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Dielectric Properties of Hevea *Latex at Various Moisture Contents*

KAIDA KHALID*, JUMIAH HASSAN* AND W. MOHAMMAD DAUD*

The dielectric properties of Hevea *latex at various moisture contents at selected frequencies between 2.45 GHz to 18.0 GHz and at the temperature of 26°C is reported. Measurement of the dielectric properties was done by using open-ended coaxial line sensor and automated network analyser with an accuracy of the measurement ± 5% for dielectric constant and ± 3% for dielectric loss. The results of the measurement are compared with the values predicted by dielectric mixture equations recommended by Weiner, Bruggeman and Kraszewski. The study suggests that the dielectric properties of* Hevea *latex are mainly due to the orientation of loosely bound water molecules.*

Hevea latex is generally visualised as a suspension of latex particle in an aqueous serum. The fresh latex consist of 55% – 80% of water, 15% – 45% rubber hydrocarbon and approximately 2% – 4% of non-rubber constituents[1]. This composition varies widely according to season, weather, soil conditions, clones, tapping system, *etc.* Field latex can be concentrated to a higher rubber content or lower moisture content to make it more uniform in its quality and economically more attractive. The present standard of latex concentrate has a dry rubber content of 60% or about 40% moisture content. Normally 0.3% – 0.5% ammonia is added as a preservative.

The variation of moisture content from fresh latex sample and latex concentrate is very broad, ranging from 40% – 80%. It is often desirable to know the variation of the dielectric properties of *Hevea* latex with moisture content since the knowledge of these parameters is useful to improve the design of moisture sensor[2,3], control industrial process and predict microwave absorption in microwave heating[4].

Data on the dielectric properties of *Hevea* latex have been reported over a frequency range of 0.1 MHz to 100 MHz[5] and 200 MHz to 2000 MHz[6]. An interesting result such as transition in the form of dielectric loss from conductive mechanism to dipole orientation of water molecules at about 2 GHz was observed. This study reports the measurement of dielectric permittivity of *Hevea* latex at selected microwave frequencies (above 2.0 GHz) as a function of moisture content. The results were compared with the dielectric properties predicted by several dielectric mixture equations which are based on the dipole orientation.

The dielectric properties considered are the relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$. The real part is referred to as the dielectric constant and the imaginary part is the dielectric loss factor.

Dielectric Mixtures

Being a biological product the prediction of the dielectric properties of *Hevea* latex is very complicated. In order to avoid complication the *Hevea* latex is treated as a biphase liquid. Although non-rubber constituents such as lipid, carotene, *etc.* are present

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*Department of Physics, Universiti Pertanian Malaysia, Serdang 43400, Selangor, Malaysia

but they are of relatively small amounts and mostly adsorbed at the surface of the rubber particles[7]. We can consider rubber particles and non-rubber consituents as a single solid phase or solid content of *Hevea* latex. This mixture of water and solid components is considered to be isotropic and randomly distributed in space.

Water which accounts for much of the constituent in *Hevea* latex is a polar molecule. When placed in an electric field, positive and negative charges move in opposite directions and the water molecules will tend to rotate so that their dipoles align with the field. The ability to polarise, namely the orientation of dipoles determines the dielectric constant of the medium, ε'. The dielectric loss, ε" reflects the ability to dissipate electromagnetic energy, that is to convert it into heat.

Previous studies have shown that for the frequency range of 2 GHz to 20 GHz the dielectric properties of liquid not only depend upon the water content but is also strongly dependent upon the geometrical shape of the water particles[8]. It is usually assumed that the shape of the water molecule is ellipsoidal.

Let us consider a high volume fraction of ellipsoidal water molecules with complex permittivity ε_w which mixes with the dispersive continuum of latex particles or solid continuum with complex permittivity ε_r. Applying average field approximation[9], the average electric displacement $\bar{D}_{av}$ and average electric field E_{av} in the mixture can be written as

$$D_{av} = \delta_w \bar{D}_w + \delta_r \bar{D}_r \qquad \ldots 1$$

$$E_{av} = \delta_w \bar{E}_w + \delta_r \bar{E}_r \qquad \ldots 2$$

where δ_w is the volume fraction of water
δ_r is the volume fraction of solid continuum
$\bar{D}_w$ is the average electric displacement in water
$\bar{D}_r$ is the average electric displacement in solid continuum.

It is assumed that the complex permittivity of the mixture ε may be written as

$$\varepsilon = D_{AV} / E_{AV} \qquad \ldots 3$$

and that for each component $\bar{D}_w = \varepsilon_w \bar{E}_w$ and $\bar{D}_r = \varepsilon_r \bar{E}_r$ where ε_w and ε_r are the complex permittivity of water and rubber respectively. From *Equations 1, 2* and *3*

$$\varepsilon = \varepsilon_w \delta_w f_w + \varepsilon_r \delta_r f_r \qquad \ldots 4$$

where $f_w = \bar{E}_w / E_{av}$ and $f_r = \bar{E}_r / E_{av}$

Equation 2 may be written as

$$\delta_w f_w + \delta_r f_r = 1 \qquad \ldots 5$$

From *Equations 4* and *5*

$$\varepsilon = \varepsilon_r + (\varepsilon_w - \varepsilon_r) f_w \delta_w \qquad \ldots 6$$

and

$$(\varepsilon - \varepsilon_w) \delta_w f_w + (\varepsilon_w - \varepsilon_r) f_r = 0 \qquad \ldots 7$$

Equations 6 and *7* present the general forms for the effective complex dielectric constant in term of average field in the water and solid continuum.

