Investigation on Gradient Dielectric Characteristics of Bamboo (*Dendrocalamus strictus*)

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ABSTRACT: Dielectric constant (ε′) and tan δ dependence on distance from the outer most skin to the center of bamboo has been determined. Dielectric measurements have been done in the temperature range from 24 to 120°C and in the frequency range from 4 to 100 kHz. Gradient behavior in dielectric constant (ε′) and tan δ has been found in bamboo. It has also been observed that the dielectric constant (ε′) and tan δ increase with the increasing temperature and decrease with the increasing frequency. Relaxation times have been calculated for the four samples at 80, 90, and 100°C temperatures, which show that relaxation time decreases with the increase of temperature due to the increased molecular mobility. A continuous increase in the hardness from the center 48 to the outer surface 70 and density from 0.45 to 0.80 g/cc has been observed.

Key words: dielectric constant; tan δ; bamboo (*Dendrocalamus strictus*); hardness

INTRODUCTION

Bamboo is a natural material, and is abundantly available natural resource in Asia and South America. It has been used traditionally for fabrication of village houses as a structural material. Shin et al.[1] reported that use of bamboo is possible if it is used as a reinforcing member in a composite.

Different types of woods and wood like materials such as bamboo are being increasingly used for insulation and lamination applications by using different polymers such as methyl methacrylate (MMA) and butyl methylacrylate (BMA). Electrical properties like resistivity and dielectric constant of both wood and wood composites have been reported with different moisture content in the past by Khan et al.[2] It has been found that dielectric constant of wood increased significantly with moisture content but no significant difference was observed in the case of wood filled polymer composites.

Bamboo or wood reinforced polymer composites can be used as an important insulating material for special applications such as spacer panels and switchboard. Chia et al.[3] reported that untreated wood had a higher dielectric constant than their polymer composite. They concluded that the presence of polymers has decreased the number of polarizable units to use bamboo for insulating applications. Chia et al.[3] found another important observation that the dielectric constants of untreated wood increased with density.

Among the natural fibers,[4,5] bamboo has low density, which have been used as reinforcement[6] and has high mechanical strength.[7–9] Specific gravity of bamboo is approximately 0.66 g/cc as compared to glass fiber, which is approximately 2.5. The reported specific tensile strength of bamboo fiber is 0.28 GNm^{-2}, which is less than that of glass fiber, which is nearly 1.3 GNm^{-2}.

Bamboo stem is composed of three parts: bamboo skin, bamboo timber, and pith. Bamboo skin is the outermost part of cross section of stem wall, where no vascular bundles are present. Pith is the part of stem wall next to bamboo cavity; it also does not contain vascular bundles. Bamboo timber is the part between skin and pith. Vascular bundles are observed on its cross section. The density of vascular bundles decreases from outer side of stem wall to inner side. The outer part where vascular bundles are dense is called bamboo green, while the inner part where vascular bundles are rare is called bamboo yellow.

Chand and Joshi have reported the dielectric properties of sisal fibers in their earlier paper.[10] The electrical properties of some natural fibers, such as volume resistivity and dielectric strength have been studied by Kulkarni et al.[11] However, very little work has been reported on the electrical properties of bamboo.

Determination of dielectric behavior of different sections of bamboo cut from the outer skin to center of the bamboo is very necessary for finding its proper applications. In this study, dielectric constant (ε′) and tan δ values of different sections cut from outer skin

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to the central core have been determined at different temperatures and frequencies. Shore D hardness, density, and relaxation time of the bamboo are also determined (Tables I and II).

EXPERIMENTAL

Materials

The bamboo (*Dendrocalamus strictus*) used in this study was collected from Sehore, India. Density of the bamboo was 0.66 g/cc.

Sample preparation

Different strips at fixed distance from the outer periphery to center were cut from the bamboo stem as shown in Figure 1. Test samples were cut from these strips. Uniformity of surfaces was obtained by polishing the sample by using a polishing cloth. Both sides of the sample were coated using an air drying type graphite conducting paint before dielectric measurements.

Testing

Dielectric measurements

Capacitance (C) and tan δ values of bamboo samples were measured using a Hewlett–Packard, LCR Meter, model 4274 A, in the temperature range 24 to 120°C and frequency range from 4 to 100 kHz. Heating rate was kept constant at 1°C/min. Dielectric constant (ε') was calculated by using the following relation

$$\varepsilon' = C/C_0$$

where C and C_0 are the capacitance values with and without dielectric, respectively; C_0 in given by $= [(0.08854\,A)/d]$ pF.

