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A Preliminary Study on the Dielectric Properties of a Malaysian "Rock" Saturated with Water and Crude Oil

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Abstract: A preliminary study on the dielectric properties of quartz crystal aggregates taken from Klang Gate's quartz ridge was conducted. The basic theory, the experimental set-up and the method of investigation are outlined. The dielectric properties of dry quartz crystal aggregates and two varieties of Malaysian crude oils were investigated. Saturating the quartz aggregate with crude oil or water has been found to increase the dielectric permittivity of the specimen. The effect of varying the frequency of the incident x-band microwave on the permittivity of the specimen was also investigated. Saturating the specimen with crude oil seem to have an additive effect on the dielectric permittivity of the quartz crystal aggregates in the frequency range employed in this experiment.

INTRODUCTION

The dielectric properties of materials are important for numerous applications. These include the use of selective dielectric heating of insect in infested grains and the determination of moisture content of cereal grains. In this preliminary investigation, we are trying to study the dielectric permittivity of a Malaysian "rock", and the effect of saturating this rock with distilled water or crude oil. The effect of changing the microwave frequency on the dielectric permittivity was also investigated.

The dielectric permittivity of any material can be represented as;

$$\begin{aligned}\varepsilon_r &= \varepsilon_r' - j\,\varepsilon_r'' \\ &= \varepsilon_r'(1 - j\tan\delta) \qquad (1)\end{aligned}$$

where ε_r' is the real part of the complex permittivity called the dielectric constant and ε_r'' is the imaginary part of the complex permittivity called the dielectric loss factor.

The system of a slotted-waveguide section after Nelson (1972) was used to obtain the information from which the values of dielectric permittivity of the materials were calculated. The values of dielectric permittivity were calculated by a computer.

BRIEF PRINCIPLES OF THE MEASUREMENT METHOD

Figure 1 represents the short-circuited end of a rectangular waveguide containing a sample of length d in contact with the short circuit. The incident wave travelling in the positive Z direction and the reflected wave combined to form standing waves in the waveguide. Figure 2 shows a voltage standing wave pattern where it can be noted that the wavelength in the sample is shorter than that of the empty part of the waveguide. In Figure 3, the standing wave pattern with and without sample at the end of the

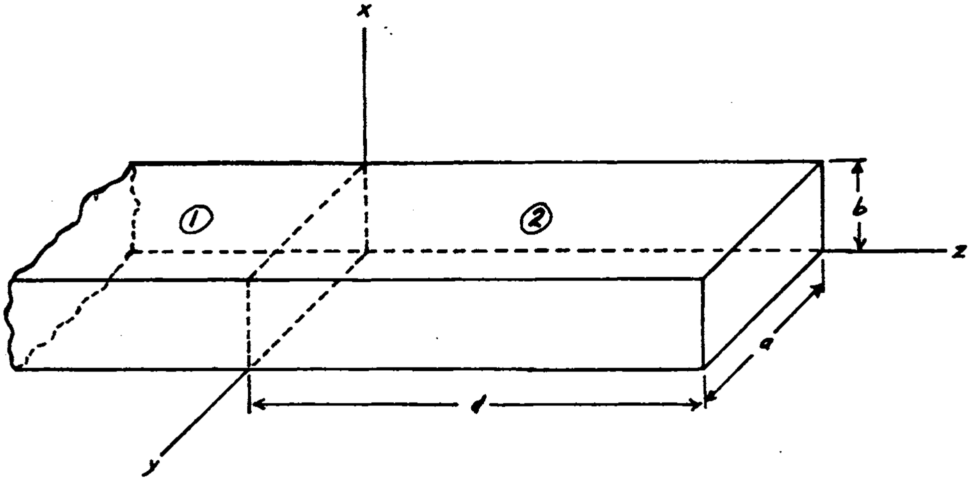

Fig. 1. Short-circuited rectangular waveguide with dielectric sample of length d at the shorted end.

