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Analysis and Optimal Design of a Microstrip Sensor for Moisture Content in Rubber Latex Measurement

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Abstract

The analysis and optimal design of a microstrip sensor for measuring the water content of rubber latex is described. The microstrip structure consists of one layer: substrate, protective layer and semi-infinite layer of wet medium. A functional relationship has been developed between the attenuation and the water content of the latex, and close agreement has been found between the computed and experimental results. A computer program has also been developed which optimizes the sensitivity for given water content. As well as the calculated values of attenuation and Dielectric Loss and dielectric constant and effective dielectric constant.

Keywords: microstrip sensor1, moisture content2, latex3

1 Introduction

Natural Rubber Latex is a cloudy, white liquid, similar in appearance to cow's milk which is produced by controlled cutting on the bark of the rubber tree and allowing the latex to exude into a collecting vessel over a period of hours collect it. The yield is approximately 70-80 gm of rubber tree or equivalent to 6 surgical gloves. In 1994 the world produces about 5.7 million tons of rubber, and most of the world's consumption goes to tires, footwear, gloves, rubber tread and foam. Typical compositions of freshly tapped natural rubber are 50-80% water, 18-45% rubber hydrocarbon and 2-5% non-rubber constituents. The basic components of non-rubber constituent (excluding water) are proteins, lipids, quebrachitol and inorganic salts [3]. The total concentration of inorganic salts is approximately 0.5% of which consist of potassium (0.12-0.25 %) and phosphate ions (0.25 %). Small percentage approximately 0.25% combinations of copper, iron, calcium, sodium and magnesium is also present. Recently, microwave technique has been used to determine the dry rubber content of fresh hevea latex [2].

2 Materials and Methods

A series of solutions of hevea rubber latex were prepared with the moisture content ranging from 20% to 84.7%. Freshly tapped latex was obtained from University Putra Malaysia field. Using standard oven drying method is the most famous way in determination of moisture content [2]. The simple calculation method to obtain the percentage of amount of true moisture content is:

$$moisture\ \text{content\%} = \frac{m_{\text{wet}} - m_{dry}}{m_{wet}} \times 100 \qquad (1)$$

Where m_{wet} is the mass before drying and m_{dry} is the mass after drying in the oven. Normally 0.3% - 0.6% ammonia gas is added to the sample to prevent the latex from being solidified. This process of drying may extent to several hours or days.

Moisture content of agricultural products is one of the most important parameters for determining quality of yield of agriculture. The optimum time for harvesting and potential for safe storage is required. It is also an important parameter in determining the market price because the moisture contents in agricultural products determine the value of the products. In the processing of some agricultural products such as grains for flour, other food products or animal feeds, moisture content in the materials is an important factor for efficient processing and achieving desired behavior of the desired high-quality products [6]. [8] Have also used microwave method to estimate the moisture content of agricultural products. In addition, the use of standard oven drying methods to measure moisture content in agricultural products require specific time periods at specified temperatures.

In twentieth century, microwave method was implemented in soil moisture detection [7], dehydration of fruit and heating [4], as well. In earlier time, many studies about the electrical resistance of vegetation have shown that electrical resistance is correlated with moisture content. The high correlation between material permittivity and water content of the material leads the usage of microwave method in sensing moisture content [5].

In this work we used Professional Network Analyzer (PNA), model N5230A, Agilent Technologies, the PNA device is used for all the microwave measurement (magnitude and phase of S_{11}, S_{21}, S_{12} and S_{22}) with frequency between 2 GHz to 3 GHz. In fact, the microstrip circular ring needs a low frequency not high frequency, because the low one is enough to make the electromagnetic field in the first and second halves of the microstrip circular ring, to take the electromagnetic field from the first half and the maximum field points in both feed lines and the ring are collinear. The same procedure is used for the microstrip linear circuit. The measurement of dielectric properties of hevea latex in this range of frequencies was done by using the two sensors used in our work (microstrip linear path and circular ring) connected by an open ended coaxial-line probe which was coupled to the PNA. All measurement was done at room temperature 27 ˚C and all the samples used in our experiment are dried by 70 ˚C oven temperature.

