ISSN: 0128-7680
Pertanika J. Sci. & Technol. **18 (1)**: 121– 138 (2010)

Microwave Dielectric Characterization of Hevea Rubber Latex at 2.6, 10 and 18 GHz

Jumiah Hassan*, Kaida Khalid and W. Mohd. Daud W. Yusoff
Department of Physics, Faculty of Science,
Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia
**E-mail: jumiah@fsas.upm.edu.my*

ABSTRACT

Dielectric properties of natural rubber *Hevea brasiliensis* latex were measured at frequencies 0.2 to 20 GHz, at temperatures of 2, 15, 25, 35, and 50ºC and around 30-98% moisture content. Measurements were done using open-ended coaxial line sensor and automated network analyzer. As expected, results showed that dielectric constant increased with increasing moisture. From 0.2 to 2.6 GHz, the losses were governed by conductive losses but for frequencies greater than 2.6 GHz, these were mainly due to dipolar losses. The former is due to conducting phases in hevea latex, while the latter is mainly governed by the orientation of water molecules. The results were analyzed at 2.6, 10, and 18 GHz, respectively. These were then compared with the values predicted by the dielectric mixture equations recommended by Weiner, Bruggeman and Kraszewski. All the measured values were found to be within the Weiner's boundaries and close to the upper limit of Weiner's model. It is also close to the predicted values of Bruggeman's model with *a/b* = 0.1. All the models including Kraszewski are suitable for predicting the dielectric properties of hevea latex for frequencies 2.6 to 18 GHz, moisture content 30 to 98% and temperatures 2 to 50ºC.

Keywords: Complex permittivity, dielectric loss factor, dipoles

INTRODUCTION

The dielectric properties of a material refer to the complex relative permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$, where ε' is the real relative permittivity, which is also known as the dielectric constant, whereas the imaginary part ε'' is the dielectric loss factor. The dielectric constant is a measure of the ability of the material to be polarised or energy stored, while the loss factor is a measure of the ability of the material to heat or energy loss by absorbing energy.

The samples are freshly tapped hevea latex, latex concentrate, diluted fresh hevea latex, diluted latex concentrate with moisture content (MC) varying from 40%-98% (wet basis) and deionised water. Hevea latex consists of 55%-80% water, 15%-45% rubber hydrocarbon and approximately 2%-4% non-rubber constituents (Chin, 1979). Excluding water, the most abundant non-rubber constituents are proteins, lipids, quebrachitol (methyl inositol), and inorganic salt of about 0.5%. These include potassium, phosphate ions and traces of copper, iron, sodium, calcium and magnesium (Chen, 1979). About 2%-3% conducting phases arise from these non-rubber constituents. This composition varies widely according to season, weather, soil condition, clone, tapping system, etc. The latex concentrate used was preserved with 0.025% tetramethyl-thiuram disulphide/zinc oxide and 0.2%-0.3% ammonia and supplied by the Rubber Research Institute of Malaysia (RRIM). Freshly tapped hevea latex was obtained from the Research Park of Universiti Putra Malaysia (UPM).

Received: 3 June 2008
Accepted: 8 December 2009
*Corresponding Author

Dielectric properties of hevea rubber latex at various moisture contents and temperature have been reported at microwave frequencies. Besides the water content, previous studies have shown that for the frequency range of 2 GHz to 20 GHz, the dielectric properties also depend on the geometrical shape of the water molecule which is ellipsoidal (Khalid and Yusoff, 1992; Khalid *et al*., 1994; Hassan *et al*., 1997). Below 2 GHz, the dielectric properties of latex are mainly due to the migration of dissolved ions which originate from the conducting phases in the latex (Gorton and Pendle, 1985).

In this study, hevea rubber latex is treated as a biphase liquid, where the rubber particles and the non-rubber constituents are considered as a single solid phase or solid content of hevea latex while the other is water. This biphase mixture of water and solid components is assumed to be isotropic and randomly distributed in space.

BIPHASE MIXTURE MODEL

The dielectric properties of mixtures containing two or more dielectrics are common. It is assumed that one component of the mixture forms a matrix, in which the other or several others sparsely in the form of particles, where in general their shape is taken to be ellipsoidal (Suresh *et al*., 1967). The complex permittivity of water and rubber can be written as:

$$\varepsilon^* = \varepsilon^*_w \delta_w f_w + \varepsilon^*_r \delta_r f_r \tag{1}$$

and

$$\delta_w f_w + \delta_r f_r = 1 \tag{2}$$

where $\varepsilon^*_r, \varepsilon^*_w$ are the complex relative permittivity of latex particles or solid continuum and complex relative permittivity of water molecules, respectively. Likewise, δ_w and δ_r are the volume fractions of moisture and latex particles respectively and f is the field ratio. From equations (1) and (2), the general forms for the effective complex dielectric constant in terms of the average field for the water and solid continuum can be expressed as:

$$\varepsilon^* = \varepsilon^*_r + (\varepsilon^*_w - \varepsilon^*_r)\delta_w f_w \tag{3}$$

and

$$(\varepsilon^* - \varepsilon^*_w)\delta_w f_w + (\varepsilon^* - \varepsilon^*_r)\delta_r f_r = 0 \tag{4}$$

The volume fraction δ_w is related to the moisture content by the following expression (Krazewski, 1974);

$$\delta_w = M_w \Big/ \left[M_w + \frac{\gamma_r}{\gamma_w}(1 - M_w) \right] \qquad [5]$$

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

From equations (3) and (4), the complex permittivity of the mixture can be written as:

$$\varepsilon^* = \varepsilon^*_r + \frac{(\varepsilon^*_w - \varepsilon^*_r)}{3}\delta_w \sum_l \frac{\varepsilon^*_r}{\varepsilon^*_r + (\varepsilon^*_w - \varepsilon^*_r)A_l} \tag{6}$$

where A_l is known as the depolarisation factor dependent on the axial ratios of the ellipsoid. Equation (6) was extended (Boned and Peyrelasse, 1983) for high concentrations of inclusion or high moisture content following Bruggeman's method (Bruggeman, 1935; Chaloupka *et al.*, 1980). In this method, the low concentration is gradually increased by the addition of volume fraction $d\delta = \frac{d\delta_w}{1-\delta_w}$ of the moisture content which gives an increment to the complex dielectric constant $d\varepsilon$ as:

$$d\varepsilon^* = \frac{d\delta_w}{(1-\delta_w)} \frac{\varepsilon^*_w - \varepsilon^*}{3} \varepsilon^* \sum_l \frac{1}{\varepsilon^* + (\varepsilon^*_w - \varepsilon^*)A_l} \tag{7}$$

