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Grau en Enginyeria Química

Treball Final de Grau

Study of the drying process of bamboo for constructive applications

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Education is the passport to the future, for tomorrow belongs to those who prepare for it today.

Malcom X

Me gustaría dar las gracias a mis familiares y a mi pareja por estar a mi lado, por su confianza y por todo su apoyo a lo largo de este proyecto.

Gracias a Mònica y a José Antonio, mis tutores de la universidad, por su ayuda y dedicación durante todo el curso.

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¡Muchas gracias a todos!

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SUMMARY

Bamboo is a natural material widely used in construction due to its easy large-scale cultivation, rapid growth, high resistance and toughness.

Before using bamboo as a constructive material, it must be properly dried to avoid its degradation by biological agents and improve their mechanical properties. Efficient and sustainable drying of bamboo remains a key challenge in obtaining this material in production zones, which in many cases are located in areas with low energy resources. Ecuador is one of the countries with the highest production of bamboo in the world and at the same time, with a low level of energy resources in which drying is one of the critical stages. The use of bamboo as a building material in this country would meet the requirements of a sustainable material (local material with low environmental footprint).

The purpose of this project is to study the drying process of bamboo to achieve the best mechanical properties for its use as a building material. For this purpose, the drying kinetics of bamboo will be studied according to parameters such as temperature, time and vacuum level. In addition, different test will be carried out to evaluate the mechanical properties such as elastic modulus, thus determining the optimal drying conditions.

Keywords: bamboo, drying process, physical and mechanical properties

RESUMEN

El bambú es un material de origen natural muy utilizado en el ámbito de la construcción debido a su fácil cultivo a gran escala, rápido crecimiento, alta resistencia y tenacidad.

Antes de utilizar el bambú como material de construcción se debe secar adecuadamente evitando su degradación por agentes biológicos y mejorar sus propiedades mecánicas. El secado eficiente y sostenible del bambú es un desafío clave en la obtención de este material en las zonas de producción, que en muchos casos se sitúan en áreas con pocos recursos energéticos. Ecuador es uno de los países con mayor producción mundial de bambú y a su vez, con un nivel bajo de recursos energéticos en el que el secado es una de las etapas críticas. La utilización de bambú como material de construcción en este país cumpliría los requisitos de un material sostenible (material de proximidad con baja huella medioambiental).

El propósito de este proyecto es estudiar el proceso de secado de bambú que permita alcanzar las mejores propiedades mecánicas para su uso como material de construcción. Para ello, se estudiará la cinética de secado del bambú en función de parámetros como la temperatura, el tiempo y el uso de vacío. Además, se realizarán diferentes ensayos para evaluar propiedades mecánicas como el módulo elástico, determinando así las condiciones óptimas de secado.

Palabras clave: bambú, proceso de secado, propiedades físicas y mecánicas

1. INTRODUCTION

This project has been performed in the Materials Science and Physical Chemistry Department of the Faculty of Chemistry in the research group Centre of Design and Optimization of Processes and Materials (DIOPMA).

This work is part of the research being carried out at the Centre DIOPMA for the manufacture of a solar oven used to dry vegetal material. In addition, this project has been carried out in collaboration with Bismark Osmany Torres Ruilova, professor of the University of Guayaquil in Ecuador, in order to investigate the different key properties of bamboo and its introduction in Europe as sustainable constructive material. The bamboo samples used for the different tests has been obtained in the harvest of the canes in the community of Dos Mangas in the province of Santa Elena on the coast of Ecuador.

1.1. BAMBOO

Bamboo (subfamily *Bambusoideae*) is part of the family *Poaceae*, one of the largest and most important botanical families, and are known more than 115 genera and 1,400 different species [1].

The structure of bamboo is similar to the other grasses, the woody ringed stems, known as culms, are typically hollow between the rings (nodes) and grow in branching clusters from a thick rhizome (underground stem). The absence of secondary growth wood causes the stems to be columnar rather than tapering. While the narrow leaves in young culms usually arise directly from the stem rings, mature culms often sprout horizontal leaf-bearing branches [1]. Bamboo have three different sections as can be seen in the Figure 1. The top of the plant is called *Sobrebasa*, it has thin walls with a high fibre content. It is usually between 3 and 5 meters. The walls of the middle section or *Basa* are slender and very light in relation to their enormous strength, maintain the outer diameter very well, are very fibrous and have a length between 6 and 10 meters. The bottom is called *Cepas*. They have a large wall thickness and short internodes with a length between 3 and 4 meters [2].

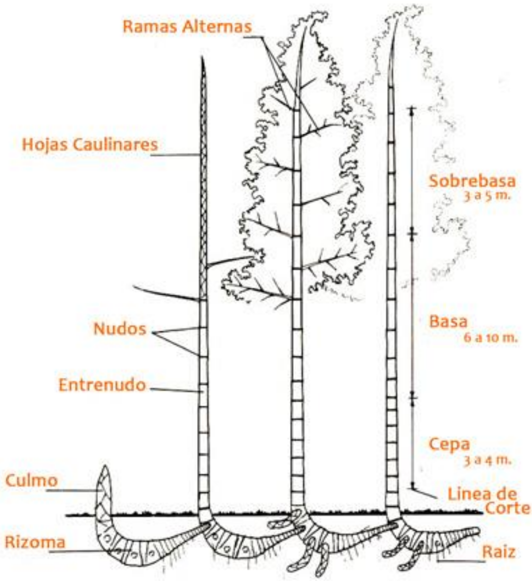

Figure 1. Sections of bamboo *Guadua Angustifolia*.
(*Source: www.bambusa.es/caracteristicas-del-bambu/bambu-guadua, 01/04/2020*)

Bamboos are typically fast-growing perennials plants. Although bamboo is technically an herbaceous plant, it can grow up to 35 meters high and reach the 30 centimetres in diameter. Bamboos include some of the fastest growing plants in the world, with species grow as much as 30 centimetres per day. The best-known giant specie is probably the *Phyllostachus Pubescens* (up to 15-20 m long, 10-12 cm in diameter), from China, where it is called 'bamboo moso'. Other known giant species are the *Guadua Angustifolia* and the *Dendrocalamus Asper*, which grow in tropical regions, both known for their enormous size (up to 25 m tall with a diameter of up to 22 cm) and good structural properties. The specie of *Guadua Angustifolia* is known in particular for its strength [3]. In first 3-4 days the bamboo plants can reach heights ranging from 10 to 15 centimetres in the majority of species (Figure 2a), in the following weeks the structure of the stem can reach the height between 1 and 2 meters (Figure 2b). During the first 6 months they grow protected by cauline leaves up to a height of approximately 7-8 meters (Figure 2c), finally at 4-5 years the woody structure of the canes is developed and they will finish maturing, measuring up to 30 meters high and reaching the 20 centimetres in diameter (Figure 2d). In this moment, the stem is considered to be of suitable maturity for use as a structural material and is proceed to its cut. If this is done well, a rhizomatic energy transfer mechanism begins in the plant and a new stem begins to be generated. Although if it grows naturally, some species spread aggressively and can form a dense undergrowth that excludes other plants [2].

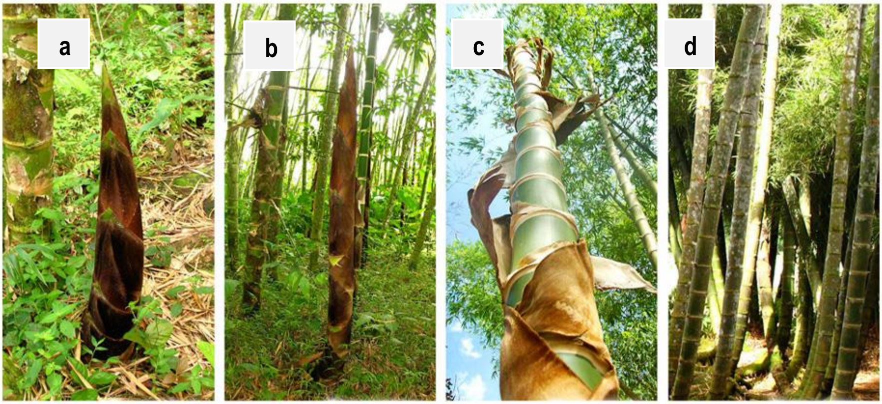

Figure 2. Growth of Guadua. a) 3-4 days, b) 2-3 weeks, c) 5-6 months and d) 4-5 years.
(*Source: www.bambusa.es/caracteristicas-del-bambu, 04/04/2020*)

Bamboo is very light, with a density (ρ) of 600-800 kg/m^3 [4]. This valour is below the densities of some plastics, such as polypropylene (890-950 kg/m^3) [5]. Bamboo has an elastic limit of 35.9-43.9 MPa, a stiffness (*S*) of 20.5-30.5 N·m^2 and an elastic modulus (*E*) or also known as Young's modulus of 15-20 GPa [4]. However, its specific module (E/density), with a value of 19.4 MPa m^3/kg, it what makes it really interesting [4]. If it is compared with the specific steel modulus (25.4 MPa m^3/kg) [4], it can be observed that it is in the same order as steel.