3 Dielectric Loss in Microstrip

The propagation of the electromagnetic wave in a dielectric material with a complex relative permittivity $\varepsilon_r = \varepsilon' - j\varepsilon''$ is usually characterized by attenuation and phase shift as seen in the following relationship [1].

$$\gamma = \alpha + j\beta = \frac{2\pi}{\lambda_o}(\varepsilon' - j\varepsilon'')^{\frac{1}{2}} \tag{2}$$

Where ε' is the dielectric constant and ε'' is the loss factor, α is the attenuation constant, β is the phase constant and λ_o is the free space wavelength. Equating the real parts of eq. (2) gives the general expression for the dielectric loss α_d in dB/m

$$\alpha_d = \frac{17.37\pi}{\lambda_o}\left[\frac{\varepsilon'}{2}\left(\sqrt{1+\tan^2\delta} - 1\right)\right]^{\frac{1}{2}} \tag{3}$$

where $\tan\delta = \dfrac{\varepsilon''}{\varepsilon'}$ is a loss tangent. When $\tan^2\delta << 1$, the series expansion gives

$$\alpha_d = \frac{8.686\pi}{\lambda_o}\sqrt{\varepsilon'}\,tan\delta \tag{4}$$

or

$$\alpha_d = \frac{27.3\sigma}{\lambda_o \omega \varepsilon_o \sqrt{\varepsilon'}} \tag{5}$$

where ω is the angular frequency and δ is the conductivity of the medium eq.(4) represents the dielectric loss of TEM mode lines. In the case of microstrip, several investigators have replaced $\tan\delta$ and ε' in eq. (5) by the effective value of loss tangent $\tan\delta_{eff}$ and dielectric constant ε_{eff}. In this way, the effect of non-homogeneity of the medium can be taken into consideration. Therefore eq. (5) becomes

$$\alpha_d = \frac{8.686\pi}{\lambda_o}\sqrt{\varepsilon_{eff}}\,\tan\delta_{eff} \tag{6}$$

Alternatively, eq. (6) can be written as

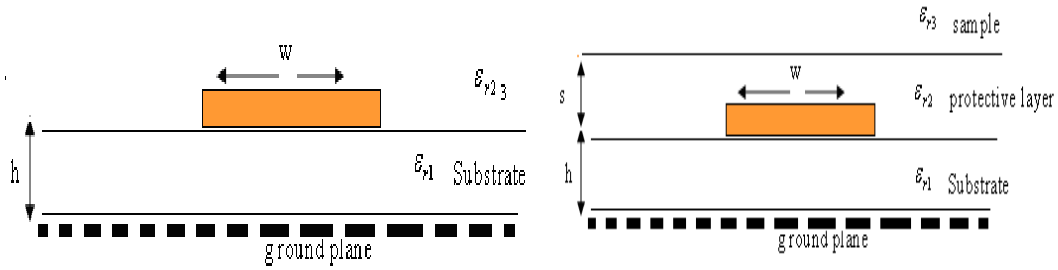
$$a_d = \frac{27.3\delta_{eff}}{\lambda_o w \varepsilon_o \sqrt{\delta_{eff}}} \quad (7)$$

Returning to the case of propagation along the double- covered microstrip with semi-infinite layer, the effective conductivity and permittivity can be written in terms of filling fraction q occupied by each dielectric as

$$\delta_{eff} = q_1\delta_1 + q_2\delta_2 + (1 - q_1 - q_2)\delta_2 \quad (8)$$

$$\varepsilon_{eff} = q_1\varepsilon_{r1} + q_2\varepsilon_{r2} + (1 - q_1 - q_2)\varepsilon_{r2} \quad (9)$$

Where σ_1, σ_2 and σ_3 are the conductivity of the substrate, protective layer respectively and q_1, q_2 are the dielectric filling fractions. These filling fractions maybe calculated by transforming the three layers of the microstrip structure of Figure 1(a) to two layers structure shown in Figure 1(b). Both structures have the same effective dielectric constant ε_{eff}. The effective dielectric constant of the upper layer of the two layers structure may be obtained by using 'regular Falsie' root seeking method



