Progress In Electromagnetics Research, Vol. 129, 559–578, 2012

THE USE OF DIELECTRIC MIXTURE EQUATIONS TO ANALYZE THE DIELECTRIC PROPERTIES OF A MIXTURE OF RUBBER TIRE DUST AND RICE HUSKS IN A MICROWAVE ABSORBER

E. M. Cheng[1, *], F. Malek[2], M. Ahmed[3], K. Y. You[4], K. Y. Lee[5], and H. Nornikman[3]

[1]School of Mechatronic Engineering, Univerisiti Malaysia Perlis (UniMAP), Pauh Putra Campus, Arau, Perlis 02600, Malaysia

[2]School of Electrical Systems Engineering, Univerisiti Malaysia Perlis (UniMAP), Pauh Putra Campus, Arau, Perlis 02600, Malaysia

[3]School of Computer and Communication Engineering, Univerisiti Malaysia Perlis (UniMAP), Pauh Putra Campus, Arau, Perlis 02600, Malaysia

[4]Radio Communication Engineering Department (RaCED), Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Skudai, Johor 81310, Malaysia

[5]Department of Electrical and Electronic Engineering, Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Setapak, Kuala Lumpur 53300, Malaysia

Abstract—A change in the relative proportions of a mixture of rubber tire dust and rice husks will cause a change in the mixture's electrical permittivity and its ability to absorb electromagnetic energy. An open-ended coaxial probe was used in conjunction with three dielectric mixture equations (the Kraszewski equation, the Landau equation and the Lichtenecker equation) to obtain the dielectric properties of a mixture of rubber tire dust and rice husks (RTDRH) over the frequency range of 7 GHz to 13 GHz. Lichtenecker's equation for dielectrics proved to be a useful practical formulation for determining the effective permittivity of homogeneous dielectric mixtures. The effectiveness of these dielectric mixture equations in determining the effective permittivity of RTDRH was investigated in this study. A newly developed mixture equation was derived based on these dielectric

Received 3 May 2012, Accepted 2 July 2012, Scheduled 13 July 2012

* Corresponding author: Ee Meng Cheng (emcheng@unimap.edu.my).

mixture equations, and it and the existing equations were assessed to determine their effectiveness in determining dielectric properties of such mixtures.

1. INTRODUCTION

The microwave absorber is a very important device in antenna measurements as well as in telecommunications research laboratories and military research laboratories [1–6]. Microwave absorbers are used to eliminate reflected signals to avoid any ambiguous signals that could scramble experimental measurements in a finite-space laboratory. Typically, microwave absorbers are made of synthetic magnetic material, such as ferrite [7], which is poisonous and costly. However, the RTDRH microwave absorber has been developed recently [8]. As shown in Figure 1, the RTDRH absorber used in this study was fabricated by mixing rubber tire dust (industrial waste) and rice husks (agricultural waste) by using a hardeneing agent. Information about the permittivity of a material is very important in the design of microwave absorber because the permittivity of a material is a parameter in determining its ability of to absorb an electric field [9–14]. Thus, many researchers have proposed various mechanisms and models to describe the permittivity of a material.

In this work, we were interested only in studying the permittivity of a mixture of materials. As is well known, there are three kinds of mixture models that describe a solid mixture of materials, i.e., Kraszewski's equation [15], Landau's equation [16] and Lichtenecker's equation [17–21]. However, these equations have been regarded generally to be semi-empirical in nature and to have no firm, practical justification for use in evaluating a wide range of mixtures. These mixture equations produce inconsistent results when there are significant differences between the dielectric permittivities of the

Figure 1. Rice husks and rubber tire dust.

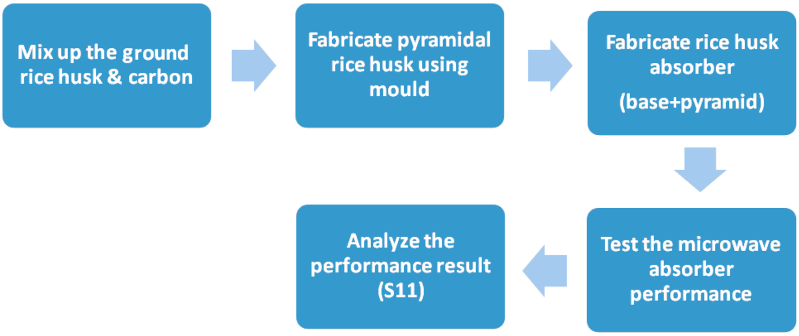


Figure 2. Development of rubber tire dust-rice husk, pyramidal microwave absorber.

individual constituents in the mixture. In this study, the three mixture models were re-examined in order to model the permittivity properties of an RTDRH absorber. Measurements were made to determine and compare the permittivities of complex mixtures [22], and the permittivities of these mixtures also were predicted using the existing and newly-developed equations [23].

2. METHODOLOGY

Figure 2 illustrate the flow of methodology for development of the pyramidal microwave absorber. The base of the pyramidal absorber was made of a combination of rice husks are added to rubber tire dust (carbon black); polyester was used as a bonding agent, and methyl ethyl ketone peroxide (MEKP) was used as a hardener agent. The purpose for the application of resin (polyester) was to bind together the particles and layers of the two constituents, one being an industrial waste and the other being an agricultural waste. The mixture was fabricated into a pyramidal shape with a square base. Methods of preparation and construction of the RTDRH absorber are similar as shown in [8] and [25], respectively. Figure 3 shows the mixture, which consisted of 75 percent rubber tire dust and 25 percent rice husks.

The relative effective permittivity, ε_r, of the RTDRH absorber was measured using a commercial dielectric probe with a P-series Network Analyzer (PNA) over the range of 7 GHz to 13 GHz, as shown in Figure 4. Microwave absorbers with various ratios of rubber tire dust to rice husks were prepared and the mixtures were measured by the setup describe earlier.