Due to its fibrillar structure, bamboo shows different behaviour in transverse and longitudinal direction. In the longitudinal direction of the fibres when it is subjected to bending, tensile and compression stresses, their strength values or elastic limits are generally higher than those of wood commonly used in construction (pine or spruce). For example, the *Guadua Anfustifolia Kunth* species can support 365-509 kg/cm^2 in a 10 minutes flexure load test while the C24 softwood species can supports only 244 kg/cm^2 [6].

Bamboo has a unique behaviour against earthquake. The typical nature of bamboo, its cylindrical shape with fibre accumulation on the outer face, and its high degree of elasticity make it especially suitable for seismic-resistant constructions due to its high capacity for absorbing energy [6].

In addition, bamboo is a material classified as suitable for construction according to the Standard of the German Institute for Standardization DIN4102 with class B2 (low flammability). The high concentration of silica on the outside slows down the propagation of the flame and can thus be assimilated to wood when carrying out fire resistance calculations. The reaction to fire value is very similar to wood and is set at 0.6 mm/min [6].

Bamboos forests are distributed in tropical and subtropical to mild temperate regions, with the heaviest concentration and largest number of species in East and Southeast Asia and on islands of the Indian and Pacific oceans, as can be observed in the coloured grey area in the Figure 3 [1].

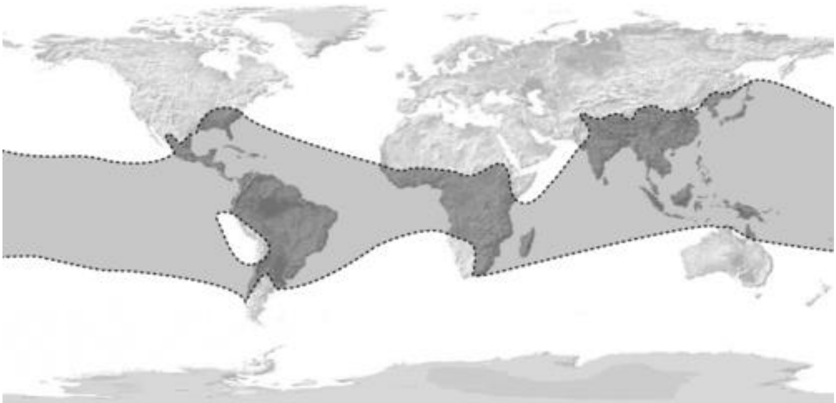

Figure 3. Worldwide bamboo distribution.
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The Food and Agriculture Organization (FAO) of the United Nations (UN) estimated that bamboo covered over 30 million hectares of land across the world. Aside from its socio-economic benefits, bamboo is a key part of biodiverse ecosystems. The giant panda, red panda, mountain gorilla, bale monkey, and the greater bamboo lemur are just some of the animals that rely on bamboo for food and shelter. Bamboo's extensive root systems mean that it binds soil and can raise the water table, making it an important part of anti-desertification projects around the world [7].

One of the countries with more presence of bamboo worldwide is Ecuador. In this country there are 46 species of bamboo with 7 different genera. The bamboo forests have a total of 600,000 hectares, 2% of the country's total area, distributed in natural areas and plantations.

The percentages of distribution of these forested areas are distributed with 66.5% on the coasts, 23.5% in the mountains and 10% in the Amazon [8].

In the Asia-Pacific the main bamboo producing countries are China, India, Japan, Myanmar, Thailand, Bangladesh, Cambodia, Vietnam, Laos, Malaysia, Indonesia and the Philippines [9]. In this area, China (7 million hectares) and India (9 million hectares) have the largest reserves of bamboo forest, accounting for half of the 32 million hectares available worldwide [3].

In Africa, Madagascar is the centre bamboo distribution. While, in Latin America, Mexico, Guatemala, Costa Rica, Nicaragua, Honduras, Colombia, Ecuador, Venezuela and Brazil, the Amazon Basin in South Tropic is the area of bamboo distribution centre [9].

The trade of bamboo products and their export and import employs millions of people worldwide, in Ecuador 12% of agricultural employment is linked to the presence of bamboo in agricultural production units and about 500,000 people are involved in the bamboo chain at the national level [8].

Bamboo has created an industry valued at about 60,000 million dollars annually. In Ecuador it contributes 0.5% of the Gross Domestic Product (GDP) and has a positive balance of 217 million dollars. In addition, it represents a saving of 460 dollars per year for the rural family that uses it in productive housing [8].

1.2. APPLICATIONS OF BAMBOO

Bamboo is a readily available material resource which has an extensive variety of applications from its function as a constructive material to its use in the daily lives of people around the world. The smart structure of bamboo endows it high strength and stability, so it is a better alternative to engineered wood for many aspects [10].

Bamboo resources have applications in architecture, handicrafts, and cuisine especially in East and Southeast Asia. The seeds of some species are eaten as grain, and the cooked young shoots of some bamboos (*Bambusa vulgaris and Phyllostachys edulis*) are eaten as vegetables, particularly in Chinese cuisines. Normally are sold in various processed shapes, and are available in fresh, dried, and canned versions. The raw leaves are a useful fodder for livestock. The pulped fibres of several bamboo species, especially *Dendrocalamus strictus* and *Bambusa bamboos*, are used to make fine-quality paper. The jointed stems of bamboo have perhaps the most numerous uses; the largest stems supply planks for houses and rafts, while both large and small stems are lashed together to form the scaffoldings used on building-construction sites. The stems are also split up to make buckets and pipes or are used to make furniture, flooring, walking sticks, fishing poles, garden stakes, and other utensils. Some species of bamboo are used as ornamentals in landscape gardens [1]. Another of the most uses is the extraction of cellulose from green bamboo fibres. Normally, the bamboo is ground using a planner machine to produce powder bamboo, then it dries and sieved for the synthesis of the cellulose fibre. The cellulose is obtained by mechanical process and chemical treatment. The use of cellulose fibres is commonly used as a reinforced material for some composites due to their high strength and stiffness combined with low weight and biodegradability [11].

One of the most important field of application of bamboo is construction. Bamboo can have different uses in construction:

- It can be used as reinforcement in concrete (with cement or lime) as an alternative to steel.
- It can be used to build the entire supporting structure, from pillars to beams, including the roof battens.
- Can be combined with any type of wall and insulation: straw, mud, vegetable fibres, mineral wool.
- Can be built on any load-bearing wall (stone, brick, thermo-clay, etc.)

Bamboo constructions have a high degree of safety in addition to this good resistance to earthquakes because, in addition to their great elasticity, the structures are particularly light and have a high capacity for absorbing energy [6].

The application of bamboo in building industry varied with regional differences due to the local forest resources, economic conditions and construction technology. Large diameter round bamboos, as an easily accessible, affordable and seismic construction material, were widely used in traditional bamboo building in the Southeast Asia and South America. As discussed above, Ecuador is one of the countries with the highest world production of bamboo, that is typically used as building material for housing in underprivileged areas or inhabited jungle zones. Normally, the bamboo is dried in a solar kiln due to the few resources and the weather condition of this country located near the equator. Then, the cane of bamboo can be used directly as wall or cut and used as a wall material. This process produces a bamboo with useful mechanical, thermal and acoustic properties, besides to its easy access and collection [12].

