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Thermal Diffusivity Behavior of Guadua angustifolia Kunth as a Function of Culm Zone and Moisture Content

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Abstract

Guadua angustifolia Kunth is a giant graminea native of Central and South America. This plant captures a lot of carbon dioxide and protects hydrographic watersheds. For this reason, the growing of Guadua a. is considered environmentally favorable. Furthermore, the use of this forest resource as a structural and decorative element for building has been promoting recently due to its special physical characteristics. However, nowadays much of the production chain is inefficiently oriented by empirical and traditional knowledge. In particular, the drying process exerts influence on cracks that disqualifies the material for some artistic and industrial applications. Thermal characterization allows making models for drying according to particular characteristics of the material. Knowledge of thermal properties is also important for applications in which heat transfer can play an important role, such as in buildings. In this work, thermal diffusivity was measured as a function of the moisture content obtained during the drying process in samples of Guadua a. taking from the bottom, middle and top culm regions of the plants. Measurements were performed using the photoacoustic technique. Results show that thermal diffusivity increases with the moisture content but its value becomes the same along the bamboo. This behavior is highly correlated with the morpho-anatomical characteristics of the plant, which were determined through scanning electron microscopy.

Keywords: Guadua angustifolia Kunth, thermal diffusivity, thermal effusivity, moisture content, photoacoustic, SEM.

Introduction

Bamboo is a cheap and fast-grown forest resource with important physical and mechanical properties. Today the bamboo market has acquired great importance. Although many kinds of wooden products are not used anymore with the spread of cheaper artificial materials, bamboo has still great potential for replacing wood in several applications. For example flexible bamboo strips are widely used in bent parts of traditional handiwork, even in the modern age of plastics. Bamboo is also used in many communities worldwide for making various daily use objects, such as cooking items, and also as a building material, applications in which knowledge of heat transfer behavior is of great importance. For many applications a drying process of the material is necessary, and to perform it in an efficient way accordingly to industrial requirements, accurate knowledge of thermal properties (e.g. thermal diffusivity, α) and their dependence with moisture is of great importance. The determination of these properties is also important because they depend strongly on other material characteristics such as structure, composition, moisture, porosity, morphology, etc. Thus in order to support the potential of bamboo as a useful industrial resource further research towards its thermal characterization becomes impetuous. It is important to notice that while mechanical properties characterization of Bamboos has been performed by several authors[1,2,3], reports on their thermal properties are scarce[4]. Thermal diffusivity is measured using of non-stationary or dynamic methods [5]. Because

$$k = \alpha C \qquad \text{.............(1)}$$

where C is the specific (volume) heat capacity, knowledge of this last parameter is necessary if the thermal conductivity is to be obtained as well. But fortunately C is nearly a constant parameter for solids being less sensitive to impurities and structure of materials, and comparatively independent of temperature above the Debye temperature, than thermal conductivity and diffusivity. This almost constant value of C can be explained by taking into account its definition as the product of the density (ρ) and the specific heat (c). The specific heat is defined as the change in the internal energy per unit of temperature change; thus, if the density of a solid increases (or decreases) the solid can store less (or more) energy. Therefore, as the density increases, the specific heat must decrease and then the product $C = \rho c$ stays constant, so that according to Eq. (1) the behavior of the thermal conductivity becomes similar to that of the diffusivity.

Among the dynamic methods for thermal diffusivity measurements the so-called photothermal techniques[6], and in particular the photoacoustic ones[7], have demonstrated their usefulness, having advantages respecting other methods because they are cheaper, non-invasive (they do not require special samples preparation for their measurement, they are measured as they are), the temperature variations involved are so small that they not modify samples properties during the measurement process, and the required sample´s volumes are relative small (typical samples dimensions are in the order of 1cm×1cm×0.05cm). Moreover the physical-mathematical formalisms behind these techniques are relatively straightforwardly allowing easily interpretation of the experimental results.

