WOOD AS AN ORTHOTROPIC DIELECTRIC MATERIAL

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ABSTRACT

When wood is treated as an orthotropic dielectric material, the relation between electrical displacement vector {D} and electrical field intensity vector {E} can be expressed as $\{D\} = \epsilon_0 [k] \{E\}$, where [k] is dielectric constant matrix. The transformation of the permittivity matrix then is $[\bar{k}] = [A] [k] [A]'$, where [A] and [A]′ are the rotational matrix and its transpose.

The validity of the transformation equation was tested on western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) specimens of various grain angle in the longitudinal-radial (LR), longitudinal-tangential (LT), and radial-tangential (RT) planes at 1 kHz and room temperature from green to oven-dry. The transformation equation applied to wood below 15% moisture content with a negligible error. The maximum dielectric constant of wood appears at the grain angle of 30 degrees in the LR plane and 15 degrees in the LT plane.

Discontinuity in the plot of the logarithm of dielectric properties versus moisture content was observed at 6 to 10% and 30 to 40% moisture content. Density of wood has little effect on dielectric properties of wood.

Additional keywords: *Tsuga heterophylla*, grain angle, moisture content, AC resistivity, moisture meter.

INTRODUCTION

Wood is treated as an orthotropic body when we study its mechanical properties (Schniewind and Barrett 1972). Because wood is a natural paracrystalline composite, one should be able to treat it as an orthotropic dielectric body to study its electrical properties. The objective of this paper is to investigate the orthotropic nature of electrical properties and study the effect of a wide range of moisture contents on low-frequency dielectric properties.

Many of the studies on dielectric properties and electrical properties are limited to the investigation of the properties along the three principal axes. Both dielectric constant and dielectric loss of wood along the grain are about twice as high as across the grain. Skaar (1948) and Hojendahl (1946) considered that the difference is attributable to molecular structure of the cell wall. The effect of grain angle on dielectric properties generally is neglected, because in practice, dielectric properties are measured either along the grain or across the grain. Dielectric properties of wood differ slightly between the tangential and radial directions. Kröner and Pungs (1953), Uyemura (1960), and Rafalski (1966) suggested that these differences resulted from cell-wall orientation rather than from microscopic structural differences in wood.

The ratio of DC resistivity of wood between the tangential and longitudinal directions is about 2 to 3.9, and that between radial and longitudinal values is from 1.9 to 3.2. These ratios are independent of moisture content. Stamm (1964) considered that the difference in resistivity in different growth directions reflects differences in the structure of wood along the three principal axes.

THEORY

According to electromagnetic theory, the relation between electric displacement vector, $\vec{D}$, and electric field intensity vertor, $\vec{E}$, in a homogeneous isotropic medium, can be expressed as:

$$\vec{D} = \varepsilon \vec{E} = \varepsilon_0 (1 + \chi) \vec{E} \qquad (1)$$

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where ϵ is the dielectric permittivity of a medium, ϵ_o is the dielectric permittivity of empty space, and χ is dielectric susceptibility of the medium.

In the case of an anisotropic body in an electric field, Eq. (1) can be rewritten as:

$$\{D\} = [\varepsilon]\{E\} \quad (2)$$

where {D} and {E} are column matrices and [ϵ] is dielectric permittivity matrix, and is a second-order tensor.

The rotational transformation of {D} and {E} is:

$$\{\bar{D}\} = [A]\{D\}$$

$$\{\bar{E}\} = [A]\{E\} \quad (3)$$

The elements of the rotational matrix [A] are directional cosines between a new coordinate axis and the original coordinate axis. [A] has a special property such that [A]′[A] = [I] where [A]′ is the transpose of matrix [A], and [I] is the unit matrix.

Consequently, from (3) and (2)

$$\begin{aligned}\{\bar{D}\} &= [A]\,[\varepsilon]\{E\}\\ &= [A]\,[\varepsilon][I]\{E\}\\ &= [A]\,[\varepsilon][A]'\{\bar{E}\}\end{aligned} \quad (4)$$

or

$$\{\bar{D}\} = [\bar{\varepsilon}]\{\bar{E}\} \quad (5)$$

if

$$[\bar{\varepsilon}] = [A][\varepsilon][A]' \,. \quad (6)$$

The constitutive relation of Eq. (2) can be expressed in suffix notation:

$$D_i = \varepsilon_{ij}E_j \quad , \quad (7)$$

where ϵ_{ij} is a second-order tensor. Furthermore,

$$\varepsilon_{ij} = \varepsilon_0(\delta_{ij} + \chi_{ij}) \quad , \quad (8)$$

where δ_{ij} is Kronecker delta (Nye 1957). Therefore, dielectric constant k_{ij}, by definition is also a second-order tensor, as,