Where A (cm^2) is the area of the electrodes and d (cm) the thickness of the sample. tan δ is the dielectric dissipation factor is defined as follows tan $\delta = \varepsilon''/\varepsilon'$, where ε'' is the dielectric loss.

Hardness

Hiroshima hardness tester (Durometer) model RHT – 1 is used to determine the hardness of bamboo specimens. The hardness is defined as the resistance of a specimen to the penetration of hardened steel truncated cone (Shore A), radiuses cone (Shore D), or a spherical flat indenter. For this test, the samples were cut from the outer surface to the inner core side. The hardness was measured at room temperature from the outer skin to the central inner core side of the bamboo.

TABLE I
Density and Hardness Values for Bamboo Gradient Samples at 24°C

Hardness (shore D)	Density (gm/cc)
70	0.8008
62	0.5822
52	0.5267
48	0.4568

TABLE II
Relaxation time τ(s) $\times 10^{-5}$ Values for Bamboo Gradient Samples at 80, 90, and 100°C and at 2 kHz

	Relaxation time		
	80 (°C)	90 (°C)	100 (°C)
Sample 1	1.7	1.69	1.6
Sample 2	1.4	1.42	1.26
Sample 3	1.63	1.56	1.32
Sample 4	1.57	1.75	1.64

Density

For this test, samples were cut into the pellet form of 2 mm thickness from the bamboo strips. The density was determined by dividing weight with volume.

Microstructure

Scanning electron microscope model JEOL JSM 5600 (Japan) was used to observe the microstructure of bamboo samples 1–4.

RESULTS AND DISCUSSION

Figure 1 shows the schematic diagram of bamboo section. Slicing done is shown from the outermost surface to the center core of the bamboo, which is numbered as sample 1, 2, 3, and 4, respectively.

Figure 2(a–d) shows the variation of dielectric constant (ε') with temperature for bamboo samples 1–4 at 4, 10, 20, 40, and 100 kHz.

Figure 2(a) shows the variation of dielectric constant (ε') with temperature for sample 1. It was observed

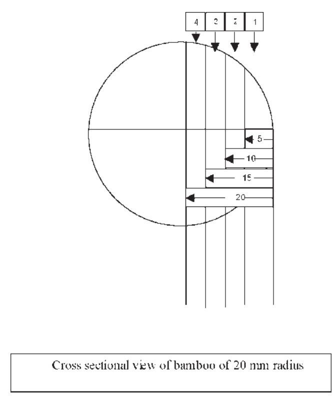

Figure 1 The schematic diagram of bamboo gradient.