At microwave frequencies, different measurement techniques can

Figure 3. Mixture of 75 percent rubber tire dust and 25 percent rice husks.

Figure 4. Defining the dielectric constant (real part, ε_r', and imaginary part, ε_r'') of the pyramidal microwave absorber using a dielectric probe.

be used, including the free-space-measurement technique, the resonant-cavity technique, the transmission-line technique, and the dielectric-probe technique [22]. Before measurements were conducted, the devices were calibrated. Three calibration media, i.e., a short block of metal (short), water (match), and air (open) were used in the calibration procedure. Precautions must be considered to avoid the possibility of systematic errors, which could cause severe discrepancies in the phase measurements.

3. DIELECTRIC MIXTURE MODEL

A dielectric mixture model is used commonly for calculating complex permittivity. The fractional volume and the permittivity of each constituent are the main parameters used in calculating the effective permittivity of the mixture. Four equations were proven to be applicable to the experimental data in our prescreening analyses. The suggested dielectric mixture equations were found in references [18, 20, 23], and they are presented below:

Kraszewski equation:

$$\sqrt{\varepsilon *} = \sum_{i=1}^{n} v_i \sqrt{\varepsilon_i} \tag{1}$$

Landau, Lifshitz, and Looyenga (Landau equation):

$$\sqrt[3]{\varepsilon *} = \sum_{i}^{n} v_i \sqrt[3]{\varepsilon_i} \tag{2}$$

Lichtenecker equation:

$$\ln \varepsilon * = \sum_{i}^{n} v_i \ln \varepsilon_i \tag{3}$$

where v_{i} = volume fraction of the ith constituent

ε_i = permittivity of the ith constituent

n = number of constituents in the sample

total volume fraction, $\sum_{i}^{n} v_i = 1$.

The fabricated sample was considered as a mixture of solids, i.e., rubber tire dust and rice husk. In the above equations, the complex permittivity of rubber tire dust and rice husks varies with frequency as shown in the next section. The mixture will never be truly dense. Therefore, air voids should be available. However, the air voids were ignored here because the sample mixture was compressed before the hardener and bonding agent (i.e., polyester and MEKP, respectively) were applied, to minimize the air voids in the mixture. We also ignored the polyester and MEKP used in this work, because the amounts used were insignificant compared to the amounts of rubber tire dust and rice husks that were used.

4. RESULTS AND DISCUSSION

In order to calculate the effective permittivity of a mixture in the microwave absorber, the amount of each constituent of the mixture, i.e., rice husks and rubber tire dust, must be determined. This can be done by using an Agilent 85070B dielectric probe to measure the constituents. The data shown in Figures 5 and 6 were the input parameters for Equations (1) through (3).

The main element in rice husks is carbon (35.8%) [24], which contributed to charge migration and dipole polarization. The excessive of carbon percentage beyond percolation thresholds (more than 5%) causes carbon contact to each other, provided the filler content exceeds percolation threshold. Above this percentage, the conductive carbon particles agglomerate, suggesting the migration of a charged species, and this lead to variations in dielectric constant and conductivity.

The consistent variations in dielectric constant for pure rice husks and rubber tire dust, as shown in Figure 5, suggest that the relaxation frequencies of the pure rice husks and the rubber tire dust in nature are higher than the applied frequency range, i.e., 7 GHz through 13 GHz. Hence, the molecules can be fully polarized because the molecules

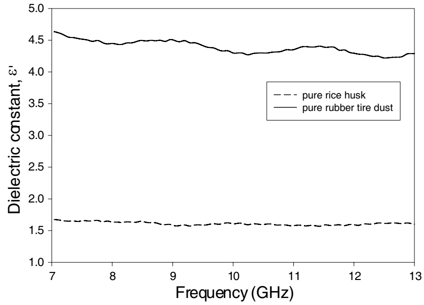


Figure 5. Dielectric constants for pure rice husks and pure rubber tire dust.

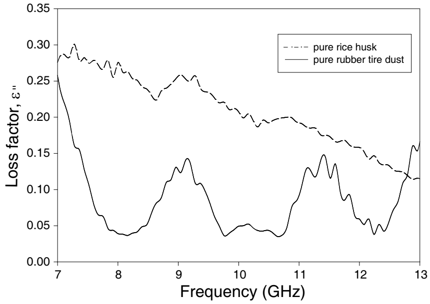


Figure 6. Loss factor for pure rice husks and rubber tire dust.

manage to synchronize with the frequency of alternating field. The relaxation frequency is determined mainly by activation energy and temperature. Since the temperature we used was room temperature (27°C), activation energy is the primary parameter used to determine relaxation frequency. Activation energy describes the strength of the bond between carbon and other constituents. Higher values of activation energy suggest higher relaxation frequencies as described in [25]:

$$f_{\text{rel}} = \frac{\exp(-Q/RT)}{2\pi\tau_0}, \tag{4}$$

where f_{rel} is the relaxation frequency, Q the activation energy, R the gas constant ($R = 8.3143\,\text{J/mol}\cdot\text{K}$), τ_0 the proportionality factor, and T the temperature (in Kelvin).

There is sufficient carbon black in rubber tire dust to make its dielectric constant greater than that of pure rice husks, which contain carbon but no carbon black. The typical composition of rubber tire dust includes about 28% carbon black by weight. The free carbon black that is present in rubber tire dust enhances its agility in creating polarization. However, the carbon in rice husks is a constituent of a polymeric hydrocarbon. Thus, in rice husks, the carbon is bond by other elements, reducing its agility during the polarization mechanism that occurs when an external, alternating field is applied. Since, as noted above, the amount of carbon black exceeds the percolation threshold [26] of 5% [27], the conductive carbon black particles form agglomerates when they are in contact, causing electron polarization.