$$k_{ij} = \frac{\varepsilon_{ij}}{\varepsilon_0} \quad . \quad (9)$$

Therefore, the transformation of dielectric constant matrix [k] takes a form similar to dielectric permittivity:

$$[\bar{k}] = [A][k][A]' \,. \quad (10)$$

According to the generalized Ohm's law, the electrical resistivity of any anisotropic body is

$$\{E\} = [r]\{j\} \quad , \quad (11)$$

where {j} is the current density and [r] is the electrical resistivity tensor. The rotational transformation of resistivity tensor can then be expressed as:

$$[\bar{r}] = [A][r][A]' \,. \quad (12)$$

The accuracy of the constitutive Eq. (5) cannot be tested directly because it is impossible to measure directly the electrical displacement vector. However, the orthotropic nature of dielectric properties of wood can be examined from the experimental data at any grain angle and compared with theoretically calculated values using Eq. (10) and (12).

EXPERIMENTAL PROCEDURE

Seven western hemlock logs about 50 cm long were collected from a sawmill in Dallas, Oregon. Logs were from the Snow Peak area in the coastal region. They were split into quarters, and flitches without any defects were machined to obtain three types of 5 by 20 by 0.3-cm specimens of 0°, 15°, 40°, 45°, 60°, 75°, and 90° grain angles from one of the growth axes. Grain angles of Type A specimens varied in the LR (longitudinal-radial) plane, Type B specimens in the LT (longitudinal-tangential) plane, and Type C specimens in the RT (radial-tangential) plane as in Fig. 1. After the specimens were sanded, washed with distilled water, and wrapped individually in several layers of Saran wrap and a polyethylene bag, they were stored at 23 C and 50% RH for two weeks before dielectric measurements were taken.

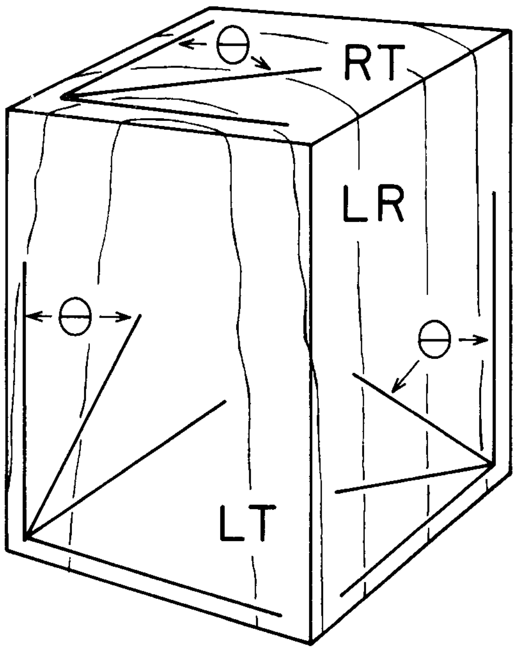

FIG. 1. Schematic presentation for cutting test specimens in various grain directions.

Specimens were sandwiched between two aluminum parallel-plate electrodes of 5 by 20 cm with 45.4 kg pressure applied with a special jig. The dielectric properties of the assembly were measured using a GR 1650 impedance bridge at 1 kHz and 7 volts peak-to-peak applied field strength. The edge effect was calculated to be less than 1% and was ignored because it was smaller than the precision of the impedance bridge. Dielectric constants of the test specimens were calculated using the relation

$$k = \frac{11.3\ A\ C_p}{d} \qquad (13)$$

where A and d are the cross-sectional area and thickness of test specimen, respectively, and C_p is the equivalent parallel capacitance in picofarads (pf). The parallel AC resistivity was calculated using the relation

$$r_{AC} = \frac{A}{\omega k \tan \delta d} \quad \text{(ohm-cm)} \qquad (14)$$

where ω is angular frequency and $\tan \delta$ the loss tangent of the specimen read directly from the bridge. When $\tan \delta$ of the wood decreased below 0.56, a GR 713 capacitance bridge was used, which measures equivalent series capacitance. It was converted to parallel capacitance before k and r_{AC} were calculated.

After each dielectric measurement, specimens were dried in air to reduce their moisture content. They were wrapped again in Saran wrap and were subjected to an equalization period of at least two weeks before dielectric measurements were taken. The procedure was repeated until moisture content reached 5%. Specimens were then oven-dried. Average weight before and after each measurement was used to determine moisture content of the specimen at test.