In this process, the permittivity of the medium around a particle slowly changes from ε^*_r to the final complex permittivity of the mixture ε^*. For the case of a spheroid $b = c$, A_l depends only on the ratio a/b and $A_a + A_b + A_c = 1$. By integrating equation (7) from 0 to δ and from ε^*_r to ε^*, the following equations can be obtained for a spheroid with $a \neq b = c$,

$$(1-\delta_w) = \left(\frac{\varepsilon^*_r}{\varepsilon^*}\right)^{3d} \left(\frac{\varepsilon^*_w - \varepsilon^*}{\varepsilon^*_w - \varepsilon^*_r}\right) \left[\frac{\varepsilon^*_r(1-3A) + \varepsilon^*_w(2-3A)}{\varepsilon^*(1-3A) + \varepsilon^*_w(2-3A)}\right]^K \tag{8}$$

where, $A = A_b = A_c$, $d = \frac{1}{\sum_l A_l^{-1}} = \frac{A(1-2A)}{(2-3A)}$ and $K = \frac{2(3A-1)^2}{(2-3A)(1-3A)}$

The complex permittivity of the mixture $\varepsilon^* = \varepsilon' - j\varepsilon''$ could be obtained from equation (8) using the numerical root seeking method (Khalid, 1994).

Another analysis was developed by Weiner where the upper and lower limits of the complex permittivity can be calculated from:

$$\frac{\varepsilon^* - 1}{\varepsilon^* + n} = \delta_w \frac{\varepsilon^*_w - 1}{\varepsilon^*_w + n} + \delta_r \frac{\varepsilon^*_r - 1}{\varepsilon^*_r + n} \tag{9}$$

The mixing condition *n* provides a means of deducing the orientation assumed by the water molecules and could be used to obtain information about the degree of binding of the water molecules in the latex solution (Hassan *et al.*, 2003). According to Weiner's theory, the complex relative permittivity reaches a maximum limit, ε^*_{max} or Weiner's upper bound when $n = \infty$. This corresponds to the case where the water molecules, in the form of ellipsoids with their major axis, are parallel to the direction of the applied field. In this manner of configuration, the water molecules are said to be loosely bound and are therefore free to move or orientate. The minimum limit, ε^*_{min} or Weiner's lower bound, is obtained when $n = 0$. This is when the major axis of the ellipsoids is perpendicular to the applied field and is tightly bound. From equation (9), the following could be obtained:

$$\varepsilon^*_{\mathrm{max}} = \delta_w \varepsilon^*_w + \delta_r \varepsilon^*_r \tag{10a}$$

$$\frac{1}{\varepsilon^*_{\mathrm{min}}} = \frac{\delta_w}{\varepsilon^*_w} + \frac{\delta_r}{\varepsilon^*_r} \tag{10b}$$

The dielectric relative permittivity of the mixture is always bound by $\varepsilon^*_{\mathrm{max}}$ in the upper range and $\varepsilon^*_{\mathrm{min}}$ in the lower range. With *n* increasing, more water molecules are aligned parallel to the applied field, whereas with decreasing *n*, more water molecules are aligned perpendicular to the field.

Kraszewski *et al.* (1976) developed a simple model for a quick analysis from the relation of the propagation constant, where the complex relative permittivity of the mixture may be written as:

$$\varepsilon^{*\,1/2} = \delta_w \varepsilon^{*\,1/2}_{w} + \delta_r \varepsilon^{*\,1/2}_{r} \tag{11}$$

MATERIALS AND METHODS

Measurement of the complex relative permittivity of latex was done using 4 mm open-ended coaxial line probes (HP 85070B), coupled with automated network analyser (HP 8720B) and computer, at the frequencies of 0.2 to 20 GHz. The sensor translates changes in the permittivity of a test sample into changes in the input reflection coefficient. The system software calculates the dielectric parameters from the phase and the amplitude of the reflected signal at the interface between the open-ended coaxial line and the sample to be analyzed. With proper calibrations (Kraszewski *et al*., 1982), the accuracy of the measurement is about ± 5% for ε' and ± 3% for ε''.

A series of solutions were prepared from the latex concentrate and freshly tapped latex. These solutions were diluted with deionised water with a difference in the moisture content of about 2 to 3%. Latex concentrate registered the minimum moisture of about 38%, whilst deionised water had the maximum of 100%. Latex concentrate was supplied by the Rubber Research Institute of Malaysia and freshly tapped latex (RRIM 600 clone) was obtained from the university's research park.

The measurements were made at the temperatures of 2 to 50°C using ice bath and water bath to cool and warm the samples, respectively (Hassan *et al*., 1997). The actual moisture content (wet basis) was obtained by oven drying three 1.5 to 2.5 grams of the samples at 70°C and the average results were recorded.

RESULTS AND DISCUSSION

The experimental values of the dielectric properties of hevea rubber latex, at 2, 15, 25, 35, and 50°C, with the values predicted from the mixture equations are summarised in *Figs. 1* to *3*. Curves show the dielectric constant, ε' and the dielectric loss factor, ε'' at the frequencies of 2.6, 10 and 18 GHz, respectively. The dielectric constant and loss factor increased with increasing moisture at all frequencies, except that the loss factor is almost independent of the moisture at 2.6 GHz. This is because the total losses are dominated by conductive losses at 2.6 GHz, and by dipolar losses above 2.6 GHz. Complex permittivity of the biphase mixture model was for identical ellipsoidal particles which were randomly distributed in space. The dielectric properties of liquid do not only depend on the content of water, but they are also strongly dependent upon the geometrical shape of the water molecules (Chaloupka *et al*., 1980). The values predicted from the mixture models include Weiner's (upper and lower bound), Kraszewski and Bruggemann, with *a/b* = 0.01, 0.1 10 and 100 (Bruggeman, 1935; Boned and Peyrelasse, 1983). Both the fitted experimental data and predicted values are tabulated in Tables 1-3. From the figures shown, all the measured values lie within the Weiner's boundaries, and they are also well below and close to the upper limit of the Weiner's model. This means that the water molecules are loosely bound and they can be easily polarised.

The measured values were very close to the predicted values of Bruggeman's model with *a/b* = 0.1 (prolate spheroid) for all temperatures and frequencies, except at 50°C for 2.6, 10 and 18 GHz and 35°C for 10 GHz, where *a/b* = 10 (oblate spheroid). A better fit of Bruggeman's model to the data is given if water molecules are treated as oblate rather than prolate spheroids at 50°C.

