DIELECTRIC PROPERTIES OF RUBBER WOOD AT MICROWAVE FREQUENCIES MEASURED WITH AN OPEN-ENDED COAXIAL LINE

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(Received December 1996)

ABSTRACT

Dielectric properties of rubber wood were studied at different microwave frequencies, structural directions, and moisture contents using an open-ended coaxial probe. Frequencies used for this study were 1.00, 2.45, 6.0, 8.0, 10.0, 14.0, and 17.0 GHz; and the measurements were carried out at a room temperature of 22–24°C. The dielectric constant and dielectric loss factor were found to increase continuously as the moisture content increased. A sharp rise in the dielectric constant and dielectric loss factor was obtained at high moisture content, and the trends became concave upward. As the frequency increased, the dielectric constant decreased, whereas the dielectric loss factor increased. The dielectric loss factor remained almost constant above the frequency of 6 GHz for all structural directions. Fourth-order polynomial equations were found suitable for the best fit curve. Dielectric constant and dielectric loss factor of oven-dry wood were higher in the longitudinal direction than in the radial and tangential directions. With respect to frequency, the dielectric loss factor exhibited a peak value around 10 GHz. The dielectric anisotropy of wood may be attributed to the microscopic and macroscopic molecular structures as well as to chemical constituents of wood.

Keywords: Dielectric constant, dielectric loss factor, moisture content, microwave frequencies, structural direction, rubber wood, *Hevea brasiliensis.*

INTRODUCTION

The study of dielectric properties is important for understanding the molecular structure of wood and wood-water interactions. It is also an important factor where wood is to be used in structures subjected to electromagnetic field. The dielectric properties of wood are greatly affected by its moisture content and are therefore important indicators of that parameter. Some other factors such as wood density, temperature, structural direction, and frequency also contribute to dielectric properties. Dielectric properties have already been studied at low frequencies and low moisture content (James 1975, 1977; Kroner and Pungs 1952; Nanassy 1972; Norimoto and Yamada 1976;

Wood and Fiber Science, 29(4), 1997, pp. 319–324

Rafalski 1967; Skaar 1948; Vermas 1974, 1975; Venkateswaran and Tiwari 1964). The dielectric behavior of wood has not been studied thoroughly at moisture content levels above 30% or over a wide range of frequencies. Most studies at microwave frequencies have been carried out with a slotted wave guide at limited frequencies (James and Hamil 1965; Jain and Dubey 1988; Peyskens et al. 1984; Tinga 1969). The present study was carried out with an open-ended coaxial probe, making it possible to use a wide range of frequencies and yet be completely nondestructive.

When wood is placed in an alternating electric field, the interaction of wood with the electric field may be described in two ways: one is the storage of electric potential energy in the form of polarization within the dielectric material, and the other is the dissipation or loss of part of this energy when the electric field is removed. The ability of the material to store energy is described quantitatively by the dielectric constant, and the rate of energy loss in the dielectric is commonly expressed by the dielectric loss factor or dissipation.

MATERIALS AND METHODS

Rubber wood (*Hevea brasiliensis*) was supplied by the Farm Department of Universiti Pertanian Malaysia. The air-dry density of the rubber wood was 590–600 kg/m^3. Specimens were prepared in the form of discs 22–30 mm in diameter and 3.5–5.0 mm in thickness in the three structural directions—longitudinal, radial, and tangential. Both surfaces of the specimens were sanded so as to make good contact with the probe. To measure the dielectric properties at different moisture contents, specimens were initially fully soaked in deionized water for a sufficiently long time to achieve full saturation. After that the specimens were weighed, and dielectric measurements were carried out at a room temperature of 22–24°C. Specimens were then held vertically and allowed to dry slowly in air so that the moisture would evaporate equally from both surfaces. This was done since dielectric measurement by this technique is a totally surface phenomenon and is highly affected by the moisture gradient. This cycle of measuring, drying, and weighing was repeated until the specimens showed no change in weight by drying. Finally the specimens were dried in an electric oven at 100±3°C for 24 h, and the oven-dry weight was taken. Moisture content of the specimens was determined based on the oven-dry weight.