(a) **(b)**

Figure 1: Semi-infinite (a) Double-Covered microstrip (b) Covered microstrip with an effective dielectric Constant of the Upper Layer ε_{23}

Knowing the values of ε_{r23} , we can write

$$\varepsilon_{eff} = q_1\varepsilon_{r1} + (1 - q_2)\varepsilon_{r23} \quad (10)$$

and

$$q_1 = \frac{\varepsilon_{eff} - \varepsilon_{r23}}{\varepsilon_{r1} - \varepsilon_{r23}} \quad (11)$$

from eqs. (7), (8) and (9), q_2 may be obtained

$$q_2 = \frac{(\varepsilon_{r3} - \varepsilon_{eff})(\varepsilon_{r3} - \varepsilon_{r1})}{\varepsilon_{r32}} \qquad (12)$$

Substituting eqs. (7), (8) and (9) in eq. (5) replacing $\lambda_0 = c/f,$ we have dielectric loss in the semi-infinite double-covered microstrip structure in db/m as:

$$\alpha_d = \frac{27.3 f}{c\sqrt{\varepsilon_{eff}}}\left[q_1\varepsilon_{r1} \tan\delta_1 + q_2\varepsilon_{r2} \tan\delta_2 + (1 - q_1 - q_2)\varepsilon_{r3} \tan\delta 3\right] \qquad (13)$$

Eq. (13) gives useful information on the loss that can be expected for a particular geometrical configuration.

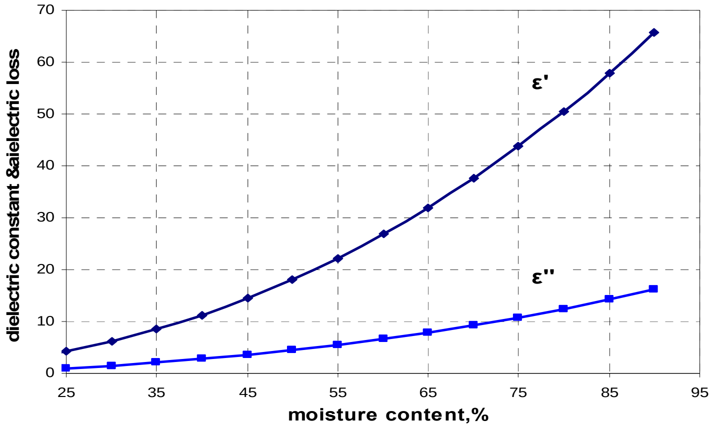
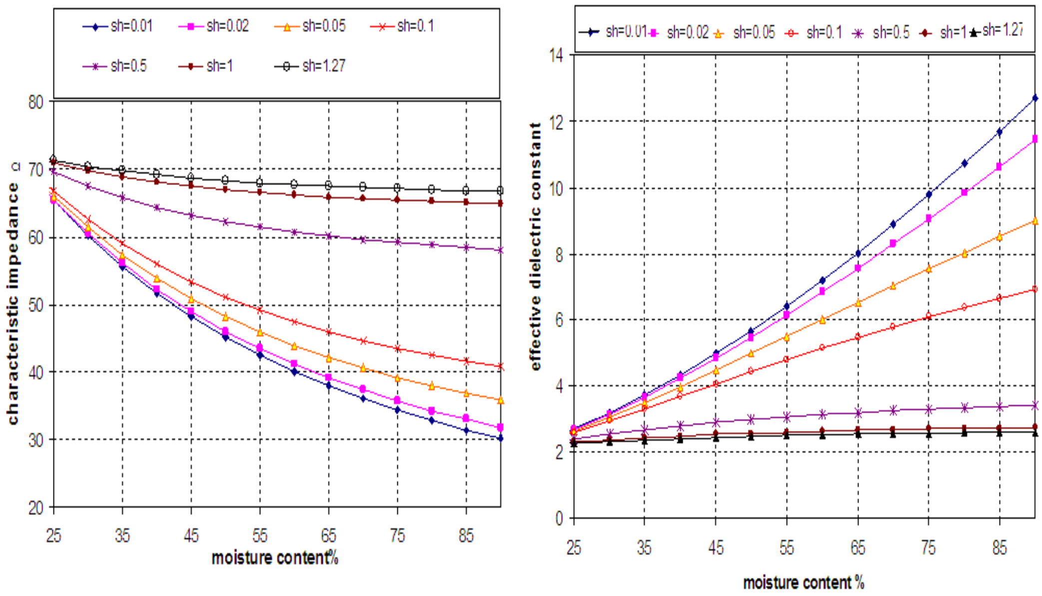