Adjustment of data

When the logarithm of k and the logarithm of r_{AC} of wood are plotted against moisture content between 10 and 35%, straight lines result with regression coefficients greater than 0.9. These linear relations were used to interpolate the dielectric properties of wood at moisture contents of 10, 15, 20, 25, 30, and 35%.

RESULTS AND DISCUSSION

Effect of moisture content on dielectric properties

As there were no commerical dielectric measuring devices available to handle high-loss capacitors, most of the earlier dielectric research at frequencies below microwave was limited to low moisture contents, because wood behaves as a high-loss dielectric material when moisture content exceeds 15%. Recent progress in scientific instrumentation resulted in developing commercial impedance bridges that can handle high-loss dielectric material and enable us to measure the dielectric properties of wood at any moisture content.

Figures 2 to 4 are plots of the logarithm of dielectric constant versus moisture content at 1 kHz along the 3 principal axes of wood. The relation can be represented by three linear segments: from oven-dry to near 8%, from 8 to 40% moisture contents, and from 40% up. Uyemura (1960)

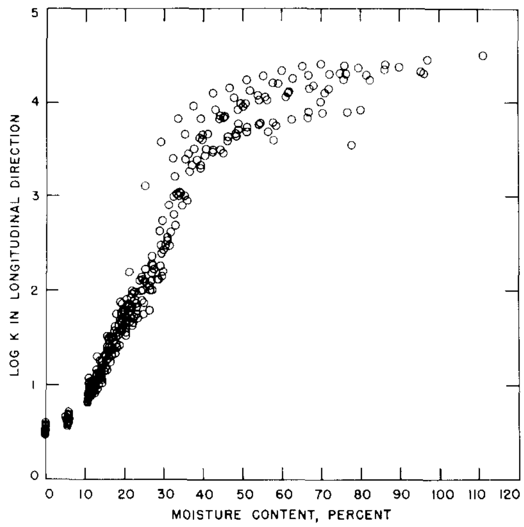

FIG. 2. Relation of the logarithm of longitudinal dielectric constant of western hemlock to moisture content.

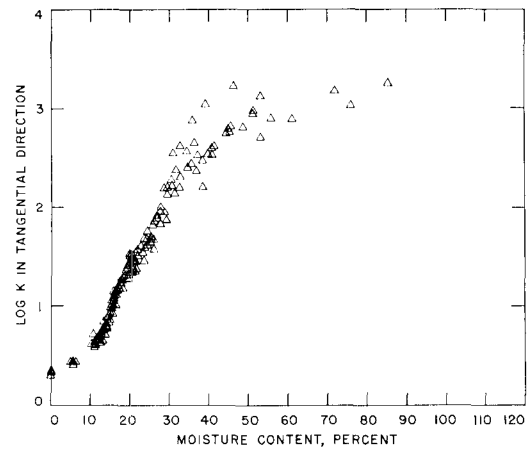

FIG. 4. Relation of the logarithm of tangential dielectric constant of western hemlock to moisture content.

reported that the plot of dielectric constant of wood shows a discontinuity at moisture contents near 6%. Similar discontinuities occur for plots of log r_{AC} versus moisture content in Figs. 5 to 7. According to Spalt (1958), the moisture content at which each sorption site of wood is occupied by a single water molecule (monomolecular layer), calculated using solid solution theory, is about 8% for desorption and about 6% for adsorption. In this experiment, the dielectric properties of wood were measured during desorption, and the observed discontinuity at the 8% level agrees with the moisture content of the monomolecular layer of sorption calculated by Spalt.

Stone and Scallan (1967) reported that the fiber saturation point of wood is 40% when measured by the pressure-plate tech-

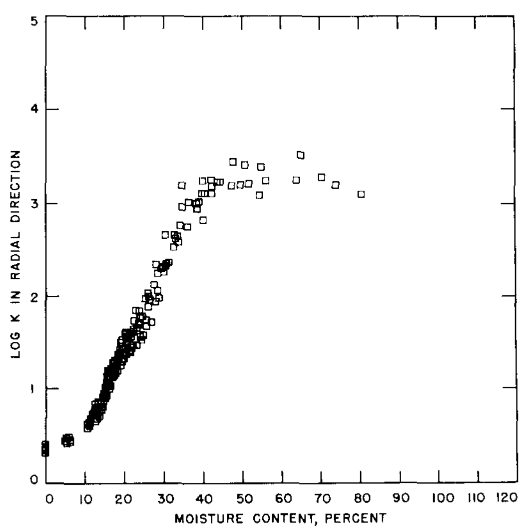

FIG. 3. Relation of the logarithm of radial dielectric constant of western hemlock to moisture content.