Due to the above mentioned constancy of *C* and the definition (1), in a plot of thermal conductivity versus thermal diffusivity solid materials typically fall along a line. Debye´s theory for specific heat shows that the slope of this line is about $C=\rho c\approx 3\times10^{6}$ J/m^{3}K at room temperature, if the volume occupied per atom in a solid is taken as about 1.4×10^{-29} m^3, an almost common value that is used by many authors. But deviations from this value could be expected for some materials due to several reasons, among them: i- heat conduction can be limited partially by the gas entrapped in the porosity; ii- heat fluxes through parallel arrangements of cylindrical layers and through embedded regions from different materials composing the plant that can modify strongly their effective thermal properties values [8],iii- high values of the Debye temperature so that the classical approximation considered above does not work anymore. In many cases the methods used for measurement of specific heat capacity involve temperatures that can modify sample´s thermal parameters during measurement, particularly in the vicinity of phase transitions and structural changes. Thus, in order to account for the specific heat capacity we resorted in this paper to its calculation using the well known relationship

$$e = C\,\alpha^{1/2} \qquad \text{............ (2)}$$

where *e* is the thermal effusivity. For the role of this parameter in heat transport phenomena the interested reader can be referred to the work of Marín[9]. It will be also determined here by the photoacoustic technique using a method based in the effective medium theory that uses the well known analogy between thermal and electrical phenomena.

Around 1200 bamboo species have been identified in the world[10] and the use of this plant has a very long history, being one of the oldest building materials used by humans [11]. One of the most important species in Central and South America is *Guadua angustifolia* (*Guadua* for short). In this paper we will study, using the PA technique aided with Scanning Electron Microscopy (SEM), the influence of moisture during the drying process on the thermal diffusivity of samples cut from three different culm zones of *Guadua* plants.

Material and Methods

Samples: Measurements were done in 600 µm thick and 1 cm diameter disc shaped samples of *Guadua* cut from the top, middle and bottom culm zones of the plant (figure 1). Different moistures values were obtained by a drying process using a Metler-Toledo balance with an internal heating system. Changes in the moisture content of the samples were avoided by storing them in a hermetically closed box with humidity and temperature control. The moisture values were normalized to the initial ones measured immediately after the sample was cut.

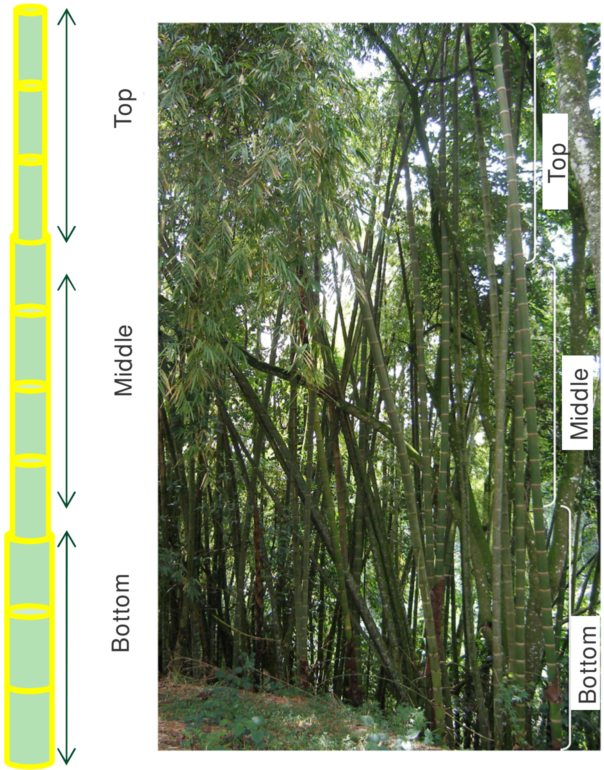


Figure-1
The Guadua culm was divided in three zones through its longitude: bottom, middle and top

Photoacoustic measurements: Thermal diffusivity: Thermal diffusivity measurements were performed using a homemade apparatus showed schematically in figure 2. Modulated light energy absorption takes place at the surface of the sample that closes the air filled chamber of a photoacoustic cell (see inset of the figure). The light source was a 514 nm Argon ion Laser (Modu-laser, Stellar-Pro ML/150) with a power of 100mW. Intensity modulation of the laser light beam has been achieved by means of an acousto-optic modulator (HB-Laserkomponenten, Helios Blanking-unit system 4).