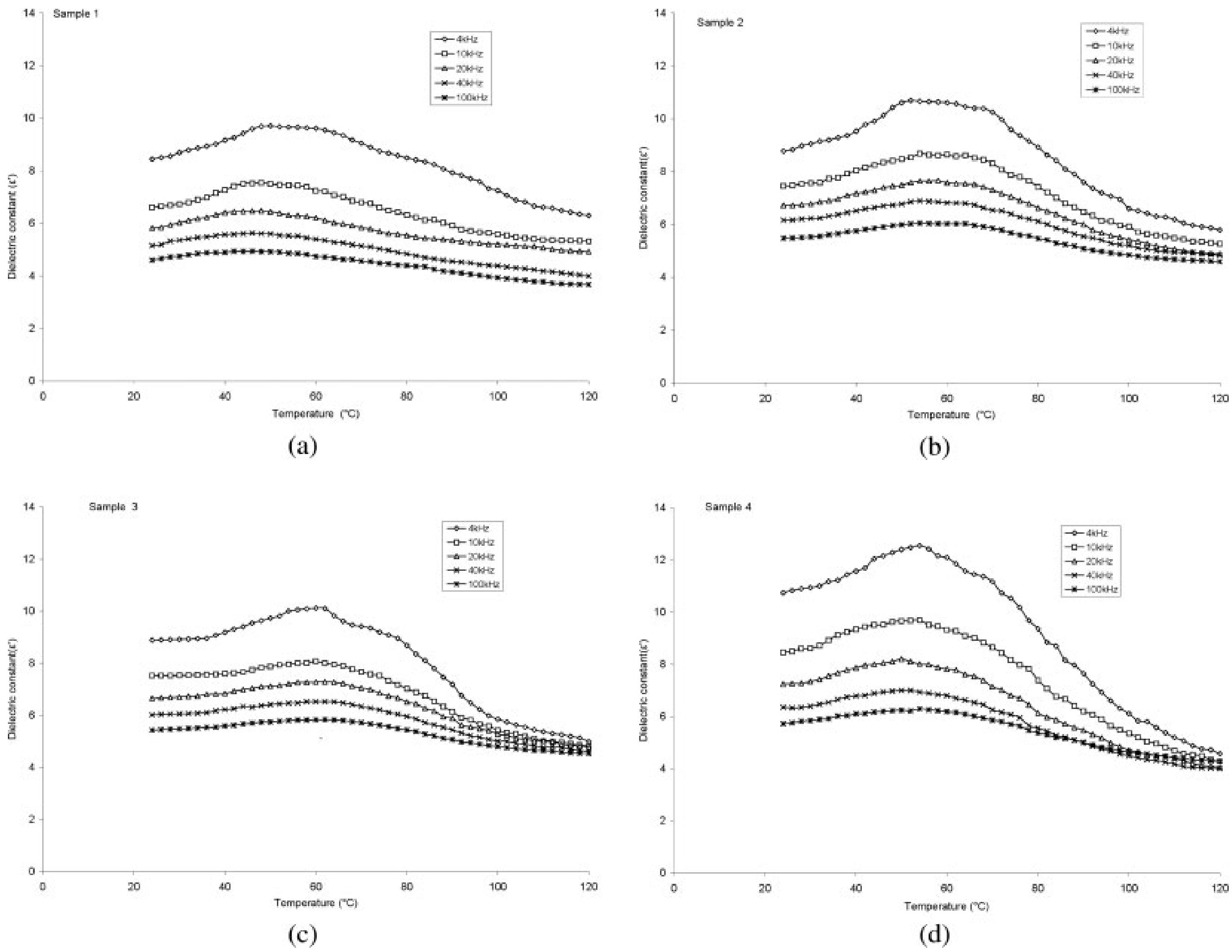

Figure 2 Variation of ε′ versus temperature for bamboo sample 1 (a), sample 2 (b), sample 3 (c), and sample 4 (d) at 4, 10, 20, 40, and 100 kHz frequency.

that dielectric constant increases initially with increasing temperature up to 50°C and then ε′ decrease with increasing temperature. ε′ decrease with increasing frequency from 4 to 100 KHz. This initial increase of ε′ is due to the increased mobility of water dipoles present in the bamboo. When the water content reduced, the value of ε′ decreased with increase of temperature.

The dielectric constant (ε′) peak height decrease with the increasing frequency in samples 1–4. Goodman et al.[12] reported that the lossy dielectric can be represented by the circuit analog of a resistance in parallel with a capacitor. At higher frequency, the capacitor offers low reactance to the sinusoidal signal, which minimizes the conductance losses in the resistor. Hence, value of dielectric loss decreases at the higher frequencies. The present observations were found in good agreement with earlier reported results.[13]

Another interesting observation in the variation of dielectric constant (ε′) with temperature is that at higher temperatures, difference in ε′ values between at all frequencies has decreased as compared to low temperature ε′ values for sample 1. Similar trend has been observed for samples 2–4.

Figure 3(a–d) shows the variation of tan δ with temperature for bamboo samples 1–4 at 4 10, 20, 40, and 100 kHz frequencies. It was observed that tan δ increases initially up to 60°C and then decrease with increasing temperature. tan δ decreased increasing of frequency from 4 to 100 kHz. The tan δ peak heights decrease with increasing frequency in samples 1–4. It was also observed that tan δ peak heights increases from samples 1–4 at all frequencies.

In Figures 4 and 5, variation of dielectric constant (ε′) and tan δ with temperature for bamboo samples 1–4 are compared. Measurements were done at 4 kHz frequency. It was observed that dielectric constant (ε′) increases with distance from the outermost surface to the inner core of bamboo up to 84°C and tan δ up to 88°C. This shows maximum ε′ and tan δ values for the outermost surface and minimum for the center of the bamboo. This is because sample 1