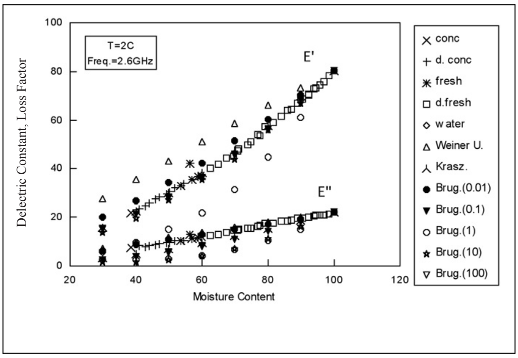

Fig. 1 (a)

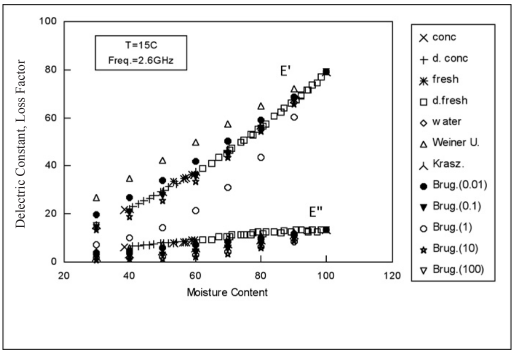

Fig. 1 (b)

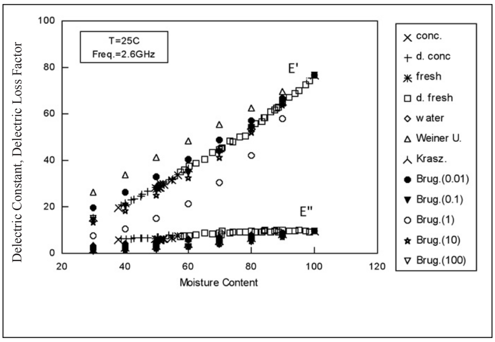

Fig. 1 (c)

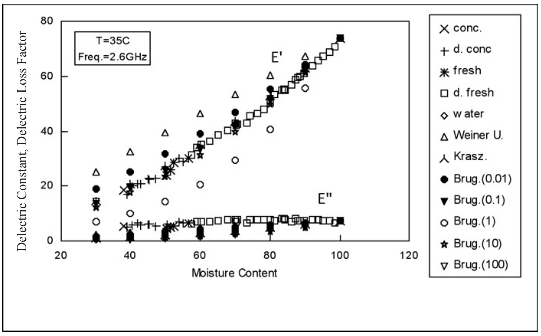

Fig. (d)

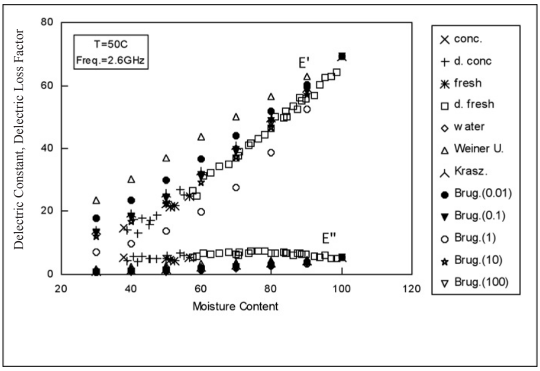

Fig. 1 (e)

Fig. 1(a-e): Experimental dielectric data for Hevea latex solution with the theoretical data calculated from the mixture equations, Weiner's upper, Bruggeman (a/b = 0.01, 0.1, 1, 10, 100) and Kraszewski at 2.6 GHz and 2, 15, 25, 35 and 50°C, respectively

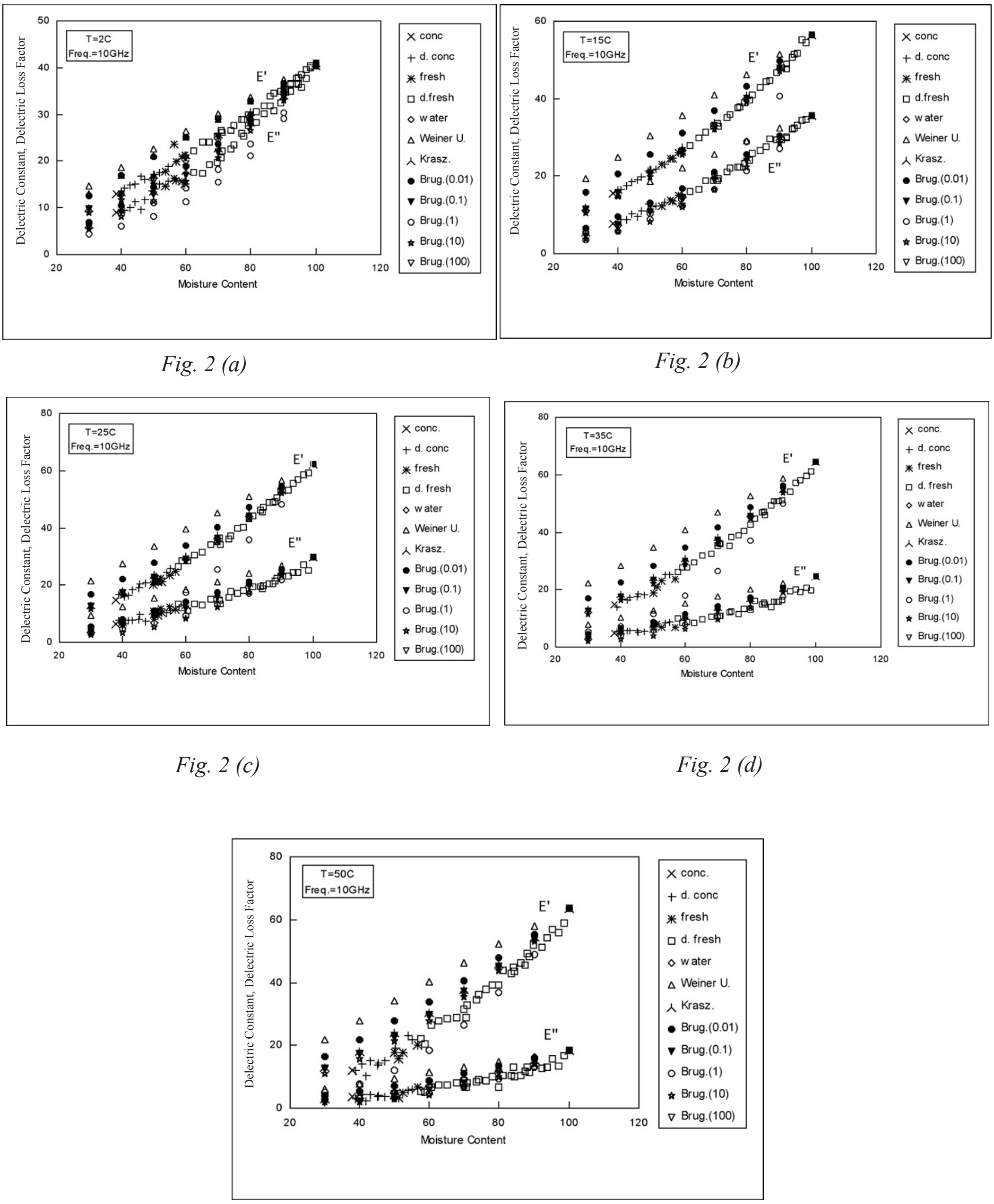

Fig. 2 (a)

