TEMPERATURE DEPENDENCE OF THE DIELECTRIC PROPERTIES OF RUBBER WOOD

Mohammed Firoz Kabir †

Post Doctoral Scientist
Department of Wood Science and Forest Products
Brooks Forest Products Center
Virginia Tech
Blacksburg, VA, 24061

Wan M. Daud, Kaida B. Khalid, and *Haji A.A. Sidek*

Associate Professors
Faculty of Science and Environmental Studies
University Putra Malaysia
43400 Serdang, Selangor, Malaysia

(Received April 2000)

ABSTRACT

The effect of temperature on the dielectric properties of rubber wood were investigated in three anisotropic directions–longitudinal, radial, and tangential, and at different measurement frequencies. Low frequency measurements were conducted with a dielectric spectrometer, and high frequencies used microwave applied with open-ended coaxial probe sensors. Dielectric constants and dielectric loss factors were measured at temperatures from 25 to 100°C. A large dielectric dispersion occurred at frequencies less than 10 Hz and at temperatures more than 60°C. The minimum peak value of the dielectric loss factors shifted towards higher frequencies at higher temperatures in all three grain directions. The tangential direction showed the highest activation energy. The dielectric constant decreased as frequency increased from 1 to 10 GHz, and thereafter remained unchanged with additional frequency increases. The dielectric constant exhibited higher values at higher temperatures. The dielectric loss factor showed a peak value at around 10 GHz at 25°C.

Keywords: Dielectric constant, dielectric loss factor, microwave frequency, temperature, polarization, activation energy, wood anisotropy.

INTRODUCTION

The dielectric properties of wood have both theoretical and practical importance. Theoretically, they give a better understanding of the molecular structure of wood and wood-water interactions. The practical applications of the dielectric properties are that the density and moisture content of wood can be determined nondestructively. It has also been reported that knots, spiral grain, and other defects can be detected by measuring dielectric properties (Martin et al. 1987). The utilization of high frequency and microwave techniques are also of growing importance for heating, gluing, drying, as well as improving the quality of wood and wood-based products.

When wood is placed in an electric field, the current-carrying properties of the wood are governed by certain properties, such as moisture content, density, grain direction, temperature; and by certain components such as cellulose, hemicellulose, and the lignin of wood. They also vary in an extremely complicated fashion with frequency. The overall effects of these parameters interact with each other and add to the complexities of the dielectric properties. The temperature dependence of wood's dielectric properties have been reported earlier by some workers using a few tropical and temperate wood species (James 1968, 1975, 1977; James and Hamil 1965; Tsutsumi and Watan-

† Member of SWST

abe 1965; Nanassy 1964, 1970). The effect of temperature on the dielectric properties at microwave frequencies has also been reported (Tinga 1969). This paper deals with variation of dielectric properties, such as dielectric constant and dielectric loss factor, with temperature at various frequencies.

MATERIALS AND METHODS

Rubber wood *(Hevea brasiliensis)* samples were supplied by the Farm Department, University Putra Malaysia. Dielectric constant and dielectric loss factor were measured at temperatures of 22°, 40°, 60°, 80°, and 100°C, using both low and microwave frequencies. Low frequency measurements were conducted at frequencies from 10^{-2} to 10^{5} Hz by using a dielectric spectrometer consisting of a Chelsea Dielectric Interface (CDI 4c/L-4, Dielectric Instrumentation, UK) and Frequency Response Analyzer (SI 1255, Schlumberger Technologies, UK). Specimens were cut into discs of 35–40 mm in diameter and 3.0–3.5 mm in thickness in longitudinal, radial, and tangential direction to the growth ring. The mean oven-dry density of the rubber wood specimens was 620 kg/m^3. Each sample was placed in a closed cell, and dielectric measurements were taken at different temperatures. The temperature was raised using a computer-controlled heating system (Polymer Laboratories, UK) and was measured by a thermocouple with an accuracy of ±0.1°C. All the samples were tested in oven-dry condition. Before measurements at each temperature, the specimen was kept at this constant temperature for 10 min to ensure that the sample stabilized at a uniform internal temperature and equilibrated with the surrounding cell temperature.