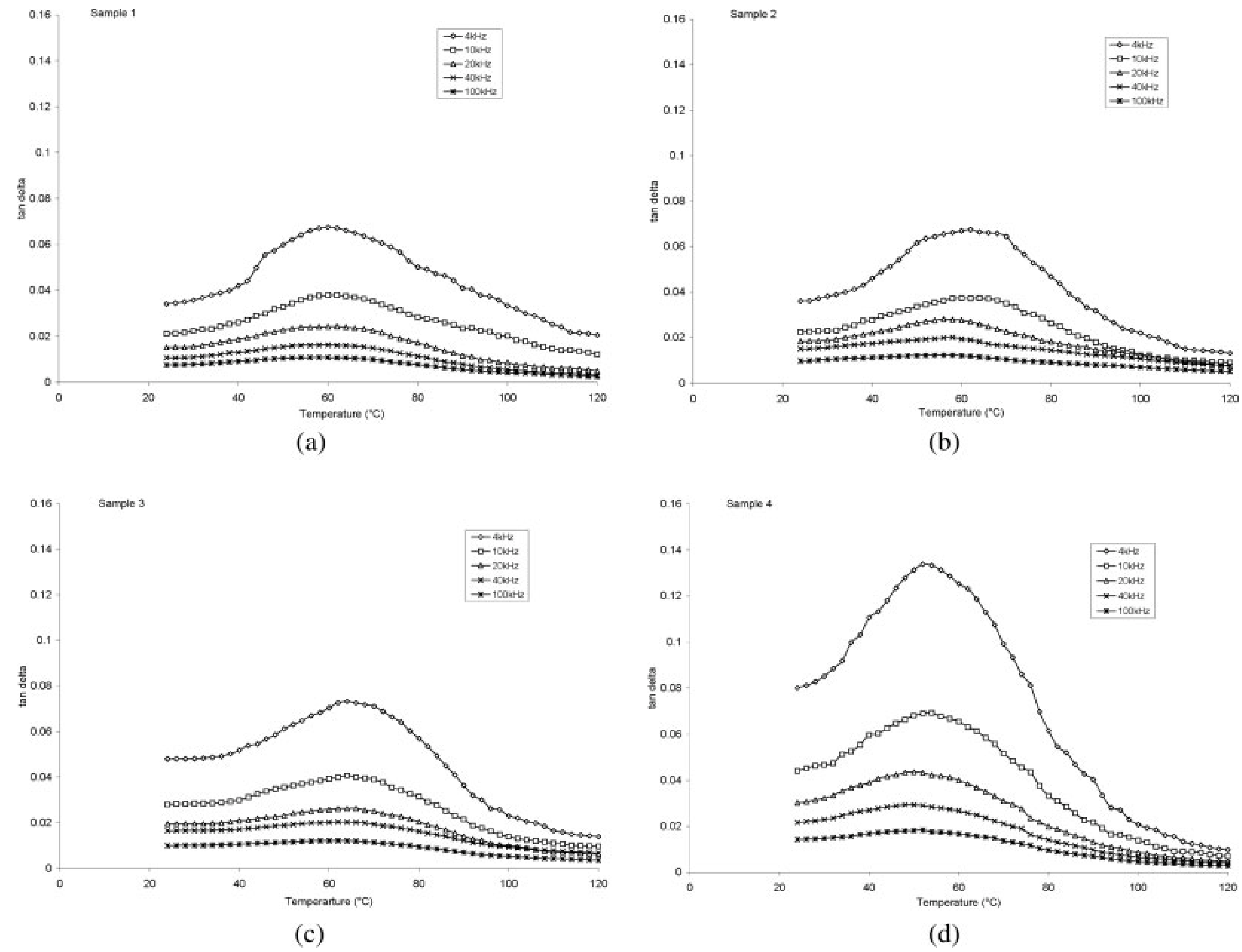

Figure 3 Variation of tan δ versus temperature for bamboo sample 1 (a), sample 2 (b), sample 3 (c), and sample 4 (d) at 4, 10, 20, 40, and 100 kHz frequency.

has minimum lignin and moisture as compared to sample 4, which has maximum lignin, volatile content and moisture. Between samples 1 and 4, there exists a gradient increase of lignin and moisture, and hence, there is a gradual increase in dielectric constant (ε') and tan δ.

