Measurement of the thermal expansion coefficient of Guadua angustifolia-Kunth using the photoacoustic technique

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Abstract. In this paper, the Linear Thermal Expansion Coefficient of Guadua angustifolia–Kunth samples was measured using the Photoacoustic (PA) technique in a heat transmission configuration and considering the thermoelastic bending as a PA signal generation mechanism in addition to the thermodiffusion ones. The obtained value of $(27\pm7)\times10^{-6}K^{-1}$ is a reasonable value compared with that reported for similar materials such as wood.

1. Introduction

Guadua angustifolia–Kunth (GAK) has high population density in Asia and South America [1]. The mechanical and thermal characterization of this plant and by-products have been reported in several works [2,3,4], proving scientifically the reason of why this material is widely used in the construction industry [5] since ancient times, being comparable in several features with concrete and mild steel [6]. Additionally, this natural material is a renewable and sustainable resource and this has application for replacing the wood and for manufacturing Natural Fibres Reinforced Composites (NFRC) [7]. In this paper the measurement of the linear thermal expansion coefficient, $\alpha_T$, of GAK is reported. Measurements were made using the photoacoustic (PA) technique [8] in heat transmission mode and using a model for data processing that takes into account the thermoelastic bending signal generation mechanism in addition to the heat diffusion process. The thermal diffusivity, $\alpha$, is reported too.

2. Materials and methods

In this study, Macana biotype GAK was taken from a harvest located in a municipality of La Tebaida, in the Quindío, Colombia, at a height of 1480 meters above the sea level. The middle part of the stem was chosen and divided through its internodals. These sections were dried using a dehumidifier system with controlled temperature (313K) until a moisture content about 15% was reached. For measurement of $\alpha$ and $\alpha_T$, thin sheets were extracted through a longitudinal cut along the fibre direction in an intermediate region.

The PA technique was used in a heat transmission configuration, in which the intensity modulated laser beam impinges and is absorbed on the sample’s surface opposite to that facing the PA air chamber. The generated PA signal was detected with a microphone connected to the air chamber by a small diameter duct and was measured with a Lock-In amplifier synchronized at the light modulation frequency, $f$.

In order to measure the linear thermal expansion coefficient measurements were performed at frequencies at which the sample is thermally thick ($ik$), so that the thermoelastic bending ($T$) signal...
generation mechanism (dependent on the \( \alpha_t \) value) becomes important, being added to the thermodiffusion \((D) \) mechanism (dependent on \( \alpha \)). To eliminate the frequency response of the detector, it was necessary to normalize the PA signal from the sample \((S_{D,tk} + S_{T,tk})\) with that of a reference sample, which in our case is in the thermally thin \((m) \) regime \((S_{D,tn} + S_{T,tn})\). The ratio of the amplitudes of both signals is given by [9]:

\[
S = \frac{S_{D,tk} + S_{T,tk}}{S_{D,tn} + S_{T,tn}} = \sqrt{f} \frac{\left(ge^{-T_{fc}} \pm \frac{2gH_{c}^{1/2}e^{-nT_{fc} \cos \left(-\pi f_{c}/f \right)}}{1 + m^{2}f_{c}^{3} + 2m^{2}f_{c}^{3} \cos \left(-\pi f_{c}/f \right)} \right)}{\left( \frac{1}{x} \right)^{1/2} + \left( \frac{1}{x} \right) \cdot \cos \left( \frac{1}{x-1} \right)} \cdot \cos \left( \frac{1}{x} \right)}
\]

(1)

Where \( g, h, m \) are constants, \( C = \left( 1 - \frac{1}{x} \right)^{2} + \left( \frac{1}{x} \right) \cdot \cos \left( \frac{1}{x-1} \right) \cdot \cos \left( \frac{1}{x} \right) \) and \( f_{c} \) is the cutoff frequency of the material, which is defined as:

\[ f_{c} = \frac{\alpha}{\pi l_{s}} \]

(2)

The methodology consists in measurement of \( S \) as a function of \( f \). Then a least squares fit of the experimental data using Equation (1) is performed, leaving \( g, h, m \) and \( f_{c} \) as fit parameters. From \( f_{c} \) the thermal diffusivity can be determined using Equation (2) if the sample’s thickness, \( l_{s} \), is well known.