At microwave frequencies, dielectric properties were measured with 4-mm open-ended coaxial line sensors (HP 85070M) and a computer-controlled Network Analyzer (HP 8720B) in the range 130 MHz to 20 GHz. The apparatus measured the input reflection coefficients of the sensor. Permittivity of the specimen was calculated using software (Athey et al. 1982; Kraszewski et al. 1982). Following calibration, the accuracy of the measurement was about ±5% for the dielectric constant and ±3% for the dielectric loss factor. Measurements at different temperatures were conducted using an electronic oven (WTB Binder, Germany). Oven temperature was displayed in the front panel with an accuracy of ±1°C. The entire apparatus, including stand, probe, etc., was placed inside the oven. Specimens were left at constant temperature for about 10 min before measurements were taken.

RESULTS AND DISCUSSION

Low frequencies

Dielectric constants and dielectric loss factors for rubber wood at 25°, 40°, 60°, 80°, and 100°C and at frequencies from 10^{-2} to 10^{5} Hz in the longitudinal, radial, and tangential directions are presented in Fig. 1. Similar results for the dielectric loss factors are shown in Fig. 2. At low frequencies, the dielectric constant of oven-dried wood increased as temperature increased from room temperature to 100°C for all grain directions (Fig. 1). An abrupt increase for dielectric constants was observed when frequency was less than 10 Hz. A large dispersion occurred at 0.01 Hz when temperature exceeded 60°C for all grain directions. Dielectric loss factors obtained a minimum value at 10^{2} Hz in the oven-dry condition (Fig. 2). These loss minima shifted towards higher frequencies with increases in temperature for the longitudinal direction. Similar results were also observed for the other two grain directions. Dielectric loss factors increased sharply for all temperatures as frequency decreased below 100 Hz, in a manner similar to Kabir et al. (1996). From Fig. 2, it is obvious that at very low frequencies, dielectric loss factors increase abruptly when the temperature is higher than 60°C.

The increase in dielectric constant with temperature can be explained by the fact that the dipolar groups are bound in the solid structures so that the dipole is a structural element

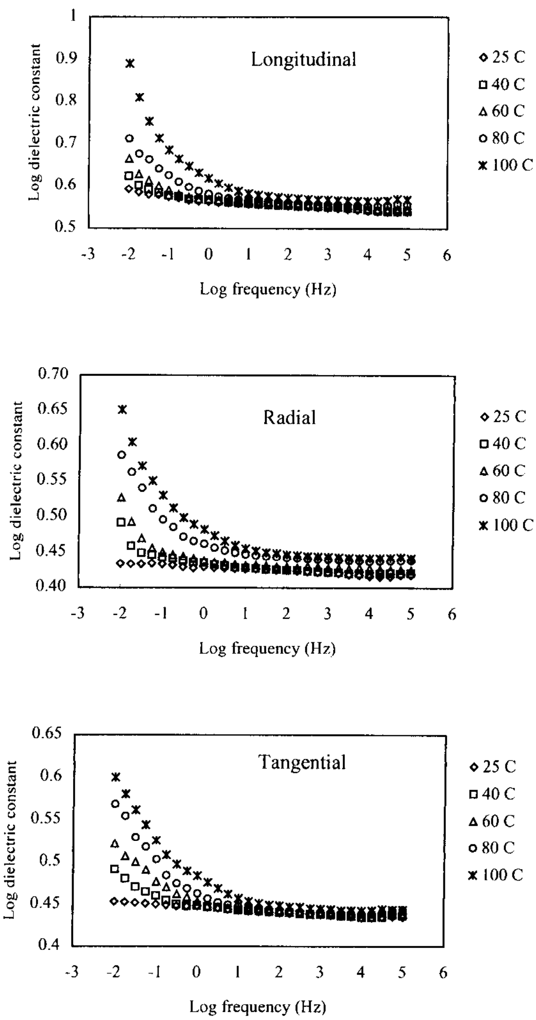

FIG 1. Dielectric constants for rubber wood at low frequencies, different temperatures, and grain directions.

