Australian Journal of Crop Science

AJCS

AJCS 5(11):1326-1333 (2011) ISSN:1835-2707

Microwave antenna sensing technique for determination of moisture content in Hevea Latex from *Hevea Brasiliensis* tree

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Abstract

This paper presents microwave antenna sensing technique for determination of moisture content in hevea latex from *Hevea brasiliensis* tree. The measurement set-up includes computer-controlled Professional Network Analyzer (PNA) (model N5230A) and monopole antenna. The relationship between reflection coefficient magnitude and moisture content in hevea latex was investigated from 2.2 GHz to 2.7 GHz. The linear functional relationship between reflection coefficient magnitude and moisture content at 2.30 GHz was used to estimate the amount of moisture content in hevea latex as well as the sensitivity and linearity of the antenna in the measuring process. Significant correlation between predicted and measured values of reflection coefficient suggests the potential of this technique for determination of moisture content in hevea latex. This technique can also estimate the amount of moisture content in hevea latex within the performance similar to commercial moisture meters.

Keywords: Hevea latex, moisture content, reflection coefficient magnitude, monopole antenna.

Abbreviations: MC-moisture content; $|\Gamma| = RC$ -magnitude of reflection coefficient; PNA-professional network analyzer; R-resistance; X-reactance; C-constant of the probe, Z_i-terminal impedance; l-length of monopole antenna; f_0-resonant frequency; PDF-probability density function.

Introduction

Moisture content (MC) amount in crop and agriculture products is very important constituent due to its influences in quality, stability and processing. MC is an important quality feature that directly influences storability of fruits and vegetables but also during long-term storage of product causes direct economic loss because of decrease in saleable weight (Vesali et al., 2011). Another important element that affects consumer's decision is the MC of products. It is obvious that the higher MC of product, the fresher it looks (Harker et al., 2008). The decrease in sample's MC not only causes weight loss, but also leads to change in cell structure and turgor pressure, which may affect the products made from hevea latex (Dupratet al., 1995). Agricultural crops and food products have several unique characteristics which set them different from engineering materials. These properties determine the quality of the fruit and identification of correlation among these properties makes the quality control easier. Therefore, the natural MC of fresh produced products should be maintained in order to preserve the quality. While the shelf life of products should be extended, trading the exact fresh quantity of product is an important matter to attention for buyer or seller which is affected by MC in the product. This is because for too high moisture products, the buyer pays too much and there is a higher probability of the product to be deteriorated. Therefore, the performance and accuracy of MC measuring instruments is of great importance in the production, trade, storage, and processing for most of crop products and natural raw materials.

Monopole antennas also play an essential role for variety of applications as transmitters and or receivers in our modern wireless society. So far no literatures implicated 2.4 GHz application of monopole antenna in crops moisture sensing. The 2.4 GHz monopole antennas act as a sensor in agriculture and crop products, firstly introduced in this paper as a new, rapid, easy and accurate technique for MC determination in hevea latex. However, many methods (Khalid, 1982; Chung and Verma, 1991; Thomasson, 1995; Jayanthy and Sankaranarayanan, 2005; Abbas et al., 2007; Ghretli et al., 2007; Sundaram et al., 2009; Lee et al., 2010; Seifi and Alimardani, 2010) exist for the determination of MC and soluble solids content in crop and agriculture products but are somehow complicated and very time-consuming leading to inaccurate measurements.

Results and Discussion

Antenna propagation in air

The resonance frequency, f_0 was measured when monopole antenna radiations propagate in air (free space) (Fig. 4). Its value is exactly 2.4 GHz corresponding to -16 dB and 0.165 magnitudes of reflection coefficient.