Volume fraction δ_w is related to the moisture content[10]

$$\delta_w = M_w / [M_w + \frac{\gamma_r}{\gamma_w} (1 - M_w)] \qquad \ldots 8$$

where M_w is wet basis moisture content, γ_r and γ_w are the relative density of the solid continuum and water respectively.

The average value of the field within a particle depends on its shape, dielectric constant and the average field and dielectric constant of the medium immediately outside it.

According to Stratton[11], the induced field inside the ellipsoid in a homogeneous field and for a random distribution of orientations, may be written as

$$f_\iota = \frac{1}{3} \sum_\iota \frac{\iota}{1 + A^\iota [\varepsilon_i/\varepsilon] - 1} \qquad \ldots 9$$

Where A_ι depends on the axial ratios of the ellipsoid known as depolarisation factor and is given by

$$A_\iota = \frac{abc}{2} \int_0^\infty \frac{d\lambda}{(\lambda + \iota^2) R_\lambda} \quad ;$$

$$R_\lambda = \left[(\lambda + a^2)(\lambda + b^2)(\lambda + c)^2\right]^{1/2} \quad \ldots 10$$

where a, b and c are the semi-axes of the ellipsoid, λ is the ellipsoidal co-ordinate, and $\iota = a, b, c$.

For the case of spheroid $b = c$ and A_ι depends only on the ratio a/b and $A_a + A_b + A_c = 1$.

From *Equations 6* and *9* the complex permittivity of the mixture may be written as

$$\varepsilon = \varepsilon_r + \frac{\varepsilon_w + \varepsilon_r}{2} \delta_w \sum_\iota \frac{\varepsilon_r}{\varepsilon_r + (\varepsilon_w - \varepsilon_r) A_\iota} \qquad \ldots 11$$

Equation 11 was obtained originally for small values of d and following the Bruggeman method[12] it can be extended[13] for a higher d by additions of volume fraction $d\gamma = \frac{d\delta}{1-\delta}$ of the moisture content which gives the increment to the complex dielectric constant $d\varepsilon$ as

$$d\varepsilon = \frac{d\delta}{(1-\delta)} \frac{\varepsilon_w - \varepsilon}{3} \varepsilon \sum \frac{1}{\varepsilon + (\varepsilon_w - \varepsilon) A_\iota} \qquad \ldots 12$$

The ε is finally obtained by integrating *Equation 12* from 0 to δ and from ε_r to ε and the following equations may be obtained for spheroid with $a \neq b = c$

$$(1-\delta) = \left(\frac{\varepsilon_r}{\varepsilon}\right)^{3d} \left(\frac{\varepsilon_w - \varepsilon}{\varepsilon_w - \varepsilon_r}\right) \left[\frac{\varepsilon_r (1 - 3A) + \varepsilon_w (2 - 3A)}{\varepsilon (1 - 3A) + \varepsilon_w (2 - 3A)}\right]^K \qquad \ldots 13$$

where $A = A_b = A_c$;

$$d = \frac{1}{\sum_\iota A^{-1}} = \frac{A(1 - 2A)}{(2 - 3A)} \quad ;$$

$$K = \frac{2(3A - 1)^2}{(2-3A)(1 - 3A)}$$

The complex permittivity of the mixture $\varepsilon = \varepsilon' - j\varepsilon''$ may be obtained from *Equation 13* by numerical root seeking method.

The above analysis involves an enormous calculation and ε cannot be simply obtained from dielectric properties and volume fractions of each component. However a simple analysis has been developed by Weiner[14] based on the uncertainty in the magnitude of the average electric field. This uncertainty, U is expressed in terms of a parameter n, known as the mixing condition and can be expressed as

$$\frac{\bar{E}_w}{\bar{E}_r} = U = \frac{\varepsilon_w + n}{\varepsilon_r + n} \qquad \ldots 14$$

Applying *Equations 1, 2* and *14* and by elimination of $\bar{E}_{av}$, $\bar{E}_w$ and $\bar{E}_r$ yields

$$\frac{\varepsilon - 1}{\varepsilon + n} = \delta_w \frac{\varepsilon_w - 1}{\varepsilon_w + n} + \delta_r \frac{\varepsilon_r - 1}{\varepsilon_r + n} \qquad \ldots 15$$

When $n \rightarrow \infty$ the complex permittivity is maximum, ε_{max} or upper bound which corresponds to the case where water molecules in the form of ellipsoids with their major axis parallel to the direction of the applied field. When the major axis of the ellipsoids is perpendicular to the applied field, then the complex permittivity is minimum, ε_{min} or lower bound, corresponding to $n = 0$. From *Equation 15* the following could be obtained

$$\varepsilon_{max} = \delta_w \varepsilon_w + \delta_r \varepsilon_r \quad \text{... 16a}$$

$$1/\varepsilon_{min} = \delta_w / \varepsilon_w + \delta_r / \varepsilon_r \quad \text{... 16b}$$

The dielectric permittivity of the mixture will always be bounded within the range of ε_{max} and ε_{min}. With increasing n, more water molecules are aligned parallel to the field. This suggests that the parameter n could be used to obtain the information about the degree of binding of the water molecules in the latex solution.