Fig. 2 (b)

Fig. 2 (c)

Fig. 2 (d)

Fig. 2 (e)

Fig. 2(a-e): Experimental dielectric data for Hevea latex solution with the theoretical data calculated from the mixture equations, Weiner's upper, Bruggeman (a/b = 0.01, 0.1, 1, 10, 100) and Kraszewski at 10 GHz and 2, 15, 25, 35 and 50^{o}C, respectively

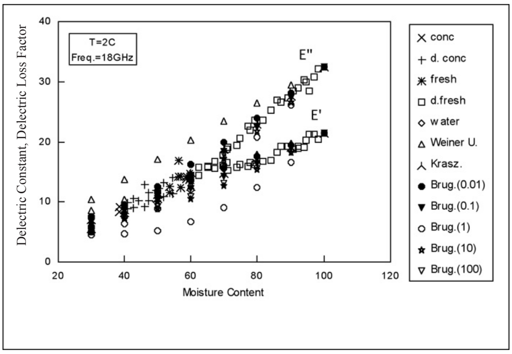

Fig. 3 (a)

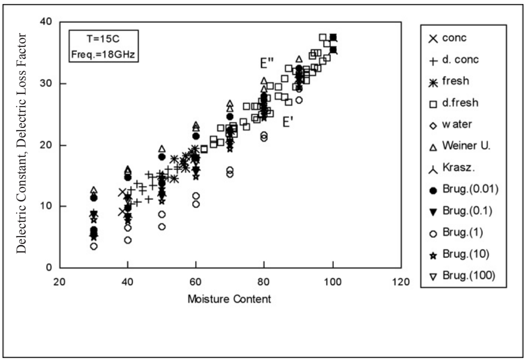

Fig. 3 (b)

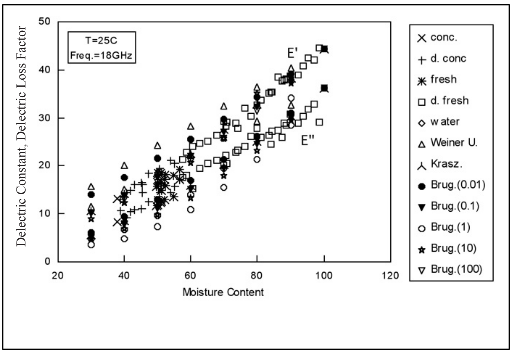

Fig. 3 (c)

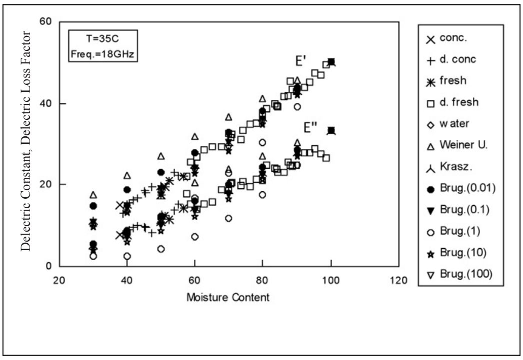

Fig. 3 (d)

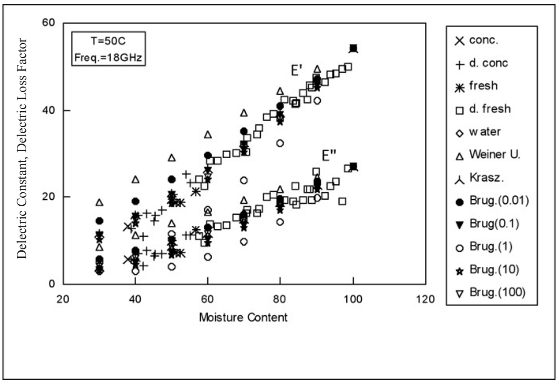

Fig. 3(e)

Fig. 3(a-e): Experimental dielectric data for Hevea latex solution with the theoretical data calculated from the mixture equations, Weiner's upper, Bruggeman (a/b = 0.01, 0.1, 1, 10, 100) and Kraszewski at 18 GHz and 2, 15, 25, 35 and 50^{o}C, respectively

TABLE 1(a)
Complex permittivities of Hevea rubber latex at 2ºC with the values estimated using the calculation from the mixed models ($\gamma w/\gamma r$ = 1.08) at 2.6 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w= 80.61-j22.31 and ε_r=2.83-j0.09															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* = 0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	17.6	5.4	20.0	6.3	15.0	2.3	5.9	2.5	13.9	1.5	15.6	2.4	16.0	3.3	27.4	7.1	4.1	0.1
40	23.3	7.6	26.8	8.5.	21.3	3.9	9.6	2.6	19.7	1.5	21.8	3.6	22.5	5.1	35.4	9.4	4.7	0.2
50	30.0	9.8	34.2	10.8	28.3	5.8	15.2	2.9	27.0	2.3	28.2	5.4	30.0	7.2	43.2	11.6	5.7	0.2
60	37.9	12.1	42.3	13.0	36.5	8.2	21.9	4.3	35.4	4.2	36.5	7.8	38.4	9.6	50.9	13.8	7.0	0.3
70	46.8	14.5	51.3	15.1	45.9	11.0	31.4	6.7	44.1	7.2	45.7	10.7	47.7	12.4	58.5	16.0	9.2	0.5
80	56.9	17.0	60.1	17.3	56.8	14.2	44.6	10.3	56.0	11.2	56.1	14.1	57.9	15.4	66.0	18.1	13.2	0.8
90	68.0	19.5	70.2	19.4	68.4	17.8	61.3	14.9	67.0	16.2	67.2	18.2	68.9	18.7	73.4	20.2	22.9	2.1