Relationship between reflection coefficient and moisture content in hevea latex

Variation of $|\Gamma|$ with percentage of MC in hevea latex from 2.2 GHz to 2.7 GHz is shown in Fig. 5. Experimental results

Table 1. Regression and sensitivity values of relationship between reflection coefficient and moisture content in hevea latex at different microwave frequencies

Frequency (GHz)	Regression value	Sensitivity (/%)
2.20	0.91930	0.01070
2.29	0.97850	0.01370
†2.30	0.98310	0.01380
2.32	0.95200	0.01300
2.34	0.78900	0.00990
2.38	0.25190	-0.00420
2.40	0.71820	-0.01080
2.41	0.75940	-0.01180
2.50	0.28510	-0.00280
2.60	0.46850	-0.00370
2.70	0.64300	-0.00650

†2.3 GHz is an optimal operating frequency because of its high regression and sensitivity value

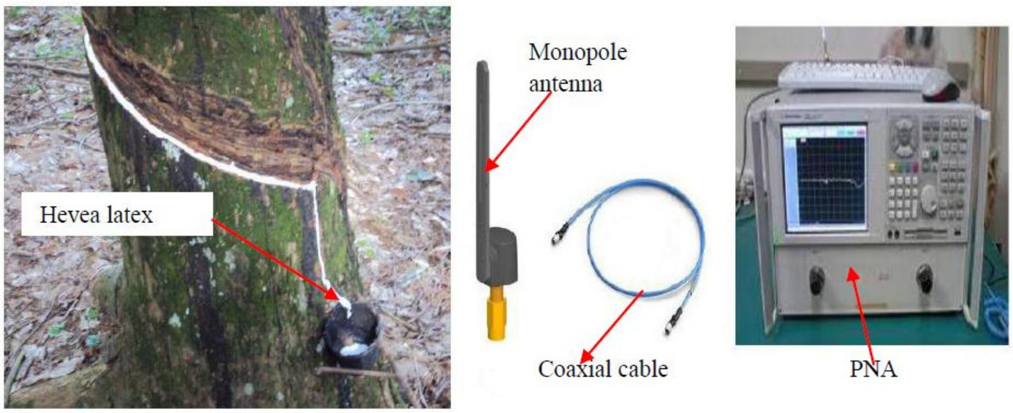

Fig 1. Measurement set-up

show that $|\Gamma|$ increases gradually with MC from 2.2 GHz to 2.3 GHz. The MC profile initially decreases with frequency up to a minimum $|\Gamma|$ close to zero and then increases with frequency to certain $|\Gamma|$ before bending away horizontal to the right. At very small $|\Gamma|$, a very high absorption is suggested because of dipolar characteristics of water molecules. The higher the amount of MC, the higher the resonant frequency for minimum $|\Gamma|$ happened. The minimum $|\Gamma|$ for lowest MC of 20% occurred at 2.29 GHz, followed by 30% MC at 2.32 GHz, 40% MC at 2.34 GHz, 50% MC at 2.38 GHz, 60% MC at 2.382 GHz and 70% MC at 2.41 GHz.

Determination of optimal frequency

The optimum frequency was obtained by plotting graphs for variation in $|\Gamma|$ with MC for all frequencies, where minimum reflections took place as shown in Fig. 5 and other selected frequencies (i.e. 2.2 GHz, 2.3 GHz, 2.4 GHz, 2.5 GHz, 2.6 GHz and 2.7 GHz). Summary of graph's sensitivities and regression coefficient values at each particular frequency are given in Table. 1. Since the selected operating frequencies and amount of MC in hevea latex were among determinant factors of the antenna performance, therefore, the difference in antenna sensitivities and regression values at each particular frequency was detected. The results showed that at 2.2 GHz the antenna sensitivity was 0.01070/% and regression value 0.91930. At 2.29 GHz sensitivity was 0.01370/% and regression value 0.97850. At 2.30 GHz the sensitivity was 0.01380/% and regression value was 0.98310 At 2.32 GHz the sensitivity was 0.01300/% and regression value 0.95200. At 2.34 GHz the sensitivity was 0.00990/% and regression value 0.78900. At 2.38 GHz the sensitivity was -0.00420/% and regression value 0.25190. At 2.40 GHz the sensitivity was -0.01080/% and regression value 0.71820. At 2.41 GHz the sensitivity was -0.01180/% and regression value 0.75940. At 2.5 GHz the sensitivity was -0.00280/% and regression value 0.28510. At 2.6 GHz the sensitivity was -0.00370 GHz and regression value 0.46850 and finally at 2.70 GHz the sensitivity was -0.00650/% and regression value 0.64300. Therefore, high regression and sensitivity values of 0.98310 and 0.01380/% were found at 2.30 GHz, indicating that 2.30 GHz is an optimum operating frequency due to its high sensitivity and high regression values when compared to other frequencies. Furthermore, the frequency of 2.30 GHz is a suitable operating frequency for moisture meters including monopole antenna because at this frequency there is a minimum effect of ionic phases as well as loss is dominated by dipole orientation of water molecules in hevea latex.