A simple model for quick analysis has been developed by Kraszewski[15] from the relation of the propagation constant. The complex permittivity of the mixture may be written as

$$\varepsilon^{1/2} = \delta_w \varepsilon_w^{1/2} + \delta_r \varepsilon_r^{1/2} \quad \text{... 17}$$

METHOD

The measurement of dielectric properties of the *Hevea* latex samples has been done by using 4 mm open ended coaxial-line probe coupled with automatic network analyser (HP 8720B) and computer. The input reflection coefficient of the sensor is related to the permittivity of the sample which is already established[16,17]. With proper calibration procedures[18], the accuracy of the measurement is about ± 5% for ε' and ± 3% for ε".

All the measurements were taken at room temperature, 26°C ± 1° and the actual moisture content of the sample was obtained by drying three 10-g samples at 70°C. The average of these results was recorded.

A series of *Hevea* latex samples was prepared ranging in dilution from 40% to 98% moisture content. The lowest moisture content sample was obtained from latex concentrate supplied by Rubber Research Institute of Malaysia. Freshly tapped latex with moisture content ranging from 30%-50% was obtained from university farm. The diluted samples were prepared by adding the latex concentrate or fresh latex with deionized water.

Figure 3 shows an overall picture of the experimental values of *Hevea* latex as a function of moisture content over a frequency range of 2 GHz to 18 GHz and at 26°C.

RESULTS AND DISCUSSIONS

The moisture-dependence of the dielectric properties of the *Hevea* rubber latex at 26°C is summarised in *Figures 1* and *2*. Curves are shown for the dielectric constants and dielectric loss at frequencies of 2.45 GHz, 6.9 GHz, 10.9 GHz, 13.6 GHz and 18.0 GHz. The lines are the values predicted from mixture equations obtained from *Equations 13* with a/b = 0.01, *16* and *17*. In *Figure 2* the prediction curves from Bruggeman's models with a/b = 1 and 100 for comparison is included. Both fitted experimental data and prediction values are summarised in *Table 1*.

From *Figure 2* all measured values lie in the region between Weiner's boundaries and almost in all figures the measured values are very close to the predicted values of Bruggeman's model with a/b = 0.01.

The experimental data is also well below and close to the upper limit of Weiner's model. This means that the water molecules in the *Hevea* latex are loosely binding and easily

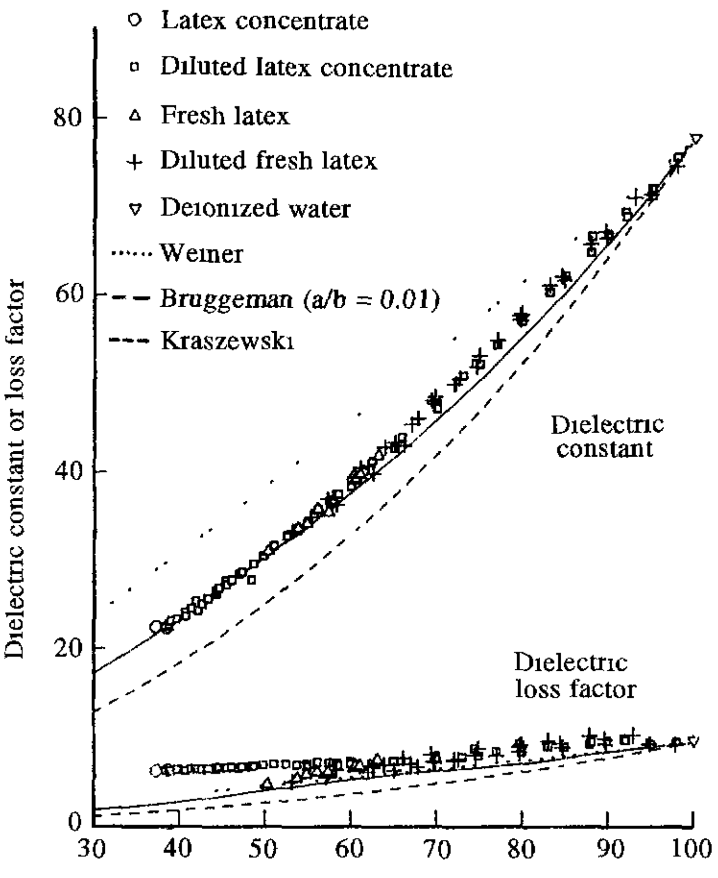

Figure 1a. Comparison of the experimental dielectric data (point marked) for Hevea *latex solutions with theoretical data calculated from mixture equations at 26°C and at frequency 2.45 GHz.*

