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Research Article

Elastic Module Study of the Radial Section of *Guadua angustifolia* Kunth Variety Bicolor

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Elastic modulus of the radial section of the *Guadua angustifolia* Kunth variety Bicolor was studied by technique of propagation of acoustic waves; the signal time delay in the samples was used as the control parameter. The studies were carried out in the culm cross-section in radial direction. The results indicate that the elastic modulus and the propagation velocity of the longitudinal wave in each of the cross-sections varied from 2.5×10^7 to 1.6×10^9 Pa and from 1370 to 250 m/s for the inside and outside region of the culm, respectively. This behavior is due to the inhomogeneity, the water concentration, the fiber density, and the silicon concentration. The Raman spectroscopy analysis showed bands associated with hemicellulose, cellulose (carbon-carbon bonds), hydroxides carbon, and lignin. Silicone polymer compounds were identified by gas chromatography/mass spectroscopy.

1. Introduction

The *Guadua angustifolia* Kunth variety Bicolor (GAKVB, Figure 1(a)) has been classified by Humboldt, Bonpland, and Kunth Kart since 1806 and it is a type of vegetal material of the Bambusa family. The GAKVB has been considered one of the most representative native plants of tropical forests and there are approximately 90 genera in the world that are classified into 1250 species that are distributed in the equatorial zone (51 degrees north latitude and 47 degrees south latitude and from sea level to 2200 meters) [1]. Vegetal cells of the GAKVB consist mainly of lignin, cellulose, and hemicellulose, which are the most abundant biopolymers in the nature with applications in traditional handicrafts, architectural structures, and industries such as paper production, automotives, and sports, and due to its density and heat capacity it is also used in the production of charcoal [2–5]. Currently, there have been studies on the mixture of the GAKVB and other plant species with synthetic polymers to produce biodegradable composite materials with innovative mechanical properties [6–8]. The GAKVB is a nonhomogeneous complex system, where the composition and structure are dynamic features that depend on the age of the bamboo. There is isotropy along the growth direction and perpendicular to it; that is, in the radial direction the anisotropy is presented; this is due to fibers volumetric density that produces different behaviors of the viscoelasticity and of the crystallinity [9]. Other species of *Bambusae* have been studied in terms of physical properties such as structure, composition and humidity [10–14]. The GAKVB is a periodical structure along the growth direction and consists of nodes and internodes (see Figure 1(a)). The GAKVB culm consists of two basic structures, a geometry of a truncated cone where the fibers are aligned in the direction of the bamboo growth and arranged in such a way that allows a significant amount of voids or saturated water and the other with circular geometry, which form the upper and lower truncated cone (Figure 1(b)). This structure is repeated in consecutive cylinders and the vascular bundles size decreases within the wall stem, while the density of the fibers increases from base to top of the culm. The culm wall is composed of parenchymal cells in the spaces between the vascular bundles and the fibers. On the other hand, the fibers