Performance characteristic of the antenna

The linearity and sensitivity of the antenna from measured $|\Gamma|$ with MC were further determined at 2.30 GHz to test performance of the antenna at different intervals of MC in

Table 2. Comparison of sensitivity, linearity and correlation of the antenna for various moisture content intervals in hevea latex

Empirical equation	Moisture Content (%)	Sensitivity (/ %)	Mean linearity error (%)	R^2
$A \Rightarrow \Gamma = 0.021MC - 0.4133$	(20-40)	0.0210	1.6009	0.989
$B \Rightarrow \Gamma = 0.0209MC - 0.502$	(40-60)	0.0209	1.4557	0.9048
$C \Rightarrow \Gamma = 0.0112MC - 0.0804$	(60-80)	0.0112	1.4782	0.9197

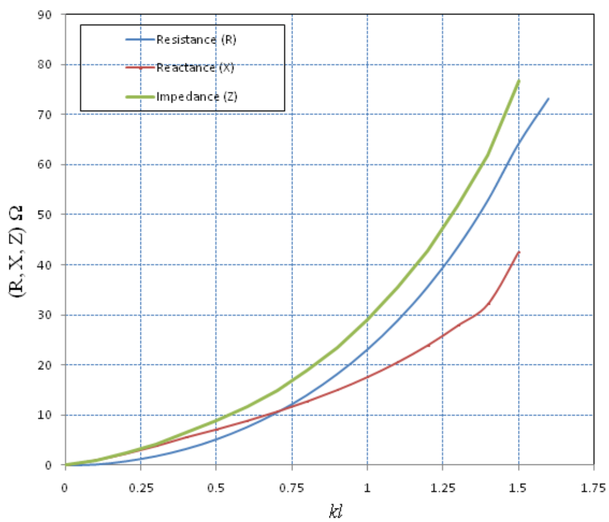

Fig 2. Variation of resistance (R), reactance (X) and impedance (Z) with the length (l) of a monopole antenna

hevea latex (Table. 2 and Fig. 6 a, b and c). This kind of performance test was done by comparing data with MC from 20% to less than 40% $(20\% \le MC < 40\%)$, from 40% to 60% $(40\% \le MC \le 60\%)$ and between 60% to 80% $(60\% < MC \le 80\%)$, respectively.

Three empirical equations A, B, and C representing the MC intervals i.e. $(20\% \le MC < 40\%)$, $(40\% \le MC \le 60\%)$ and $(60\% < MC \le 80\%)$, were respectively constructed. In addition, relation of $|\Gamma|$ and MC in hevea latex has been also developed as shown in Table. 2 and Fig. 6 a, b and c, respectively. High sensitivity value of 0.0210/% as well as high mean linearity error of 1.6009% and high correlation value of 0.989 were found in equation A as shown here:

$$A \Rightarrow |\Gamma| = 0.021MC - 0.4133 \quad (12)$$

Equation (12) can be used to calculate amount of MC in hevea latex at a specific interval ranging from 20% to 40% for given value of the $|\Gamma|$. Furthermore, low sensitivity values of 0.0209/% and 0.0112/% as well as low mean linearity errors of 1.4557% and 1.4782% and low correlation values of 0.9048 and 0.9197 were obtained from equations B and C as shown in Fig. 6 b and c, respectively.