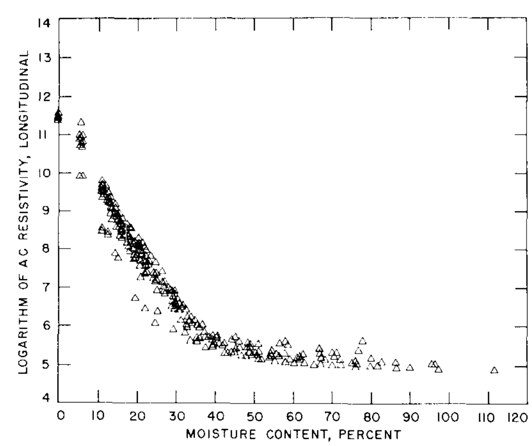

FIG. 5. Relation of the logarithm of longitudinal AC resistivity of western hemlock to moisture content.

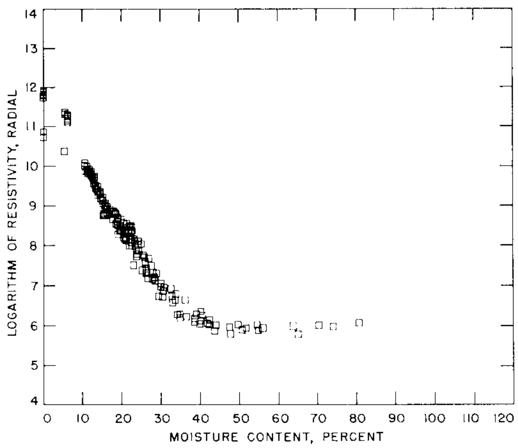

FIG. 6. Relation of the logarithm of radial AC resistivity of western hemlock to moisture content.

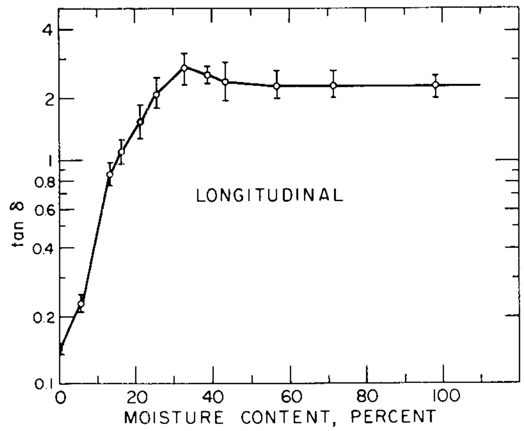

FIG. 8. Relation of the longitudinal loss tangent of western hemlock to moisture content.

nique, even though Stamm (1964), Kollmann and Côté (1968), and lately Skaar (1972) have cited that the fiber saturation point of wood is between 24 and 30%. The discontinuity in the plot of log k versus moisture content at 40% moisture level coincides with the fiber saturation point determined by Stone and Scallan for spruce wood.

Because of the discontinuity in the plot of log k versus moisture content at 40%, calibrations of capacitance-type moisture meters should be performed with care near this region if accurate moisture content estimations are desired.

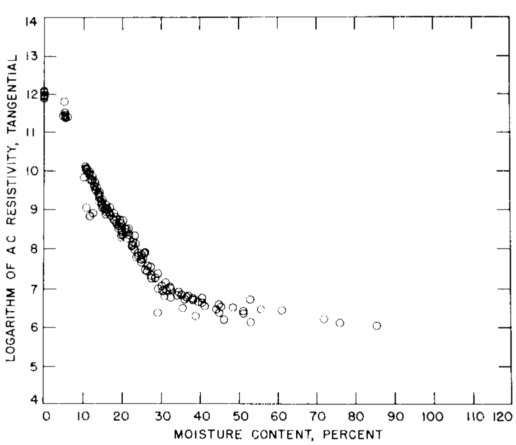

FIG. 7. Relation of the logarithm of tangential AC resistivity of western hemlock to moisture content.

Note that the dielectric constant of the wood-water aggregate exceeded that of water ($k_{H_2O} = 81$, $\log k = 1.91$) when the moisture content was above 28%. On the basis of the dielectric-mixture theory (Van Beek 1967), the dielectric constant of a wood-water system always must lie within the range of $k_{wood} < K_{mixture} < k_{H_2O}$. Tinga (1969) demonstrated that the above principle holds for a wood-water system at a microwave frequency of 2240 MHz, where interfacial polarization and loss of electrical energy by conduction are ineffective. At a frequency of 1 kHz, interfacial, dipolar, ionic, and electronic polarizations take place; hence the dielectric properties of the aggregate will be influenced by both the minute quantities of impurities that exist in cell-wall substances and the electrokinetic phenomena present at wood-water interfaces. When moisture content is high, water in wood should behave as water containing electrolytes, which has a considerably higher dielectric constant than that of pure water.