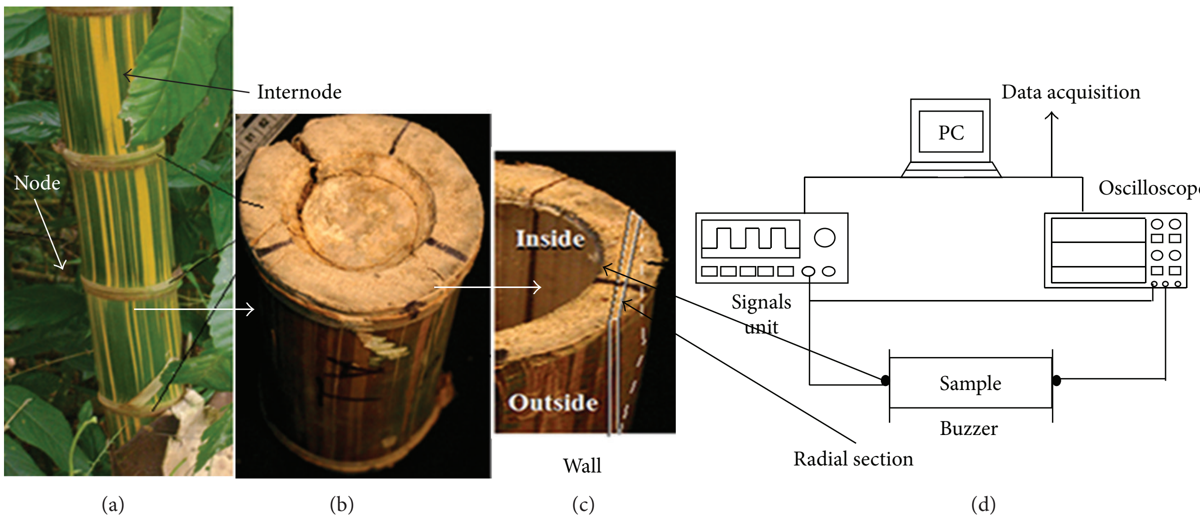

FIGURE 1: *Guadua angustifolia* Kunth variety Bicolor: (a) nodes and internodes, (b) culm, and (c) experimental setup.

constitute 40–50% of total culm tissue and 60–70% of their weight [5]. The culm is made up of 52% parenchyma tissue, 40% fibers, and 8% conductive tissues; these values vary according to the species of the bamboo. For the GAKVB case, this composition is 51, 40, and 9%, respectively. The xylem is the principal water-conducting tissue of vascular plants and is divided in primary xylem which consists of protoxylem that has an active stretch in its youth and the metaxylem which begins in the mature plant, but after elongation it is stretched and is destroyed. Micrographs of the GAKVB culm are shown in Figures 2(a) and 2(b). Figure 2(a) illustrates the fibers distribution around the vascular bundles with sizes around 120 μm. In the surface outside of the culm white dots are highlighted known as trichomes, and are associated with silica (see Figure 2(d)) [15]. For orthotropic materials such as wood, where mechanical properties in the perpendicular directions are unique and independent, the speed of longitudinal and transverse waves in each of the principal axes depends on the density, the direction of propagation, and elastic constants [16]. Wood is an example of an orthotropic material and the propagation phenomena of ultrasonic waves are considered complex. The Christoffel equation relates the elastic constants to the velocities of ultrasonic waves in an anisotropic solid as [17, 18]

$$\left|C_{ijkl}n_i n_j - \delta_{ik}\rho v^2\right| = 0, \qquad (1)$$

where C_{ijkl}, n_i, n_j, δ_{ik}, ρ, and v are the stiffness tensor, the unit vectors in the directions i and j, the Kronecker delta, wood density, and wave velocity, respectively. Nine constants are obtained by solving the Christoffel equation along the three axes of symmetry. There is one longitudinal wave and two transverse waves in each of the principal axes, which are related to material density and wave velocity by $C_{ii} = v_{ii}^2\rho$; the density of the culm is obtained by volumetric methods [19, 20]. The GAKVB is hygroscopic and an anisotropic porous structure whose mechanical properties depend on humidity. The sonic pulse method is nondestructive and integrity of the material affected is also inexpensive and can be implemented by a simple technology. The transmission of ultrasonic waves depends on the compression and stretching of chemical bonds of materials, being widely used in the identification of mechanical properties in different types of metallic and nonmetallic materials among others [19, 21]. For frequencies from 20 to 200 KHz, the sonic pulses are not affected by the nonhomogeneity of the materials and the distribution of the acoustic wave beam has a spherical wavefront whose center is at the emitter-detector [20]. When the two devices, transmitter and receptor, are placed opposite to each other, the sound wave will travel the shortest distance and speed depends essentially on the mechanical properties of the material. The sound wave loses energy and amplitude due to the fact that plant materials are not perfectly elastic; this scattering occurs at the borders of the emitter-sample-receptor, as well as on reflection and interference generated there, and that should be taken into account for the determination of the mechanical parameters.