The variation of loss factor, ε_r'', with frequency was described in reference [28], as shown below:

$$\varepsilon''(f) = \frac{\sigma_0}{2\pi f} + \varepsilon''_R(f), \tag{5}$$

where σ_o is the conductivity of the material and ε''_R the loss factor contributed from relaxation effects. The conductivity terms for pure rubber tire dust that have significant influences are those for carbon black and steel (constituents used in manufacturing rubber tires), but natural rubber and synthetic rubber are not conductive. Even though the free carbon black is conductive and is not a dielectric, it does not show conductive behavior when it is encapsulated (i.e., dispersed at low percentage) in a dielectric matrix in which the content of carbon black is less than 10% [29]. However, it makes up 28% of rubber tire dust and exceeds the percolation threshold, as noted above. At this percentage, the carbon black agglomerates, thereby creating significant conductivity. As expected, the steel exhibits conductivity as well, but its effect is secondary to that of the agglomerated carbon black because it only makes up about 15% of the total composition of a rubber tire. The conductivity that has been mentioned contributes to the first term in Equation (5). A final factor that affects the loss factor is the relaxation effect. The loss factor in blends of conductive filler dispersed in a dielectric matrix is due to a phenomenon known as Maxwell-Wagner polarization, i.e., the polarization that occurs at the interfaces between natural/synthetic rubber and carbon black. When the material is subjected to an electric field, dipoles can be induced at the interfaces, and the dependence of the loss factor on frequency can be explained by the relaxation of those dipoles. This implies that the relaxation term contributes to the second term in Equation (5). In summary, the conductive fillers (carbon black and steel) in pure rubber tire dust account for the dust having a higher loss factor than pure rice husks, as illustrated in Figure 6.

The adsorption properties of a material can also be described by using loss tangent.

$$\tan\delta = \frac{\varepsilon''_r}{\varepsilon'_r} \tag{6}$$

Absorption takes place through heat dissipation, and it is a very important dielectric parameter in determining the optimum condition when designing a panel for a microwave absorber. When the microwave energy penetrates the absorbing material, such as the blend of rubber tire dust and rice husks, the amounts of transmitted and reflected waves become indicators of the absorbability of the material. Normally, reflection loss is the indicator.

An optimal absorber should absorb 100% of the signal in the dielectric material, with none of the signal passing through the

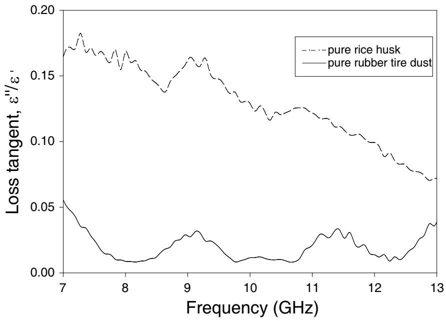


Figure 7. Loss tangent for pure rice husks and rubber tire dust.

interconnection network. However, this is an ideal case that would never occur in real-world application. If the blend of materials can convert most of the incoming microwaves to heat (heat dissipation), the microwave absorber would be considered to have accomplished its intended function. Loss tangent is the ratio of the energy dissipated (term of loss factor) to the energy stored (in terms of dielectric constant) in the dielectric material.

The lower dielectric constant, ε_r', and the higher loss factor, ε_r'', will lead to the high loss tangent that a material with good absorbability should possesses. The results presented in the Figures 5 and 6 illustrate this desirable situation. Then, Figure 7 shows that the loss tangent of pure rice husks is greater than that of pure rubber tire dust. The rich amount of carbon in pure rice husks is the main factor that contributes to the greater loss tangent, and this is due to its charge migration and dipole polarization.

The relationships between both dielectric constants, ε', and loss factor, ε'', of the blend of rubber tire dust and rice husks from 7 GHz to 13 GHz at various percentages of rubber tire dust in the absorber are shown in Figures 8(a) and (b). It has been observed that the dielectric constant is almost constant at low percentages of rubber tire dust (10%–30%). The difference of dielectric constant between 10% and 20% as well as 20% and 30% seems constant, and this is due to the low dispersion when the percentage of rubber tire dust is low. When the percentages of rubber tire dust are low, the rubber tire dust may be bound by the rice husks, as occurs at higher percentages in the absorber. When the percentage is low, the molecules of carbon black are attached to other ingredients in the absorber due to the induction of the dipole moment. The dipole moment exists due to the non-uniform distribution of electrons. When molecules of carbon black are subjected to an electromagnetic field, the mobility of the

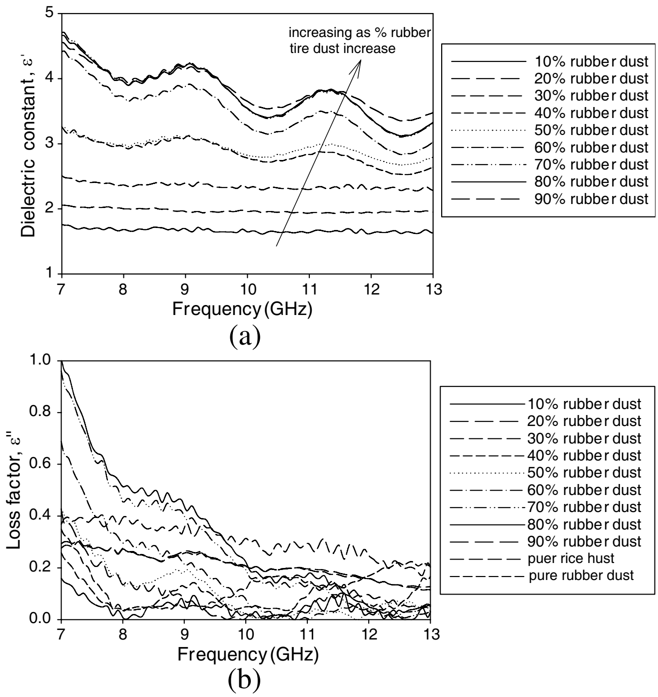


Figure 8. Relationship between (a) dielectric constant and (b) loss factor at various percentages of rubber tire dust blended with rice husks.

electron/charge carrier is restricted in terms of its mobility during the polarization. Therefore, the dielectric constant is almost constant at low percentages of rubber tire dust. When the percentage of rubber tire dust is 40% and more, the free molecules of carbon black and some other constituents easily can be polarized fully and yield to the high dielectric constant.