TABLE 1(b)
Complex permittivities of Hevea rubber latex at 15ºC with the values estimated using the calculation from the mixed models ($\gamma w/\gamma r$= 1.07) at 2.6 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w = 79.29-j13.42 and ε_r = 2.81-j0.2															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* = 0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	17.1	4.3	19.9	3.7	14.4	1.9	7.2	1.6	13.4	1.0	15.2	1.5	15.6	2.2	26.9	4.4	4.0	0.3
40	22.8	6.1	26.8	4.6.	20.7	2.3	10.7	1.6	18.8	1.1	20.9	1.9	22.0	3.3	34.7	5.7	4.7	0.3
50	29.5	7.8	34.1	5.7	27.7	3.1	14.4	2.1	25.6	1.2	27.6	2.7	29.3	4.5	42.3	7.0	5.6	0.4
60	37.3	9.3	42.0	7.0	35.8	4.2	21.4	3.0	33.6	2.0	35.6	3.9	37.6	6.0	49.9	8.3	6.9	0.5
70	46.1	10.7	50.2	8.4	45.0	5.8	31.1	4.4	43.4	3.5	44.7	5.4	46.8	7.6	57.4	9.6	9.0	0.7
80	56.0	11.8	59.2	9.9	55.5	7.8	43.4	6.2	54.6	5.8	55.0	7.3	56.8	9.4	64.8	10.9	12.9	1.1
90	66.9	12.8	68.9	11.6	67.1	10.3	60.2	8.5	65.8	8.8	67.4	9.5	67.6	11.3	72.1	12.2	22.3	2.1

TABLE 1(c)

Complex permittivities of Hevea rubber latex at 25ºC with the values estimated using the calculation from the mixed models ($\gamma w / \gamma r$ = 1.07) at 2.6 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w= 76.75-9.71 and ε_r=2.9-j0.08															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		a/b =0.1		a/b = 1		a/b = 10		a/b = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	15.2	4.6	19.6	2.7	14.2	1.0	7.3	1.4	13.2	1.1	14.9	0.9	15.4	1.5	26.1	3.1	4.2	0.1
40	21.3	5.7	26.1	3.7	20.2	1.3	10.4	1.6	18.5	1.5	20.4	1.1	21.6	2.3	33.6	4.1	4.8	0.1
50	28.3	6.8	33.1	4.6	27.1	1.9	15.0	2.1	24.9	2.1	26.9	1.6	28.6	3.2	41.1	5.1	5.8	0.2
60	36.1	7.7	40.6	5.6	35.0	2.8	21.4	2.9	32.4	3.0	34.6	2.5	36.6	4.2	58.4	6.0	7.1	0.2
70	44.8	8.5	48.6	6.6	43.9	3.9	30.4	4.1	41.4	4.1	43.4	3.6	45.5	5.4	55.6	7.0	9.3	0.3
80	54.3	9.1	57.3	7.6	53.9	5.4	42.3	5.7	51.9	5.5	53.3	5.1	55.1	6.7	62.8	7.9	13.2	0.5
90	64.6	9.6	66.7	8.7	65.0	7.1	57.8	7.6	63.7	7.1	64.6	6.9	65.6	8.2	69.8	8.8	22.6	1.2

TABLE 1(d)

Complex permittivities of Hevea rubber latex at 35ºC with the values estimated using the calculation from the mixed models ($\gamma w / \gamma r$= 1.07) at 2.6 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w = 73.86-j7.35 and ε_r =2.79-j0.06															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		a/b =0.1		a/b = 1		a/b = 10		a/b = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	13.4	4.4	18.8	1.7	13.6	1.0	6.9	1.0	12.5	1.2	14.3	0.6	14.8	1.1	25.1	2.4	4.2	0.1
40	19.2	5.4	25.2	2.5.	19.4	1.0	10.0	1.0	17.8	1.3	19.6	0.6	20.7	1.7	32.4	3.1	4.8	0.1
50	25.9	6.2	31.9	3.3	26.1	1.3	14.4	1.3	23.8	1.5	25.9	0.9	27.6	2.4	39.5	3.8	5.8	0.2
60	33.4	6.9	39.1	4.2	33.7	1.8	20.7	1.9	31.4	2.0	33.2	1.5	35.2	3.2	46.6	4.6	7.1	0.2
70	41.9	7.3	46.9	5.0	42.2	2.6	29.4	2.9	39.8	2.7	41.7	2.4	43.8	4.1	53.5	5.3	9.3	0.3
80	51.2	7.5	55.2	5.8	51.9	2.7	40.7	4.2	50.0	3.7	51.2	3.6	53.0	5.1	60.4	6.0	13.2	0.5
90	61.5	7.6	64.2	6.6	62.5	5.1	55.6	5.8	61.3	5.0	62.0	5.0	63.1	6.2	67.2	6.7	22.6	1.2

TABLE 1 (c)

Complex permittivities of Hevea rubber latex at 50ºC with the values estimated using the calculation from the mixed models (γ_w / γ_r = 1.06) at 2.6 Ghz.

Moisture	Fitted		Calculation by mixed equations with ε_w= 69.3-j5.23 and ε_r=2.73-j0.07															
Content, % (Wet basis)	Experimental data		Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* = 0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	8.4	6.3	17.7	0.8	12.9	0.5	6.8	0.7	12.0	1.1	13.4	0.5	14.0	0.8	23.5	1.7	3.9	0.1
40	14.6	10.3	23.6	1.0.	18.3	0.5	9.7	0.8	16.6	1.5	18.4	0.5	19.5	1.3	30.3	2.2	4.5	0.1
50	21.5	14.5	29.9	1.4	24.5	0.6	13.8	1.0	22.4	1.9	24.3	0.8	25.9	1.7	37.0	2.7	5.4	0.1
60	29.1	19.2	36.7	1.9	31.6	0.9	19.7	1.4	29.2	2.3	31.0	1.2	33.0	2.3	43.6	3.2	6.7	0.2
70	37.5	24.2	44.1	2.5	39.6	1.5	27.6	1.9	37.4	2.8	39.0	1.8	41.0	2.9	50.1	3.7	8.6	0.3
80	46.6	29.6	51.8	3.2	48.7	2.3	38.7	2.5	46.7	3.4	47.8	2.5	49.7	3.6	56.6	4.2	12.3	0.4
90	56.5	35.3	60.3	4.1	58.6	3.3	52.6	3.3	57.3	3.9	58.3	3.4	59.2	4.4	63.0	4.7	20.9	0.8

TABLE 2(a)