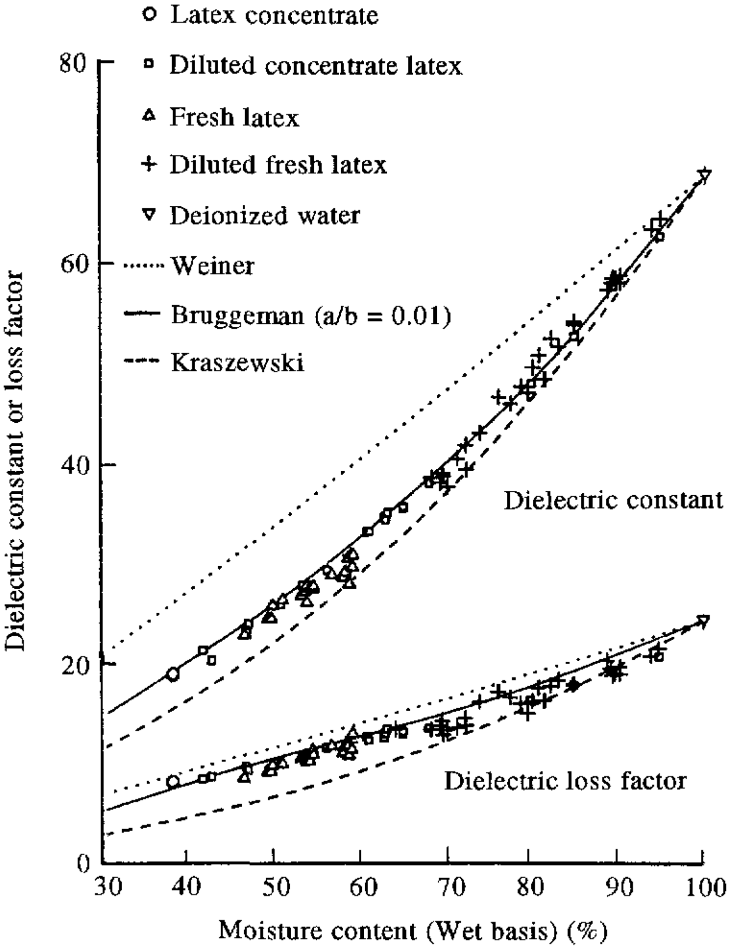

Figure 1b. Comparison of the experimental dielectric data (point marked) for Hevea *latex solutions with theoretical data calculated from mixture equations at 26°C and at frequency 6.9 GHz.*

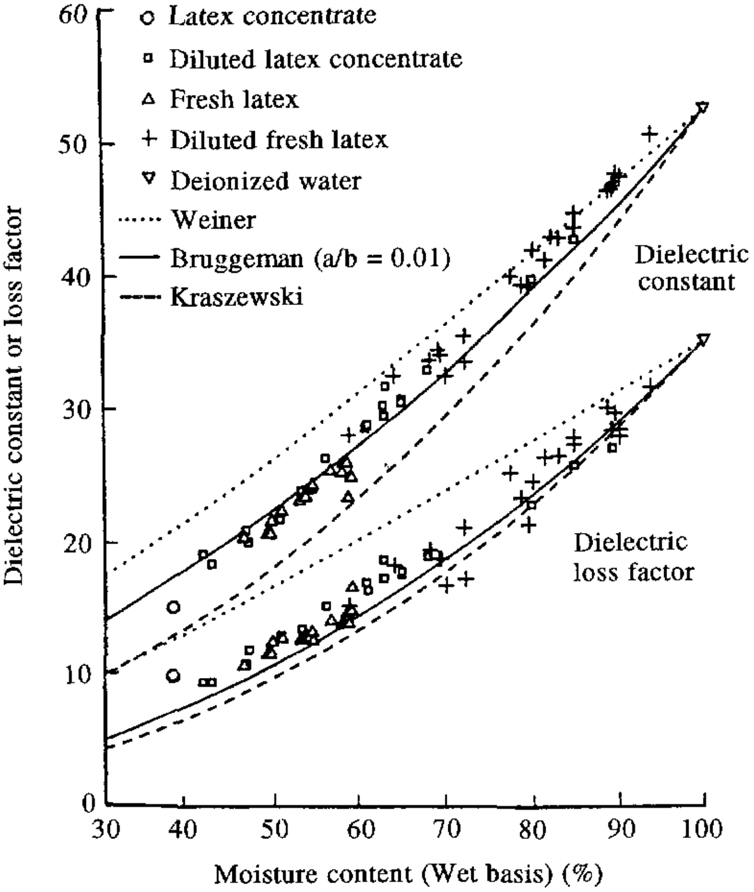

Figure 1c. Comparison of the experimental dielectric data (point marked) for Hevea *latex solutions with theoretical data calculated from mixture equations at 26°C and at frequency 13.6 GHz.*