In this work, elastic modulus of the radial section of the *Guadua angustifolia* Kunth variety Bicolor was studied by technique of propagation of acoustic waves; the signal time delay in the samples was used as control parameter. The studies were carried out in the culm cross-section in radial direction.

2. Experimental Details

Figure 1(c) illustrates the experimental setup consisting of a wave generator (Agilent 33220A) that sends a sinusoidal pulse every 20 ms to the piezoelectric buzzer, which is coupled to the system via an impedance bridge circuit (Z_I, Z_O). The pulse amplitude was 8 V_{pp} with an excitation pulse width of 67.5 μs and a data acquisition time of 2 μs. The signal passes through the sample and is sent to a phase-sensitive lock-in amplifier and subsequently processed in the PC using the software of Labview 8.5. The wave velocity (v_m) through the

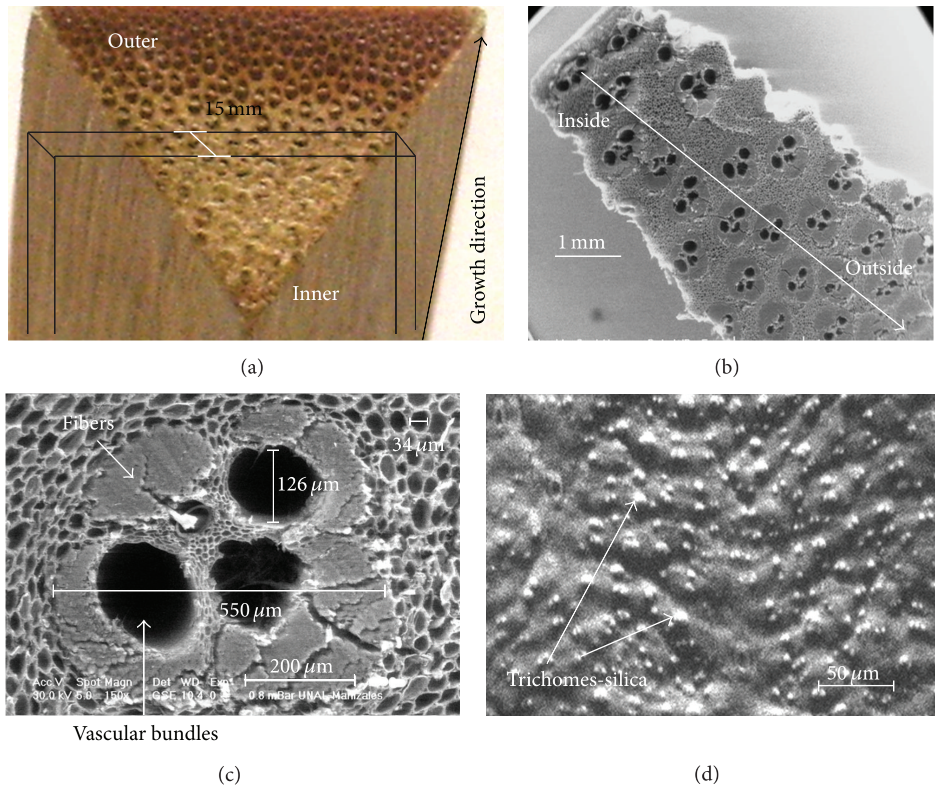

FIGURE 2: Micrographs of the GAKVB culm: (a) radial section, (b) distribution of vascular bundles, (c) fibers and vascular bundles, and (d) Trichomes silica in the surface of the GAKVB.