The sinuous behavior that results when the percentage of rubber tire dust ranges from 40% to 90% may be due to the dispersion of the relaxation frequency due to different constituents in the rice husks and the rubber tire dust. The fact that absorber blends with 40% to 50% and 70% to 90% of rubber tire dust exhibit a monotonic relationship between dielectric constant and frequency may be due to non-uniform blending of the rice husks and the rubber tire dust.

Other than polarization which causes the dielectric loss, the conductivity, which contributes to the conductive loss, is the main parameter in determining the loss factor. This can be explained on the basis of the percolation threshold for the blend of rubber tire dust and rice husks.

Although polarization plays a role in the imaginary part, free electrons have a greater effect due to the good electrical conductivity of carbon black [30]. Various percentages of rubber tire dust exhibit decreasing loss factors when frequency increases, as shown in Figure 8.

The loss factor, ε'', decreases when the frequency increases because of the effect of conductivity; σ is inversely proportional to frequency. The higher frequency of applied electromagnetic field suggests the lower probability of collision among electrons and atoms during electron migration and hopping [31]. This is because the length of travel of an electron during one cycle is generally short compared to the dimensions of the conducting region. Nevertheless, the blend with the lowest percentage, i.e., 10% rubber tire dust, exhibited a sinusoidal variation with frequency without any significant decrement. The most probable explanations of this observation are that the dispersion of the rubber tire dust was not uniform and the phenomenon of bound molecules, as noted above. However, it is improper to describe the loss factor as an indicator for adsorption but loss tangent because the loss tangent explains the tendency of material in energy absorption or dissipation.

The ratio of the energy dissipated to the energy stored in the dielectric material is known as loss tangent. The more energy that is dissipated into the material, the less energy that will penetrate the dielectric material. This dissipated energy typically is converted to heat. Eddy currents and skin effects can be considered as explanation for the loss tangent.

Figure 9 shows that the trendline of the pure rubber tire dust is close to 10% and 20% percentage of rubber tire, which may due to the rice husks still having the dominant effect compared to the rubber tire

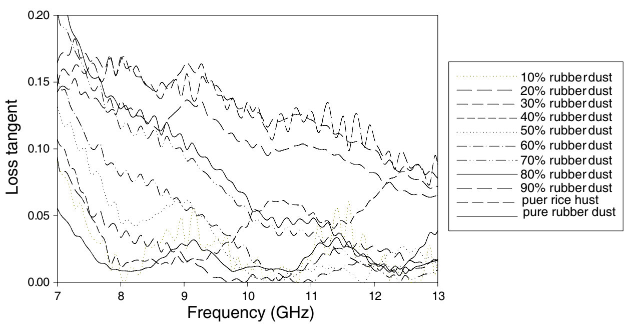


Figure 9. Variation of loss tangent with frequency at various percentages of rubber tire dust in the absorber.

dust. The significant difference in terms of loss tangent between pure rice husks and the rubber tire dust explains this phenomenon. When the percentage is increased to 30%, the loss tangent makes a significant approach toward that of pure rice husks. Both constituents show the highest loss tangent. For the frequency range below 10 GHz, the loss factor increases when the percentage increases from 50% to 80%, and it approaches that of pure rice husks. Beyond 10 GHz, the loss tangents for all percentages were cluster with each other. When it increases to 90%, the rubber tire dust has the dominant effect, and the loss tangent is the same as that for pure rubber tire. A 10% composition of rice husks did not have an effect in the absorber. In summary, the blend of 30% rubber tire dust and 70% rice husks had the highest loss tangent, implying that the fabrication of an optimum microwave absorber cannot be based on the use of pure rice husks, as published in [32]. The other industrial waste, i.e., rubber tire dust can be an auxiliary material in the fabrication of a microwave absorber that uses rice husks.

The anomalous behavior shown in Figure 9 may due to the low tolerances during the measurement of loss factors, which attributed to the low sensitivity of the measurements for the S_{11} parameter, since the dielectric measurement was based on the measurement of this parameter. Normally, this occurred when the loss factor was significantly lower than the dielectric constant.

The frequency of 7 GHz displayed a remarkable trend line that showed very high loss tangent, ranging from 40% to 100% (for pure rubber tire dust). However, this was observed only at a specific lower frequency, i.e., 7 GHz, and this could most probably be attributed to the frequency of 7 GHz within this percentage range being the same as the relaxation frequency. Hence, a higher probability of electron collisions exists, which, in turn, generate significant heat loss as a result of the collisions. On the other hand, it can be observed that the trend line of loss tangent for pure rice husks (0%) and 30% rubber tire dust content as shown in Figure 9 shows the higher loss tangent, on average. Relatively, pure rice husks and 30% rubber tire dust exhibited higher loss tangents in the wider frequency range than other percentages of rubber tire dust in the absorber. This is consistent with the findings in Figures 9 and Figure 10, in which 30% rubber tire dust was the same as pure rice husks in terms of loss tangent.