$$B \Rightarrow |\Gamma| = 0.0209MC - 0.502 \quad (13)$$

$$C \Rightarrow |\Gamma| = 0.0112MC - 0.0804 \quad (14)$$

Equation (13) and (14) can also be used to calculate amount of MC in hevea latex at the intervals of 40% to 60% and 60% to 80%, respectively for a given values of $|\Gamma|$. The correlation coefficient of A seemed to be higher compared to B and C. This is simply because of the water molecules that are closely bound together at low MC. The ideal straight-line equations of A, B and C are shown in each figure and their mean linearity errors, sensitivities and correlation values (R^2) are given in Table. 2. These results imply that, the antenna is very sensitive at low MC and has a little bit high mean linearity error for measurement of MC, less than 40% in hevea latex, when compared with the MC from 40% to 60% as well as from 60 to 80%, respectively. These experimental results derive a conclusion that, for commercial application and especially for measuring low MC in hevea latex the antenna is highly recommended and fits well to be used as a moisture sensor at 2.3 GHz. It can also be used in higher percentage measurement of MC because the sensitivities are high enough. Approximately for every 1% of MC in hevea latex the antenna can produces about 0.02 of $|\Gamma|$ and even error in linearity is still small that can be ignored. The performance of this technique was validated by measured plotting and calculated results of $|\Gamma|$ and MC in hevea latex as shown in Fig. 7. The result is linear and correlated within a correlation coefficient of 0.967 and related by the regression equation

$$RC = 0.0159MC - 0.2867 \quad (12)$$

Equation (12) can be used to calculate amount of MC in hevea latex from 20% to 80% for a given measured values of the $|\Gamma|$. The PDF test of the technique in Fig. 8 illustrates that the error occurred during measurement was distributed in a bell-shaped curve. This result implies that, the distribution of errors during measurement is almost symmetric with a numeric value of skewness equal to zero. This also indicates that, the error is more consistent around the mean. In other words, it can be considered that the measurement data is free from any systematic error caused by instrumental and measurement set up during measurement. The mean relative error between measured and calculated data of MC was 0.03 as shown in Fig. 9. The data points of error were not gathered at common percentage point of MC an indication that the technique did not contain any instrumental error during measurement of MC in hevea latex. Therefore, the overall results obtained from this study suggest the potential of this technique for determination of MC amount in hevea latex from 20% to 80% at a frequency of 2.3 GHz. This technique is also simpler ccomparing with other previous methods such as the one used by Khalid (1982), Singh et al. (2004), Jayanthy and Sankaranarayanan (2005), Abbas et al. (2007), Sudaram et al. (2009) when they all calculating MC from different samples. In this method, an electronic balance, monopole antenna and PNA were used to estimate MC of hevea latex and as mentioned in result section, the method achieved a proper accuracy. As MC depends on weather conditions, this technique can be used for other environmental conditions than those in Malaysia. The results obtained from this study can also be used for re-designing monopole antenna for specific percentage measurement of MC in hevea latex as well as other crops and agriculture products.

Materials and methods

Sample preparation

This study was carried out at the Department of Physics, Faculty of Science, Universiti Putra Malaysia. Freshly tapped hevea latex (Fig. 1) obtained from Research Park of Universiti Putra Malaysia and used in this study in order to determine the amount of MC. Whereby, about four plates, including 1.5 g to 2.5 g of wet and fresh hevea latex each, tapped early in the morning from hevea latex *brasiliensis* tree. The prepared latex then weighted before drying using electronic balance of model (HA3203A) from Fujian, China (Mainland).

Measurement setting up

The measurement set-up includes computer controlled Professional Network Analyzer (PNA) of model (N5230A) from Agilent Technologies Company (Santa Clara, California, United States of America USA) and 2.4 GHz monopole antenna (Antenova Limited, Far Field House, Cambridge, United Kingdom). The antenna was connected to