Figure (2) Relationship between dielectric constant ε' and Dielectric Loss ε''of hevea rubber latex versus moisture content% at 27 °C when frequency (2.4) GHz

Figure 2 shows the variation of ε' and ε'' with moisture content at frequency (2.4) GHz. Throughout these figures ε' demonstrates a linear relationship with moisture content and is almost unaffected by the type of solutions. However ε'' shows a spreading in its value which depends very much on the conducting phases in the solution and ε"is slowly decreased as moisture content increases.

4 Effect of Moisture Content on Characteristic Impedance Z_0, and Effective Dielectric Constant ε_{eff}

The change in permittivity of the mixture with moisture content means that the Z_0 and ε_{eff} also change with moisture content as shown in Figure 3a and Figure 3b. The figures also show that both Z_0 and ε_{eff} are drastically affected by the thickness of the protective layer for range of moisture content of interest. It is clear that the impedance is matched to 50 Ω at 84.7% moisture content with s/h = 0.05. Different the impedance matching alone is not enough to determine the best ratio of s/h. The sensitivity of the sensor must also be considered.



(a) (b)

Figure 3: (a) Relationship between characteristic Impedance with moisture content (b) Relationship between effective dielectric constant with moisture content % for rubber latex at various s/h ratios

5 Effect of moisture content for rubber latex on attenuation (dB) with various s/h ratios

The below Figure 4 shows the variation in attenuation with moisture content for different thickness of the covering layer of the exposed section of the microstrip sensor with ε_{r1}= 2.2 and w/h = 1.467. The sensitivity of the sensor which is the slope of the attenuation curve is shown to be drastically reduced as s/h increases. Although the sensor at s/h = 0.02 does not show the highest sensitivity, it has the advantages of lower attenuation level and thicker protective layer compared to s/h = 0.01. Furthermore the attenuation curves at s/h = 0.02 is still linear in the range of 40% to 60% moisture content with mean sensitivity of 0.03 dB% m.c. Thus this ratio of s/h provides the best compromise between the sensitivity and level of attenuation required for maximum performance of the sensor

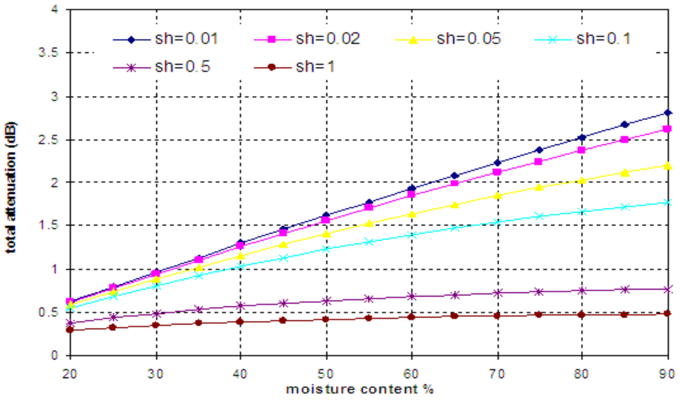


Figure 4: Variation in attenuation (dB) with moisture content % of rubber latex at various s/h ratios

6 Relationship between moisture content and attenuation of Microstrip circular ring sensor and Microstrip linear path sensor