The configuration of the commercial sensor and the calculation of permittivity were determined initially using the procedure given in [20] and [33] at various frequencies, i.e., from 7 GHz to 13 GHz at room temperature. It can be observed that the loss tangent changes with percentage of rubber tire dust in sixth-order polynomial form, as shown in Figure 11. The relationship between the loss tangent based on the percentage of rubber tire dust and frequency is described by Equation (6)

$$\frac{\varepsilon_r''}{\varepsilon_r'} = \left|a_0 + a_1c + a_2c^2 + a_3c^3 + a_4c^4 + a_5c^5 + a_6c^6\right|, \qquad (7)$$

where f is the operational frequency (in GHz), c the percentage of

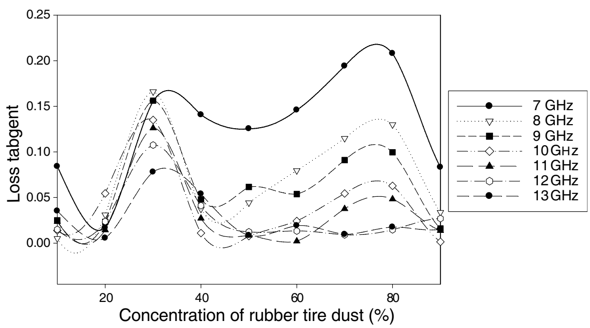
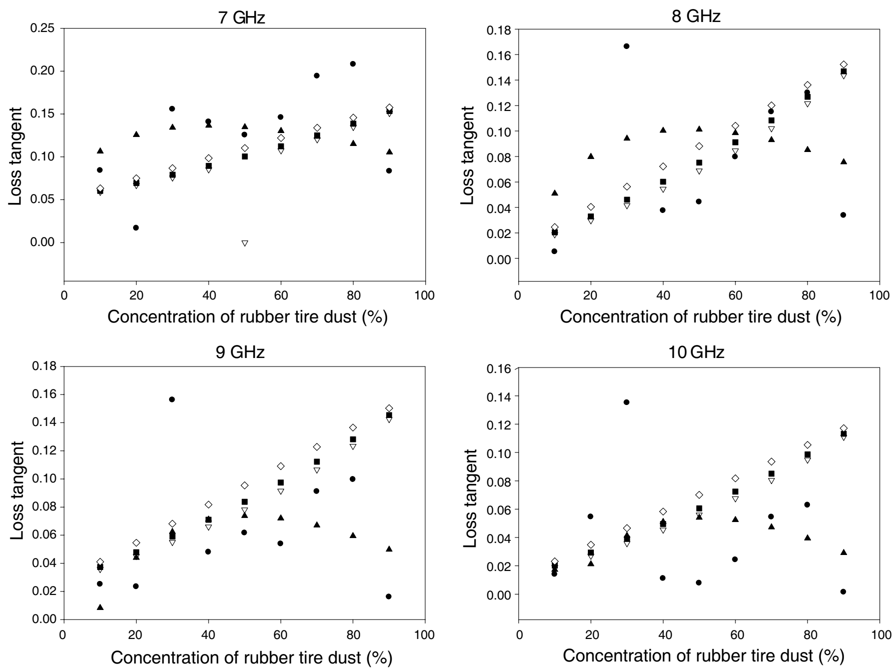


Figure 10. Variation of loss tangent with percentage of rubber tire dust in the absorber at various frequencies.



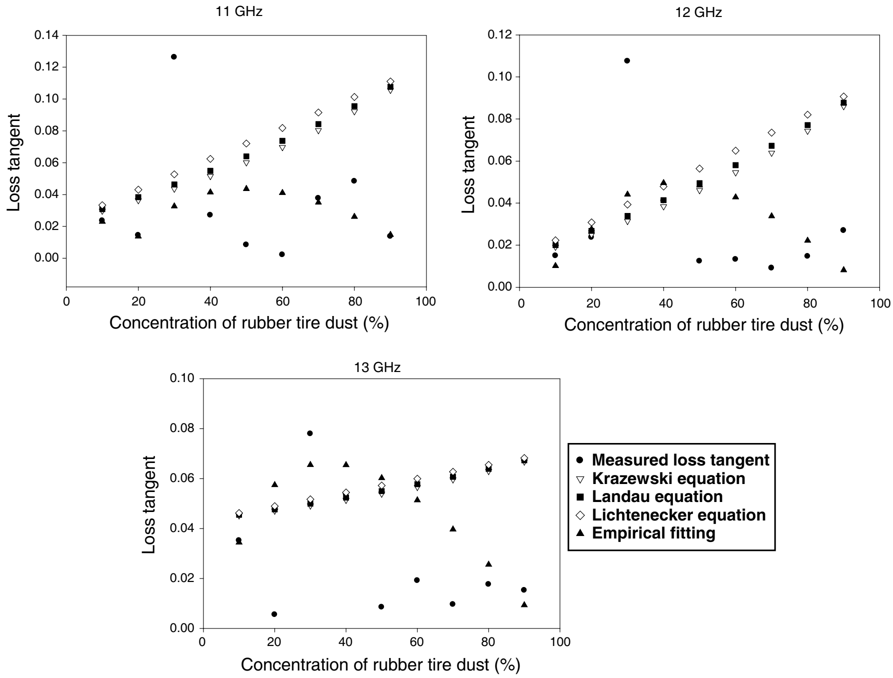


Figure 11. Relationship between loss tangent and moisture content for experimental results, Kraszewski, Landau, and Lichtenecker mixture models, and empirical fitting from 7–13 GHz.

rubber tire dust in terms of ratio, and a_j $(j = 0, 1, 2, \ldots 6)$ the unknown variables and functions of frequency as described in Equations (8a) through (8g) .