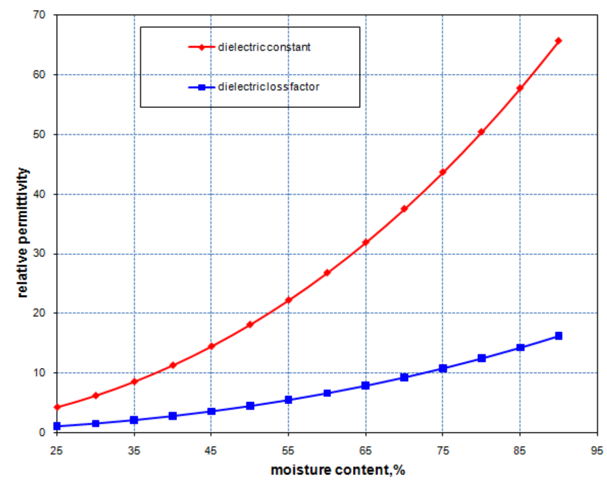

Fig 3. Variation of complex relative permittivity and moisture content (%) in hevea latex .

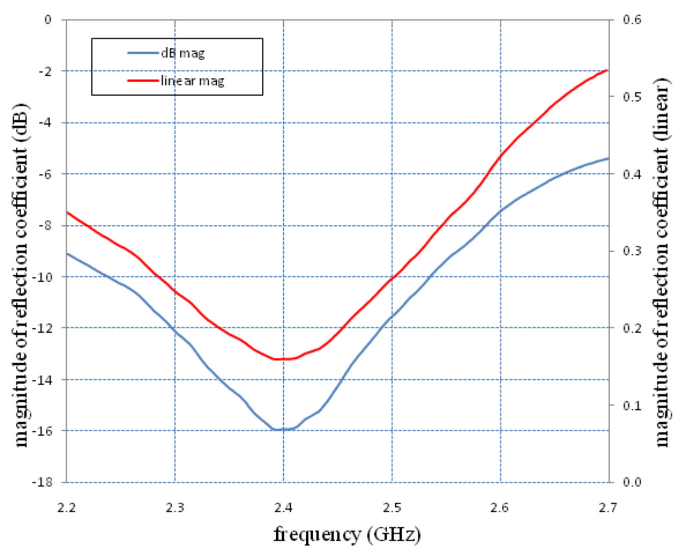

Fig 4. Monopole antenna resonance frequency measurement from 2.2 GHz to 2.7 GHz

the PNA using low-loss coaxial cable to measure the magnitude of reflection coefficient ($|\Gamma|$) in a sample of hevea latex from 2.2 GHz to 2.7 GHz as shown in Fig. 1. The measurement of the complex relative permittivity of hevea latex was measured from 2.2 GHz to 2.7 GHz using 4 mm open-ended coaxial line probes (model HP 85070B, Hewlett-Packard Company, Santa Rosa, USA) which was also connected to the PNA using low-loss coaxial cable. The dependence of dielectric properties on MC, frequency and feasibility of using the dielectric properties to sense quality of crops and agriculture products was studied by Nelson et al. (2007) and Nelson et al. (2008). Also Sirikulrat et al. (2008) demonstrated that the relative permittivity of the fresh soybean decreases as the bean matures. All of these researches show employing dielectric properties in sensing quality parameters and other properties of agricultural products.

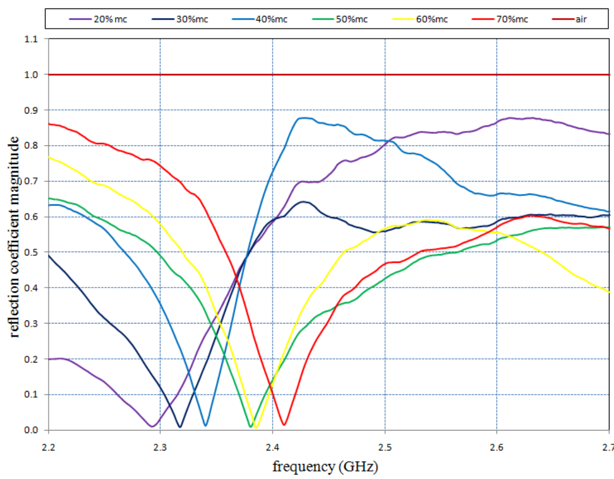

Fig 5. Variation of reflection coefficient magnitudes versus frequency for various moisture contents (%) from 20% to 70%.