The use of this type the renewable energy generates a bamboo with low cost and sustainable process capable of being applied in other developed countries around the world [12].

1.2.1. DRIED BAMBOO

Bamboo, just like all the woods, have a natural moisture content depending by the specie and age. This content decreases from the bottom to the top and horizontally from the outer layer to the inner layers. A higher content of parenchyma cells, which are actively involved in photosynthesis, secretion, food storage and form the majority of the plant tissue, increases the water holding capacity [13]. Greater dimensional changes during its use would ultimately occur if the bamboo has not been dried before being used [14].

Fresh bamboo has a big moisture content which must be removed to prevent microbial damage and improve its properties before being ready for further storage, transport, processing and use. To date, the use of bamboo as a structural material is limited by the lack of scale production of well-treated raw materials, semi-finished or standardized products [15].

Bamboo drying is a step that needs energy and time, making it a limiting step in the manufacturing process. Currently, most bamboo products are dried by using conventional technology like air drying or kiln drying which usually requires high time and energy-consuming process. However, the use of a solar kiln reduces energy consumption considerably. The drying process also produces cracking, shrinkage and other defects due to uneven heating, so it must be carried out under right conditions [15].

One of the most used drying methods of bamboo is drying in solar kiln. This is a simple and safe method of drying bamboo. The use of solar energy provides sustainable process with a low environmental impact. This type of solar drying is used in areas with few energy resources where the use of bamboo as a construction material abounds. In addition, a slow drying with a mild temperature for a relatively long period of time does not cause significant deformations as shrinkage or cracking in bamboo culms [14].

Shrinkage occurs during the drying process, when the water molecules bound to the cell wall are removed as the drying occurs. The shrinkage rate varies along the different directions of the bamboo samples and it gradually increases as the temperature rise. In addition, the increase in the evaporation rate of water produces to a higher pressure in the cell cavity which can lead to broke. Under the effect of pressure difference, the water moving rate generates a higher and faster change in shrinkage rate. Due to density of round bamboo increases from bottom to top, the shrinkage is higher at the top than at the bottom [15].

Cracking of bamboo culms can happen during drying process as their moisture content drop. This phenomenon can be affected by their own physical properties and also by external drying factors like temperature, drying time or vacuum. When bamboo is dried under higher temperature and power level, moisture is expelled faster, and the shrinkage is also exacerbated. Therefore, cracking can more easily occur [15].

However, drying processes brings a guarantee of quality on bamboo products, reducing their moisture content and improving its physical and mechanical properties. Thus, a simple, fast, efficient and sustainable drying technology for bamboo is a key step in the industrial use [15].

1.3. ENVIROMENTAL BENEFITS OF BAMBOO

The environmental protection, climate change and energy supply are the main concern of many world organizations and countries. For this reason, in recent years natural and renewable resources have drawn worldwide attention. Natural resources are defined as set of components that exists in the nature susceptible to being used by the human being to satisfy their needs and renewable is related to that it can be restored or renew through a natural procedure, bamboo is an example of natural and renewable resource [16].

Bamboo forest contributes to substantial carbon storage, mitigating the effects of climate change and CO_2 emissions. The bamboo plants are one of the largest collectors of environmental CO_2 on the planet stands out. One hectare of bamboo can store up to 250 T of carbon and its wood, once harvested, can sustain it for an average of 80 years. Each year, the hectare absorbs 5.1 T of new carbon, the equivalent in CO_2 that a person in more developed countries like Spain or the United States generates [17]. Bamboo does not release the trapped CO_2 as it stays captures inside the plant, even after the harvested timber is used in value added products for construction, flooring, panels, etc. it still functions as a carbon vessel. Furthermore, bamboo is a sustainable and renewable resource because it continuously spreads without the need of humans. This allows the formation of forests much faster compared to most other tree species, where trees must be clear, cut and replanted [18].

In particular, bamboo forests cover an area over $1.8 \cdot 10^9$ ha in East and South Asia, accounting for more than 80% of the total land area of bamboo forests worldwide. A study estimated that carbon stocks in bamboo stands in China will increase from $727.08 \cdot 10^6$ T of carbon in 2010 to $1017.54 \cdot 10^6$ T of carbon in 2050, a 40% increase over a 40-year span. That is why, the bamboo forest has increased by 10% in many countries situated in Asia and South America, like China planning to continue its expansion in upcoming years [16].

Natural bamboo resources are advantageous for energy conservation and the reduction of CO_2 emissions, carbon storage, and biochemical fuel substitution. Another great advantage of using some varieties of this giant grass against the intensive use of trees is that in just 4 years it will be ready for cutting and use as a structural material. In addition, bamboo is industrially processed into products with high additional value such a floor tiles and wall panels as an alternative for wood-polymer composites, but also its commercial use has been expanded as green and clean product. For this reason, given the destruction of forest resources and the increasing demand for wooden materials, these properties render bamboo a suitable replacement for many constructive materials [16].

Although bamboo has been consolidated as an ecological and sustainable resource, the Life Cycle Assessment (LCA) of bamboo products will allow us to know some important data about their environmental impact. The LCA evaluates the environmental impacts associated with all the stages of the lifecycle of a product obtention, manufacture process, use and end of life. Most of these environmental impacts originate during the manufacturing phases, including the raw material supplying and processing phases. The environmental impact of little-processed bamboo materials is mainly attributed to the natural gas used during drying processes. For highly processed bamboo materials, the production process requires treatments such as sawing, cutting, and hot pressing, and the power consumption during processing accounts for more than 50% of the environmental impact of bamboo building materials [16].

Also have been investigated the environmental impacts of imported bamboo materials in Europe. The results demonstrate the sustainability of bamboo as a building material in Europe:

the high CO_2 fixation values during the life of the plant, the low energy resources required for handling and treatment compensate for and exceed the energy consumption required for its transport. The *Guadua Angustifolia Kunth* presents a negative CO_2 footprint and also negative values of the Accumulated Energy Demand (AED) in all the stages of manufacture process. The carbon footprint from cradle to door is -12.75 kg CO_2, -17.97 kg CO_2 and -21.88 kg CO_2 for the 6 cm, 8 cm and 12 cm length *Guadua* bamboo rods respectively and the AED values are -129.3 MJ, -183.7 MJ and -224.5 MJ for the 6 cm, 8 cm and 12 cm length *Guadua* bamboo rods respectively [19]. In addition, some imported bamboo products, regardless of whether they are processed before shipping, have a lower environmental impact than do broadleaf hardwoods. These types of products are analysed by the eco-costs, which are the costs of the environmental burden of a product on the basis of prevention of that burden. In general, are the costs which should be made to reduce the environmental pollution and materials depletion. For example, Strand Woven Bamboo (SWB) scores 0.52 eco-cost/kg and the teak, with a certificate of Forest Stewardship Council (FSC), scores 1.70 eco-cost/kg [20].

The life cycle assessment revelated that the production of bamboo products has a lower environmental impact compared with other building materials due to their fast growth, short rotation age and its contribution to the global forestation to decrease climate change and CO_2 emissions, further the great mechanical properties as specific elastic modulus and specific tensile strength obtained with low environmental impact during the manufacturing process [20].

1.4. BAMBOO IN EUROPE

Bamboo is naturally present on all continents except in Europe. For this reason, many associations and companies intend to cultivate bamboo on this continent in order to create a new sustainable market, help in the creation of jobs in rural areas and fight the climate change. An example of these new emerging companies is BambooLogic, a star-up whose objective is to cultivate bamboo in various European countries such as Portugal, Spain, Italy or Greece. These countries have the right characteristics for planting bamboo due to their climate and soil composition. The program of this company includes the plantation of 2,000 hectares of bamboo, as well as the creation of primary processing factories of bamboo providing the European market with one of the sustainable commodities for the future minimising the transport costs and import taxes, making easier the quality controls and currency fluctuations [21].

2. OBJECTIVES

The aim of this project is to determine the optimal drying conditions to obtain bamboo samples with the better mechanical properties suitable for its use as a building material in the production zones.

For this purpose, a study of drying kinetics as function of different variables as drying temperature and time have been carried out in the laboratory.

In addition, it is intended to use the obtained results by drying in an electric oven as a reference to those that could be obtained by drying in a solar oven to analyse the environmental footprint of the process.

