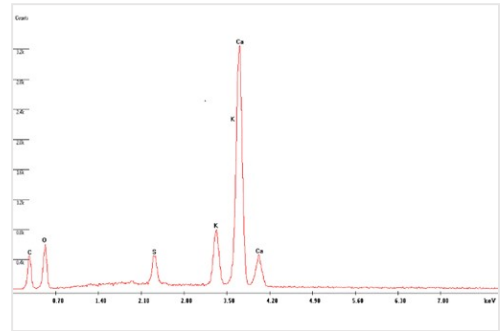
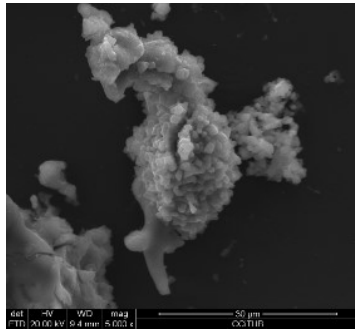
Figure 5: samples number 1: (left) SEM images of the species of wood studied. Tangential section. (right) Corresponding EDS spectra of each one. Samples number 2: (left) calcined samples. (middle) SEM images of calcination residue. (right) Corresponding EDS spectra of each one.



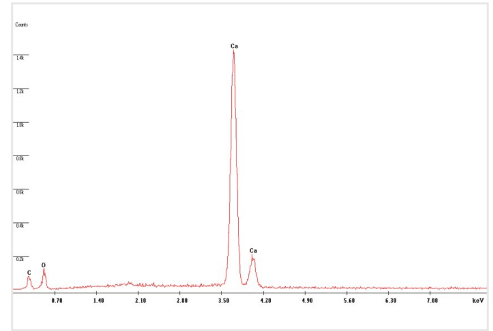
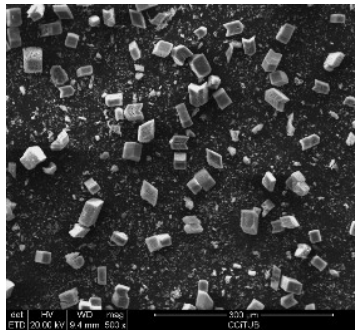
SH-2



LA-2



CA-2



TC-2

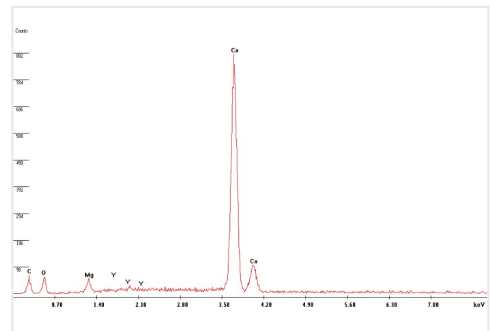
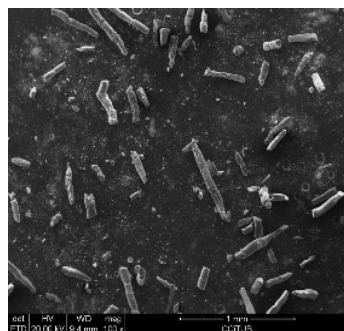


Figure 6: (left) calcined samples. (middle) SEM images of calcination residue. (right) Corresponding EDS spectra of each one.

T. Hosoya et al. mentioned the influence of inorganic substances on the higher production of glycoaldehyde, hydroxyacetone and carbonized products during the wood pyrolysis [8]. K. Raveendran et al. found that the amount of potassium or zinc together with the lignin content modify the pyrolysis of biomass [9]. In general, inorganic matter is believed to increase char formation and inhibit the formation of volatile products [10]. On the other hand, S. Liidakis et al. did not detect a significant influence of the inorganic phases on the ignitability of wood [11]. This observation is in good agreement with the fact that the ignition time determined in the flammability test seems to be mainly dependent on the density of wood.

Figure 7 depicts the TG curves of the different wood samples. H. Yang et al. studied the decomposition of hemicellulose, cellulose and lignin and observed that hemicellulose decomposes between 220-315°C; cellulose in the range of 315-400°C and lignin decomposes at a low rate in a broad range of temperatures, from 25 to 900°C [12]. The results obtained show that TD decomposes at significantly lower temperatures than the rest of the wood samples, probably due to the presence of high levels of hemicellulose and reduced contents of cellulose and lignin. Dense wood samples, like CA and TC, show a similar decomposition with higher thermal stability and smooth curves, mainly in the last step. The elevated contents of lignin are probably responsible of this behaviour. The rest of the samples exhibit TG curves with similar patterns, where three steps can be identified.