In this section, the two sensors were used to estimate the moisture content of rubber latex from 20% to 84.7% of moisture content. There are two ways to predict moisture content of rubber latex. There are using attenuation measurement and Q-factor measurement. Once we can predict the moisture content of rubber latex, it will help the factory to recognize the purity of rubber latex. The prediction of moisture content for rubber latex was done at frequency 2.44 GHz since the resonant frequency of air (without sample). The attenuation of rubber latex was calculated using

$$Attenuation\,(\mathrm{dB}) = 20\log_{10}\left(\frac{S_{21\,with\ sample}}{S_{21\,\mathrm{without\ sample}}}\right) \qquad (14a)$$

or

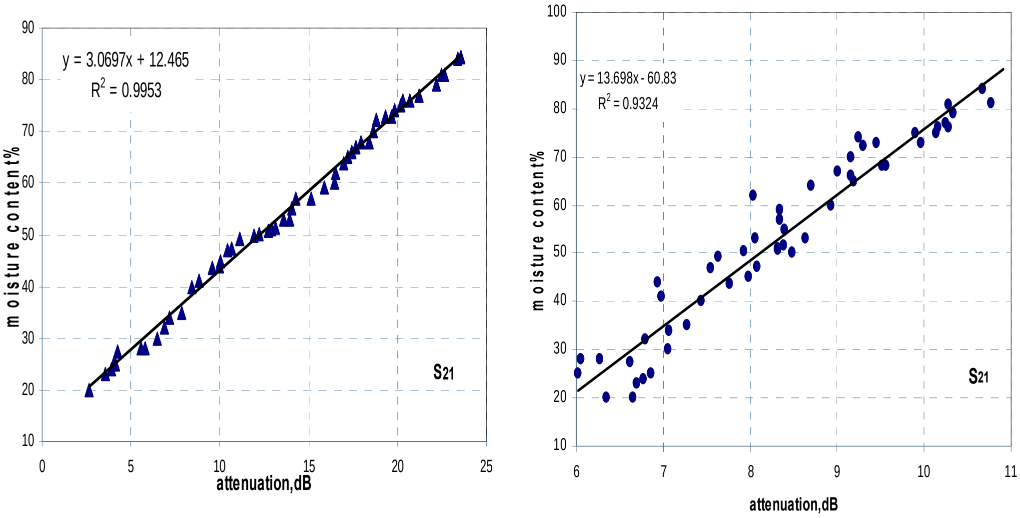
$$Atenuation\,(\mathrm{dB}) = \mathrm{S}_{21}(dB)_{with\ \mathrm{sample}} - S_{21}(dB)_{without\ \mathrm{sample}} \qquad (14b)$$

The Equation (14a) and (14b) are used to calculate the attenuation of rubber latex. The Equation (14a) was used when the magnitude of S_{21} is in linear form while the Equation (14b) was used when the magnitude of S_{21} is in decibel (dB) form. Figure 5(a) and 5(b) show that the relationship between moisture content and attenuation for microstrip circular ring sensor and microstrip linear path sensor respectively. It was found that the relationship between moisture content and attenuation is almost linear for both sensors and can be represented as:

$$MC = 3.0697\,A + 12.465 \qquad (15a)$$

$$MC = 13.698A - 60.83 \tag{15b}$$

Where the Equation (15a) and (15b) represents the empirical equation for microstrip circular ring and microstrip linear path sensor respectively for attenuation measurement.



(a) (b)

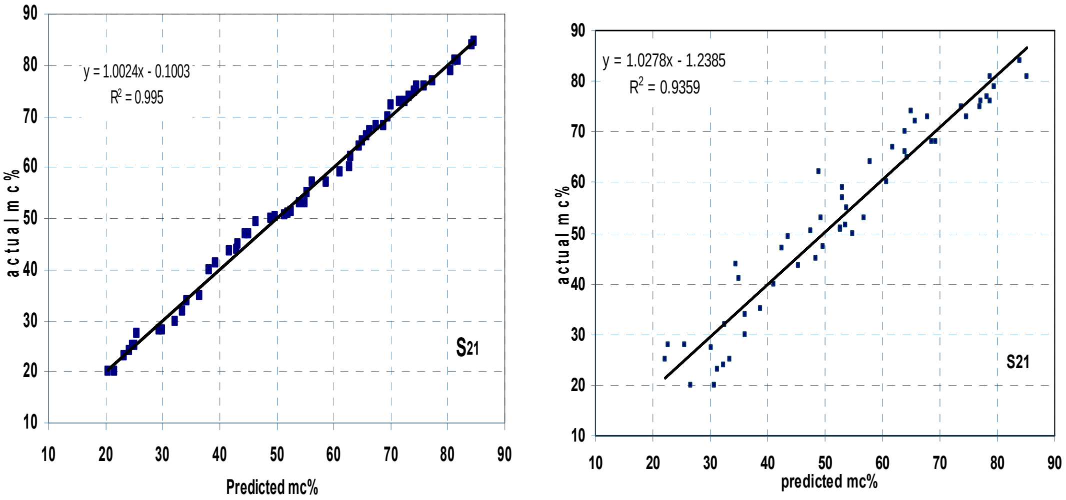
Figure 5: Relationship between moisture content and attenuation (a) Microstrip circular ring sensor (b) Microstrip linear path sensor.