Measurement of moisture content

The actual MC (wet basis) was obtained by microwave oven drying of sample at 70 ^{0}C for about 17 hours. During the drying process, the sample was kept at room temperature before weighing again to verify exact weight of dry latex. This step was repeated until the weight reading become constant and then the mean result of each sample were recorded. The MC of hevea latex was calculate in percentage as

$$MC = \frac{m_{wet} - m_{dry}}{m_{wet}} \times 100\% \quad (1)$$

where, m_{wet} and m_{dry} are the mass of hevea latex before dried and after dried, respectively.

Theoretical analysis of data

Measurement of reflection coefficient ($|\Gamma|$) illustrates impedance mismatch situation between a transmission line of impedance Z_0 and the terminal load impedance Z_i (Arai, 2001). The measured ($|\Gamma|$) from terminal impedance Z_i is defined as:

$$|\Gamma| = \frac{Z_i - Z_0}{Z_i + Z_0} \quad (2)$$

For a non-magnetic medium, the antenna modelling theorem (Burdette et al., 1980) can be expressed mathematically as

$$\frac{Z_i(\omega, \varepsilon^{'})}{\eta} = \frac{Z_i(n\omega, \varepsilon_0)}{\eta_0} \quad (3)$$

where, $\omega = 2\pi f$ is the angular frequency (radians), $\eta = \sqrt{\mu_0 / \varepsilon^*}$ is the complex intrinsic impedance of the dielectric medium, $\eta_0 = \sqrt{\mu_0 / \varepsilon_0}$ is the intrinsic impedance of free space, ε_0 and μ_0 are the free space permittivity and permeability, respectively, and $n = \sqrt{\varepsilon^* / \varepsilon_0}$ is the complex refractive index of the dielectric medium relative to that of air.

The input impedance as given in equation (3) for a short monopole antenna (λ/10 or less in length) is given by

$$Z(\omega, \varepsilon^*) = A\omega^2 \sqrt{\left(\frac{\varepsilon^{'}}{\varepsilon_0}\right)(1 - j\tan\delta)} + \frac{1}{jC\omega\left(\left(\frac{\varepsilon^{'}}{\varepsilon_0}\right)(1 - j\tan\delta)\right)} \quad (4)$$

Equation (4) can be replaced in the form of $Z = R + jX$ which reduced to two real equations to give

$$R = \frac{\sin 2\delta}{2\left(\frac{\varepsilon^{'}}{\varepsilon_0}\right)\omega C} \quad (5)$$

and

$$X = \frac{\cos^2 \delta}{\left(\frac{\varepsilon^{'}}{\varepsilon_0}\right)\omega C} \quad (6)$$

The parameters *R* and *X* are the real and imaginary components of the measured impedance, known as resistance and reactance while *C* is a constant of the probe known as capacitance. The values of input (terminal) impedance, Z_i in (7) were obtained using the values of both *R* and *X* from equation (5) and (6) while the value of *C* was obtained from (Tai, 1961).

$$Z_i = \sqrt{R^2 + X^2} \quad (7)$$

Fig 2. shows the variation of Z_i, *R* and *X* with length *l* of monopole antenna. While Fig. 3 shows the variation of complex relative permittivity with MC in hevea latex.

Sensitivity as used in this study is the rate of change in magnitude of reflection coefficient ($|\Gamma|$) respect to moisture content (MC). The gradient of the graph is simply explained by the following equation:

$$\text{Sensitivity} = \frac{d(|\Gamma|)}{d(MC)} / (\%) \quad (8)$$

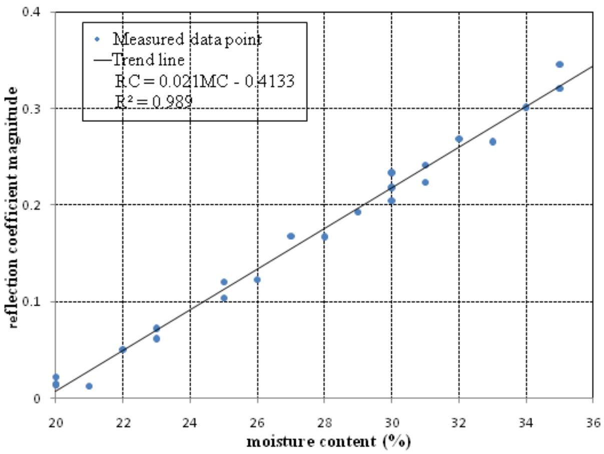

Fig 6 (a). Variation of reflection coefficient magnitudes versus moisture contents (MC) from $\left(20\% \leq MC < 40\%\right)$

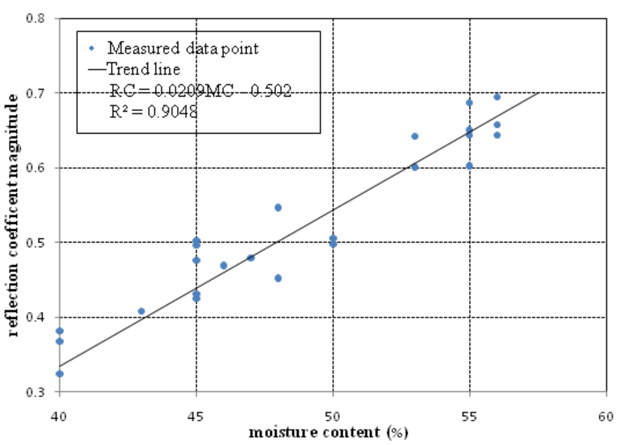

Fig 6 (b). Variation of reflection coefficient magnitudes versus moisture contents (MC) from $\left(40\% \leq MC \leq 60\%\right)$

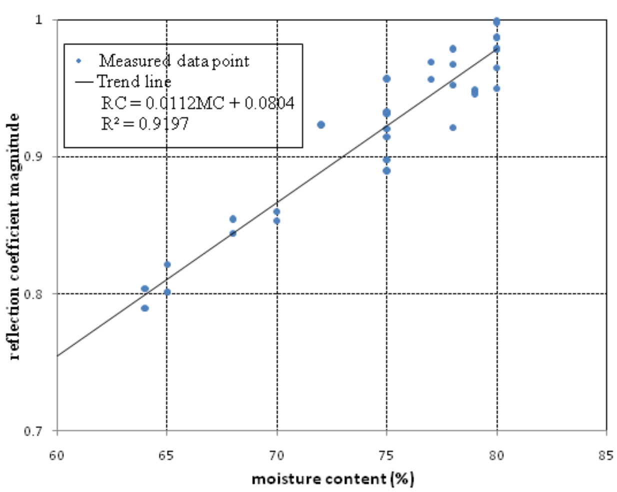

Fig 6 (c). Variation of reflection coefficient magnitudes versus moisture contents (MC) from $\left(60\% < MC \leq 80\%\right)$

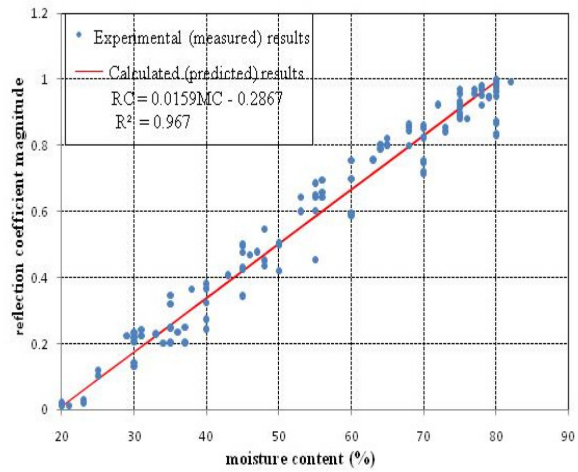

Fig 7. Variation of reflection coefficient magnitude versus moisture contents from 20% to 80% for measured and calculated results