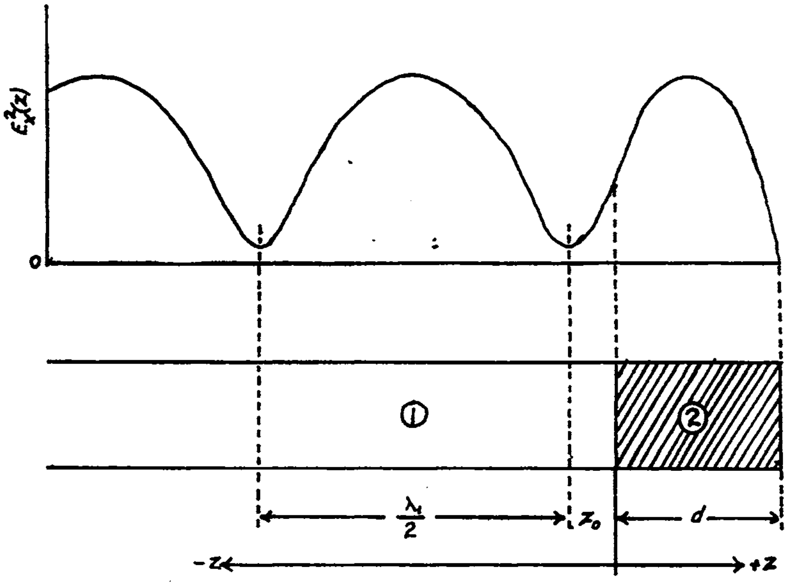

Fig. 2. Relationship of voltage standing-wave pattern to shorted waveguide with dielectric sample.