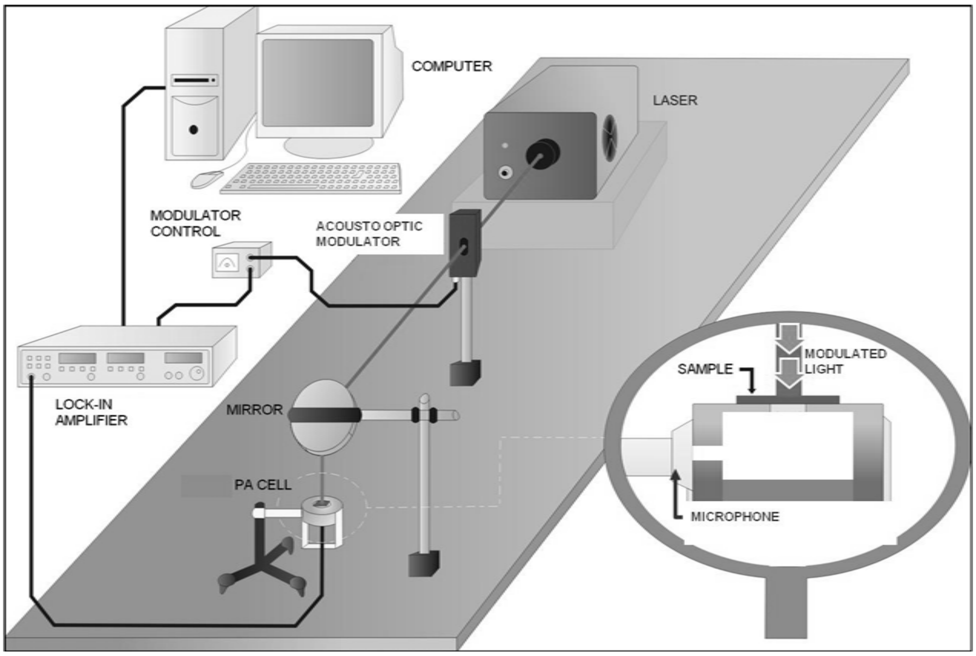


Figure-2
Schematic view of the PA system for thermal diffusivity measurements
The inset shows the used open PA cell described in the text