3. EXPERIMENTAL PROCEDURE

Different assays have been carried out in the different laboratories of the departmental section of Science and Materials Engineering in the research group Centre of Design and Optimization of Processes and Materials (DIOPMA), in order to determine the properties of dried bamboo samples. The aim of this tests was to determine the parameters of the drying process that allow us to obtain the better physical and mechanical properties in bamboo samples for their later use as a building material. It is expected to find an optimal temperature and drying time with the least environmental impact. For this reason, it is planned to use the obtained results in this work by drying in an electric or vacuum oven as a reference to those that could be obtained by drying in a solar oven. Drying in a solar oven is intended to achieve the same properties and reduce the environmental footprint of the process.

The tests have been carried out on four years old samples, which were previously submerged in a boric acid solution to remove the biologicals agents. The tested samples are rectangular, as can be seen in the Figure 4, and they have been cut excluding the nodes. They have a specified width of 30 mm and a thick of 4.5 mm approximately. For each performed test, three different samples have been used. The results shown in Results and Discussion section are the average of the three values obtained for each test.

Figure 4. Bamboo test samples.

3.1. TEST SAMPLES DIMENSIONS

The length of the samples, for the bending test, has been determined according to the standard of the American Society for Testing and Materials ASTM-D3043 [22]. According to this standard since the width (*w*) is about 30 mm and the main direction of the folds of the face is perpendicular to the palm, the sample length (*L*) in mm should not be less than the determined by the following the Equation 1:

$$L = 24 \cdot t + 25 \quad \text{Equation 1}$$

Where *t* is the thickness in mm. The length of the samples must be higher than 133 mm. In our case, the length was 170 mm approximately.

In addition, the standard of the International Organization for Standardization ISO-22157 [23] have been followed to achieve accuracy during the dimension measurement. The length has been determined by a metric tape with an accuracy of 1 mm, the width and the thickness have been determined with an electronic vernier caliper with an accuracy of 0.01 mm. All the samples have been measured at three points (at both ends and in the centre) due to the nature of the samples, just before drying and just after drying.

3.2. TEST SAMPLES WEIGHT

The weight of the test samples has been determined according to the standard ISO-22157 [23]. Due to the availability of an analytical balance in the laboratory, the weight of the test samples has been determined with a better accuracy of 0.0001g. Samples have been weighed just before and after the drying test.

3.3. DRYING TEST

The drying test have been carried out in a J.P.Selecta lab stove and in Vaciotem-T vacuum lab stove. After a revision of the related bibliography [15], temperatures of 100, 80 and 60 °C and the times of 1, 2 and 4 hours have been selected to perform the drying test and a pressure of -1 bar for the vacuum test to determine the optimal drying conditions to obtain the best mechanical properties without cracking of the test samples.

The temperatures were measure digitally with an error of ± 2 °C according to the standard ASTM-D143 [24].

The time has been measured since the sample has been placed in the lab stove at the drying temperature, not since the sample has reached the drying temperature into de lab stove chosen for the test.

3.4. MOISTURE CONTENT

The moisture content of the test samples has been determined according to the standard ISO-22157 [23]. The moisture content (*MC*) corresponds to the removed water in the samples and it is determined by weighing. It is expressed as a percentage between the values of the mass of the sample before drying test (m_0) and mass of the sample after drying test (*m*), as can be seen in the Equation 2:

$$MC = \frac{m_0 - m}{m} \cdot 100$$ Equation 2

3.5. DENSITY

The density (*ρ*) of the test samples has been determined in kg/m^3 according to the standard ISO-22157 [23]. Density was determined following the Equation 3:

$$\rho = \frac{m}{V}$$ Equation 3

Where *m* is the mass of the test sample after drying test in kg and *V* is the volume in m^3. The volume was determined from the dimensions of the test sample found out in section 3.1.

3.6. SHRINKAGE

The shrinkage (*s*) of the test samples due to the drying process has been determined according to the standard ISO-22157 [23]. For a better shrinkage determination, the dimensions have been measured in barns previously made to ensure that the measurements were carried out at the same points before and after drying. Shrinkage is calculated by Equation 4, for each dimension, from initial value (I_v) and final value (F_v) and it is expressed as a percentage.

$$s = \frac{I_v - F_v}{I_v} \cdot 100$$ Equation 4

3.7. STATIC THREE-POINT BENDING TEST

For the static bending test has been used a universal Zick/Roell machine model Zmart.Pro and specifics bending clamps. It has been followed the standard ASTM-D3043 [22] for the static three-point bending test due to do not exist a specific standard for the available bamboo samples. This standard not include the test of bamboo samples, but it is used for samples of wood with similar properties and dimensions. The test conditions are shown below in the Table 1.

Table 1. Static three-point bending test conditions.

Distance between support points [mm]	Displacement rate [mm/min]	Maximum deflection [mm]
50	2	5

An image of the static three-point bending test performed is shown in the Figure 5. In it can be see the specific bending clamps and a bamboo sample between the support points.

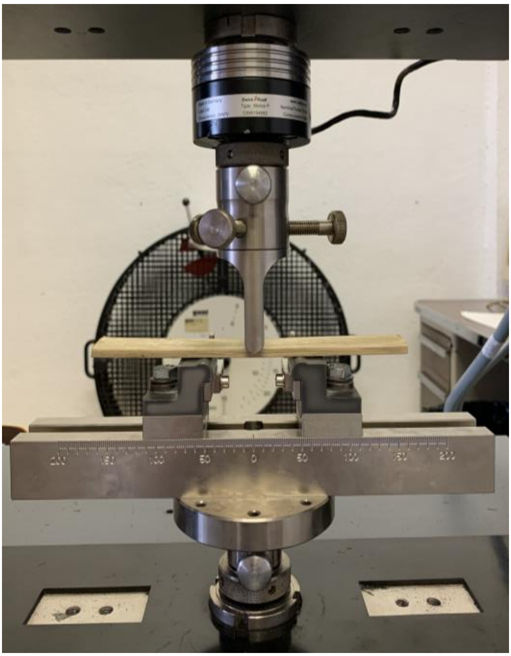

Figure 5. Static three-point bending test.

3.7.1. ELASTIC MODULUS

The values of the Young's Modulus or elastic modulus (*E*) for each sample has been determined through the assay of the static three-point bending test. This test provides, with the help of a TestXpert II software, a graphic of the applied force, *F*, in Newtons against elongation, *δ*, in mm. This graphic allows calculate the stiffness (*S*) as the slope of the elastic zone, as is shown in Equation 5.

$$S = \frac{F}{\delta}$$ Equation 5

In a static bending test, elongation can be expressed by Equation 6. Where *D* is the value of the distance between supports, 50 mm for all the test samples. The constant C_1 depends on the type of clamping and have a value of 48 in this case. The Moment of Inertia or Second Moment of Area (*I*) which depends on the geometry and the dimensions of the width (*w*) and the thickness (*t*) of the sample, calculated by Equation 7 as well as of the applied force, *F*, and the value of the elastic modulus (*E*) which is an intrinsic property of the material.

So the elastic modulus (*E*) can be calculated combining previous equations by Equation 8.

$$\delta = \frac{F \cdot D^3}{C_1 \cdot E \cdot I}$$ Equation 6

$$I = \frac{w \cdot t^3}{12}$$ Equation 7

$$E = \frac{F \cdot D^3}{C_1 \cdot I\ \delta}$$ Equation 8

4. RESULTS AND DISCUSSION

The results of the test done to study the properties of the bamboo samples after the drying process will be shown next. Due to the nature of the samples and to achieve a useful statistical study of the results, three different test samples have been analysed for each test. The results have been summarized in different figures which shows the moisture content, the density and the shrinkage after the drying process and the mechanical properties of the test samples. The average and the standard deviation values of the obtained results corresponds to the three samples studied during the test. In addition, has been characterized a sample which has not been treated thermally, named reference sample. The properties of this sample have been compared with the samples treated thermally in the density test and in the static three-point bending test.