Complex permittivities of Hevea rubber latex at 2ºC with the values estimated using the calculation from the mixed models (γ_w / γ_r = 1.08) at 10 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w= 41.0-j40.4 and ε_r =2.6-j0.29															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* =0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	10.5	7.6	12.6	6.9	9.8	5.9	6.6	4.3	9.0	5.5	9.6	5.9	10.1	6.5	14.7	13.0	3.7	0.5
40	13.7	9.7	16.9	10.5.	13.0	9.0	8.6	6.0	11.8	8.1	12.3	9.0	13.4	9.7	18.7	17.1	4.3	0.6
50	17.2	12.7	21.0	14.5	16.6	12.7	11.0	8.2	15.1	11.5	15.7	12.7	17.2	13.6	22.5	21.1	5.2	0.7
60	21.1	16.6	25.1	18.8	20.7	17.0	14.2	11.3	19.1	15.7	19.6	17.0	21.3	18.0	26.3	25.1	6.4	1.0
70	25.5	21.3	29.0	23.6	25.1	21.9	18.3	15.5	23.6	20.7	24.1	21.9	25.7	22.8	30.1	29.0	8.3	1.5
80	30.3	26.9	32.9	28.8	30.0	27.5	23.6	21.2	28.7	26.5	29.1	27.3	30.5	28.2	33.8	32.8	11.7	2.6
90	35.4	33.4	36.7	34.3	35.2	33.6	30.4	29.1	34.4	33.1	34.8	33.4	35.6	34.1	37.4	36.6	19.4	6.2

TABLE 2(b)

Complex permittivities of Hevea rubber latex at 15ºC with the values estimated using the calculation from mixed models (γ_w / γ_r= 1.07) at 10 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w= 56.55-j35.78 and ε_r =2.45-j0.3															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* =0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	12.7	6.4	15.8	6.5	11.4	4.5	5.2	3.4	10.6	3.9	11.6	4.9	12.0	5.5	19.5	11.5	3.5	0.5
40	16.5	8.6	20.6	9.6.	15.8	7.2	7.4	5.7	14.8	5.7	15.5	7.6	16.5	8.4	25.0	15.1	4.1	0.5
50	21.1	11.5	25.7	13.1	20.9	10.4	10.4	8.7	19.8	8.4	20.3	10.8	21.7	11.8	30.4	18.6	4.9	0.7
60	26.5	15.0	31.1	16.9	26.7	14.3	14.6	12.3	25.6	12.1	25.8	14.7	27.6	15.7	35.8	22.2	6.0	0.9
70	32.7	19.2	36.9	21.1	33.1	18.8	20.5	16.6	32.1	16.7	32.3	19.0	34.0	20.0	41.1	25.6	7.9	1.3
80	39.7	24.1	43.1	25.6	40.2	23.9	28.9	21.5	39.3	22.2	39.5	24.0	41.0	24.8	46.3	29.1	11.2	2.0
90	47.5	29.6	49.7	30.4	48.0	29.6	40.7	27.0	47.3	28.7	47.6	29.5	48.5	30.1	51.5	32.4	19.2	4.6

TABLE 2(c)

Complex permittivities of Hevea rubber latex at 25ºC with the values estimated using the calculation from the mixed models (γ_w / γ_r = 1.07) at 10 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w= 76.75-9.71 and ε_r=2.9-j0.08															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* =0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	11.9	6.2	16.9	5.3	12.5	3.4	5.4	3.1	11.7	2.6	12.6	3.9	13.1	4.6	21.4	9.5	3.8	0.3
40	16.3	7.6	22.1	7.9	17.3	5.7	7.2	4.5	16.5	3.5	17.0	6.0	18.1	6.9	27.5	12.5	4.5	0.4
50	21.6	9.6	27.8	10.8	22.9	8.4	11.2	6.7	22.1	5.4	22.4	8.6	23.9	9.7	33.5	15.5	5.3	0.5
60	27.8	12.1	33.9	14.0	29.2	11.7	17.3	9.4	28.4	8.3	28.6	11.7	30.3	13.0	39.4	18.4	6.6	0.7
70	34.9	15.2	40.3	17.5	36.3	15.4	25.5	12.9	35.6	12.3	35.7	15.3	37.4	16.6	45.3	21.3	8.6	0.9
80	42.9	18.7	47.2	21.2	44.2	19.7	35.7	17.0	43.5	17.4	43.7	19.4	45.1	20.6	51.0	24.1	12.2	1.6
90	51.8	22.7	54.5	25.3	52.9	24.4	48.1	21.8	52.2	23.4	52.6	24.1	53.4	25.0	56.7	26.9	20.7	3.7

TABLE 2(d)

Complex permittivities of Hevea rubber latex at 35ºC with the values estimated using the calculation from the mixed models (γ_w / γ_r = 1.07) at 10 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w = 64.5-j24.6 and ε_r=2.63-j0.27															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* =0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	11.2	5.1	17.0	4.7	12.6	2.8	5.4	2.8	11.7	2.1	12.8	3.2	13.3	3.9	22.1	7.9	3.8	0.4
40	15.5	5.6	22.5	6.7	17.6	4.5	7.4	4.0	16.6	2.6	17.4	4.9	18.5	5.9	28.4	10.4	4.4	0.5
50	20.9	6.8	28.4	8.9	23.4	6.7	11.6	5.6	22.3	4.0	22.9	7.1	24.4	8.2	34.6	12.8	5.2	0.6
60	27.3	8.5	34.8	11.5	30.0	9.3	17.9	7.8	28.9	6.4	29.4	9.6	31.1	10.9	40.7	15.3	6.5	0.8
70	34.7	10.9	41.6	14.3	37.4	12.5	26.4	10.6	36.4	9.7	36.8	12.6	38.5	13.8	46.8	17.6	8.4	1.1
80	43.2	13.9	48.8	17.4	45.6	16.0	37.0	13.8	44.7	14.0	45.1	16.0	46.5	17.1	52.8	20.0	11.9	1.7
90	52.6	17.5	56.4	20.8	54.6	20.1	49.8	17.6	53.9	19.1	54.4	19.8	55.2	20.7	58.7	22.3	20.4	3.6

TABLE 2(e)

Complex permittivities of Hevea rubber latex at 50ºC with the values estimated using the calculation from the mixed models (γ_w / γ_r = 1.06) at 10 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w= 63.79-j18.27 and ε_r =2.61-j0.2															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* = 0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	8.1	3.4	16.4	4.0	12.4	1.6	5.2	2.8	11.1	2.0	12.6	1.8	13.0	2.9	21.7	5.8	3.7	0.3
40	12.2	3.7	21.8	5.3.	17.4	2.4	7.6	2.9	15.8	2.0	17.2	3.0	18.1	4.3	27.9	7.7	4.3	0.4
50	17.5	4.5	27.7	6.9	23.2	3.7	12.0	3.5	21.4	2.8	22.6	4.6	24.0	6.0	34.1	9.5	5.2	0.4
60	24.0	5.8	34.0	8.8	29.8	5.6	18.3	4.7	28.0	4.4	29.0	6.5	30.6	8.0	40.2	11.3	6.4	0.6
70	31.6	7.7	40.7	11.0	37.1	8.0	26.6	6.7	35.4	6.8	36.3	8.8	37.9	10.2	46.2	13.1	8.3	0.8
80	40.4	10.0	47.8	13.4	45.2	11.0	36.8	9.5	43.8	10.0	44.5	11.5	45.9	12.7	52.1	14.8	11.7	1.2
90	50.3	12.8	55.4	16.1	54.0	14.5	49.0	13.0	53.2	13.9	53.7	14.5	54.5	15.4	58.0	16.6	20.0	2.6