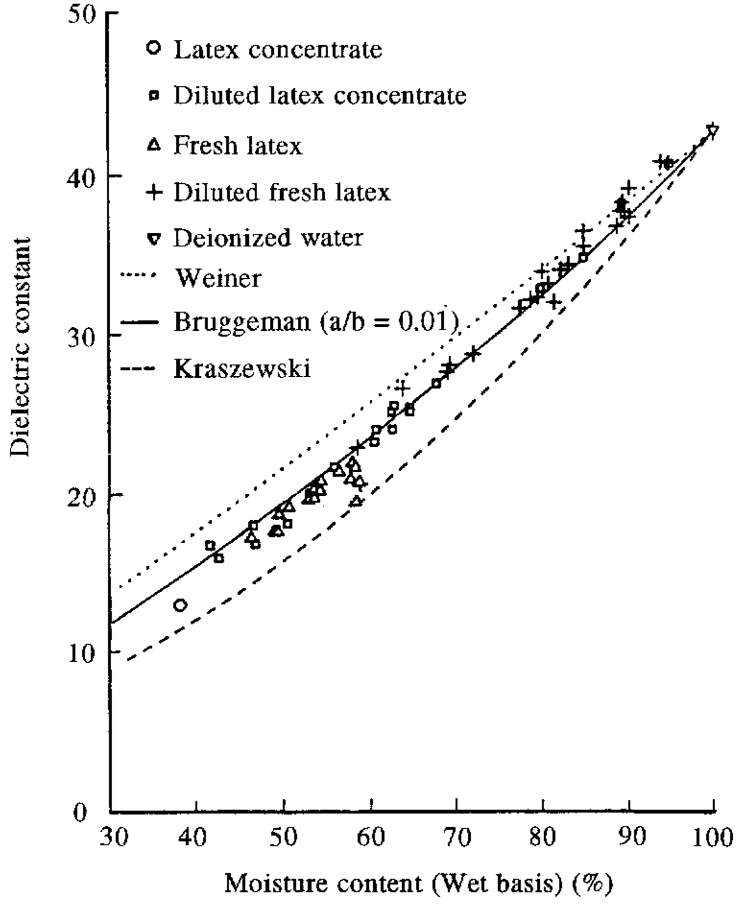

Figure 1d. Comparison of the experimental dielectric data (point marked) for Hevea *latex solutions with theoretical data calculated from mixture equations at 26°C and at frequency 18.0 GHz.*

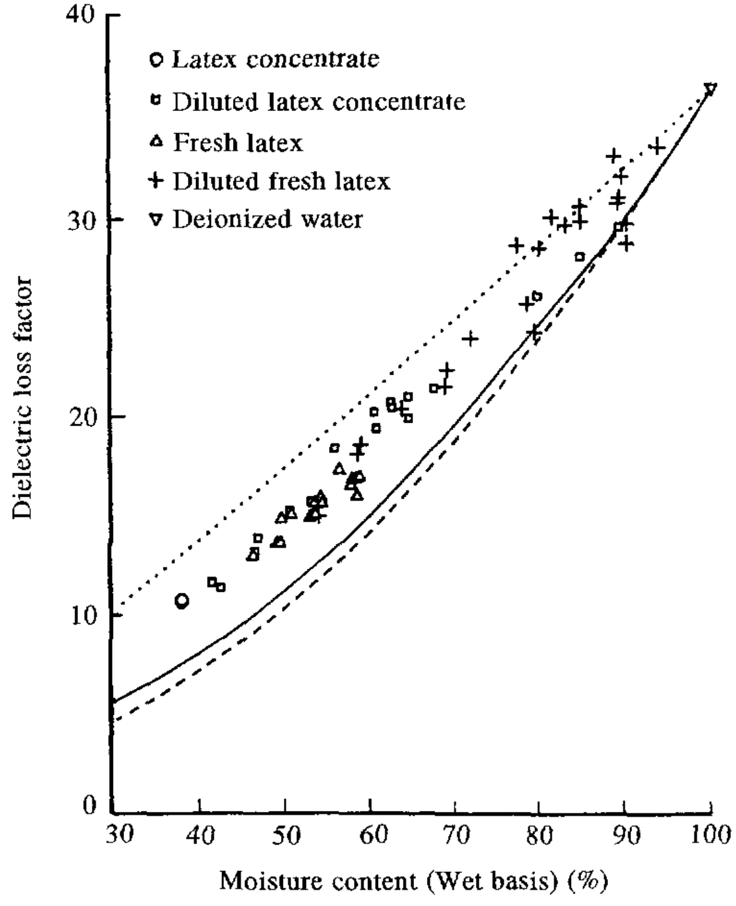

Figure 1e. Comparison of the experimental dielectric data (point marked) for Hevea *latex solutions with theoretical data calculated from mixture equations at 26°C and at frequency 18.0 GHz.*

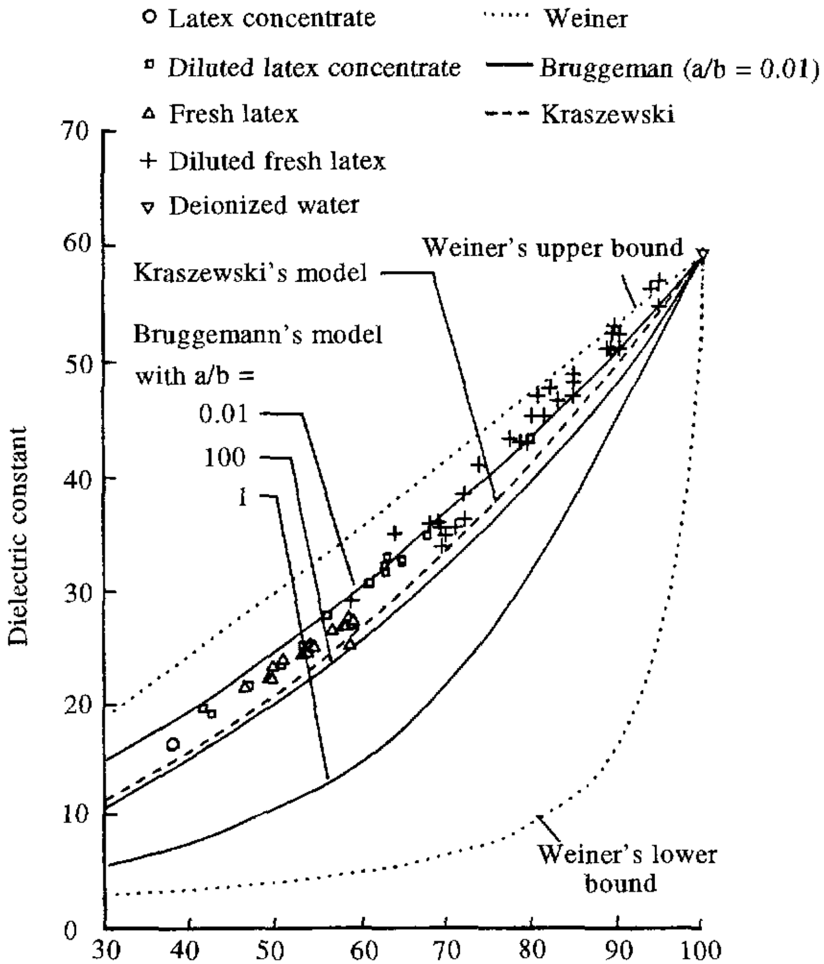

Figure 2a. Comparison of the experimental dielectric data for Hevea *latex solution with theoretical data calculated from mixture equations at 10.9 GHz and 26°C.*