$$a_0=0.0028f^5-0.1384f^4+2.6788f^3-25.443f^2+118.25f-213.42 \quad (8a)$$
$$a_1=-0.0799f^5+4.0028f^4-79.127f^3+770.66f^2-3692.9f+6933.9 \quad (8b)$$
$$a_2=0.7023f^5-35.413f^4+705.31f^3-6930.6f^2+33568f-63895 \quad (8c)$$
$$a_3=-2.7191f^5+137.53f^4-2748.9f^3+27128f^2-132085f+253133 \quad (8d)$$
$$a_4=5.0748f^5-257.15f^4+5151.2f^3-50968f^2+248937f-478978 \quad (8e)$$
$$a_5=-4.474f^5+227.04f^4-4555.5f^3+45158f^2-221039f+426435 \quad (8f)$$
$$a_6=1.5114f^5-76.824f^4+1544.2f^3-15337f^2+75235f-145519 \quad (8g)$$

The unknown variables a_j $(j = 0, 1, 2, \ldots 6)$ were obtained by the Gaussian elimination method. The unknown variables as a function of moisture content are tabulated in Table 2. The empirical fitting for the determination of loss tangent is presented in Figure 11. An empirical

Table 1. Absolute error for calculated loss tangent.

Frequency	Percentage of rubber tire dust	Kraszewski (Equation (1))	Landau (Equation (2))	Lichtenecker (Equation (3))	Empirical (Equation (6))
7 GHz	10	0.0251	0.0238	0.0207	0.0014
	20	0.0503	0.0527	0.0583	0.0063
	30	0.0798	0.0764	0.0687	0.0128
	40	0.0554	0.0512	0.0422	0.0150
	50	0.0297	0.0250	0.0152	0.0042
	60	0.0385	0.0336	0.0239	0.0056
	70	0.0738	0.0691	0.0602	0.0114
	80	0.0732	0.0692	0.0622	0.0017
	90	0.0678	0.0703	0.0744	0.0036
	Mean	0.0548	0.0524	0.0473	0.0069
8 GHz	10	0.0137	0.0154	0.0195	0.0005
	20	0.0013	0.0018	0.0094	0.0097
	30	0.1246	0.1201	0.1099	0.0362
	40	0.0171	0.0226	0.0347	0.0495
	50	0.0246	0.0308	0.0438	0.0126
	60	0.0050	0.0116	0.0245	0.0350
	70	0.0129	0.0066	0.0051	0.0278
	80	0.0083	0.0031	0.0062	0.0042
	90	0.1099	0.1132	0.1186	0.0091
	Mean	0.0353	0.0361	0.0413	0.0205
9 GHz	0.1	0.0108	0.0123	0.0159	0.0094
	0.2	0.0217	0.0245	0.0312	0.0267
	0.3	0.1012	0.0972	0.0881	0.0362
	0.4	0.0180	0.0230	0.0338	0.0320
	0.5	0.0166	0.0222	0.0339	0.0347
	0.6	0.0378	0.0436	0.0553	0.0093
	0.7	0.0155	0.0212	0.0317	0.0068
	0.8	0.0238	0.0286	0.0370	0.0208
	0.9	0.1265	0.1294	0.1343	0.0127
	Mean	0.0413	0.0447	0.0512	0.0210
10 GHz	10	0.0051	0.0063	0.0093	0.0080
	20	0.0275	0.0251	0.0196	0.0068
	30	0.0993	0.0960	0.0885	0.0260
	40	0.0345	0.0385	0.0473	0.0506
	50	0.0482	0.0528	0.0623	0.0042
	60	0.0434	0.0481	0.0575	0.0047
	70	0.0261	0.0307	0.0392	0.0214
	80	0.0320	0.0358	0.0425	0.0030
	90	0.1095	0.1118	0.1158	0.0082
	Mean	0.0473	0.0495	0.0536	0.0148
11 GHz	10	0.0062	0.0072	0.0098	0.0089
	20	0.0220	0.0240	0.0286	0.0231
	30	0.0826	0.0799	0.0735	0.0275
	40	0.0244	0.0278	0.0353	0.0189

	50	0.0517	0.0556	0.0637	0.0274
	60	0.0675	0.0716	0.0797	0.0111
	70	0.0427	0.0466	0.0539	0.0034
	80	0.0439	0.0472	0.0529	0.0193
	90	0.0919	0.0939	0.0973	0.0112
	Mean	0.0481	0.0504	0.0550	0.0168
12 GHz	10	0.0042	0.0051	0.0073	0.0017
	20	0.0014	0.0031	0.0071	0.0006
	30	0.0761	0.0736	0.0682	0.0187
	40	0.0026	0.0003	0.0068	0.0167
	50	0.0337	0.0371	0.0440	0.0136
	60	0.0413	0.0448	0.0517	0.0317
	70	0.0548	0.0582	0.0644	0.0197
	80	0.0597	0.0625	0.0674	0.0544
	90	0.0591	0.0608	0.0637	0.0708
	Mean	0.0370	0.0384	0.0423	0.0253
13 GHz	10	0.0100	0.0103	0.0110	0.0011
	20	0.0416	0.0422	0.0435	0.0040
	30	0.0288	0.0280	0.0262	0.0070
	40	0.0025	0.0015	0.0006	0.0029
	50	0.0454	0.0465	0.0487	0.0051
	60	0.0374	0.0386	0.0408	0.0156
	70	0.0500	0.0511	0.0531	0.0101
	80	0.0454	0.0463	0.0479	0.0071
	90	0.0515	0.0521	0.0530	0.0021
	Mean	0.0347	0.0352	0.0361	0.0061

model was developed to estimate the loss tangent as a function the percentage of rubber tire dust in the microwave absorber, and this loss tangent was compared with measured and calculated loss tangents that were determined by using the Kraszewski, Landau and Lichtenecker equations.