AC resistivity of wood decreases continuously with increasing moisture content (Figs. 5 to 7). The behavior of r_{AC} is similar to r_{DC} except that r_{AC} is smaller than r_{DC}. Discontinuities in r_{AC} also appear at the 8% and 40% levels.

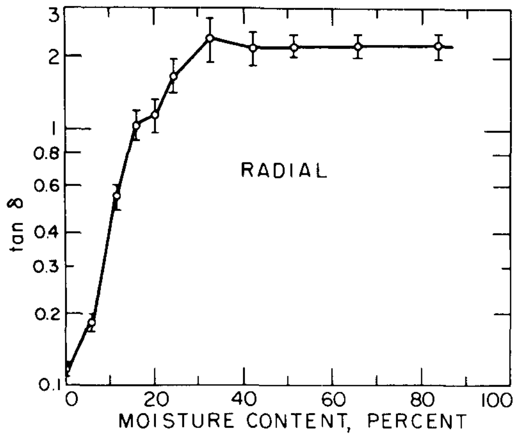

FIG. 9. Relation of the radial loss tangent of western hemlock to moisture content.

Anomalous dielectric loss behavior

Change in dielectric loss with a change in moisture content of green wood is hardly noticeable at moisture contents above 40% (Figs. 8 and 9). Furthermore, dielectric loss showed a maximum at moisture contents in the region of 30%. James and Hamill (1965) observed that the dielectric loss of green wood at microwave frequencies is lower than that at 30% moisture content. This implies that power loss-type moisture meters will not be effective when the moisture content of wood is above 30%.

For a resistance-capacitance, parallel-circuit model, loss tangent of dielectric material can be expressed as

$$\tan \delta = \frac{1}{\omega C_p R_p} , \qquad (15)$$

where R_p is the equivalent parallel resistance. Recall that the dielectric constant of wood, hence the equivalent capacitance of the specimen, *decreases*, and the resistance of wood *increases* with decreasing moisture content. According to Eq. (15), loss tangent is a function of the product of capacitance and resistance. Therefore, depending upon the rate of change of capacitance and resistance with respect to the reduction in moisture content, loss tangent may remain constant, increase, or decrease with decreasing moisture content.

From a molecular standpoint, a decrease in dielectric constant with decreasing moisture content above the fiber saturation point is caused primarily by a reduction in the number of polar groups in the wood-water aggregate. The increase in resistance with decreasing moisture content above the fiber saturation point is caused primarily by a reduction in the number of charge carriers, provided that the concept of ionic conduction mechanism applies.

Below fiber saturation, drying affects the dielectric constant not only by reducing the number of polar molecules that can interact with an applied external field, but also by restricting the freedom of motion of polar groups in wood. Drying, on the other hand, reduces primarily the number of charge carriers (Brown et al. 1963), but the magnitude of change in the number of charge carriers may be far greater than the change in the number of available polar groups, because water-soluble extractives and other ionizable impurities contribute more significantly to the conduction mechanism than the polarization mechanism.

Effect of density and specific gravity

The role of density of dielectric properties was examined critically, and the results are presented in Table 1. Density is based on weight and volume of a specimen at test and is influenced by moisture content, but specific gravity is based on ovendry weight and volume at test.

Stepwise regression analysis considering logarithm of dielectric properties (log k, log r, log (tan δ)) as dependent variables, and moisture content, density, and specific gravity as independent variables, suggests that moisture content alone accounts for more than 94% of the variability in dielectric constant and 84% for AC resistivity and tan δ. Incorporation of density as an additional independent variable improved the regression very little, but specific gravity has no effect at all in improving the regression model; t-tests of the regression coefficient contributed by density and specific gravity showed no significance.

Skaar (1948) showed that density has a

TABLE 1. *Square of the correlation coefficient (R^2) obtained with stepwise linear regression analysis for logarithms of dielectric properties versus moisture content, density, and specific gravity of western hemlock.*

Dependent variables	R^2		
	Moisture content only[1]	Moisture content and density	Moisture content, density, and specific gravity
Log K			
Longitudinal	0.938	0.940	0.940
Radial	.961	.961	.961
Tangential	.969	.970	.970
Log Y_{AC}			
Longitudinal	.840	.841	.840
Radial	.966	.967	.967
Tangential	.950	.950	.950
Log (tan δ)			
Longitudinal	.844	.844	.844
Radial	.910	.911	.911
Tangential	.925	.926	.926

[1]Moisture content ranged from 10% to 30%.