TABLE 3(a)

Complex permittivities of Hevea rubber latex at 2ºC with the values estimated using the calculation from the mixed models ($\gamma_w / \gamma_r = 1.08$) at 18 GHz

Moisture	Fitted		Calculation by mixed equations with $\varepsilon_w = 21.51\text{-}j32.59$ and $\varepsilon_r = 2.47\text{-}j0.18$																	
Content, % (Wet basis)	Experimental data		Bruggeman										Kraszewski		Weiner's					
			a/b = 0.01		*a/b* = 0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound			
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''		
30	7.9	6.1	7.5	5.9	6.9	5.3	5.1	4.6	6.4	4.9	6.6	5.1	7.0	5.5	8.5	10.4	3.5	0.3		
40	9.7	8.6	9.6	9.2	8.5	7.9	5.1	6.4	7.4	7.2	7.7	7.6	8.7	8.2	10.4	13.7	4.1	0.4		
50	11.6	11.6	11.6	12.6	10.3	11.0	5.2	8.9	8.8	10.1	9.2	10.6	10.6	11.3	12.4	17.0	4.9	0.6		
60	13.4	14.9	13.6	16.2	12.2	14.5	6.7	12.1	10.6	13.4	11.0	14.1	12.6	14.8	14.2	20.2	6.0	0.9		
70	15.3	18.7	15.6	20.0	14.2	18.4	9.1	16.1	12.8	17.3	13.1	18.0	14.7	18.7	16.1	23.4	7.8	1.5		
80	17.2	23.0	17.5	24.0	16.5	22.7	12.4	20.7	15.4	21.7	15.5	22.4	16.9	23.0	17.9	26.5	10.7	2.8		
90	19.1	27.7	19.4	28.1	18.9	27.4	16.6	26.1	18.3	26.7	18.3	27.2	19.1	27.6	19.7	29.6	16.6	7.3		

TABLE 3(b)

Complex permittivities of Hevea rubber latex at 15ºC with the values estimated using the calculation from the mixed models ($\gamma_w / \gamma_r = 1.07$) at 18 GHz

Moisture	Fitted		Calculation by mixed equations with $\varepsilon_w = 35.45\text{-}j37.55$ and $\varepsilon_r = 2.4\text{ -}j0.17$															
Content, % (Wet basis)	Experimental data		Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		*a/b* 0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	11.1	6.0	11.4	6.2	8.7	5.5	5.5	3.6	7.9	5.1	8.6	5.3	9.0	5.8	12.8	11.9	3.4	0.3
40	13.1	10.0	14.7	9.8.	11.4	8.4	6.6	4.5	10.1	7.6	10.9	8.1	11.9	8.9	16.2	15.7	4.0	0.4
50	15.5	14.1	18.1	13.7	14.5	11.8	8.7	6.7	12.9	10.9	13.7	11.6	15.1	12.5	19.5	19.5	4.8	0.5
60	18.4	18.4	21.4	17.9	17.9	15.9	11.8	10.3	16.2	14.8	17.0	15.6	18.6	16.5	22.8	23.2	5.9	0.7
70	21.8	12.9	24.7	22.4	21.7	20.4	15.9	15.3	20.1	19.5	20.8	20.2	22.4	21.1	26.0	26.9	7.7	1.1
80	25.7	27.6	27.9	27.3	25.9	25.6	21.1	21.6	24.5	24.9	25.2	25.4	26.5	26.1	29.2	30.5	10.8	2.1
90	30.0	32.4	31.1	32.5	30.4	31.3	27.2	29.2	29.5	31.0	30.0	31.1	30.8	31.6	32.3	34.0	17.9	5.5

TABLE 3(c)

Complex permittivities of Hevea rubber latex at 25°C with the values estimated using the calculation from the mixed models (γ_w/γ_r= 1.07) at 18 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w= 44-j36.16 and ε_r=2.66-j0.16															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		a/b =0.1		a/b = 1		a/b = 10		a/b = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	9.9	5.9	14.1	6.1	10.2	5.0	4.9	3.5	9.0	4.7	9.9	5.2	10.6	5.6	15.8	11.5	3.8	0.3
40	13.7	9.7	17.7	9.4	13.7	7.8	6.6	4.8	12.4	6.8	13.0	7.9	14.2	8.5	20.0	15.1	4.4	0.4
50	18.0	13.6	21.5	13.0	17.7	11.1	9.7	7.3	16.3	9.7	16.6	11.2	18.2	11.9	24.2	18.8	5.3	0.5
60	22.6	17.5	25.5	17.0	22.1	15.0	13.9	10.8	20.7	13.5	20.9	15.1	22.7	15.9	28.4	22.3	6.5	0.7
70	27.6	21.4	29.8	21.3	26.9	19.4	19.4	15.5	25.7	18.0	25.8	19.5	27.6	20.3	32.5	25.9	8.4	1.0
80	33.0	25.3	34.3	26.0	32.2	24.5	26.2	21.4	35.2	23.3	31.3	24.5	32.8	25.1	36.5	29.3	11.9	1.9
90	38.8	29.2	39.1	31.0	38.0	30.1	34.1	28.4	37.3	29.5	37.5	30.0	38.4	30.4	40.5	32.8	19.8	5.0

TABLE 3(d)

Complex permittivities of Hevea rubber latex at 35°C with the values estimated using the calculation from the mixed models (γ_w/γ_r = 1.07) at 18 GHz

Moisture Content, % (Wet basis)	Fitted Experimental data		Calculation by mixed equations with ε_w= 50.33-j33.43 and ε_r=2.58-j0.2															
			Bruggeman										Kraszewski		Weiner's			
			a/b = 0.01		a/b =0.1		a/b = 1		a/b = 10		a/b = 100				Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
30	10.2	5.2	14.9	5.6	10.8	4.6	5.4	2.5	9.8	4.1	10.8	4.7	11.3	5.2	17.6	10.6	3.7	0.3
40	15.0	8.5	18.8	8.9	14.9	7.0	7.9	2.6	13.4	6.0	14.2	7.2	15.3	7.8	22.5	14.0	4.3	0.4
50	20.1	11.9	23.2	12.4	19.2	10.0	11.7	4.2	17.7	8.8	18.4	10.2	20.0	11.0	27.3	17.4	5.1	0.5
60	25.5	15.3	27.9	16.1	24.2	13.6	16.7	7.2	22.8	12.2	23.4	13.8	25.1	14.6	32.0	20.7	6.3	0.7
70	31.3	18.8	32.9	20.1	30.3	17.7	23.0	11.7	28.5	16.5	29.0	17.9	30.7	18.7	36.7	23.9	8.2	1.0
80	37.3	22.4	38.3	24.3	36.1	22.4	30.5	17.6	35.0	21.4	35.4	22.5	36.8	23.2	41.3	27.1	11.6	1.8
90	43.6	26.0	44.1	28.8	42.8	27.6	39.2	25.0	42.1	27.2	42.4	27.6	43.3	28.1	45.8	30.3	19.5	4.4