The measurements were carried out with 4-mm open-ended coaxial-line sensors (HP-85070M) and a computer-controlled Network Analyzer (HP-8720B) having frequency ranges from 130 MHz to 20 GHz. The directions of the applied field with respect to the structural direction are shown in the insets of Fig. 1. The system measured the input reflection coefficient of the sensors, from which the permittivity of the sample was calculated by software using established relationships (Athey et al. 1982; Kraszewski et al. 1982). Following the proper calibration method, the accuracy of the measurement was about ±5% for the dielectric constant and ±3% for the dielectric loss factor.

RESULTS AND DISCUSSION

The dielectric constants of rubber wood at different moisture contents and frequencies are presented in Fig. 1 in three anisotropic directions—longitudinal, radial, and tangential. Frequencies used in this study were 1.0, 2.45, 6.0, 8.0, 10.0, 14.0, and 17.0 GHz and were chosen depending on their importance in potential applications. The relationships of the dielectric loss factor to moisture content at different frequencies and structural directions are shown in Fig. 2. The relationships of the dielectric constant and dielectric loss factor to frequency at different structural directions in the oven-dry condition are shown in Fig. 3. Fourth-order polynomial equations of the type $Y = ax^4 + bx^3 + cx^2 + dx + e$ were used for curve-fitting the dielectric constant and dielectric loss factor as a function of moisture con-

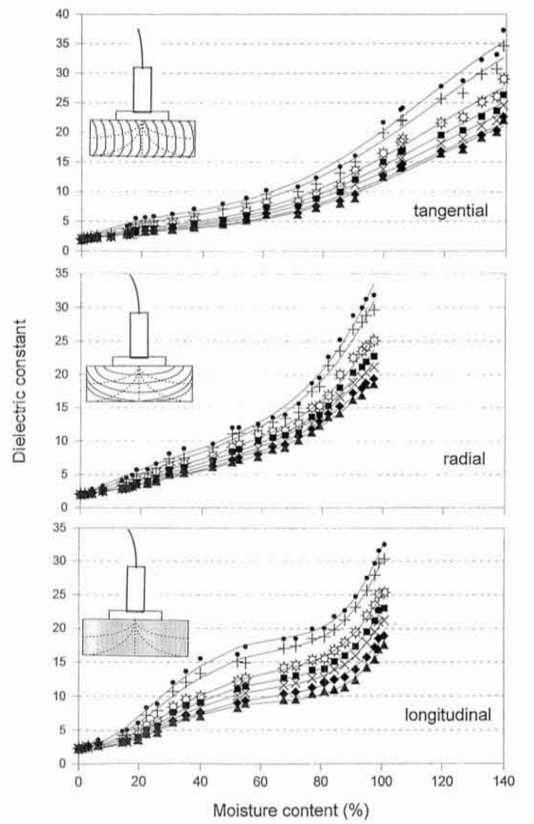

FIG. 1. Dielectric constant vs. moisture content of rubber wood in three structural directions at different frequencies. The sketches shown in inset of each curve indicate the direction of applied field with respect to the structural direction. ● = 1.0 GHz; ✡ = 6.0 GHz; × = 10.0 GHz; ▲ = 17.0 GHz; + = 2.45 GHz; ■ = 8.0 GHz; ♦ = 14.0 GHz.