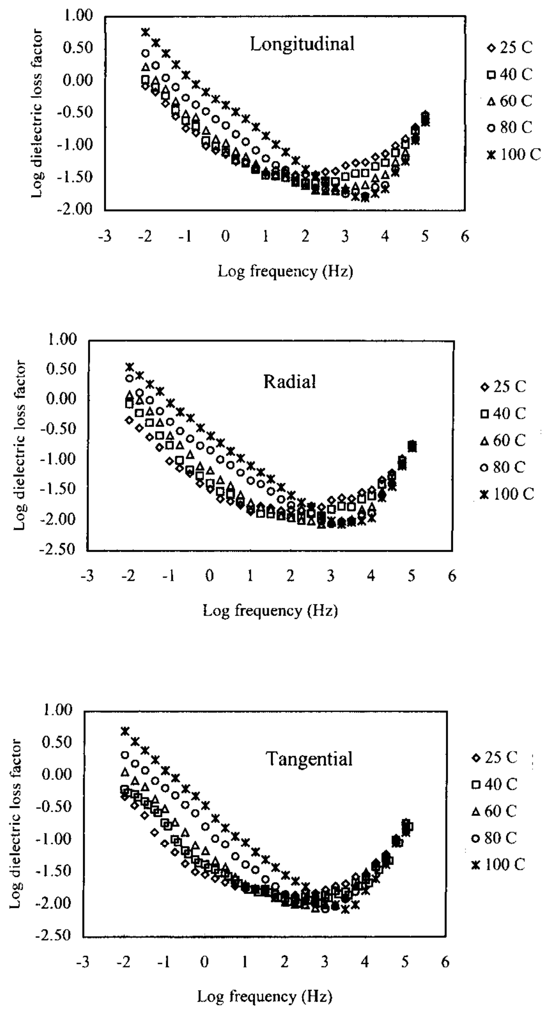

FIG. 2. Dielectric loss factors for rubber wood at low frequencies, different temperatures, and grain directions.

of the solid lattice and the rigidity of the lattice hinders the orientation of the dipoles (Nanassy 1970). At elevated temperatures, the dipoles acquire energy, which allows them to reorient; consequently an increase in the dielectric constant results. These results support the findings of Tsutsumi and Watanabe (1965), who showed that the dielectric constant of wood increased with temperature and also showed a strong relationship with frequency. It is assumed that the fixed dipole moment of the cellulose molecules and the interfacial polarization at lower frequencies are both activated by thermal energy.

A minimum value for the loss factor in the same frequency region (30 to 10^6 Hz) was also reported by Norimoto and Yamada (1970) for kusunoki wood. They provided three reasons for the energy absorption: first, the orientation polarization by the segmental motion of molecules, namely cellulose, hemicellulose, and lignin; second, the interfacial polarization at the boundary between crystalline and amorphous region of cellulose; and finally, the interfacial polarization by the sub-microscopic

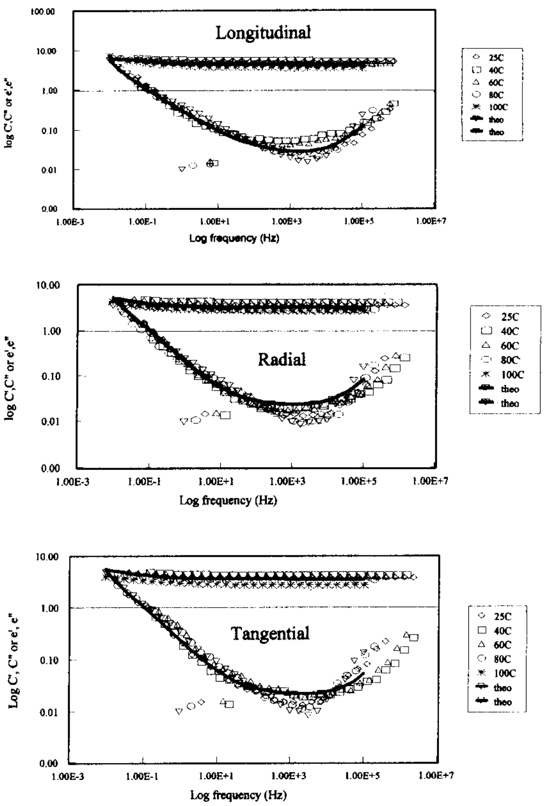

FIG. 3. Normalized data fitted with theoretical value from equivalent circuit for different grain directions.