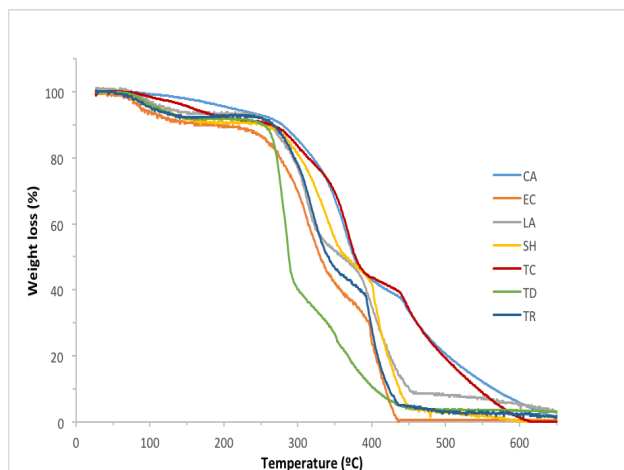


Figure 7: TG curves of all wood species studied.

7 CONCLUSIONS

The results show that density of wood is an important factor for a good fire performance. However, in some tropical wood species the composition, content of

minerals and morphology may exert more influence. All these aspects deserve to be studied in depth.

Fire testing shows that fire performance is related with wood density. Particularly the delay in the ignition seems to be directly correlated with the increase in density. However, in the tropical woods studied some other factors play an important role. The morphology, the content of each of the three main constituents of wood and the characteristics and amount of inorganic substances might exert a remarkable influence in the fire behaviour. The experiments carried out so far reveal that the morphology together with differences in the inorganic constituents significantly affect the combustion process of wood.

However, in order to obtain a more comprehensive map for the analysis of each species the study has to be completed with the analysis of extractives and exudates.

8 ACKNOWLEDGMENTS

This research has been carried out within the framework of the COST Action 1404.

The authors express their gratitude to the Michoacana University of San Nicolás de Hidalgo Research Programme 2015-2016 for supplying the samples of tropical wood for this research.

This work is supported by MINECO (Spain) under the project BIA2014-52688-R. The authors would also like to thank the Catalan Government for the quality accreditation given to the research group GICITED (2014 SGR 1298).

REFERENCES

- [1] Juan Manuel Torres Rojo.: Estudio de tendencias y perspectivas del sector forestal en América Latina al año 2020: Informe Nacional México. Document Repository FAO.
- [2] White, Robert H.: and Mark A. Dietenberger. "Fire safety of wood construction." *Interface* 18: 3.2003.
- [3] Babrauskas, V.: Charring rate of wood as a tool for fire investigations. *Fire Saf J* 40:528–554. 2005.
- [4] Aseeva et al.: *Fire Behavior and Fire Protection in Timber Buildings: Elsevier Series in Wood Sciences*. 2014.
- [5] Zule, J., & Dolenc, J.: Distribution of Mineral Substances in Different Wood Tissues of European Larch (*Larix decidua* Mill.): *Drvna industrija*, 63(1), 19-25. 2012.
- [6] Stelzer, R.; Holste, R.; Groth, M.; Schmidt, A.: Xray microanalytical studies on mineral concentrations in vacuoles of needle tissues from *Larix decidua* (L.) Mill. *Botanica Acta*.106 (4):325-330. 1993.
- [7] Stanley, r.g.: Extractives of wood, bark, and needles of the southern pines. *Forest Products Journal*. vol 19 (11). pp 50-56. 1969.

- [8] Hosoya T., Kawamoto H., Saka S., Cellulose–hemicellulose and cellulose–lignin interactions in wood pyrolysis at gasification temperature. *J. Anal. Appl. Pyrolysis.* 80, 118-125, 2007.
- [9] Raveendran K., Ganesh A., Khilar K. C., Influence of mineral matter on biomass pyrolysis characteristics. *Fuel.* 74 (12), 1812-1822, 1995.
- [10] Hosoya T., Kawamoto H., Saka S., Influence of inorganic matter on wood pyrolysis at gasification temperature. *J. Wood Sci.* 53, 351-357, 2007.
- [11] Liodakis S., Bakirtzis D., Dimitrakopoulos A., Ignition characteristics of forest species in relation to thermal analysis data, *Thermochimica Acta* 390, 83–91, 2002.
- [12] Yang H., Yan R., Chen H., Lee D. H., Zheng C., *Fuel* 86, 1781-1788, 2007.