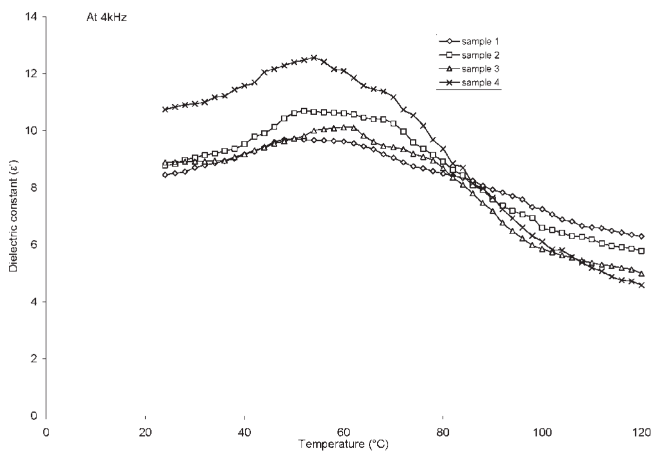

Figure 4 Variation of ε' versus temperature for bamboo samples 1 and 4 at 4 kHz frequency.

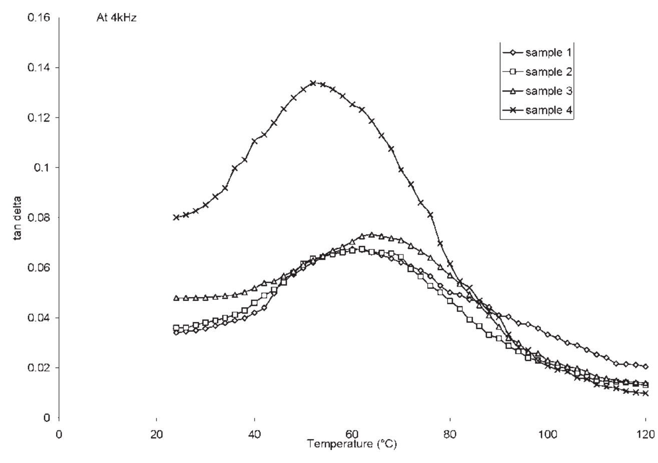

Figure 5 Variation of tan δ versus temperature for bamboo samples 1 and 4 at 4 kHz frequency.

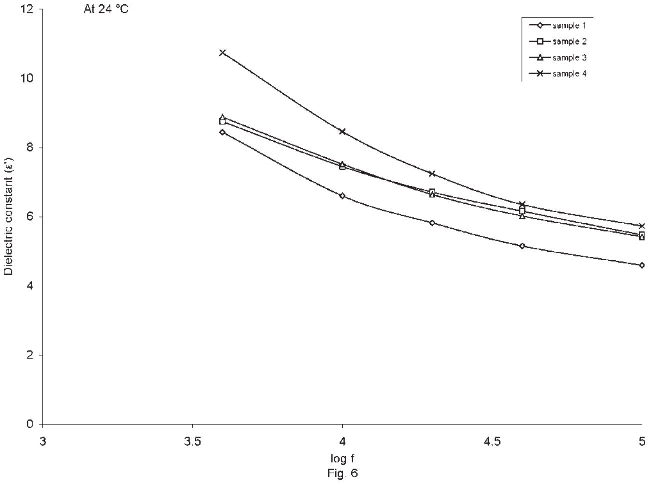

Figure 6 Variation of ε′ versus log *f* for bamboo samples 1 and 4 at 24°C.

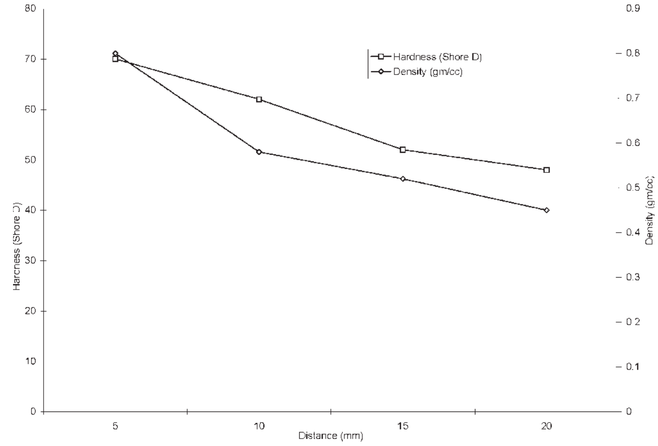

Figure 8 Variation of hardness and density versus distance for bamboo 24°C.

Another reason of grading is the porosity present in the bamboo: outer most has highest porosity and hence it has minimum ε′.

In Figures 6 and 7, variation of dielectric constant (ε′) and tan δ with log of frequency for bamboo samples 1–4 are compared. Measurements were done at 24°C. This shows that dielectric constant (ε′) and tan δ decreased with increasing of frequency for bamboo samples 1–4, respectively. This is due to relaxation of the polar radicals with respect to macromolecules, which form the microfibrils, which is similar to wood.