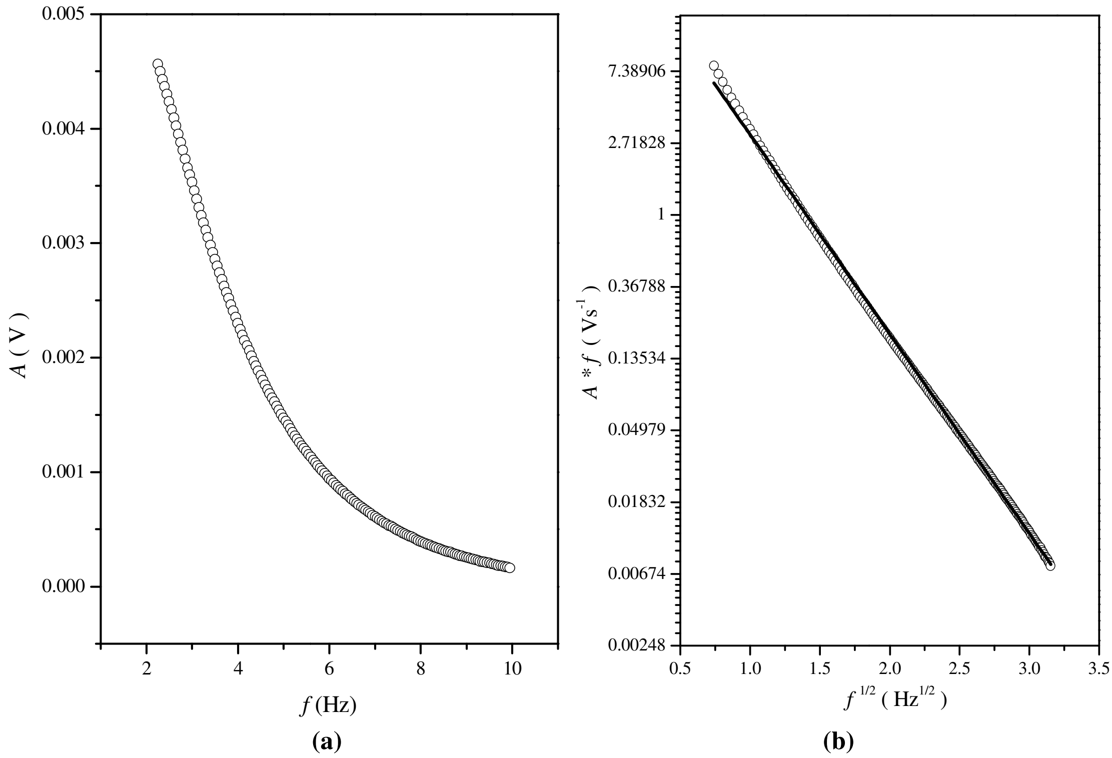


Figure-3
(a) Typical curve of the PA signal amplitude (*A*) as a function of the modulation frequency (*f*) for a sample with 11.8 % of moisture content taken from the middle zone of *Guadua* culm. (b) Logarithm of the *A*f* product plotted as a function of the square root of the modulation frequency for the same sample considered in (a). The solid line corresponds to the best least squares linear fit as given by the Rosencwaig-Gersho model for an opaque and thermally thick sample (Eq. (2))

The periodically generated heat is transmitted through the sample to the air inside the cell inducing pressure oscillations that are detected by an electret microphone (Radio Shack 270-092C) already enclosed in the chamber. The amplitude of the microphone signal is measured as a function of the modulation frequency, *f*, using a Lock-in Amplifier (Stanford Research, SR-830). For this configuration the Rosencwaig-Gersho (RG) model [12] for the PA signal generation predicts, for the amplitude of the measured signal, the result:

$$\log(A * f) = -l\left(\frac{\pi f}{\alpha}\right)^{1/2} \qquad \text{………. (3)}$$

where l is the sample´s thickness. In arriving to eq. (2) it has been supposed that the sample is optically opaque at the excitation light wavelength and thermally thick (the sample's thickness is much greater than thermal diffusion length defined as $(\alpha/\pi f)^{1/2}$). From the fit of the experimental data to this equation the sample's thermal diffusivity can be determined in a straightforwardly way.

Thermal effusivity: Using a model based in the well known analogy between electrical and thermal phenomena, the effective thermal diffusivity of a two layer series system can be defined as [13]:

$$\alpha_e = \frac{1}{\dfrac{x^2}{\alpha_1} + \dfrac{(1-x)^2}{\alpha_2} + x(1-x)\left(\dfrac{\lambda}{\alpha_1} + \dfrac{1}{\lambda\alpha_2}\right)} \qquad \text{…… (4)}$$

where $x = l_1/(l_1 + l_2)$ is the ratio of the thicknesses of the involved materials (subindices 1 and 2 refer to each of them) and $\lambda = k_1/k_2$, is the ratio of their conductivities. Using eq. (1) this ratio can be expressed as:

$$\lambda = \frac{k_1}{e_2\sqrt{\alpha_2}} \qquad \text{…………(5)}$$

The effective thermal diffusivity of a sample composed by the investigated bamboo (material 2 in our model, for which thermal diffusivity, α_2, is known from a previous measurement using the procedure described above) and a sample of another material (a reference sample 1 with well known thermal properties α_1 and k_1) attached to it can be measured as described in the preceding subsection. If x is known then the parameter λ can be determined using eq. (4). From it the thermal effusivity, e_2, can be calculated straightforwardly using eq. (5).

Scanning electron microscopy: Micrographs of longitudinal and transversal cuts of samples were taken using an Scanning Electron Microscope (SEM) JEOL JSM-6390LV at amplification of 500x and acceleration voltage of 20kV. This kind of Microscope has been selected because it allows measurements under low vacuum conditions so that water evaporation from the samples is minimized [14].