The result for the empirical model showed good agreement with the experimental results compared with the selected mixture models. Figure 11 shows the relationship between the empirical and measured data. The accuracy of Equation (6) can be described using absolute error. The absolute errors for the empirical model and the mixture model were based on the measurement data as described in Equation (9).

$$\text{absolute error} = |\text{Measured} - X|, \tag{9}$$

where the measured data was obtained from the measurements using Agilent 85070B in conjunction with the P-series network analyzer, and X was the selected mixture equations or empirical fitting. The absolute errors and mean absolute errors for the empirical model (6), the Kraszewski mixture model (1), the Landau mixture model (2) and

Table 2. Average mean error for the frequency range of 7 GHz to 13 GHz.

Frequency (GHz)	Kraszewski (Equation (1))	Landau (Equation (2))	Lichtenecker (Equation (3))	Empirical (Equation (6))
7	0.0548	0.0524	0.0473	0.0069
8	0.0353	0.0361	0.0413	0.0205
9	0.0413	0.0447	0.0512	0.021
10	0.0473	0.0495	0.0536	0.0148
11	0.0481	0.0504	0.055	0.0168
12	0.037	0.0384	0.0423	0.0253
13	0.0347	0.0352	0.0361	0.0061
Average	0.0406	0.0424	0.0466	0.0174

the Lichtenecker mixture model (3) are shown in Table 1 for the loss tangent.

Tables 1 shows that the empirical model gave the smallest absolute error for the loss tangent at various frequencies compared to the selected dielectric mixture models. The absolute errors for the calculated loss tangents using the dielectric mixture models were higher than those for the empirical model. This was because the anomalous behavior at a 30% percentage of rubber tire dust was taken into account in the empirical model during fitting. The selected dielectric mixture models exhibited a linear relationship with percentage for the rubber tire dust in the microwave absorber. As a result, the dielectric mixture models were ideal and impractical, since many issues in real measurements were not considered. In addition, the average mean errors that are listed in Table 2 implied that Kraszewski (Equation (1)), Landau (Equation (2)) and Lichtenecker (Equation (3)) exhibited similar average mean errors. It can be observed that the averages mean error for Equations (1), (2) and (3), as listed in Table 2, were similar, i.e., 0.0406, 0.0424. and 0.0466. Therefore, the results in Table 2 led the authors to propose a new, empirical model for predicting dielectric prediction for which the average mean error was 0.0174.

5. CONCLUSIONS

The rich carbon content in rice husks and rubber tire dust is the main constituent that yields to electromagnetic wave absorption. Relatively, the pure rice husks have richer carbon content, i.e., 35.8% compared with rubber tire dust, which contained 28% carbon black content. The measurements indicated that the loss tangent of pure rice husks was greater than that of rubber tire dust in the range of 7 GHz to 13 GHz. Further measurements obtained with the mixture of pure rice husks and rubber tire dust in the same frequency range showed that only the combination of 30% rubber tire dust and 70% pure rice husks exhibited a comparable loss tangent to that of pure rice husks. Even though the mixture did not exceed the performance of pure rice husks in terms of loss tangent or absorbability, it was made clear that the microwave absorber design did have to depend exclusively on rice husks. Rubber tire dust can be used in the fabrication of a microwave. Such use would indirectly reduce the likelihood that rubber tire dust will become a pollutant that is hazardous to our environment. The performance of the empirical equation in predicting the loss tangent was commendable compared to the performances of the selected dielectric mixture equations, as is described in Tables 1 and 2. This equation had the best performance for the prediction of loss tangent between 10% and 90% of rubber tire dust with its mean absolute error ranging from 2.53E-3 to 6.1E-3. This model is applicable only in the frequency range of 7 GHz to 13 GHz.

REFERENCES

1. Asi, M. J. and N. I. Dib, "Design of multilayer microwave broadband absorbers using central force optimization," *Progress In Electromagnetics Research B*, Vol. 26, 101–113, 2010.
2. Zhu, B., C. Huang, Y. Feng, J. Zhao, and T. Jiang, "Dual band switchable metamaterial electromagnetic absorber," *Progress In Electromagnetics Research B*, Vol. 24, 121–129, 2010.
3. Zivkovic, I. and A. Murk, "Characterization of magnetically loaded microwave absorbers," *Progress In Electromagnetics Research B*, Vol. 33, 277–289, 2011.
4. Gu, C., S. Qu, Z. Pei, H. Zhou, J. Wang, B.-Q. Lin, Z. Xu, P. Bai, and W.-D. Peng, "A wide-band, polarization-insensitive and wide-angle terahertz metamaterial absorber," *Progress In Electromagnetics Research Letters*, Vol. 17, 171–179, 2010.
5. Huang, H., F.-H. Xue, B. Lu, F. Wang, X.-L. Dong, and W.-J. Park, "Enhanced polarization in tadpole-shaped (NI, AL)/ALN nanoparticles and microwave absorption at high frequencies," *Progress In Electromagnetics Research B*, Vol. 34, 31–46, 2011.
6. Lee, H.-M. and H.-S. Lee, "A dual-band metamaterial absorber based with resonant-magnetic structures," *Progress In Electromagnetics Research Letters*, Vol. 33, 1–12, 2012.
7. Razavi, S. M. J., M. Khalaj-Amirhosseini, and A. Cheldavi,

"Minimum usage of ferrite tiles in anechoic chambers," *Progress In Electromagnetics Research B*, Vol. 19, 367–383, 2010.