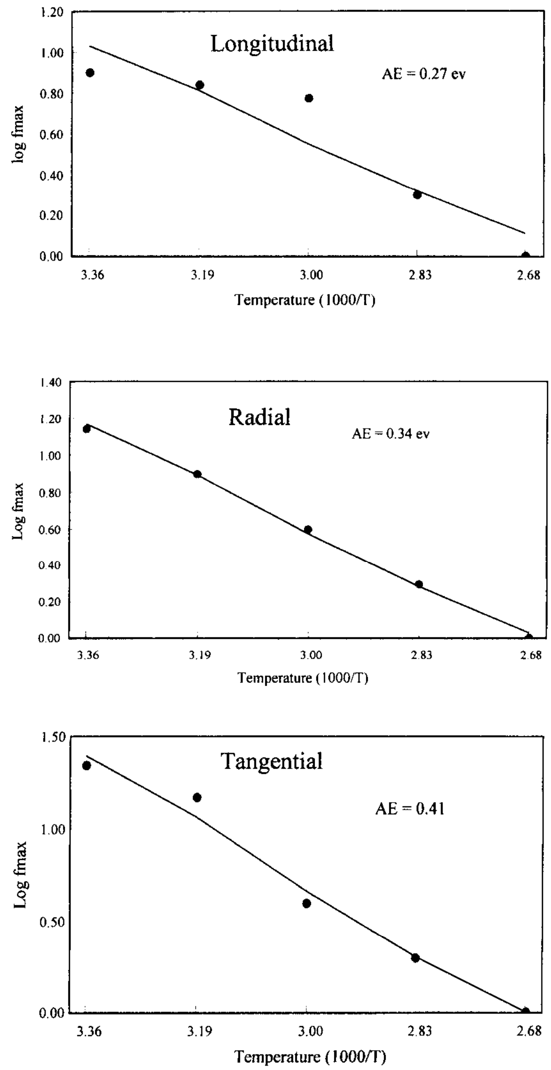

FIG. 4. Activation energies for different grain directions.

heterogeneous structures of wood, such as lamellar structures.

As seen in Fig. 2, the lowest dielectric loss factor values shift toward higher frequencies as temperature increases. The temperature pattern is almost the same as shifting of the lowest peak towards the higher temperature. Therefore, the data of dielectric constant and dielectric loss factor can be normalized to produce a single "master curve" as outlined by Jonscher (1983). These master curves are shown in Fig. 3 for each direction. The data for each temperature were moved to make a master curve, and the corresponding translation of the data points are shown in the reference point as symbol in the figure. It is found that an equivalent circuit (Kabir et al. 2000) can be used for fitting the experimental data. Activation energies (AE) were calculated using the equation.

$$f = f_0 \exp(-E/kT) \qquad (1)$$

where k is the Boltzman constant, E is the activation energy, and T is the absolute temperature. Arrhenius plots are shown in Fig. 4 for the each grain direction. The AE for longitudinal, radial, and tangential directions are 0.27 ± 0.03 ev, 0.34 ± 0.05 ev, and 0.41 ± 0.06 ev, respectively. The longitudinal direc-