Results and Discussion

The figure 3 (a) shows a typical curve of the PA signal amplitude (A) as a function of the modulation frequency (f) for a sample taken from the middle zone of a *Guadua* culm with 11.8 % of moisture content. To achieve the optical opacity condition of the RG model the samples were coated with a thin carbon black layer on the surface where light absorption takes place. Similar curves have been recorded for the other samples. In part (b) of the figure we show the logarithm of the $A*f$ product as a function of the square root of the modulation frequency, so that according to eq. (3) the value of α was calculated from the slope of the graph, namely [15] $l(\pi/\alpha)^{1/2}$.

Following the above described methodology the thermal diffusivities of all investigated samples were determined. They are plotted in figure 4 as a function of moisture content for samples collected from the top, middle and bottom regions of the *Guadua* culms. Each represented value is a mean value of 10 independent measurements in different samples prepared under the same conditions. The results of these independent measurements were highly repetitively.

It can be seen that thermal diffusivity increases as a function of moisture content approaching a saturation value at higher moisture values, being the behavior very similar for samples from the three different regions of the *Guadua* culm, i.e. thermal diffusivity is the same for the three investigated *Guadua* culm zones. This behavior is consistent with previous results obtained for some mechanical properties such as Brinell-hardness of samples taken from the same regions, which do not show appreciable variations between the ranges of the experimental uncertainties[16].

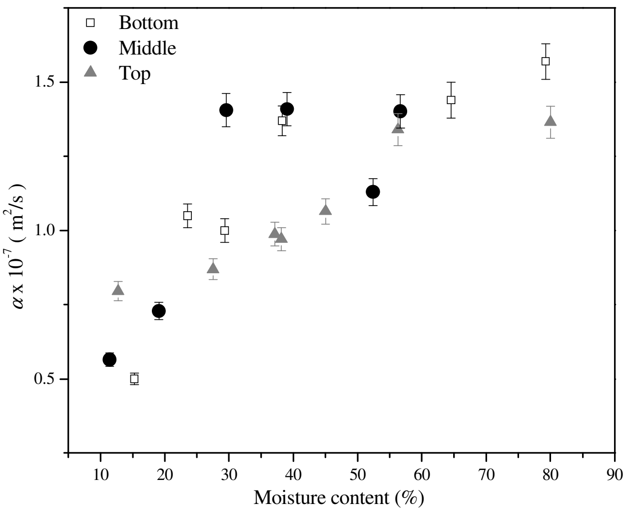
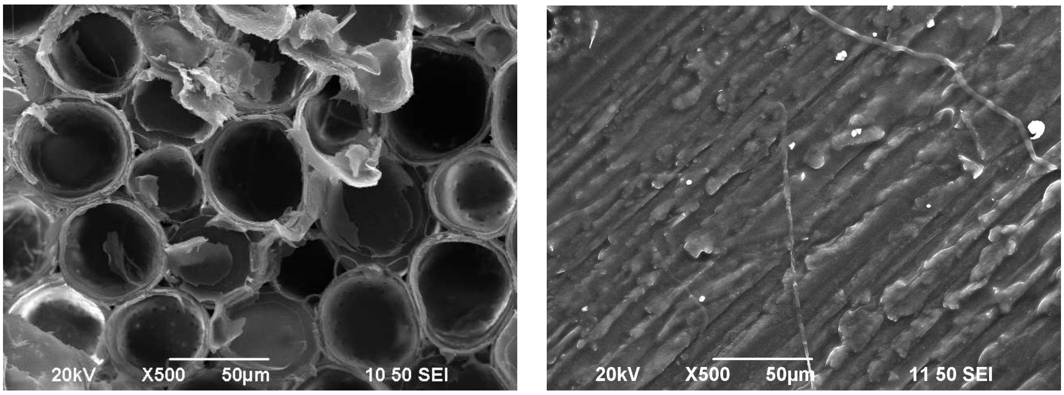
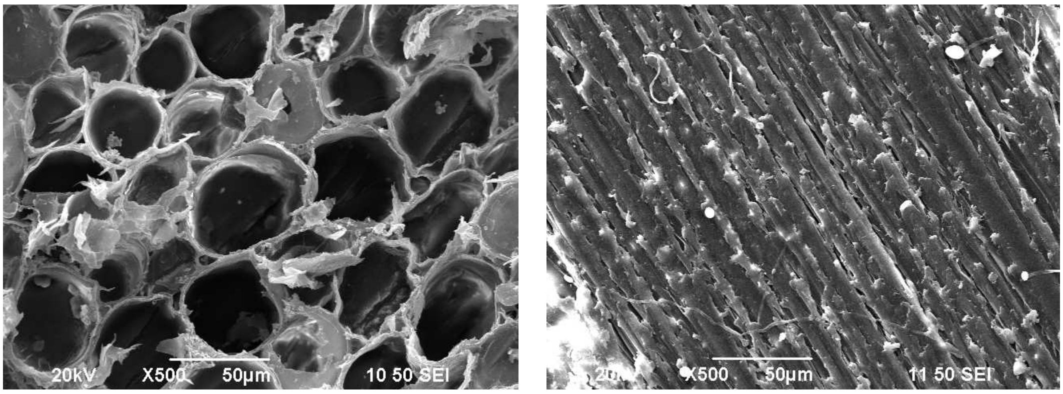