On the other hand, \( \alpha_t \) can be obtained using the following expression [9]:

\[
\alpha_{Te} = \frac{4\pi^{2}a_{g}^{1/2}h}{3R^{2}a_{s}T_{0} \cdot g}
\]

(3)

In which this parameter was redefined as \( \alpha_{Te} \). This experimental value will agree with the expected \( \alpha_t \) only under conditions in which the sample is in the ideal thermally thick regime, i.e. when \( f_{c} \to 0 \) [9].

Measurements were performed in seven samples of different thicknesses. From the slope of the plot of \( f_{c} \) as a function of \( l_{s}^{-2} \) the thermal diffusivity was determined using Equation (2), while \( \alpha_t \) is calculated from the \( \alpha_{Te} \) versus \( f_{c} \) graph as the \( \alpha_{Te} \) for \( f_{c} \to 0 \).

3. Results

The measured values of thicknesses, \( f_{c} \), \( \alpha_{t} \) and \( \alpha_{Te} \) of the samples are presented in Table 1.

Figure 1(a) shows the dependence of \( f_{c} \) on \( l_{s}^{-2} \) which a value \( \alpha = (0.11 \pm 0.01) \times 10^{-6} \text{m}^{2} \text{s}^{-1} \) was obtained following the methodology described in previous section. This value agrees well with that reported previously [10] for this kind of material and can be considered as a mean value of those obtained for the individual samples (Table 1).

Figure 1(b) shows \( \alpha_{Te} \) as a function of \( f_{c} \). A decreasing behaviour is observed, which can be fitted using the Equation 4.

\[
\alpha_{Te} = \frac{-f_{c}}{a_{1}e^{a_{2}} + a_{2}}
\]

(4)

Where \( a_{1}, t_{1} \) and \( a_{2} \) are fit parameters, for which the values \((25 \pm 7) \times 10^{-6} \text{K}^{-1} \), \((2.0 \pm 0.2) \times 10^{-6} \text{K}^{-1} \) and \((0.12 \pm 0.03) \text{ Hz} \) were obtained respectively. Note that when \( f_{c} \to 0 \), the linear thermal expansion coefficient becomes \( \alpha_{Te} = \alpha_{T} = a_{1} + a_{2} = (27 \pm 7) \times 10^{-6} \text{K}^{-1} \). To the best of our knowledge, there is not a previous report on this parameter. However, the order of magnitude is preserved when the obtained value is compared with that corresponding to some types of wood. For example, the \( \alpha_{t} \) value of wood varies between about \( 2 \times 10^{-6} \text{K}^{-1} \) and \( 30 \times 10^{-6} \text{K}^{-1} \) [11] in the transversal direction, and for composites
reinforced with bamboo fibres $\alpha_T$ is larger than $40 \times 10^{-6} K^{-1}$ [12,13], a value which increases with respect to those corresponding to its separate components (fibre-matrix). Therefore, we believe that the linear thermal expansion coefficient found in this study for GAK is a reasonable value.

Table 1. Results of thermal diffusivity and experimental thermal expansion coefficient of Guadua angustifolia-Kunth.

| Thickness (µm) | $f_c$ (Hz)    | $\alpha_z$ (m$^2$s$^{-1}$)$\times10^6$ | $\alpha_T$ ($^\circ$K$^{-1}$)$\times10^6$ |
|---------------|---------------|----------------------------------------|----------------------------------------|
| 212±8         | 0.737±0.007   | 0.104±0.008                            | 2.4±0.4                               |
| 241±9         | 0.684±0.001   | 0.130±0.020                            | 1.7±0.3                               |
| 254±6         | 0.510±0.030   | 0.103±0.005                            | 2.9±0.6                               |
| 289±9         | 0.367±0.006   | 0.963±0.006                            | 3.1±0.9                               |
| 357±7         | 0.282±0.002   | 0.110±0.030                            | 4.5±0.9                               |
| 423±6         | 0.216±0.002   | 0.122±0.003                            | 6.3±0.8                               |
| 508±9         | 0.158±0.0005  | 0.129±0.005                            | 8.9±0.04                              |

Figure 1. (a) $f_c$ as a function of $l_g^{-2}$. The solid line is the result of the best least squares linear fit (b) $\alpha_T$ as a function of $f_c$ and best least squares fit using Equation (4).

4. Conclusions
The linear thermal expansion coefficient of GAK was obtained using the PA technique. The obtained value is comparable with that of similar materials such as wood. This technique has advantages respecting common used methods for measurement of this parameter, because it makes use of samples with small dimensions without any preparation, and without the need of impose large temperature gradients that can affect the samples properties during the measurement. The methodology presented allowed also the measurement of the thermal diffusivity of GAK in agreement with literature reported values.

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