4.1. MOISTURE CONTENT

The moisture content (*MC*) corresponds to the removed water in the samples during the drying process. This parameter has been studied in order to find the optimal drying conditions that allows to obtain the dried samples without the degrading its fibres. Due to the removed water in the samples, the loss in mass is shown below in the Figure 6 as a function of the drying temperature and time.

As can be seen in the Figure 6, it is show a rising trend given that the loss in mass increase as the drying temperature and time increase. The loss in mass from the test carried out at 100 °C with and without vacuum is much higher than in the test carried out at 80 °C and 60 °C without vacuum. As is shown in the Figure 6 the loss in mass during 2 hours at 100 °C is 6.7 %, while at 80 °C is 3.8 % and at 60 °C is 2.1 %.

In addition, a significant increase in loss mass is observed in the Figure 6 when the vacuum is applied. The assay carried out at 100 °C under vacuum show a greater loss in mass compared to the other experiments, even at the same temperature without vacuum. This was due that the boiling point of water decreased with the vacuum, so there was a faster evaporation rate of water compared to atmospheric pressure conditions. As can be seen in the Figure 6 the loss in mass during 1 hour at 100 °C under vacuum is 7.2 %, while at 100 °C without vacuum is 5.2 %.

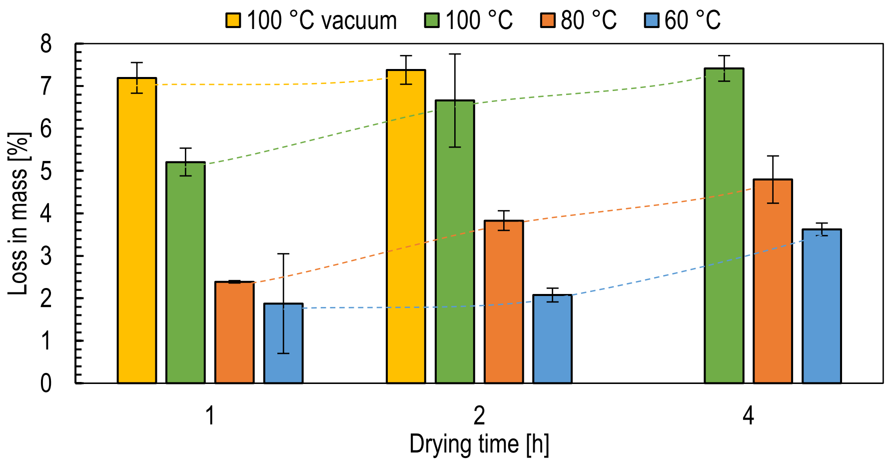

Figure 6. Loss in mass of the test samples as a function of drying temperature and time.

The loss in mass values for the assay carried out at 100 °C during 4 h and the assays carried out under vacuum at 100 °C during 1 and 2 h seem to reach a maximum value around of 7.2 %. However, it would be necessary to conduct further experiments at higher drying times to confirm this maximum value of the loss in mass. In addition, these further assays will permit to know the maximum values of loss in mass for the assays carried out at 80 °C and 60 °C that not have been found until now.

The dispersion obtained in the results of Figure 6 could be attributed to the nature of the test samples, as not all the studied samples must have the same initial moisture content and, in addition, the removal of water during the drying process could take place at different rate depending on this initial moisture content. Therefore, percentage of different mass losses are obtained.

4.2. DENSITY

The determination of the density values would permit to obtain specific mechanical properties of bamboo. These specific properties are calculated by dividing the value of that property by the value of the density, so they can help us to compare the properties of bamboo with others materials commonly used in the construction field taking into account simultaneously the mechanical property and density.

The density (ρ) of the test samples calculated through the Equation 3, as explained in the section 3.5, are shown below in the Figure 7.

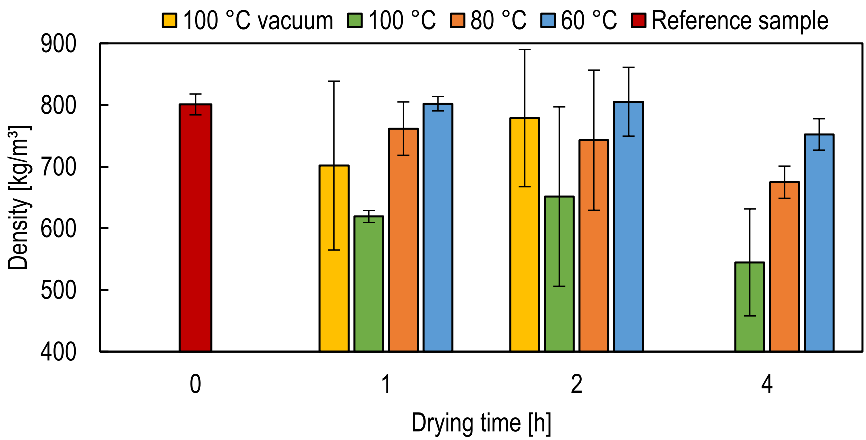

Figure 7. Density of the test samples as a function of drying temperature and time.

The average values of the density (Figure 7) obtained through the assays are within the limits of the reference values (600-800 kg/m^3) [4] cited previously in the section 1.1.

As can be seen in the Figure 7 for each time the values of the density are higher for the low drying temperatures. For example, the value of the density for the samples dried during 2 h at 60 °C is 780 kg/m^3, while the value of the density for the samples dried at 100 °C is 650 kg/m^3. In addition, for the same drying temperature, when drying time increase density decrease. For example, the value of the density for the samples dried at 60 °C during 1 h is 800 kg/m^3, while the value of the density for the samples dried at 60 °C during 4 h is 750 kg/m^3.

However, the values of the density obtained for the samples dried at 100 °C under vacuum during 1 h and 2 h are higher than expected. For example, the density of the samples dried during 1 h at 100 °C is 620 kg/m^3, while the value of the density for the samples dried at 100 °C under vacuum is 700 kg/m^3. This higher value could be attributed to some different mechanism of water removal when it is performed under vacuum conditions.

For the assay carried out at 100 °C during 4 h exist a minimum density value of 550 kg/m^3. However, it would be necessary to perform future assays at higher drying times to confirm this minimum density value.

In addition, in the Figure 7 it is observed a large dispersion for the density values due to the nature of the samples. The natural origin of the samples studied implies different initial conditions, dimensions and weights that make difficult to obtain similar results for the same drying temperature and time. A higher number of test samples should be analysed to minimize the dispersion obtained and counteract this intrinsic factor of the natural samples.

4.3. SHRINKAGE

The length, width and thickness shrinkage (*s*) has been studied to determine how the drying process affects the dimensions of the test samples. Since bamboo is an anisotropic material it is important to evaluate the shrinkage considering the direction of the fibres in the test samples. The length corresponds to the parallel direction to the fibres, while the width and the thickness corresponds to the perpendicular directions to the fibres in the test samples.

The average values of length shrinkage for the test samples after the drying process are shown below in the Figure 8.

Despite the great dispersion of the results obtained, two trends are observed in Figure 8. On the one hand the length shrinkage increases for each drying temperature if the time increases and, on the other hand, for the same time, the length shrinkage increases if the drying temperature used is higher. However, values obtained for 80 °C (orange) at 1 h don't follow these two trends. For example, the value of the length shrinkage for the samples dried at 80 °C during 1 h is 0.25 %, while the value of the length shrinkage at 80 °C and 2 h is 0.1 %.

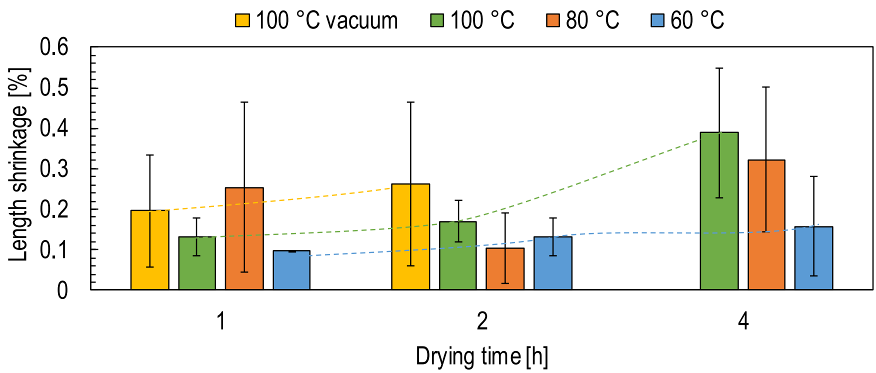

Figure 8. Length shrinkage of the test samples as a function of drying temperature and time.