TABLE 2. *The ratio of theoretically calculated dielectric constants to the experimental values for western hemlock at various grain angles.*

Grain angle	Moisture contents, %						
	0	5	10	15	20	25	30
LR PLANE							
15	0.969	0.966	0.892	0.917	1.024	1.085	*1.265*
30	0.972	0.995	0.882	0.854	0.890	0.889	0.970
45	1.003	0.912	0.956	0.904	0.909	0.883	0.925
60	1.011	0.997	0.931	0.821	*0.750*[1]	*0.672*	*0.638*
75	0.980	0.966	0.950	0.832	*0.737*	*0.650*	*0.584*
LT PLANE							
15	0.987	0.972	0.926	0.926	0.954	1.014	1.117
30	1.017	0.985	0.941	0.946	0.984	1.061	1.188
45	1.050	0.984	1.063	1.008	0.993	1.020	1.096
60	1.020	0.936	1.034	0.987	0.976	1.004	1.084
75	0.983	0.869	1.035	0.952	0.893	0.857	*0.849*
RT PLANE							
15	1.024	1.125	1.083	1.136	1.217	*1.329*	*1.475*
30	1.029	1.144	1.206	1.185	1.192	1.228	*1.292*
45	1.012	1.157	1.202	1.044	0.931	0.853	0.803
60	0.996	0.988	1.134	1.055	1.002	0.976	0.974
75	1.062	1.253	1.141	1.088	1.051	1.031	1.027

[1]Values in italics varied more than 25% from experimentally derived values.

TABLE 3. *The ratio of theoretically calculated AC resistivity to the experimental values for western hemlock at various grain angles.*

Grain angle	Moisture contents, %						
	0	5	10	15	20	25	30
LR PLANE							
15	1.109	1.238	1.224	*1.260*[1]	*1.296*	*1.335*	*1.375*
30	1.241	*1.453*	*1.435*	*1.540*	*1.656*	*1.781*	*1.918*
45	*1.731*	*1.719*	*1.274*	*1.379*	*1.507*	*1.600*	*1.725*
60	1.218	*1.417*	*1.455*	*1.646*	*1.862*	*2.108*	*2.388*
75	1.106	1.211	*1.404*	*1.584*	*1.788*	*2.019*	*2.279*
LT PLANE							
15	1.126	1.136	*1.305*	*1.281*	*1.263*	*1.251*	1.245
30	1.178	*1.360*	*1.391*	*1.358*	*1.336*	*1.323*	*1.319*
45	1.210	1.055	*1.257*	*1.296*	*1.344*	*1.400*	*1.466*
60	1.206	*1.343*	*1.279*	*1.328*	*1.382*	*1.442*	*1.508*
75	1.082	*1.652*	1.246	*1.293*	*1.301*	*1.311*	*1.321*
RT PLANE							
15	1.150	1.098	0.879	0.826	0.777	*0.732*	*0.691*
30	0.990	0.987	0.865	0.918	0.979	1.049	1.128
45	0.918	0.901	0.860	1.013	1.198	*1.423*	*1.697*
60	0.910	1.084	0.877	0.940	1.010	1.087	1.170
75	0.871	0.906	0.818	0.857	0.898	0.942	0.989

[1]Values in italics varied more than 25% from experimentally derived values.

consistent effect on the dielectric constant of wood. His observation applies over wide ranges of wood of different species and different density. Within a single species, however, the variability that may originate because of different proportions of cell-wall substances overshadows any possible effect of density and specific gravity on the dielectric properties.

Orthotropic nature of wood

Dielectric constant and AC resistivity of wood at grain angles of 15°, 30°, 45°, 60°, and 75° were calculated from the measured values at 0° and 90° grain angles using Eq. (10) and (12). The ratios of the calculated values and the experimental observations then were compared in Tables 2 and 3. As the standard deviation of electrical properties for a given moisture content is about 25%, any calculated values of dielectric constant and AC resistivity that vary more than 25% from experimentally measured values were considered to be substantial and are shown in Tables 2 and 3 in italic type.

According to Table 2, wood behaves as an orthotropic dielectric material without introducing serious error when the moisture content of wood is below 15%. Above 15% moisture, the deviation of theoretically calculated values from experimental values becomes significant in the LR plane. AC resistivity does not fit the orthotropic treatment very well. Theoretically calculated AC resistivity of wood is consistently higher than the experimental observation in both the LT and LR planes when grain angle is varied from parallel-to-fiber axis to transverse-to-fiber axis.