TABLE 3(e)

Complex permittivities of Hevea rubber latex at 50ºC with the values estimated using the calculation from the mixed models ($\gamma_w / \gamma_r = 1.06$) at 18 GHz

Moisture	Fitted		Calculation by mixed equations with ε_w = 54.37-j27.07 and ε_r =2.62-j0.16																
Content, % (Wet basis)	Experimental data						Bruggeman								Kraszewski		Weiner's			
			a/b = 0.01		*a/b* =0.1		*a/b* = 1		*a/b* = 10		*a/b* = 100						Upper bound		Lower bound	
	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''			ε'	ε''	ε'	ε''	ε'	ε''
30	6.7	1.8	14.5	5.8	11.3	3.3	5.0	3.1	10.2	3.1	11.1	4.0			11.8	4.1	18.8	8.6	3.7	0.3
40	13.0	5.4	19.2	7.8	15.6	5.1	7.5	3.0	14.0	4.6	14.8	6.1			16.1	6.3	24.0	11.3	4.3	0.3
50	19.5	9.0	24.2	10.2	20.6	7.4	11.5	4.1	18.7	6.8	19.3	8.6			24.0	21.1	29.2	14.0	5.2	0.4
60	26.0	12.4	29.5	13.0	26.1	10.2	17.0	6.3	24.1	9.6	24.7	11.5			26.7	11.8	34.4	16.7	6.4	0.6
70	32.6	15.7	35.1	16.1	32.2	13.6	23.9	9.7	30.4	13.0	30.9	14.7			32.8	15.1	39.5	19.3	8.3	0.8
80	39.2	18.9	41.0	19.7	39.0	17.6	32.4	14.2	37.5	17.1	37.9	18.3			39.5	18.7	44.5	21.9	11.7	1.2
90	45.9	22.0	47.3	23.6	46.3	22.1	42.3	20.0	45.3	21.9	45.7	22.3			46.7	22.7	49.5	24.5	19.6	3.5

Generally, the mixture models from Kraszewski and Bruggeman are suitable for predicting the dielectric properties of hevea latex for frequencies 2.6 to 18 GHz, moisture content of 30 to 98% and temperatures of 2 to 50°C.

CONCLUSION

Dielectric properties of natural rubber *Hevea brasiliensis* latex were measured at microwave frequencies from 0.2 to 20 GHz. The dielectric constant was found to increase with increasing moisture. The losses are governed by conductive losses for frequencies of up to 2.6 GHz and by dipolar losses for frequencies greater than 2.6 GHz. The conductive losses are due to the conducting phases which arise from the non-rubber constituents in hevea latex, while the dipolar losses are mainly governed by the orientation of the water molecules or dipoles. The biphase mixture model from Weiner, Kraszewski and Bruggeman (a/b = 0.1) are therefore suitable for predicting the dielectric properties of hevea latex. All the measured values lie within the Weiner's boundaries and are close to the upper limit of the Weiner's model. This suggests that the water molecules are loosely bound and they can be easily polarised.

ACKNOWLEDGEMENTS

This work was supported by Universiti Putra Malaysia (UPM) through a short term research grant (50205-93-14). The authors wish to thank the technical staff, En. Roslim Mohd. at the Applied Electromagnetic Laboratory, Department of Physics for his invaluable help. The authors would also like to thank the Rubber Research Institute of Malaysia and the University Research Park of UPM for supplying the latex.

REFERENCES

Boned, C. and Peyrelasse, J. (1983). Some comments on the complex permittivity of ellipsoids dispersed in continuum media. *Journal of Physics D: Appllied Physics, 16*, 1777-1784.

Bruggeman, D.A.G. (1935). Dielektrizitatskonstanten und Leitfahigkeiten Der Mischkorper aus Isotropen Substanzen. *Ann. Phys. Lpz, 24*(5), 636.

Chaloupka, H., Ostwald, O. and Schiek, B. (1980). Structure independent microwave moisture measurements. *Journal of Microwave Power, 15*(4), 221.

Chen, S.F. (1979). *Composition of Hevea Latex*. *Training Manual on Analytical Chemistry*. Kuala Lumpur: Rubber Research Institute of Malaysia.

Chin, H.C. (1979). *Methods for measuring the dry rubber content of field latex*. *Training Manual on Analytical Chemistry*. Kuala Lumpur: Rubber Research Institute of Malaysia.

Gorton, A.D.T. and Pendle, T.D. (1985). The use of electrical conductimetry in the examination of natural rubber lattices. *Natural Rubber Technology, 16*(3), 45-51.

Hassan, J., Khalid, K. and W.Yusoff, W.M.D. (1997). Microwave dielectric properties of hevea rubber latex in the temperature range of -30°C to 50°C. *Pertanika Journal of Science & Tech*nology, *5*(2), 179-190.

Hassan, J., Khalid, K. and W. Yusoff, W.M.D. (2003). Microwave measurement on the degree of binding of water in hevea rubber latex. *Journal of Rubber Research, 6*(2), 94-106.

Khalid, K. and W. Yusoff, W.M.D. (1992). Dielectric properties of natural rubber latex at frequencies from 200 MHz to 2500 MHz. *Journal of Naturtal Rubber Research, 7*(4), 281-289.

Khalid, K., Hassan, J. and W. Yusoff, W.M.D. (1994). Dielectric properties of hevea rubber latex at various moisture content. *Journal of Natural Rubber Research, 9*(3), 172-189.

Krazewski, A. (1974). Determination of the strength of water suspension using microwave technique. *Journal of Microwave Power, 9*, 295.

Kraszewski, A., Kulinski, S. and Matuszewski, M. (1976). Dielectric properties and a model of biphase water suspension at 9.4 GHz. *Journal of Appllied Physics, 47*, 1275-1277.

Kraszewski, A., Stuchly, M.A. and Stuchly, S.S. (1982). ANA calibration method for measurements of dielectric properties. *IEEE Trans., IM-32*, 385-387.

Suresh, N., Callaghan, J.C. and Creelman, A.E. (1967). Microwave measurement of the degree of water absorbed in soils. *Journal of Microwave Power, 2*(4), 129-137.