material is obtained from the sample length (L_m) and delay time (t_R), according to the following equation:

$$v_m = h\frac{L_m}{t_R}. \quad (2)$$

t_R is obtained from the phase difference between the two signals, the reference signal and the signal obtained in the detector, and it is corrected by $t_R = t_m - t_I$, where t_m and t_I are the time measured in the detector and the instrumental time delay, respectively, and h is the instrumental correction due to the coupling impedances (Z_I, Z_O). In the first approximation, the longitudinal C_{22} elastic constant in a radial direction is obtained by

$$C_{22} = \rho v_m^2. \quad (3)$$

The GAKVB samples that have been used for measurements were obtained by cutting sections from the center to outside in radial direction with dimensions of 15 mm thickness and 4 cm^2 surface area; see Figure 2(a). The micrographs and the elemental quantification of the silicon concentration were obtained with an environmental scanning electron microscopy (ESEM) Philips XL-30TMP equipped with a standard probe (EDAX). The Raman spectra were recorded with a LabRam HR-800 Confocal Microscope (Horiba Jobin Yvon), using a 473 nm blue laser. The gas chromatography/mass spectroscopy (GC/MS) was performed with Agilent Technologies 6580 Series I, with mass spectroscopy detection (MSD Insert 5975B, Agilent Technologies) and with column (HP-INNOWAX Polyethylene Glycol Capillary).

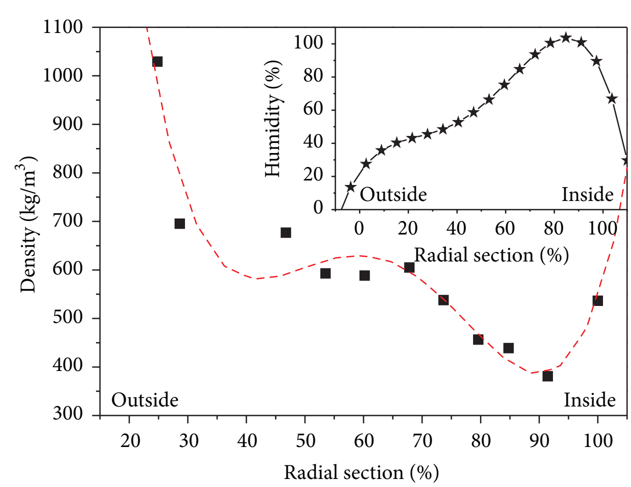

FIGURE 3: Density and humidity content of the GAKVB as a function of radial section percentage of the GAKVB.

3. Results and Discussion

The density ρ for each of the different regions of the cross-section of GAKVB samples shown in Figure 3 has values which are between 380 and 1030 kg/m^3 and are of the same

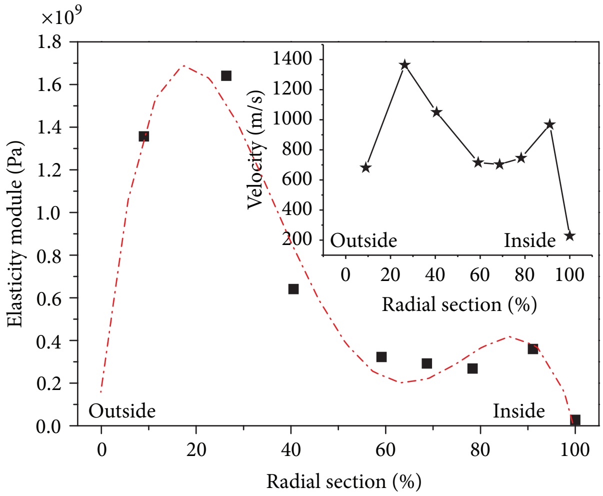

FIGURE 4: Elasticity modulus and velocity of the GAKVB as a function of radial section percentage.