For attenuation measurement, the S-parameter measurement was involved is only S_{21} measurement. It was clearly seen that the microstrip linear path sensor shows a good sensitivity compared to microstrip circular ring sensor with 13.698 %/dB and 3.0697 %/dB respectively.

7 Reliability of the Calibration Equation

The empirical equation for predicting amount of moisture content was established as shown in Equation 15(a) and (b). The validation process has been done to validate these equations. The validation has been made by new measurement and was carried out by using new sample of rubber latex with a variety of moisture contents. The comparison between predicted and measured moisture contents is shown in Figures 7(a) and (b) by Equation 15(a) and (b), respectively. This was followed by relative error between actual and predicted moisture content. Actual moisture contents were found by using conventional oven method. The equations 15(a) and (b) are valid only for moisture content between 20% and 84.7% and frequency 2.44 GHz. The errors between actual and predicted moisture content were calculated by using

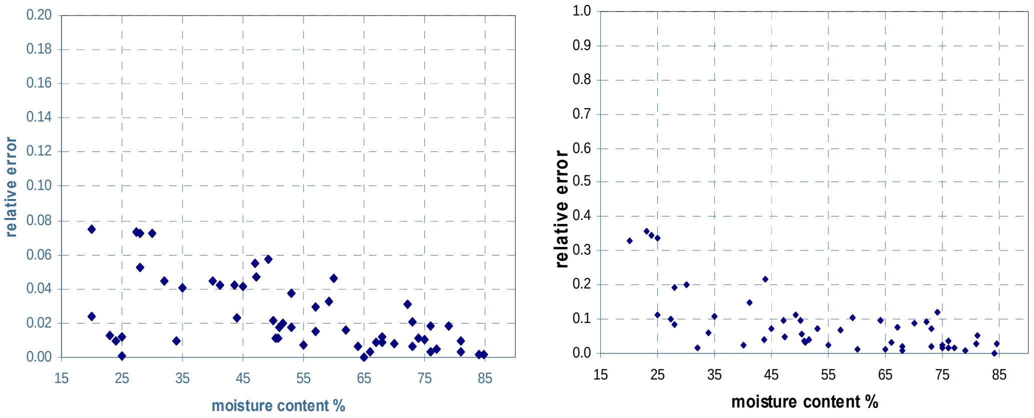
$$\text{relative error} = \left|\frac{\text{Actual MC} - \text{predicted MC}}{\text{actual MC}}\right| \times 100 \tag{16}$$



(a) (b)

Figure 6: The comparison between actual and predicted moisture content, MC of rubber latex (a) Equation (15a) (b) Equation (15b)

Figures 7(a) and (b) show relative errors for predicted moisture content for attenuation measurement using Equation 15(a) and (b), respectively. It was found that the mean relative errors for microstrip circular ring and microstrip linear path sensor are 0.023 and 0.095, respectively. The microstrip circular ring sensor shows a good performance with relative error below 8% for all moisture contents compared to microstrip linear path sensor.