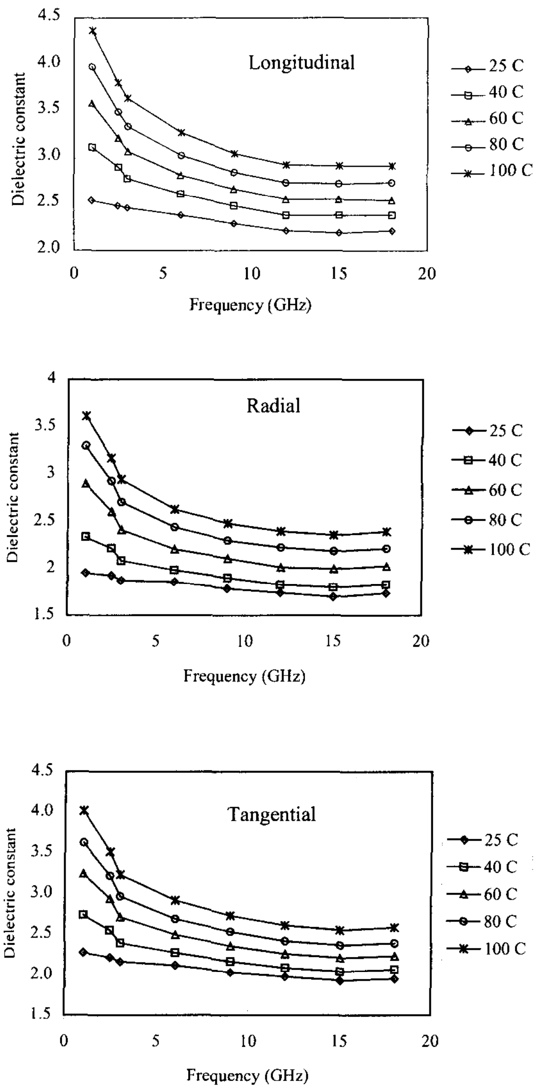

FIG. 5. Dielectric constants for rubber wood at microwave frequencies, different temperatures, and grain directions.

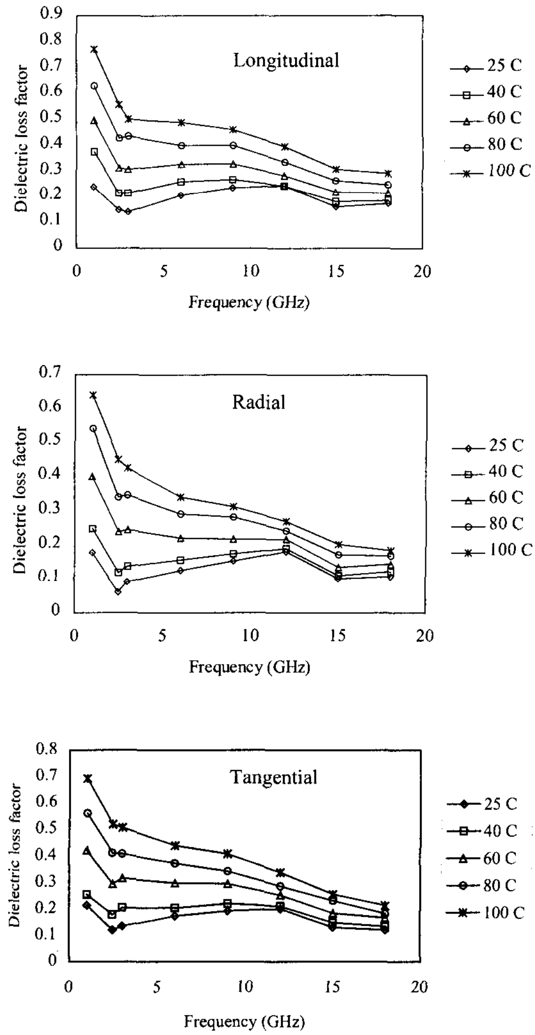

FIG. 6. Dielectric loss factors for rubber wood at microwave frequencies, different temperatures, and grain directions.

tion exhibited the lowest AE, whereas tangential direction had the highest AE. These AE values are similar to those obtained for Japanese wood species (Norimoto and Yamada 1976).

Microwave frequencies

Dielectric data for microwave frequencies from 1 to 18 GHz and at different temperatures are presented in Figs. 5 and 6. The dielectric constant decreases with frequency for all grain directions and temperatures (Fig. 5). It is clear from these graphs that the frequency dependence of the dielectric constant at temperatures greater than 40°C is characterized by a critical point at 3 GHz. Below 3 GHz, the dielectric constant increases abruptly with decreasing frequency. Above 3 GHz, it decreases slightly with increasing frequency. Below 10 GHz, dielectric constant decreased with increasing frequency, while frequency has little effect above 10 GHz. Linear relationships were found between the dielectric constant and temperature for each grain direction as shown in Fig. 5.