For each drying temperature and time in the Figure 8 a very high dispersion is observed in the values of the length shrinkage, this is due to the nature of the samples and that length measurements for each sample have been made with an accuracy of 1 mm measured with a metric tape.

The average values of width shrinkage for the test samples after the drying process are shown in the Figure 9 as a function of the drying temperature and time.

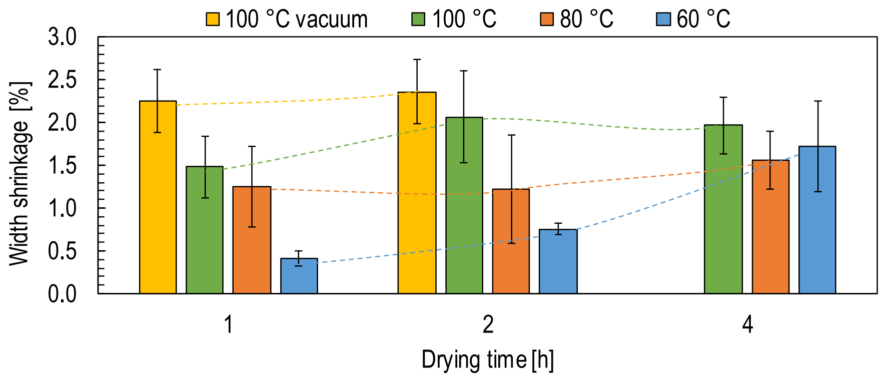

Figure 9. Width shrinkage of the test samples as a function of drying temperature and time.

As in Figure 8, in Figure 9 two trends are observed despite of the high dispersions obtained in the results. The width shrinkage increases for each drying temperature if the time increases and for the same drying time the width shrinkage increases if the drying temperature used is higher. For example, the value of the width shrinkage for the samples dried during 1 h at 60 °C is 0.4 %, while the value of the width shrinkage at the same temperature for the time of 4 h is 1.7 %. In addition, the value of the width shrinkage for the samples dried at the same time of 2 h are 2.2 % for the temperature of 100 °C and 0.7 % for the temperature of 60 °C.

It is also observed in Figure 9 that the use of vacuum increases significantly the width shrinkage in the samples. As can be seen in the Figure 9 the value of the width shrinkage for samples dried during 1 h at 100 °C under vacuum is 2.3 %, while the value at 100 °C for the same drying time without vacuum is 1.5%.

Compared to the Figure 8, in the Figure 9 has been an increase in width shrinkage in all samples for each drying temperature and time. This phenomenon is due to the width shrinkage is carried out in the perpendicular direction to the fibres.

In addition, a much smaller dispersion is also observed in Figure 9 compared to the Figure 8 due to the use of an instrument with a higher accuracy. In this case, a vernier caliper with an accuracy of 0.01 mm.

The average values of thickness shrinkage for the test samples after the drying process are shown below in the Figure 10.

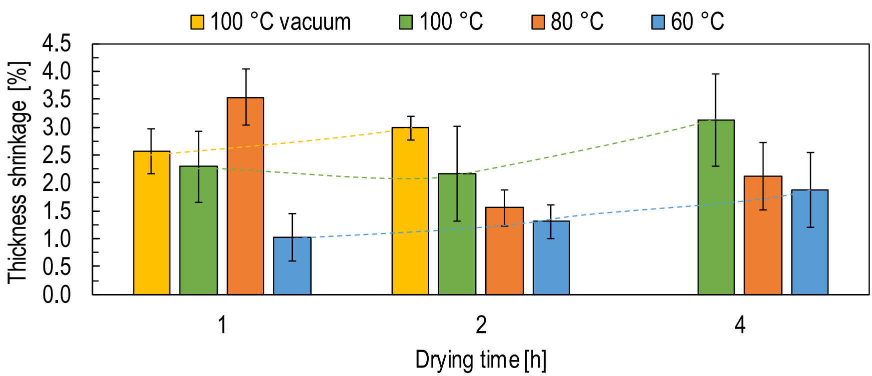

Figure 10. Thickness shrinkage of the test samples as a function of drying temperature and time.

In despite of the high dispersions of the values obtained in the Figure 10, the thickness shrinkage increases for each drying temperature if the time increases. In addition, for the same drying time, the thickness shrinkage increases if the drying temperature used is higher, although the values obtained for the samples dried at 80 °C during 1 h don't follow these two trends. The value of the thickness shrinkage for the samples dried at 80 °C during 1 h is 3.5 %, while the value of the thickness shrinkage for the samples dried at 80 °C during 2 h is 1.6%.

As in the Figure 9 shrinkage levels are similar to those shown in the Figure 10, which are higher than those shown in the Figure 8, due to the thickness shrinkage is performed in the perpendicular direction to the fibres.

Is also observed in Figure 10 a lower dispersion in the results obtained for thickness shrinkage than for length shrinkage. It could be due to the use of an instrument with a higher accuracy. In this case, a vernier caliper with an accuracy of 0.01 mm.

The percentage of shrinkage in width and thickness is greater than in length. Whereas the maximum values of the width and the thickness shrinkage are between 2.5 % and 3.5 %, the maximum value of the length shrinkage is 0.4%. The difference in the results obtained could be due to the direction where the shrinkage takes place. A higher shrinkage is observed in the two perpendicular dimensions to the direction of the fibres. It would be necessary to conduct further experiments at higher drying times to confirm these maximum values of shrinkage for the test samples. In addition, it would be advisable to repeat the assay carried out at 80 °C during 1 h to confirm the two trends observed in the Figure 8, Figure 9 and Figure 10.

4.4. MECHANICAL PROPERTIES

4.4.1. ELASTIC MODULUS

An example of a graphic of the applied force (*F*) against elongation (δ) obtained of one test sample provided by the static three-point bending test, that as have been explained in section 3.7.1, is shown in the Figure 11.

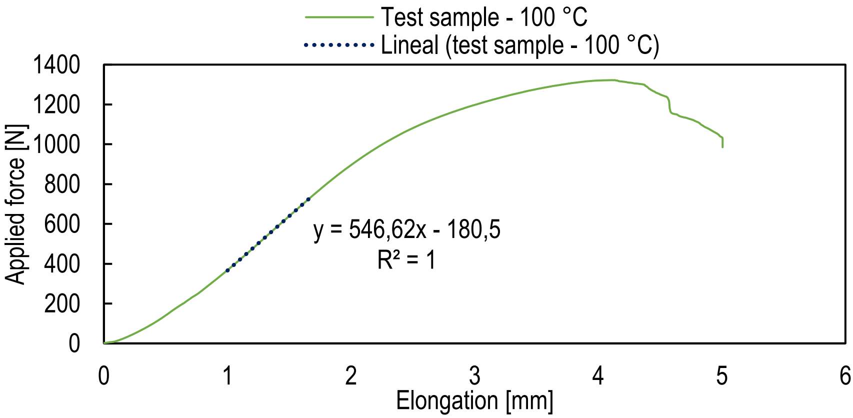

Figure 11. Applied force against elongation of the test sample dried at 100 °C during 1h.

In the curve of the static three-point bending test for the test sample dried during 1 h at 100 °C (Figure 11) it can be seen in first place a linear zone, also called elastic zone, ranging from an approximate elongation of 1 mm to 1.8 mm where the bamboo sample has an elastic behaviour. From this point, where the linearity between the applied force and the generated elongation is lost begins the plastic deformation zone. In this zone, the applied force increases until a maximum value, from which the samples breaks and the force decays. At the end of the test, the bamboo sample shows fibres breakage and a permanent deformation as can be seen in the Figure 12.