(a) **(b)**

Figure 7: Relationship between relative errors and moisture content for attenuation measurement (a) Microstrip circular ring sensor (b) Microstrip linear path sensor

8 Sensor Characteristic

The sensor characteristic is a critical interest when making a selection of sensors for a given application and is the one among the important parts in measurement. There are two parts of sensor characteristic that will be discussed in this section. The first part is a linearity and sensitivity while the other part is a Probability Density Function (PDF). These two sensor characteristic is discussed in detail for both microstrip circular ring and linear path sensor in the next sections

8.1 Linearity and Sensitivity

Linearity error which is also called non-linearity can be defined as a difference between actual and ideal linear line path as

$$Linearity \quad \text{error} = \text{MC}_{\text{ideal}} - MC_{actual} \qquad (17)$$

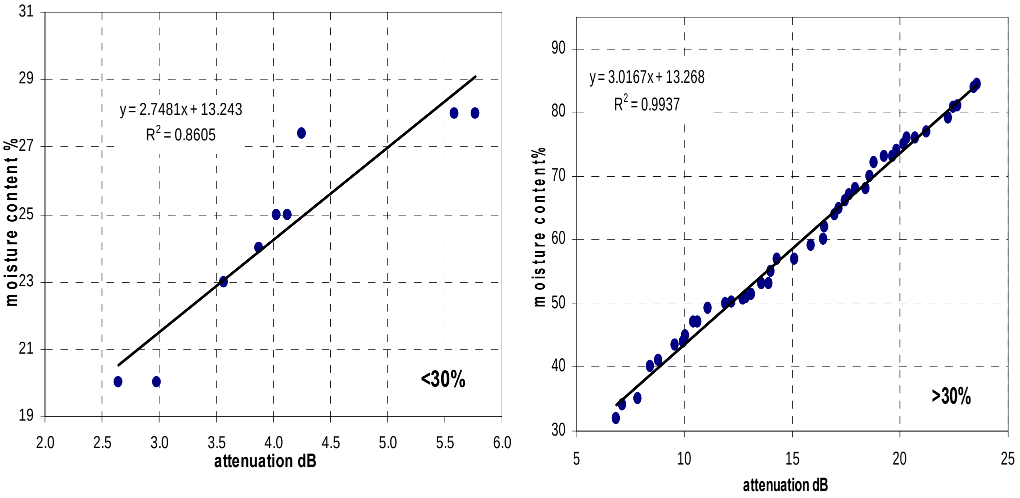
Whereas, the MC_{ideal} is the moisture content define from ideal linear path equation and MC_{actual} is measured moisture content. Sensitivity is the rate of change of moisture content with respect to attenuation, which is the gradient of the graph

(Bentley, 1943). In this section, the analysis of linearity and sensitivity is discussed in two part of moisture content. The first part is less than 30% and the second part is greater than 30% of moisture content.

Figures 8(a) and (b) show a relationship between moisture content and attenuation for microstrip circular ring sensor for moisture content which is less and greater than 30% respectively. It was clearly seen that the moisture content greater than 30% shows a good relationship compared to less than 30% of moisture content whereby the mean linearity errors are 0.818 and 1.03 for moisture content less and greater than 30%, respectively. This is due to the bound water effect inside the rubber latex which caused non-uniform moisture content distribution inside the sample.

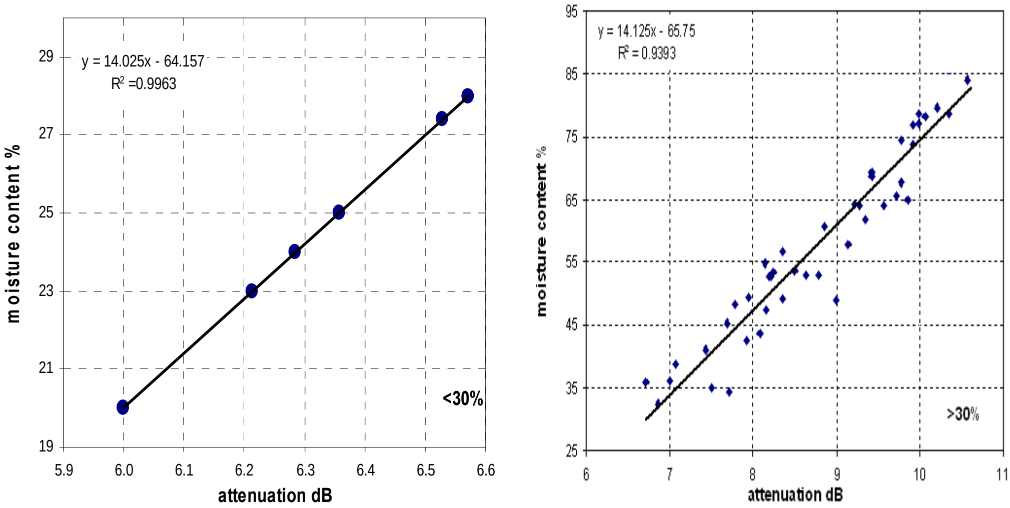
The relationship between moisture content and attenuation for microstrip linear path sensor was shown as illustrated in Figures 9(a) and (b). The former shows,