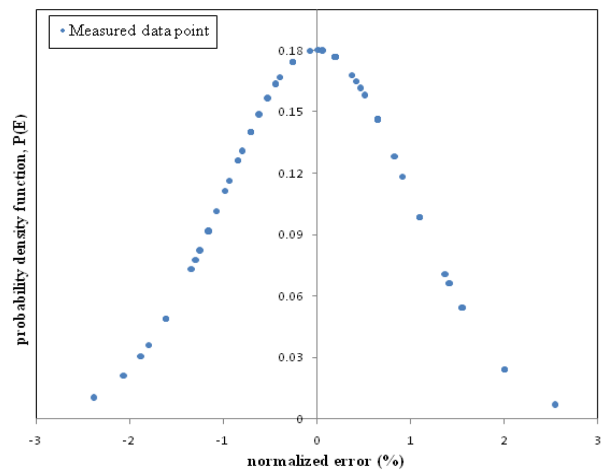

Fig 8. Variation of probability density function versus normalized error during moisture content determination in hevea latex

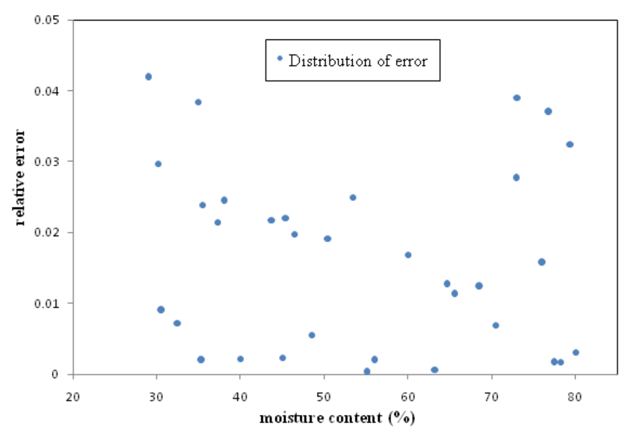

Fig 9. Variation of relative error distribution versus moisture content (%) in hevea latex from 20% to 80%

Whereby the linearity defines how well the device performs across a specified operating range and approximates a straight-line. Linearity error which also called non-linearity is the difference between actual and ideal straight line graph of MC behaviour given by

$$Linearity error = MC_{ideal} - MC_{actual} \quad (9)$$

Whereby MC_{ideal} is the moisture content defined from ideal straight-line (calibration) equation and MC_{actual} is the measured moisture content from microwave drying oven. Probability density function (PDF) was used in this study to detect existence of systematic errors during measurement. A good result can be obtained if the probability density of error is normally distributed. Normal PDF can be calculated as follow:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{\left(x - \bar{x}\right)^2}{2\sigma^2}\right] \quad (10)$$

where, σ is the standard deviation or error, *x* and x bar are means error of MC, respectively.

Relative error is the difference between actual and predicted MC against the actual MC. It can be calculated as:

$$\text{Relative error} = \left|\frac{MC_{actual} - MC_{predicted}}{MC_{actual}}\right| \quad (11)$$

where, MC_{actual} is the measured moisture content from microwave drying oven, and $MC_{predicted}$ is the moisture content defined from calibration equation.

Conclusions

This paper successfully introduced a new and low cost monopole antenna for quick and accurate measurement of MC in hevea latex. The established performance characteristics for analysis of sensitivity and linearity, probability density of error and the mean relative error of the antenna during measurement provide the evidence for the suitability of this technique in determining the amount of MC in hevea latex. The technique used seems to be the best for determination of MC amount in hevea latex from 20% to 80% at a frequency of 2.30 GHz within the accuracy of 0.03 mean relative errors. But also the technique can be used for some other crops and agriculture products directly or by re-calibrating the sensor/antenna. This research suggests a continuation toward the use of this technique in other crop products with a new configuration. Since different crops have different properties (such as MC), then they need different permittivity models. This in turn will give different impedance values which requires detailed analysis on the relationship between impedance and moisture content.

Aknowldegements

The authors acknowledge the support from Malaysia Technical Cooperation Programme (MTCP) under Scholarship Division of Ministry of Higher Education Malaysia.

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