Figures 10 to 14 show the three-dimensional plot of average dielectric constant and AC resistivities versus grain angle and moisture content. According to Figs. 10 and 11, the maximum dielectric constant and minimum AC resistivity (Figs. 13 and

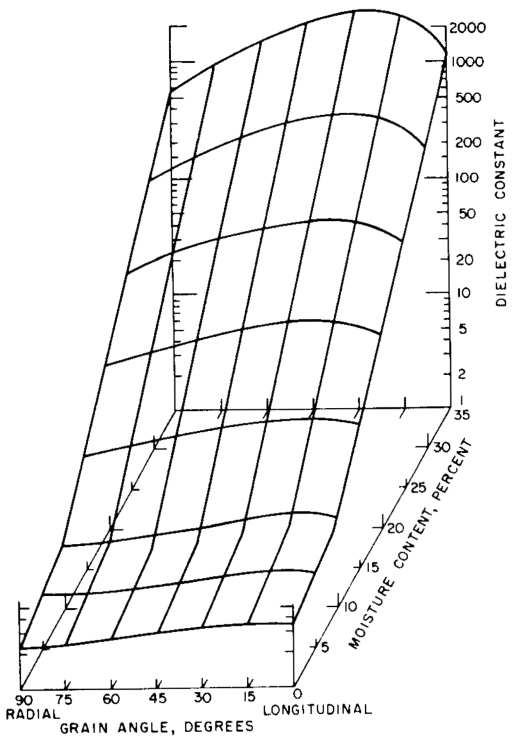

FIG. 10. Effect of grain orientation in LR-plane and moisture content on dielectric constant of western hemlock.

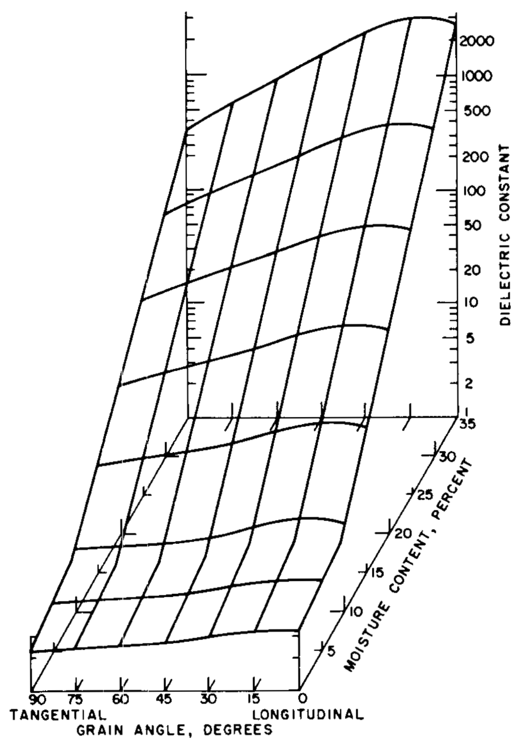

FIG. 11. Effect of grain orientation in LT-plane and moisture content on dielectric constant of western hemlock.

14) did not appear in the longituidinal direction ($\theta = 0°$), but appeared in the vicinity of 30° (θ_{max}) in the LR plane (Figs. 10 and 13), and 15° in the LT plane (Figs. 11 and 14) when the moisture content of wood was high. According to published data, the mean orientation of microfibrils with respect to longitudinal cell axes in the S_2 layer of softwood tracheids ranges between 30° and 37° in the radial wall and between 17° and 20° in the tangential wall, respectively (Tang 1973). The appearance of maximum dielectric constant and minimum AC resistivity of wood at a grain angle other than the longitudinal grain axis is caused primarily by the microfibril angle of the S_2 layer of tracheids.

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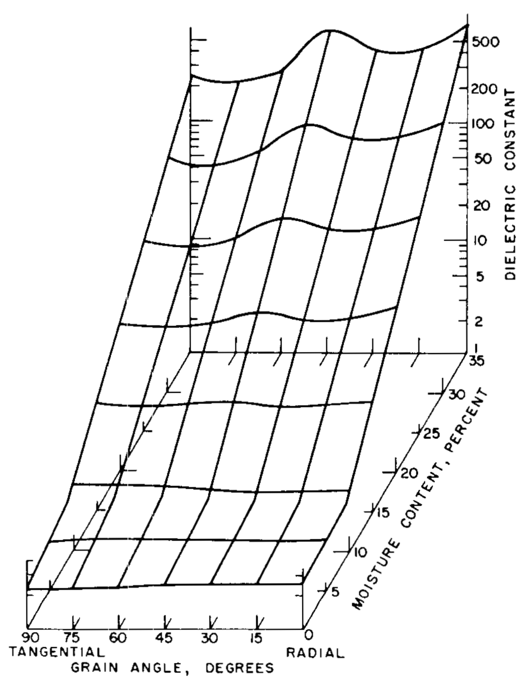

FIG. 12. Effect of growth-ring orientation in RT-plane and moisture content of western hemlock on its dielectric constant.