Figure-4
Thermal diffusivity values as a function of moisture content for three longitudinal sections of the Guadua: bottom, middle and top

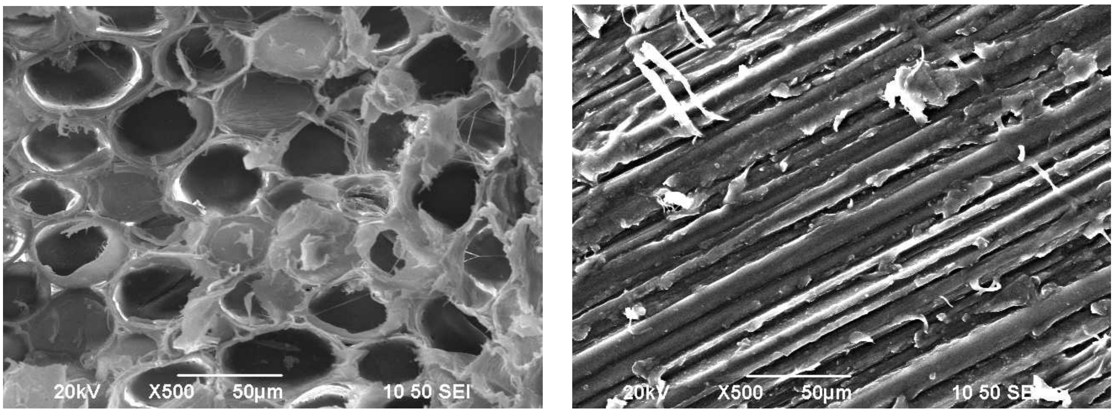
The proportional relationship between thermal diffusivity and moisture content is somewhat an awaited result. If we consider the *Guadua* as a composite material made by cylindrical tubes with solid walls (figure 5) that for low moisture contents are mainly filled with air and that become filled with a higher than air diffusivity material, as water is, when moisture increases, then effective medium theories[17] predict an enhancement of the effective thermal diffusivity with the concentration of the second material. According to this we observed how thermal diffusivity enhances from an initial value of 0.05×10^{-6} m^2/s (can be a value for a porous dry wood sample) at the lowest moisture content and approaches a saturation value of 0.15×10^{-6} m^2/s (similar as for some typical woods [6, 18]).