moisture content less than 30% while the latter shows moisture content greater than 30%. It was clearly shown that the moisture content greater than 30% has a good performance with smaller mean linearity error and higher sensitivity compared to less than 30% moisture content. The mean linearity error for moisture contents less and greater than 30% are 5.825 and 3.7, respectively. While the sensitivity of microstrip linear path sensor for moisture content less and greater than 30% are 14.025 and 14.125 respectively.



(a) (b)

Figure8: Relationship between moisture content attenuation for microstrip circular ring sensor (a) Moisture content <30% (b) Moisture content > 30%



(a) **(b)**

Figure9: Relationship between moisture content attenuation for microstrip linear path sensor (a) Moisture content <30% (b) Moisture content > 30%

8.2 Probability density Function (PDF)

Probability density function is a function that describes the relative likelihood for this random variable to occur at a given point in the observation space. The graph of normal probability density function show that where is the higher probability density of error occur in measurement. Normal probability density function can be calculated using

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\bar{x})^2}{2\sigma^2} \right] \tag{18}$$

where σ represents a standard derivation, x and $\bar{x}$ represent error and mean error of moisture content, respectively.

Figures 10 show the probability density function versus normalized error of moisture content in hevea rubber latex for microstrip circular ring and linear path sensor, respectively. The mean error for moisture content measured by using microstrip circular ring and linear path sensor are 0.023 and 0.98, respectively. The mean error was obtained by calculation using

$$Mean\ \ Error = \left| \frac{MC_{actual} - MC_{predicted}}{number\ \ of\ \ error} \right| \tag{19}$$

Where $mc_{predicted}$predicted moisture is content obtained from Equation 15 (a) and (b) for microstrip circular ring and linear path sensor. The actual moisture content mc_{actual} was found using standard oven method as previously discussed in Chapter four. The error was normalized in the Figure 5.16 using

$$\text{Normalized Error} = \frac{x - \bar{x}}{\sigma} \qquad 20$$

where σ represents a standard deviation, x and $\bar{x}$ is represent an error and mean error of moisture content, respectively.

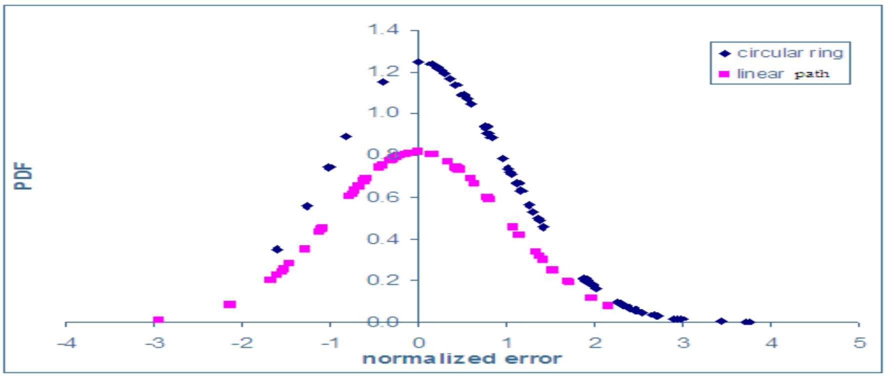


Figure10: Probability Density Function versus normalized error of moisture content for Microstrip circular ring sensor and Microstrip linear path sensor.

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