Figure 8 shows the variation of hardness and density with distance from the outer most surface to the center of bamboo at 24°C. Maximum 70 and minimum 48, shore D hardness values were observed, for samples 1 and 4 respectively. It is found that hardness values were very high at the outermost surface where silica content and vascular fiber bundles density is highest as compared with those at the center of the bamboo. Similarly, density was in the range from 0.80 to 0.45 g/cc.

Figure 9(a–d) shows the microstructure for bamboo samples 1–4 respectively. These show that the surface has maximum cellulosic cells, while as we go toward the center, amorphous lignin and volatile content increases.

The relaxation time dependence on temperature can give the idea about the mobility of chain present in the bamboo. Generally, there are three types of relaxations present in the woody materials: β-relaxation, γ-relaxation, and σ-relaxation. The β-relaxation in polysaccharides (cellulose) is related to the segmental motion of the polysaccharides chains via the glucosidic bond.

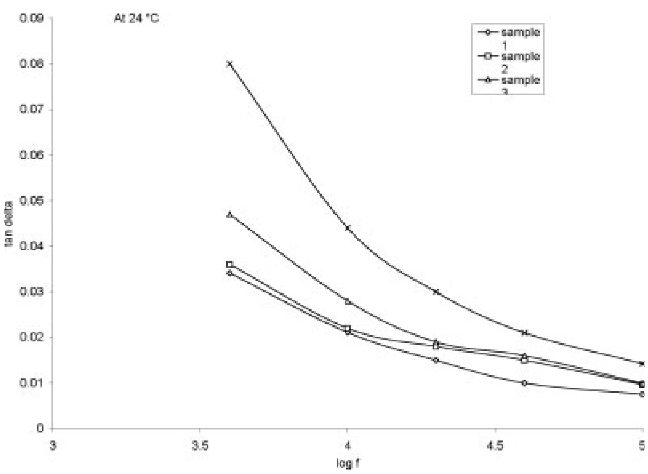

Figure 7 variation of tan δ versus log *f* for bamboo samples 1 and 4 at 24°C.

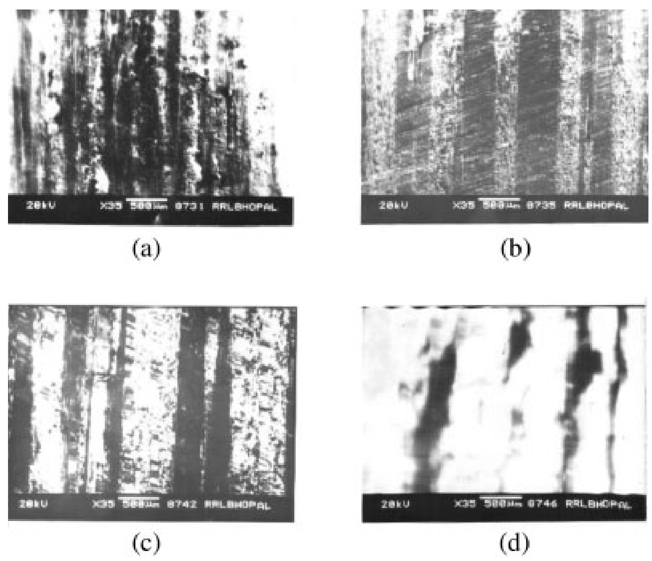

Figure 9 The SEM of bamboo sample 1 (a), sample 2 (b), sample 3 (c), and sample 4 (d).

Relaxation time for different bamboo samples from the outermost surface to the inner core calculated by the equation reported by Chand[14] at 80, 90, and 100°C is given by

$$\tau(s) = 1/\omega[\sqrt{((\varepsilon_0 - \varepsilon_\infty)/(\varepsilon' - \varepsilon_\infty)) - 1}]$$

It has been found that the increase of temperature decreased the relaxation time by increasing the molecular mobility.

CONCLUSIONS

(a) Gradient in dielectric constant (ε'), tan δ, density, and hardness exist in bamboo.

(b) A continuous increase in the hardness from 48 to 70 and density from 0.45 to 0.8 g/cc has been observed in the samples from the central core to the outer surface.

(c) Dielectric constant and tan δ decreased with distance from the center core to periphery outer surface.

(d) Dielectric constant and tan δ increased with the increase of temperature and decreased with the increase of frequency.

(e) Relaxation time decreased with the increase of temperature.

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