Fiugre 5 (a)



Fiugre 5 (b)



Fiugre 5 (c)

SEM micrographs of samples taken from: (a) bottom, (b) middle and (c) top of longitudinal zone in Guadua with 11.8% moisture content. The three images showed on the top correspond to a cross-section view while those of the bottom are photographs of a lateral view

Thermal effusivity measurements were performed using the methodology outlined in Section Material and Methods. A 100 µm silver slab was used as the reference material 1, which was glued using a very thin layer of thermal conductive silver paste to the bamboo's samples, assuring a good thermal contact. The thicknesses of the bamboo´s samples varied between 200 and 400 µm. The effectiveness of the method used to attach one sample to another has been proved by independent measurements of the thermal effusivity of wood (eucalyptus), stainless steel and glass test samples. For the effective thermal diffusivity measurements the composite samples were located in such a way that they were illuminated on the reference silver sample side, which has been previously carbon blackened for guarantying the optical opacity condition.

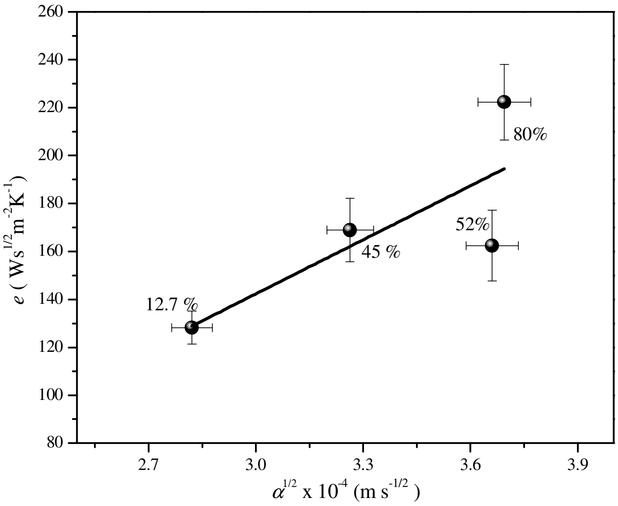


Figure-6
Thermal effusivity as a function of the square root of the thermal diffusivity for samples taken from the top culm region of the Guadua for different moisture contents, the solid line is the best least squares linear fit whose slope is equal to the volume specific heat, ρC

The figure 6 shows the measured thermal effusivity as a function of the square root of the thermal diffusivity for samples taken from the top culm region of the Guadua for different moisture contents. Following eq. (2) the slope of the curve resulting from the best linear least squares fit of the data is the specific heat capacity. We obtain the value $C=(0.8\pm0.1)\times10^{-6}$ J/m^{3}K that is about one order of magnitude smaller than the value of 3×10^{-6} J/m^{3}K predicted for most solids, but, as expected, is in good agreement with that reported for some porous materials such as foams, cork and some woods [19]. For these materials due to their low density there are fewer atoms per unit volume so that ρC becomes low. This is also the case of the bamboos studied here. The principal result is that they have low thermal conductivities and diffusivities, a fact that make them appreciate materials to be used for insulation.

The SEM images of figure 5 show micrographs of the cross-section and a lateral view of samples from the bottom, middle and top zones. It is possible to see that the vascular bundles diameter is uniformly distributed along *Guadua*. From the micrographs the average diameter of these fibers was estimated as 43.8±1.3 µm, 37.5±1.3 µm and 36.1±1.1 µm for bottom, middle and top zone, respectively. The homogeneity in thermal properties values obtained along *Guadua* culm can be explained considering the size distribution of the vascular bundles, from which we expect that heat propagation takes place through tubes of thin wall with similar composition (the most important elements detected using energy dispersive spectroscopy –EDS JED/2300- were C, O, Si, K, Ca).

Conclusions

We demonstrate that the photoacoustic technique allows measurement in a cheap, efficient and non-destructive (in the sense that the technique does not require the use of electrical contacts, as in some more conventional methods) way of the principal properties involved in heat transfer of *Guadua*. Thermal diffusivity was measured using this technique for samples from different *Guadua* sections: bottom, middle, and top. Results show that thermal diffusivity increases with moisture content, but it not shows important changes along *Guadua* culm, a fact that has been explained on the basis of the homogeneity in morphological characteristics evidenced by SEM microphotographs taken from cross and longitudinal section of the bamboos. These images showed that the area occupied by the vascular bundles (parenchyma and other fibers in the stem) remains approximately invariable along *Guadua* culm.

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