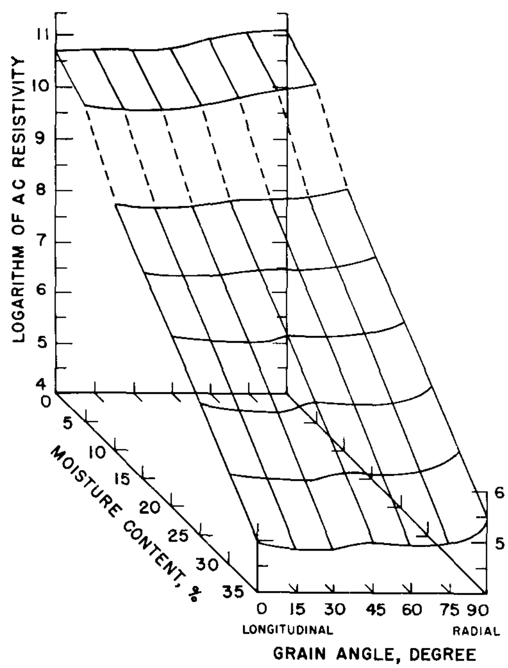

FIG. 13. Effect of grain orientation in LR-plane and moisture content on AC resistivity of western hemlock.

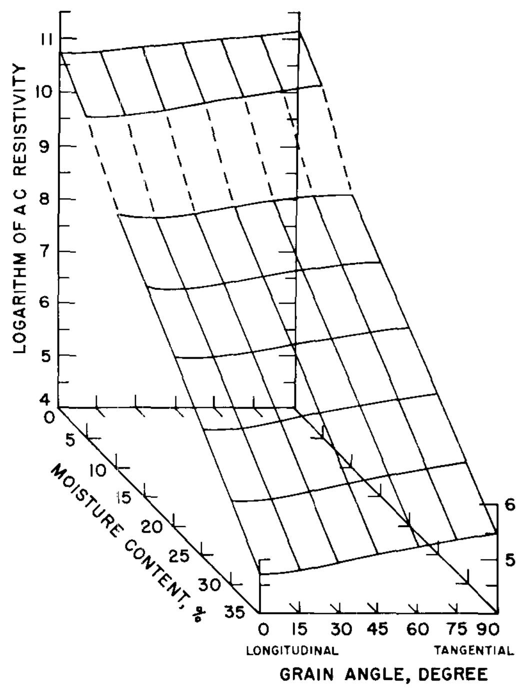

FIG. 14. Effect of grain orientation in LT-plane and moisture content on AC resistivity of western hemlock.

Note that θ_{max} is influenced by moisture content. When oven-dry, θ_{max} in the LR plane (Figs. 10 and 12) existed near 15°. At 10% moisture content, θ_{max} existed between 15 and 30 degrees. Because dielectric properties of wood are highly sensitive to moisture content, I consider that the change in θ_{max} with moisture content may be associated with the preferential directional polarization of water molecules absorbed in cell-wall substances.

The dielectric constant of wood in the radial direction is higher than that along the tangential direction. Existence of ray cells and higher microfibril angles along radial surfaces of tracheids may be the cause of this difference in the dielectric properties.

CONCLUSIONS

The major practical application of dielectric properties of wood has been to estimate moisture content of wood and fiber composites. A moisture meter based on both the capacitance principle and the AC resistivity principle may be useful to determine the moisture content of wood and fiber composites above fiber saturation. Dielectric loss-type moisture meters may not be sensitive enough to determine moisture content above fiber saturation, because dielectric constant increases and AC resistivity decreases with increasing moisture content above fiber saturation. The variability affects the accuracy of moisture meter readings. The higher the moisture content, the higher is the variability in wood dielectric properties and hence the prediction of moisture content by moisture meters would be less accurate.

Recently, an innovation has been reported to determine the grain angle of lumber by dielectric means (McLauchlan et al. 1973). I recommend careful study of any new dielectric devices for nondestructive testing. They should be measured against the statistical variability of wood properties before they are offered for production control purposes.

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