8. Malek, F. B. A., E. M. Cheng, O. Nadiah, H. Nornikman, M. Ahmed, M. Z. A. Abd Aziz, A. R. Osman, P. J. Soh, A. A. H. Azremi, A. Hasnain, and M. N. Taib, "Rubber tire dust-rice husk pyramidal microwave absorber," *Progress In Electromagnetics Research*, Vol. 117, 449–477, 2011.
9. Nornikman, H., B. H. Ahmad, M. Z. A. Abdul Aziz, F. B. A. Malek, H. Imran, and A. R. Othman, "Study and simulation of an edge couple split ring resonator (EC-SRR) on truncated pyramidal microwave absorber," *Progress In Electromagnetics Research*, Vol. 127, 319–334, 2012.
10. He, X.-J., Y. Wang, J. Wang, T. Gui, and Q. Wu, "Dual-band terahertz metamaterial absorber with polarization insensitivity and wide incident angle," *Progress In Electromagnetics Research*, Vol. 115, 381–397, 2011.
11. Huang, L. and H. Chen, "Multi-band and polarization insensitive metamaterial absorber," *Progress In Electromagnetics Research*, Vol. 113, 103–110, 2011.
12. Li, M., H.-L. Yang, X.-W. Hou, Y. Tian, and D.-Y. Hou, "Perfect metamaterial absorber with dual-bands," *Progress In Electromagnetics Research*, Vol. 108, 37–49, 2010.
13. Faruque, M. R. I., M. T. Islam, and N. Misran, "Design analysis of new metamaterial for EM absorption reduction," *Progress In Electromagnetics Research*, Vol. 124, 119–135, 2012.
14. Bucinskas, J., L. Nickelson, and V. Sugurovas, "Microwave scattering and absorption by a multilayered lossy metamaterial — Glass cylinder," *Progress In Electromagnetics Research*, Vol. 105, 103–118, 2010.
15. Kraszewski, A., "Prediction of the dielectric properties of two-phase mixtures," *J. Microwave Power*, Vol. 12, No. 13, 215–222, 1977.
16. Landau, L. D., E. M. Lifshitz, and L. P. Pitaevskii, *Electrodynamics of Continuous Media*, Vol. 8, 42–44, Pergamon Press, London, 1984.
17. Lichtenecker, K. and K. Rother, "Die herleitung des logarithmischen mischungs-gesetzes aus allegemeinen prinzipien der stationaren stromung," *Physikalische Zeitschrift*, Vol. 32, 255–260, 1931.
18. Liu, Y. H., J. M. Tang, and Z. H. Mao, "Analysis of bread dielectric properties using mixture equations," *Journal of Food Engineering*, Vol. 93, 72–79, 2009.

19. You, K. Y. and Z. Abbas, *Open-ended Coaxial Sensor Handbook: Formulations, Microwave Measurements and Applications*, LAP Lambert Academic Publishing, 2010.
20. Jusoh, M. A., Z. Abbas, J. Hassan, B. Z. Azmi, and A. F. Ahmad, "A simple procedure to determine complex permittivity of moist materials using standard commercial coaxial sensor," *Measurement Science Review*, Vol. 11, No. 1, 2011.
21. Neelakantaswamy, P. S., K. F. Aspar, A. Rajaratnam, and N. P. Das, "A dielectric model of the human blood," *Biomed. Tech.*, Vol. 28, Nos. 1–2, 18–22, 1983.
22. Agilent Technologies Inc., "Agilent basics of measuring the dielectric properties of materials," 1–32, Santa Clara, California, United States of America, 2005.
23. Subedi, P. and I. Chatterjee, "Dielectric mixture model for asphalt-aggregate mixtures," *Journal of Microwave Power and Electromagnetic Energy*, Vol. 28, No. 2, 1993.
24. Nornikman, H., F. Malek, P. J. Soh, A. A. H. Azremi, F. H. Wee, and A. Hasnain, "Parametric studies of the pyramidal microwave absorber using rice husks," *Progress In Electromagnetics Research*, Vol. 104, 145–166, 2010.
25. Nyfros, E. and P. Vainikainen, *Industrial Microwave Sensors*, Artech House, Inc., Norwood, MA, 1989.
26. Hsu, W. Y., W. G. Holtje, and J. R. Barkley, "Percolation phenomenon in polymer/carbon composites," *Journal of Materials Science Letters*, Vol. 7, 459–462, 1988.
27. Kwon, S. K., J. M. Ahn, G. H. Kim, C. H. Chun, J. H. Lee, and J. S. Hwang, "Microwave absorbing properties of carbon black/silicone rubber blend," *Polymer Engineering Science*, Vol. 42, No. 11, 2165–2171, 2002.
28. Achour, M. E., M. El Malhi, J. L. Miane, F.Carmona, and F. Lahjomri, "Microwave properties of carbon black-epoxy resin composites and their simulation by means of mixture laws," *J. Appl. Polym. Sci.*, Vol. 73, Vo. 6, 969–973, 1999.
29. Moon, K. S., H. D. Choi, A. K. Lee, K. Y. Cho, H. G. Yoon, and K. S. Suh, "Dielectric properties of epoxy-dielectrics-carbon black composite for phantom materials at radio frequencies," *J. Appl. Polym. Sci.*, Vol. 77, No. 6, 1294–1302, 2000.
30. Chung, D. D. L., "Electromagnetic interference shielding effectiveness of carbon materials," *Carbon*, Vol. 39, No. 2, 279–85, 2001.
31. Cao, M.-S., W.-L. Song, Z.-L. Hou, B. Wen, and J. Yuan., "The

effects of temperature and frequency on the dielectric properties, electromagnetic interference shielding and microwave-absorption of short carbon fiber/silica composites," *Carbon*, Vol. 48, 788–796, 2010.

32. Nornikman, H., M. F. B. A. Malek, M. Ahmed, F. H. Wee, P. J. Soh, and A. A. H. Azremi, "Setup and results of pyramidal microwave absorbers using rice husks," *Progress In Electromagnetics Research*, Vol. 111, 141–161, 2011.
33. Blackham, D. V. and R. D. Pollard, "An improved technique for permittivity measurements using a coaxial probe," *IEEE Trans. on Instrum. Meas.*, Vol. 46, No. 5, 1093–1099, 1997.