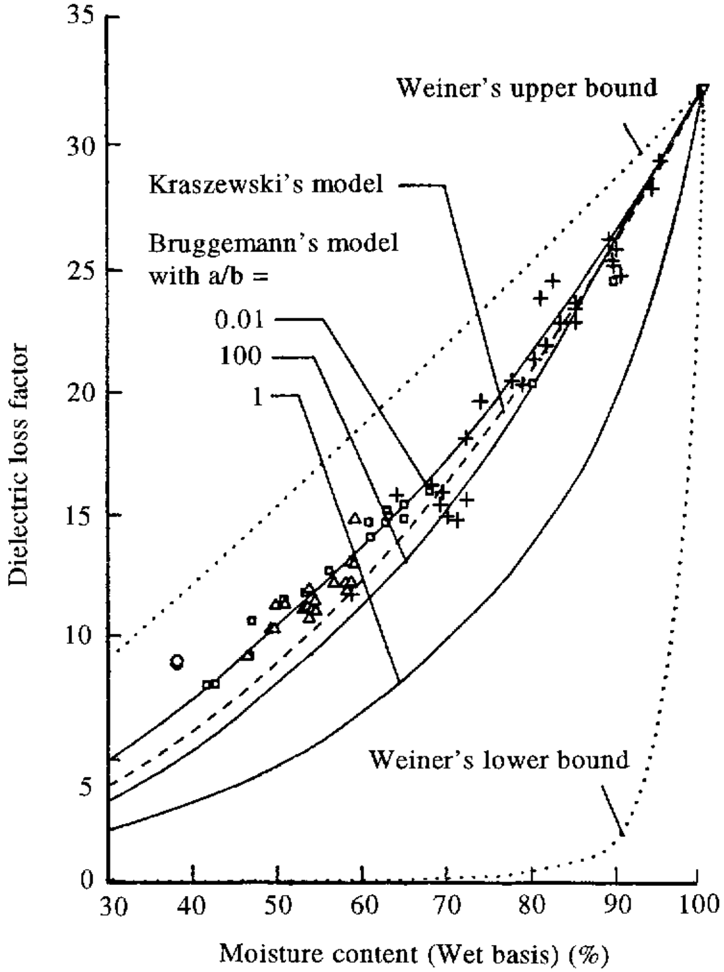

Figure 2b. Comparison of the experimental dielectric data for Hevea *latex solution with theoretical data calculated from mixture equations at 10.9 GHz and 26°C.*

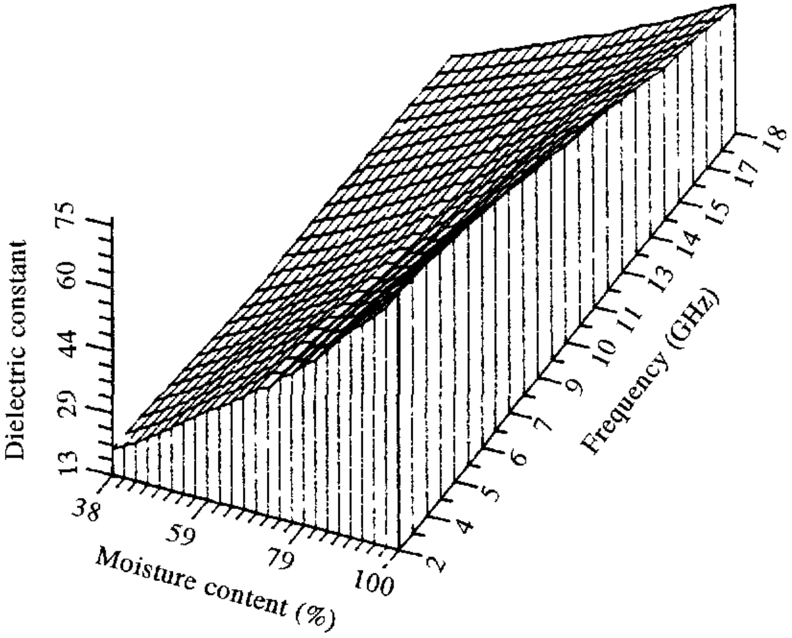

Figure 3a. Isometric plots for the experimental values of dielectric properties of Hevea l*atex as a function of moisture content over a frequency range of 2 GHz to 18 GHz and at 26°C.*