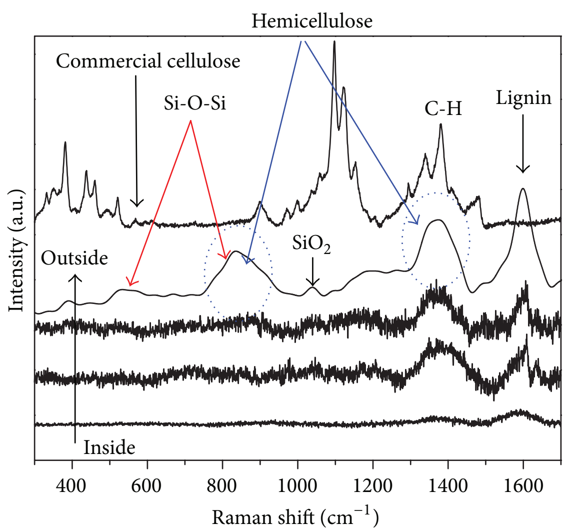

FIGURE 5: The Raman spectra of different radial sections of the GAKVB as well as commercial cellulose.

order of magnitude compared with other plant materials that have been reported [6, 22]. The behavior of ρ is due to the concentration of silicon and has been associated with nonuniform distribution through the wall of the microfibers and metaxylem and phloem ducts, and these channels are sites where water molecules are more likely to be trapped. The vascular bundles shown in SEM micrographs (see Figure 2(c)) have an average diameter of about 120 μm, an average density of 2.2 per mm^2, and a maximum at a radial position of 20% of the thickness of the bamboo with respect to the outside surface. The above results agree with those obtained in the humidity curve (inset Figure 3), indicating that there is a greater accumulation of water in a region between 60 and 100% measured from the outside surface of the bamboo. Sound velocity and the elastic modulus of the GAKVB were obtained by (2) and (3), respectively.

The velocity of wave propagation was obtained between 250 m/s and 1370 m/s (inset Figure 4); these values agree with those reported for other plant species [23]. As the wave propagates perpendicularly to the fibers, the velocity takes the maximum value when these fibers are closer together, that is, in 20% of the radial position measured from the outside surface. The elastic modulus C_{22} is shown in Figure 4 and the values obtained are comparable with those reported in the literature by using nanoindentation techniques [16]. In the measurements carried out on the time delay of the signal, the fibers were oriented perpendicular to the contact surface of the detector. The behavior of C_{22} on the outside wall of the GAKVB has been associated with a higher content of silicon within the structure and contributes to the high rigidity and impermeability of the outside surface as evidenced by the behavior of the relative humidity. The highest concentration of water is associated with nonuniform distribution through the wall of the microfibers and tubes (metaxylem and phloem) and acquires a maximum value at a depth of 20% measured from the inside of the bamboo wall. At this depth the C_{22} module acquires a minimum value, because the water produces a plasticizing effect associated with the tendency for water molecules located in these regions to allow the mobility of the polymer chains. Vibrational spectroscopy has been widely used because it provides information about the local structural features of inorganic solids. The Raman spectra were obtained in the range 400–1650 cm^{-1} at room temperature. In Figure 5, spectra of the commercial cellulose as well as the different sections in radial direction (outside, middle, and inside) of the GAKVB are shown. The peaks are associated with cellulose phases, hemicellulose, lignin, and silicates [24–26]. The bands around 530, 830, and 1366 cm^{-1} are assigned to hemicellulose phase. The peak around 1584 cm^{-1} is associated with lignin. The silicates (SiO_2, 830 cm^{-1}) and the C–H compounds are increased in the outside region of the GAKVB. The Raman spectra indicate that hemicellulose phases and silicates have proportions higher in the outside than in the inside region.

4. Conclusions

The sound pulse technique indicated that the elastic modulus C_{22} and the velocity of wave propagation of the *Guadua angustifolia* Kunth variety Bicolor varied between 2.5×10^7 and 1.6×10^9 Pa and 250 and 1370 m/s, respectively. ρ values are between 380 and 1030 kg/m^3 and are due to the radial distribution of the vascular bundles. The behavior of C_{22} is due to the concentration of silicon and water present in the structure, as well as inhomogeneous distribution across the wall of the microfibers, metaxylem, and phloem conduits, and acquires a minimum value, because the water produces a plasticizing effect associated with the tendency for water molecules located in these regions allowing mobility of the polymer chains. In the outside region of the GAKVB the highest concentration of silicon is due to the compounds of silicates.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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