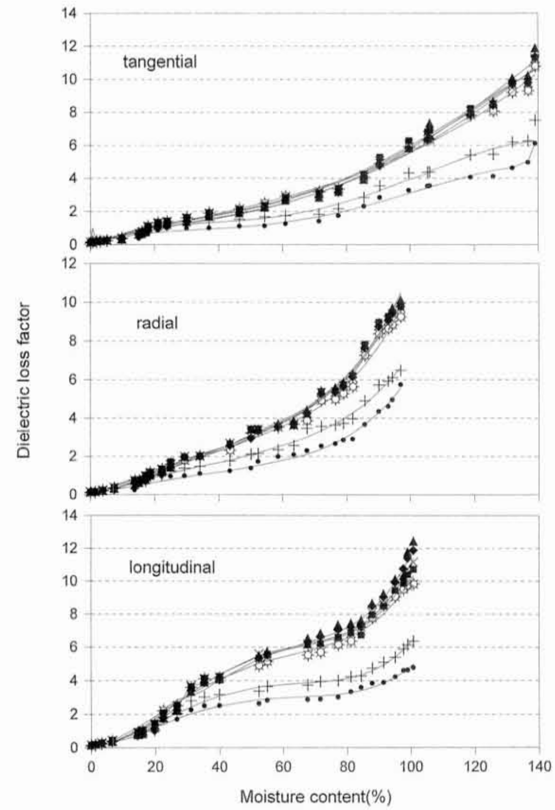

FIG. 2. Dielectric loss factor vs. moisture content of rubber wood in three structural directions at different frequencies. ● = 1.0 GHz; ✡ = 6.0 GHz; × = 10.0 GHz; ▲ = 17.0 GHz; + = 2.45 GHz; ■ = 8.0 GHz; ♦ = 14.0 GHz.

tent. The values calculated from the equation of curve-fitting are shown by solid lines (Figs. 1 and 2).

Figures 1 and 2 show that the dielectric constant and dielectric loss factor increased continuously as the moisture content increased in all structural directions and frequencies. Abrupt changes in the dielectric properties were observed at very high moisture content and the curves became concave upward. The dielectric constant and dielectric loss factor varied almost linearly at lower moisture content levels from 0 to 30%. Free water molecules, i.e., the moisture content above 30%, interact with the microwave field independently of the cell-wall substances and bound water (below 30%). Therefore, the change in the dielectric content and dielectric loss factor of the wood above the fiber saturation point is determined mainly by the dielectric properties and volume of free moisture. The study by Torgovnikov (1993) revealed that the dielectric properties of moisture extracted from freshly felled trees do not differ from those of pure water. The present study also supports these findings since a higher dielectric constant and dielectric loss factor were observed due to higher moisture content in the tangential direction (Figs. 1 and 2). Moreover, with increasing moisture content, the amount of water within the wood matrix increases and that water is characterized by high dielectric values. As the moisture content increases from the oven-dry condition, the polar component of the cell wall and the cellulose get more freedom of rotation, leading to high dielectric behavior (James and Hamil 1965; Lin 1967; Peyskens et al. 1984). Once the fiber saturation point has been reached, the importance of the polar groups of the wood does not increase because their freedom of rotation reaches maximum, and thereafter the dielectric properties may be affected only by the amount of water present in the wood.

The relationship between the moisture content and dielectric constant so far reported is either linear or curvilinear at lower moisture content levels at microwave frequencies (James and Hamil 1965; Jain and Dubey 1988; Norimoto and Yamada 1970; Peyskens et al. 1984; Tiuri et al. 1980). Jain and Dubey (1988) and Peyskens et al. (1984) showed that second-order equations are suitable for the best fit curve for a moisture content below 30%. The fourth-order polynomial equations were found suitable for the best fitted curve for the data presented here both for the dielectric constant and dielectric loss factor. The higher order of the equations may be due to the wide range of moisture content beginning from 0 to around 100%.

The measurement frequency also affected the dielectric properties considerably. As the frequency increased, the dielectric constant decreased, and the loss factor increased (Figs. 1 and 2). The dielectric properties changed abruptly at frequencies greater than 2.45 GHz. Little variation in the loss factor was observed at frequencies from 6 to 17 GHz for all the structural directions (Fig. 2). The interaction of the electromagnetic field with wood substance at higher frequencies differs from the interaction at lower frequencies, as the period of field oscillation at microwave frequencies can be compared with relaxation time of the molecules (Torgovnikov 1993). A phase shift therefore arises between the field strength vector and the polarization vector, resulting in a reduction of the dielectric constant and an increase of the loss factor with frequency. The decrease of dielectric constant and increase of loss factor have also been reported by James and Hamil (1965), Torgovnikov (1993), and Tiuri et al. (1980) for some other wood species. James (1975) mentioned that at high frequencies, the dielectric constant decreases to a value typical of homogeneous polar solids as the frequency increases, indicating that the contribution of interfacial polarization becomes insignificant and the predominant polarization is molecular. At this stage, the energy is absorbed in the form of induced dipole moment of the molecule, and in the form of alignment of the molecules having fixed dipole moment. The role of water at these higher frequencies is to increase the polarizability of the cellulose molecules simply by adding hygroscopically bound polar groups to the cellulose molecules, thereby increasing the fixed dipole moment and increasing the energy absorbed by the distorted molecules under an electric field.