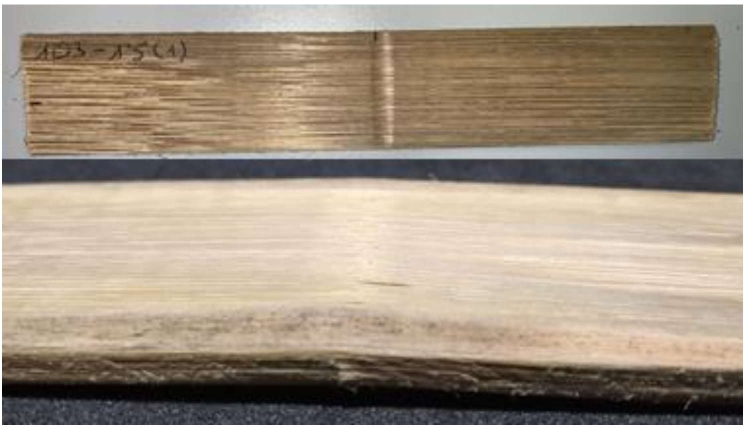

Figure 12. Bamboo test samples after the static three-point bending test.

The linear adjustment at the lineal zone of the static three-point bending test for the test sample is shown in the Figure 11. This linear adjustment supplies the value of the slope of the elastic zone or also named stiffness (*S*) and allows calculate the value of the elastic modulus for the test sample following the Equation 7, noted previously in the section 3.7.1. The elastic modulus indicates the material's resistance to be deformed elastically.

It is expected that the results obtained for the elastic modulus should follow a specific trend. A maximum value of the elastic modulus should be obtained for each drying temperature at a certain drying time and for the remaining drying times lower values of the elastic modulus must be obtained. The drying test is used to reduce the moisture content of the samples in order to obtain better mechanical properties, but if this drying process is carried out excessively, the fibres that form the samples will be degraded, which will reduce the value of the elastic modulus.

The average values of the elastic modulus shown in the Figure 13 are below the reference values (15-20 GPa) [4] cited previously in the section 1.1. However, for the drying time of 1 h the values of the elastic modulus are similar or higher than the value of the reference sample (7 GPa) at all drying temperatures.

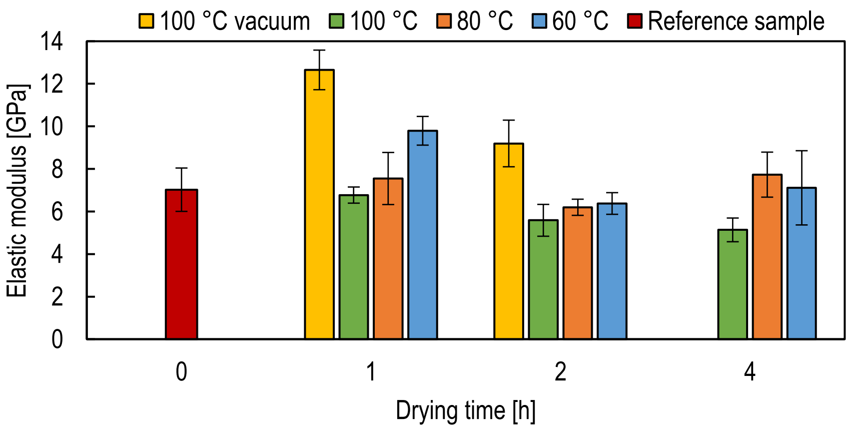

Figure 13. Elastic modulus of the test samples as a function of drying temperature and time.

As can be seen in the Figure 13, the values of the elastic modulus for the assays carried out at 100 °C, 80 °C and 60 °C without vacuum are higher for low drying times. For example, the value of the elastic modulus for the samples dried during 1 h at 100 °C is 6.7 GPa, while the value of the elastic modulus for the samples dried during 2 h at 100 ° is 5.6 GPa.

In the other hand, higher elastic modulus values are obtained for low drying temperatures at the same time. The elastic modulus at 60 °C for 1 h is 9.8 GPa while at 80 °C for 1 h is 7,6 GPa. This trend is due to the drying process, since the drying test at 60 °C produces less degradation in the fibres of the test samples than the drying test carried out at 80 °C and 100 °C.

The maximum value of the elastic modulus, 13 GPa, has been obtained for the samples dried under vacuum at 100 °C during 1 h. This maximum value is due to the fact that the drying process carried out under vacuum produces an optimal drying without degrade the fibres giving to the samples better mechanical properties.

Because of the results obtained in the Figure 13, further assays should be carried out during 1.5 and 0.5 h at 100 °C, 80 °C and 60 °C without vacuum to find the optimal drying time which do not produces degradation in the fibres of the test samples and provides a maximum value of the elastic modulus, that is, better mechanical properties in the test samples.

The dispersions in the results observed in the Figure 13 are due to the anisotropic structure of the test samples and small number of assays carried out in the laboratory. With an increase of analysed test samples can be achieved minimize the dispersions of the values of the elastic modulus.

5. CONCLUSIONS

After performing all the tests to study the bamboo samples after the drying process, it can be concluded that:

- High values of dispersion have been obtained for the results of the assays due to the nature of the samples and the small number of replicates for each drying condition test.
- The values of the loss in mass in the samples increase as the temperature and the drying time increase. In addition, a significant increase in loss mass is observed when the vacuum is applied.
- A maximum value in loss in mass of around 7.2 % has been obtained for the samples dried at 100 °C during 4 h and the samples dried under vacuum at 100 °C during 1 and 2 h.
- The values of the density of the test samples are within the limits of the reference values. However, it is obtained a large dispersion for the density values due to natural origin of the test samples.
- For each drying time the values of the density are higher for the low drying temperatures and for the same drying temperature, when drying time increase density decrease.
- The water removal mechanism is different when the drying process is carried out with or without vacuum.
- A minimum value of the density of around 550 kg/m^3 has been obtained for the samples dried at 100 °C during 4 h.
- The values of the length, width and thickness shrinkage increase if the drying temperature and time increases. In addition, the application of vacuum increases the shrinkage.
- The values of the length shrinkage are lower than the values obtained for the width and thickness shrinkage due to the length shrinkage is carried out in the direction of the fibres.

- A high dispersion is observed in the length shrinkage compared to the width and the thickness shrinkage due to the less accuracy of the measure.
- It would be necessary to conduct further experiments at higher drying times to confirm the minimum value of the density and the maximum values of loss in mass and shrinkage for the test samples.
- The drying process improves the mechanical properties of bamboo samples, especially when vacuum drying is applied.
- The maximum values of the elastic modulus of the test samples dried without vacuum at the same temperature have been obtained for the time of 1 h.
- A maximum value of the elastic modulus of 13 GPa has been obtained for the samples dried under vacuum at 100 °C during 1 h.
- It would be necessary conduct further assays during 0.5 and 1.5 h to determine the optimal drying time that allow to obtain the maximum value of the elastic modulus for the assays carried out at 100 °C, 80 °C and 60 °C without vacuum.

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ACRONYMS

AED	Accumulated Energy Demand
ASTM	American Society for Testing and Materials
DIOPMA	Centre of Design and Optimization of Processes and Materials
FSC	Forest Stewardship Council
FAO	Food and Agriculture Organization
DIN	German Institute of Standardization
GDP	Gross Domestic Product
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
SWB	Strand Woven Bamboo
UN	United Nations

SYMBOLS

ρ	Density
D	Distance between supports
E	Elastic modulus or Young's modulus
δ	Elongation
F_v	Final value
I_v	Initial value
L	Length
m	Mass of the sample after drying test
m_0	Mass of the sample before drying test
MC	Moisture Content
I	Moment of Inertia or Second Moment of Area
s	Shrinkage
p	Slope of elastic zone
S	Stiffness
t	Thickness
V	Volume
w	Width

APPENDICES

APPENDIX 1: PROPERTIES OF BAMBOO TEST SAMPLES

Table A1.1. Dimensions and weight of the reference test samples.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions [mm]						
Length	170.8	±0.2	170.7	±0.2	170.5	±0.7
Width	29.43	±0.39	29.31	±0.23	29.78	±0.15
Thickness	3.92	±0.35	4.25	±0.13	4.21	±0.15
Weight [kg]	16.2491	-	16.5179	-	17.2130	-

Table A1.2. Dimensions and weight of the test samples dried at 100 °C under vacuum for 1 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	171.8	±0.6	169.7	±0.5	168.2	±0.2
Width	28.92	±0.11	29.61	±0.12	28.92	±0.10
Thickness	4.30	±0.11	3.89	±0.32	4.34	±0.11
Dimensions after drying test [mm]						
Length	171.3	±0.6	169.7	±0.5	167.7	±0.5
Width	28.19	±0.12	28.87	±0.11	28.42	±0.18
Thickness	4.21	±0.08	3.77	±0.34	4.22	±0.09
Weight before drying test [kg]	18.3607	-	14.6878	-	11.1734	-
Weight after drying test [kg]	17.2081	-	13.6566	-	10.4103	-

Table A1.3. Dimensions and weight of the test samples dried at 100 °C under vacuum for 2 h.