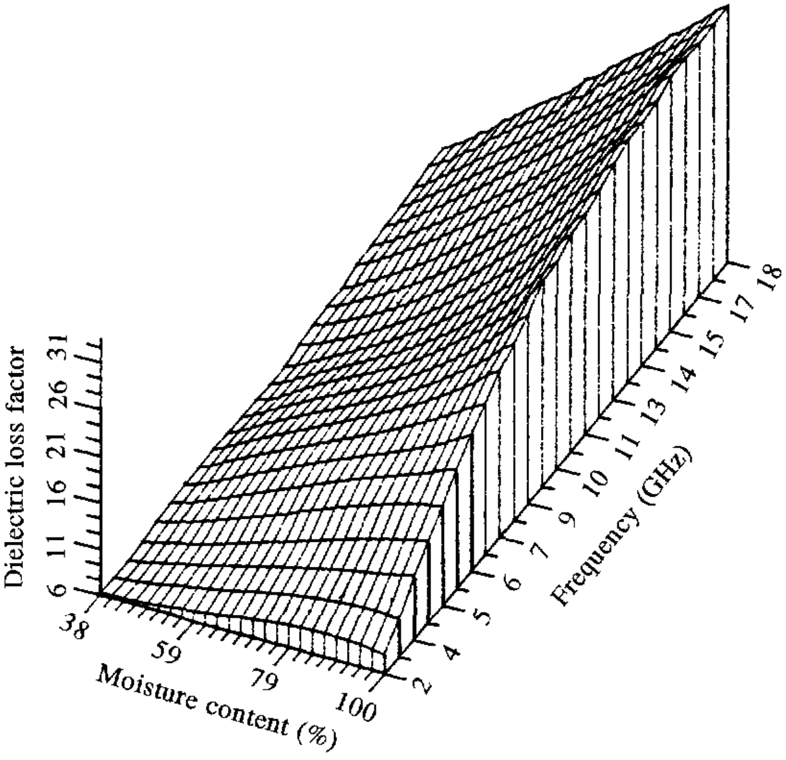

Figure 3b. Isometric plots for the experimental values of dielectric properties of Hevea *latex as a function of moisture content over a frequency range of 2 GHz to 18 GHz and at 26°C.*

TABLE 1A. COMPARISON OF PERMITTIVITIES MEASURED ON *HEVEA* LATEX AT 26°C AND VALUES ESTIMATED BY CALCULATION WITH MIXED MODELS ($\gamma_r = 0.91$ and $\gamma_w = 1.0$) AT 2.45 GHz

Moisture content, % (Wet basis)	Least square fitted experimental data		Calculation by mixed equations with $\varepsilon_w = 77.5 - j\,9.5$ and $\varepsilon_r = 2.28 - j\,0.06$					
			Bruggeman		Kraszewski		Weiner's upper bound	
	ε'	ε"	ε'	ε"	ε'	ε"	ε'	ε"
30	14.5	5.3	17.2	1.9	12.8	1.2	23.6	2.2
40	23.2	2.9	23.3	2.8	18.4	1.9	30.8	3.7
50	31.3	6.6	30.3	4.1	25.1	2.7	38.3	4.6
60	39.1	7.2	37.6	5.3	32.9	3.7	45.9	5.6
70	47.2	7.9	46.0	6.3	42.1	4.9	53.6	6.5
80	55.9	8.5	55.3	7.3	52.5	6.2	61.4	7.5
90	65.8	9.2	65.7	8.5	64.3	7.7	69.4	8.5

TABLE 1B. COMPARISON OF PERMITTIVITIES MEASURED ON *HEVEA* LATEX AT 26°C AND VALUES ESTIMATED BY CALCULATION WITH MIXED MODELS ($\gamma_r = 0.91$ and $\gamma_w = 1.0$) AT 6.9 GHz

Moisture content, % (Wet basis)	Least square fitted experimental data		Calculation by mixed equations with $\varepsilon_w = 69.3 - j\,24.6$ and $\varepsilon_r = 2.13 - j\,0.12$					
			Bruggeman a/b = 0.01		Kraszewski		Weiner's upper bound	
	ε'	ε"	ε'	ε"	ε'	ε"	ε'	ε"
30	16.4	6.0	14.9	5.4	11.6	3.0	21.1	7.0
40	20.2	8.3	20.5	8.1	16.6	4.8	27.7	9.4
50	25.4	10.4	26.5	10.8	22.6	6.9	34.3	11.9
60	32.2	12.4	33.3	13.0	30.0	9.5	41.1	14.3
70	40.2	14.5	40.8	15.4	37.8	12.5	48.0	16.8
80	49.2	17.1	48.8	18.1	47.1	16.1	55.0	19.4
90	59.2	20.2	58.7	21.3	57.6	20.1	62.0	22.0

TABLE 1C. COMPARISON OF PERMITTIVITIES MEASURED ON *HEVEA* LATEX AT 26°C AND VALUES ESTIMATED BY CALCULATION WITH MIXED MODELS ($\gamma_r = 0.91$ and $\gamma_w = 1.0$) AT 10.9 GHz