The structural directions have a substantial effect on the dielectric constant and loss factor in the oven-dry condition, as shown in Fig. 3. The longitudinal direction showed higher dielectric constant and dielectric loss factor compared to radial and tangential directions (Fig. 3). With increasing frequency, the dielectric constant decreased, whereas the loss factor showed a peak vlaue around 10 GHz. Perhaps the presence of latex-type compounds in rubber wood accounts for this absorption peak. The higher dielectric constant and dielectric loss factor were also obtained by Norimoto et al. (1978), Norimoto and Yamada (1970, 1971, 1972), James and Hamil (1965), and Peyskens et al. (1984). This dielectric anisotropy results from the differences in wood structures from microscopic to macroscopic stages as well as the molecular level in the three directions. Norimoto et al. (1978) concluded that the difference in dielectric properties between the logitudinal and the radial and tangential directions is attributable to the differences in the arrangement of the cell wall and lumen in addition to the anisotropy of the cell-wall substances. The greater dielectric

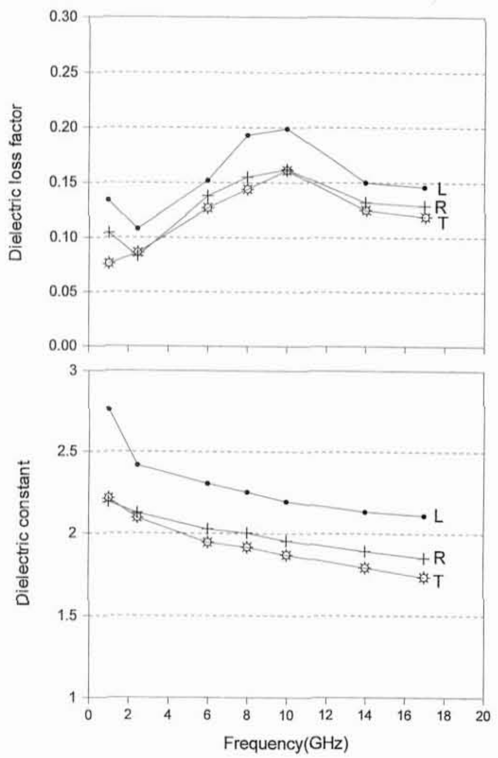

FIG. 3. Dielectric constant and dielectric loss factor vs. frequency of rubber wood at different structural direction in oven-dry condition; L—longitudinal, R—radial and T—tangential.

constant in the longitudinal direction has been explained by Norimoto and Yamada (1970) on the basis that the transition probability of dipole jump to an adjacent site when the field is applied in the longitudinal direction is considerably greater than that when electric fields are applied in other directions. The chemical constituents of wood may also contribute to dielectric anisotropy as explained by Norimoto and Yamada (1972). Their work revealed that the dielectric properties of wood are strongly influenced by cellulose and mannan in the longitudinal direction, but in the transverse direction the dielectric properties are influenced by lignin. According to Lin (1967), the hydroxyl groups of the cellulose should have more freedom of rotation in the longitudinal direction. It appears from Fig. 3 that there exists a slight difference in dielectric properties between radial and tangential directions in the oven-dry condition. Norimoto et al. (1978) suggested that at least three factors should be taken into account, for the anisotropy in these directions, namely the percentage of the latewood, the ratio of the cell-wall area to cell area, and the irregular arrangement of the cell. It is noted that the anisotropy of radial and tangential directions also depends on the wood species and moisture content (Peyskens et al. 1984).

CONCLUSIONS

Moisture content, structural direction, and measurement frequency affected both the dielectric constant and dielectric loss factor of rubber wood. The dielectric constant and dielectric loss factor were found to increase with the increase of moisture content across the range of moisture content from oven-dry to saturation. At high moisture content, the trend is concave upward for all structural directions and frequencies. The lower the frequency, the higher the dielectric constant, while reverse trends were observed for the dielectric loss factor. Frequencies above 6 GHz have less effect on the dielectric loss factor. Fourth-order polynomial equations can be used for estimating the dielectric properties of rubber wood as a function of moisture content at microwave frequencies. The structural directions also have a substantial effect on the dielectric constant and dielectric loss factor in the oven-dry condition. The values of the dielectric constant and dielectric loss factor in the longitudinal direction are higher than in the radial and tangential direction.

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