	Sample 1		**Sample 2**		**Sample 3**	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	168.5	±0.4	169.3	±0.5	168.5	±0.4
Width	29.43	±0.23	28.88	±0.34	29.36	±0.16
Thickness	3.87	±0.37	4.49	±0.05	4.09	±0.03
Dimensions after drying test [mm]						
Length	168.5	±0.4	168.5	±0.4	168.0	±0.0
Width	28.62	±0.22	28.35	±0.30	28.64	±0.22
Thickness	3.75	±0.35	4.36	±0.02	3.97	±0.05
Weight before drying test [kg]	16.7220	-	13.9685	-	17.4173	-
Weight after drying test [kg]	15.5902	-	12.9530	-	16.2717	-

Table A1.4. Dimensions and weight of the test samples dried at 100 °C for 1 h.

	Sample 1		**Sample 2**		**Sample 3**	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	170.8	±0.2	168.8	±0.2	168.3	±0.5
Width	30.00	±0.18	31.15	±0.86	33.41	±0.70
Thickness	4.49	±0.14	4.40	±0.06	4.45	±0.09
Dimensions after drying test [mm]						
Length	170.7	±0.5	168.5	±0.4	168.2	±0.6
Width	29.62	±0.13	30.78	±0.84	32.74	±0.74
Thickness	4.34	±0.12	4.31	±0.10	4.37	±0.06
Weight before drying test [kg]	14.6225	-	14.5698	-	15.3379	-
Weight after drying test [kg]	13.8375	-	13.8782	-	14.6108	-

Table A1.5. Dimensions and weight of the test samples dried at 100 °C for 2 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	168.5	±0.4	171.1	±0.5	169.2	±0.2
Width	29.96	±0.64	29.13	±0.19	30.16	±0.10
Thickness	4.58	±0.01	4.56	±0.05	4.48	±0.02
Dimensions after drying test [mm]						
Length	168.2	±0.2	171.2	±0.8	168.8	±0.2
Width	29.51	±0.66	28.31	±0.10	29.60	±0.06
Thickness	4.50	±0.09	4.49	±0.06	4.33	±0.05
Weight before drying test [kg]	10.9173	-	18.2975	-	16.2404	-
Weight after drying test [kg]	10.0889	-	17.2808	-	15.3382	-

Table A1.6. Dimensions and weight of the test samples dried at 100 °C for 4 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	171.0	±0.8	171.2	±0.2	174.7	±0.5
Width	29.87	±0.38	30.34	±0.09	29.96	±0.68
Thickness	4.29	±0.13	4.56	±0.05	4.37	±0.08
Dimensions after drying test [mm]						
Length	170.0	±0.8	170.5	±0.4	174.0	±0.0
Width	29.23	±0.47	29.66	±0.10	29.51	±0.59
Thickness	4.20	±0.14	4.41	±0.02	4.19	±0.07
Weight before drying test [kg]	14.9561	-	11.0956	-	11.6368	-
Weight after drying test [kg]	13.8694	-	10.3437	-	10.8609	-

Table A1.7. Dimensions and weight of the test samples dried at 80 °C for 1 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	171.7	±2.1	169.7	±0.6	169.5	±0.4
Width	29.35	±0.19	29.36	±0.02	29.64	±0.34
Thickness	4.33	±0.19	4.04	±0.09	4.31	±0.26
Dimensions after drying test [mm]						
Length	171.2	±1.6	169.7	±0.5	168.7	±0.2
Width	29.09	±0.26	28.80	±0.22	29.37	±0.32
Thickness	4.19	±0.15	3.91	±0.12	4.00	±0.19
Weight before drying test [kg]	15.9829	-	16.0468	-	14.5242	-
Weight after drying test [kg]	15.6048	-	15.6778	-	14.1851	-

Table A1.8. Dimensions and weight of the test samples dried at 80 °C for 2 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	171.7	±1.2	171.2	±1.0	172.5	±0.4
Width	29.16	±0.29	26.90	±0.66	31.22	±0.23
Thickness	4.21	±0.02	3.53	±0.05	4.33	±0.06
Dimensions after drying test [mm]						
Length	171.3	±1.4	170.8	±1.3	172.3	±0.2
Width	28.65	±0.22	26.47	±0.71	31.11	±0.22
Thickness	4.13	±0.02	3.49	±0.08	4.26	±0.04
Weight before drying test [kg]	15.5194	-	14.5158	-	14.3792	-
Weight after drying test [kg]	14.9025	-	13.9882	-	13.8820	-

Table A1.9. Dimensions and weight of the test samples dried at 80 °C for 4 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	174.0	±0.8	172.7	±0.5	167.7	±0.5
Width	30.78	±0.43	29.99	±0.26	29.22	±0.10
Thickness	4.31	±0.02	4.32	±0.07	4.06	±0.05
Dimensions after drying test [mm]						
Length	173.0	±0.0	172.3	±0.5	167.3	±0.2
Width	30.41	±0.35	29.54	±0.22	28.63	±0.20
Thickness	4.18	±0.03	4.23	±0.07	4.00	±0.07
Weight before drying test [kg]	14.8956	-	14.9961	-	14.3725	-
Weight after drying test [kg]	14.2442	-	14.3839	-	13.6151	-

Table A1.10. Dimensions and weight of the test samples dried at 60 °C for 1 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	170.2	±0.2	169.7	±0.5	171.5	±0.4
Width	29.39	±0.32	30.11	±0.05	29.34	±0.16
Thickness	3.79	±0.60	4.10	±0.22	4.05	±0.31
Dimensions after drying test [mm]						
Length	170.0	±0.4	169.5	±0.4	171.3	±0.5
Width	29.29	±0.31	29.95	±0.04	29.23	±0.16
Thickness	3.73	±0.62	4.06	±0.22	4.03	±0.30
Weight before drying test [kg]	14.8497	-	17.0616	-	16.6206	-
Weight after drying test [kg]	14.6641	-	16.4817	-	16.4817	-

Table A1.11. Dimensions and weight of the test samples dried at 60 °C for 2 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	168.2	±0.2	167.3	±0.5	167.7	±0.5
Width	29.40	±0.36	29.49	±0.02	29.54	±0.03
Thickness	4.13	±0.20	4.41	±0.01	4.45	±0.02
Dimensions after drying test [mm]						
Length	168.0	±0.4	167.2	±0.2	167.3	±0.2
Width	29.15	±0.41	29.29	±0.05	29.32	±0.00
Thickness	4.08	±0.15	4.34	±0.02	4.41	±0.01
Weight before drying test [kg]	17.9940	-	16.9380	-	16.6023	-
Weight after drying test [kg]	17.6247	-	16.6272	-	16.2345	-

Table A1.12. Dimensions and weight of the test samples dried at 60 °C for 4 h.

	Sample 1		Sample 2		Sample 3	
	Average	**Standard deviation**	**Average**	**Standard deviation**	**Average**	**Standard deviation**
Dimensions before drying test [mm]						
Length	167.8	±0.2	170.0	±0.0	170.0	±0.0
Width	29.95	±0.02	29.92	±0.10	30.39	±0.25
Thickness	4.31	±0.04	4.22	±0.15	3.98	±0.13
Dimensions after drying test [mm]						
Length	167.3	±0.5	169.7	±0.5	170.0	±0.0
Width	29.44	±0.24	29.60	±0.05	29.67	±0.45
Thickness	4.20	±0.05	4.14	±0.17	3.94	±0.09
Weight before drying test [kg]	16.5603	-	16.4862	-	14.7707	-
Weight after drying test [kg]	16.0078	-	15.9120	-	14.2281	-