The dielectric loss factor showed peaks around 10 GHz at 25°C in the longitudinal direction (Fig. 6). These peaks disappear at temperatures of 80°C and 100°C. The radial and tangential directions also exhibited similar trends. Below 3 GHz, the dielectric loss factor increased sharply with a decrease in frequency (Fig. 6). This is due to conductive loss, which is dominating at these lower frequencies. Similar results below this frequency were also reported for oil palm mesocarp (Khalid et al. 1996). Dielectric loss factor also increased linearly with temperature.

CONCLUSIONS

The dielectric constant of oven-dried rubber wood increases with increase of temperature. In the low frequency region, large dispersion occurred relatively at higher temperature and lower frequency. After 10 GHz, measurement frequency does not have much effect on dielectric constant. The dielectric loss factor exhibited minimum values, which were shifted to the higher frequency at higher temperature. Below 3 GHz, the dielectric loss factor increases with decrease of frequency, which may be attributed due to the conduction loss. It showed loss peak at about 10 GHz at 25°C for all grain directions. The minimum activation energy was found in the longitudinal direction.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the partial financial support for this work by Southern Research Station, U.S. Forest Service. Authors are also thankful to the Farm Department of University Putra Malaysia for providing rubber wood and the Ministry of Science and Technology, Government of Malaysia, for providing IRPA research grant.

REFERENCES

ATHEY, T. W., M. A. STUCHLY, AND S. S. STUCHLY. 1982. Measurement of RF permitivity of biological tissues with an open-ended coaxial line. IEEE Trans. MTT. 30: 82–86.

JAMES, W. L. 1968. Effect of temperature on readings of electric moisture meters. Forest Prod. J. 18(10):23–31.

———. 1975. Dielectric properties of wood and hardboard. Variation with temperature, frequency, moisture content, and grain direction. Res. Pap. FPL-245, USDA Forest service, Forest Prod. Lab., Madison, WI. 33 pp.

———. 1977. Dielectric behavior of Douglas-fir at various combinations of temperature, frequency, and moisture content. Forest Prod. J. 27(6):44–48.

———, AND D. W. HAMIL. 1965. Dielectric properties of Douglas-fir measured at microwave frequencies. Forest Prod. J. 15(2):51–56.

JONSCHER, A. K. 1983. Dielectric relaxation in solids. Chelsea Dielectric Press, London, UK.

KABIR, M. F, W. M. DAUD, H. A. A. SIDEK, AND K. KHALID. 1996. Dielectric behaviour of rubber wood. Bull Malaysian Solid State Sci. Technol. 6(2):57–67.

———, ———, ———, and ———. 2000. Equivalent circuit modeling of the dielectric properties of rubber wood at low frequency. Wood Fiber Sci. 32(4):450–457.

KHALID, K., Z. ZAKARIA, AND W. M. DAUD. 1996. Variation of dielectric properties of oil palm mesocarp with moisture content and fruit maturity at microwave frequencies. Elaeis 8(2):83–93.

KRASZEWSKI, A., M. A. STUCHLY, AND S. S. STUCHLY. 1982. ANA calibration method for measurement of dielectric properties. IEEE Trans. IM. 32(2):385–387.

MARTIN P., R. COLLET, P. BARTHELEMY, AND G. ROUSSY. 1987. Evaluation of wood characteristics: Internal scanning of the material by microwaves. Wood Sci. Technol. 21:361–371.

NANASSY, A. Z. 1964. Electric polarization measurement on yellow birch. Can. J. Physics 42: 1270–1281.

———.. 1970. Overlapping of dielectric relaxation spectra in oven-dry yellow birch at temperature from 20 to 100°C. Wood Sci. Technol. 4:104–121.

NORIMOTO, M., AND T. YAMADA. 1970. The dielectric properties of wood. IV. On the dielectric dispersion of oven-dried wood. Wood Res. 50:36–49.

———, AND ———. 1976. Dielectric properties of wood. Wood Res. 59/60: 106–152.

TINGA, W. R. 1969. Dielectric properties of Douglas-fir at 2.45 GHz. J. Microwave Power 4(3):162–164.

TSUTSUMI, J., AND H. WATANABE. 1965. Studies on dielectric behaviour of wood. I. Effect of frequency and temperature on ϵ' and ϵ''. Mokuzai Gakkaishi. 11(6):232–236.