Moisture content, % (Wet basis)	Least square fitted experimental data		Calculation by mixed equations with $\varepsilon_w = 59.3 - j\,32.2$ and $\varepsilon_r = 2.19 - j\,0.02$											
			Bruggeman						Kraszewski		Weiner			
			a/b = 0.01		a/b = 100		a/b = 1				Upper bound		Lower bound	
	ε'	ε"	ε'	ε"	ε'	ε"	ε'	ε"	ε'	ε"	ε'	ε"	ε'	ε"
30	15.9	7.5	14.3	5.1	10.5	3.6	4.8	1.7	10.6	13.8	18.3	9.1	3.0	0.05
40	17.9	8.7	18.6	7.7	14.5	5.3	6.8	2.4	15.0	6.1	23.9	12.3	3.5	0.06
50	22.4	10.7	22.6	10.4	19.5	2.2	8.2	3.5	20.1	8.9	29.6	15.4	4.1	0.09
60	28.6	13.4	27.7	13.1	24.2	10.1	12.0	5.6	26.1	12.3	35.3	18.7	5.0	0.15
70	36.1	16.8	34.3	16.9	31.1	13.8	12.8	8.8	32.9	16.3	41.2	22.0	6.5	0.26
80	44.2	20.9	40.6	21.7	39.9	18.6	26.0	13.9	40.7	20.9	47.1	25.3	9.2	0.55
90	52.1	25.7	50.1	26.7	49.0	24.6	43.2	20.8	49.5	26.2	53.2	28.7	16.2	1.8

TABLE 1D. COMPARISON OF PERMITTIVITIES MEASURED ON *HEVEA* LATEX AT 26°C AND VALUES ESTIMATED BY CALCULATION WITH MIXED MODELS ($\gamma_r = 0.91$ and $\gamma_w = 1.0$) AT 13.6 GHz

Moisture content, % (Wet basis)	Least square fitted experimental data		Calculation by mixed equations with $\varepsilon_w = 52.4 - j\,35.2$ and $\varepsilon_r = 2.2 - j\,0.02$					
			Bruggeman a/b = 0.01		Kraszewski		Weiner's upper bound	
	ε'	ε"	ε'	ε"	ε'	ε"	ε'	ε"
30	13.8	6.9	14.4	4.9	9.9	4.2	18.0	9.9
40	17.1	9.3	18.2	7.7	13.7	6.7	21.3	13.3
50	21.7	12.2	22.5	10.7	18.3	9.8	26.2	16.8
60	27.3	15.7	27.3	14.5	23.5	13.5	31.3	20.3
70	33.6	19.7	32.6	18.8	29.5	17.8	36.4	23.9
80	40.5	24.3	39.0	23.0	36.3	22.8	41.6	27.5
90	47.5	29.5	45.1	28.9	43.9	28.5	47.0	31.3

TABLE 1E. COMPARISON OF PERMITTIVITIES MEASURED ON *HEVEA* RUBBER LATEX AT 26°C AND VALUES ESTIMATED BY CALCULATION WITH MIXED MODELS ($\gamma_r = 0.91$ and $\gamma_w = 1.0$) AT 18.0 GHz

Moisture content, % (Wet basis)	Least square *fitted* measured data		Calculation by mixed equations with $\varepsilon_w = 42.8 - j\,36.4$ *and* $\varepsilon_r = 2.3 - j\,0.12$					
			Bruggeman a/b = 0.01		Kraszewski		Weiner's upper bound	
	ε'	ε"	ε'	ε"	ε'	ε"	ε'	ε"
30	9.3	10.9	11.9	5.7	9.0	4.7	3.8	10.4
40	14.1	11.7	15.6	8.2	12.2	7.3	7.8	13.9
50	18.8	14.5	19.5	11.4	15.8	10.5	1.7	17.5
60	23.6	18.1	23.6	15.5	20.0	14.4	5.8	21.2
70	28.4	22.2	28.0	19.6	24.8	18.8	9.9	26.9
80	33.1	26.8	32.5	24.7	30.2	24.0	4.1	28.7
90	37.9	31.5	37.4	30.0	36.1	29.8	8.4	32.5

aligned to the electric field. It is shown that beyond 40% moisture content the degree of binding remains almost constant.

Generally the models from Kraszewiski and Bruggeman (with a/b 0.01) are suitable for predicting the dielectric properties of *Hevea* latex for a range of frequencies from 2.5 GHz to 18 GHz and with moisture content ranging from 60% to 100%. The deviation between predicted values [Bruggeman (a/b = 0.01)] and measured values are within 3%.

The experimental results suggest that in the above region of frequencies and moisture contents the dielectric properties of latex are due to the orientation of water molecule, and the shape of this molecule is prolate spheroid. Non-rubber constituents and ammonia solution do not contribute much to the dielectric properties of *Hevea* latex except at 2.45 GHz. In *Figure 1a* the experimental result for dielectric loss is higher than the predicted values based on the dipolar mechanism. These properties may be contributed by other form of loss . mechanism such as 'conduction mechanism' influenced by conducting phases in non-rubber constituents and preservative.

CONCLUSION

According to the analysis and discussion of the experimental phenomenon, some dielectric properties of *Hevea* latex in the range of 2.5 GHz to 18 GHz can be summarised as follows:

- The results of the measurement agree reasonably with predicted values from mixture models of Bruggeman and Kraszewski and below but near the Weiner's upper bound. This experimental data suggest that the dielectric behaviour in *Hevea* latex is mainly due to the orientation of water molecules.
- The polarisation and absorption properties of *Hevea* latex are related to the moisture content. The larger the moisture content, the higher the values of ε' and ε''. Although *Hevea* latex is a very complex material, there exists a good relationship between the dielectric properties and moisture content without any influence from the preservative.

The experimental data and predicted values of dielectric properties of *Hevea* latex give valuable information for the analysis and design of microwave moisture meter or dry rubber content meter, estimating microwave absorption of *Hevea* latex in microwave heating and process control in latex based industries.

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