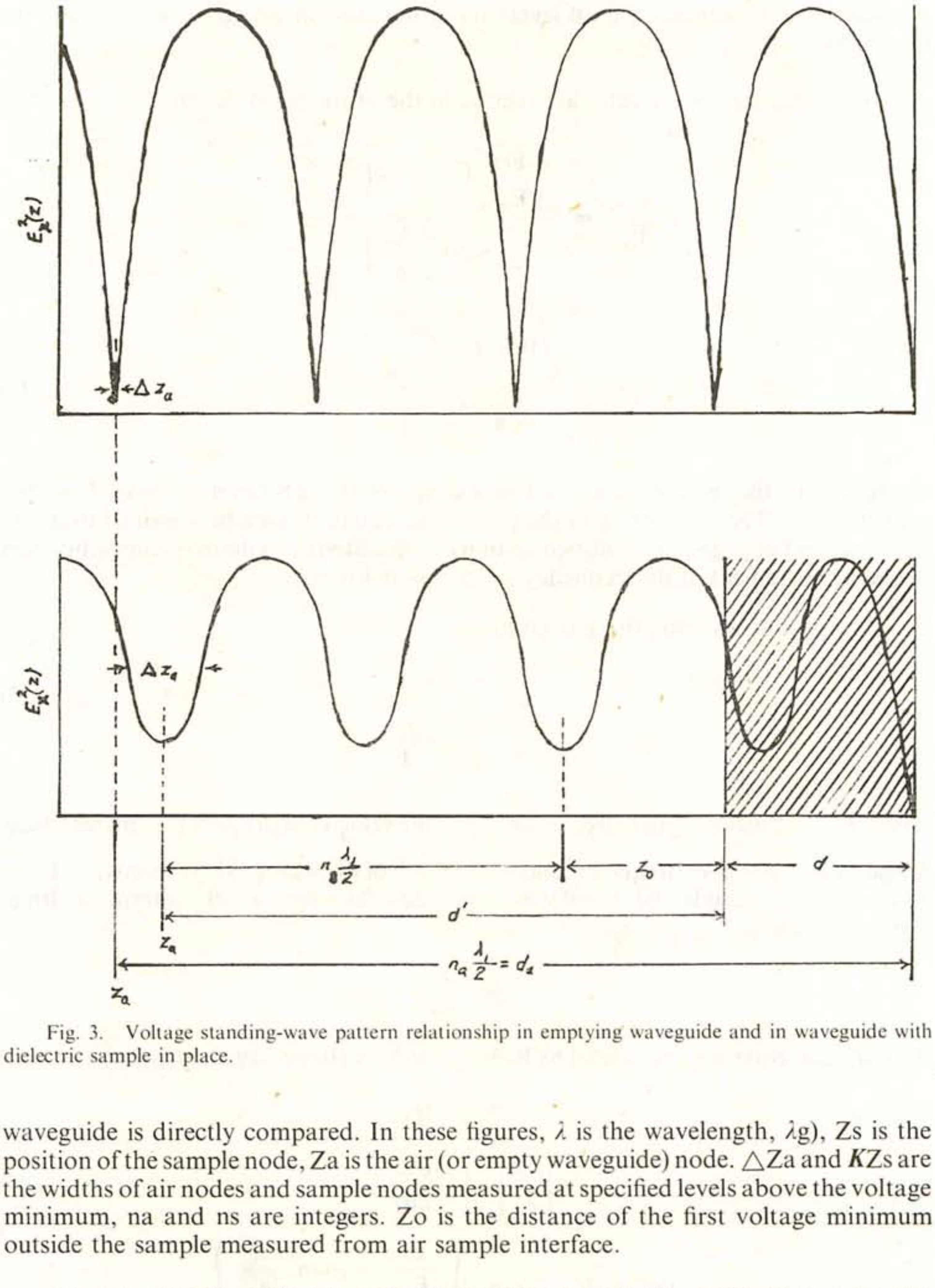

Fig. 3. Voltage standing-wave pattern relationship in emptying waveguide and in waveguide with dielectric sample in place.

waveguide is directly compared. In these figures, λ is the wavelength, λg), Zs is the position of the sample node, Za is the air (or empty waveguide) node. $\triangle$Za and ***K***Zs are the widths of air nodes and sample nodes measured at specified levels above the voltage minimum, na and ns are integers. Zo is the distance of the first voltage minimum outside the sample measured from air sample interface.

To calculate the dielectric permittivity of a sample, we need to know Za, Zs, standing wave ratio with and without sample, the length of the sample, d, and either the frequency or the guided wavelength. The standing—wave ratios are obtained from the measured $\triangle Z$ values and the dB levels above the minium where the node width are measured.

The standing—wave ratio are related to the other quantities by;

$$\frac{E_{max}}{E_{min}} = \frac{\sqrt{\left[\frac{E(z)}{E_{min}}\right]^2 - \mathrm{Cos}^2\left(\frac{\pi \triangle z}{\lambda g}\right)}}{\mathrm{Sin}\left(\frac{\pi \triangle z}{\lambda g}\right)}$$

$$= \frac{\sqrt{Pr - \mathrm{Cos}^2\frac{(\pi \triangle z)}{\lambda g}}}{\sin\left(\frac{\pi \triangle z}{\lambda g}\right)} \tag{2}$$

where Pr is the power ratio corresponding to the dB level employed in the measurement. The value of λg in the preceeding equation may be obtained from the measurement of $\frac{1}{2}\lambda g$ with the slotted section or calculated from the frequency employed in the measurement, if the frequency is accurately known.

The guided wavelength λg is given by;

$$\lambda g = \frac{\lambda_0}{\sqrt{1 - \frac{(fc)}{f}}} \tag{3}$$

where λ_0 is the wavelength in free space $= \frac{c}{f}$, c, the velocity of propagation in free space, fc and λc are the cut off frequency and wavelength of the waveguide respectively. For a rectangular waveguide, the cut off wavelength $\lambda c = 2a$, where a is the internal width of the waveguide. fc is given by;

$$fc = \frac{c}{\lambda c} \tag{4}$$

The original equations presented by Robert and Von Hippel (1946) may be written as;

$$\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$$

$$= \left[\frac{\lambda_0}{\lambda_c}\right] - \left[\frac{\gamma_2 d \lambda_0}{2\pi d}\right]^2 \tag{5}$$

$$\text{and } \frac{\tanh \gamma_2 d}{\gamma_2 d} = -\frac{j\lambda g}{2\pi d}\left\{\frac{\frac{E_{min}}{E_{max}} - j\tan\frac{2\pi z_0}{\lambda g}}{1 - j\frac{E_{min}}{E_{max}}\tan\frac{2\pi z_0}{\lambda g}}\right\} \tag{6}$$

The values of $\gamma_2 d$ used in equation 5 have to be extracted from equation 6. The value of $\frac{E_{min}}{E_{max}}$ can be obtained from equation 2, λg from equation 3, z_0 and d can be obtained from the experiment. The right hand side of equation 6 can be reduced to a complex number Ce^{js} and $\gamma_2 d$ may be obtained from charts of complex hyperbolic function, or calculated from a series of approximation. (Nelson et al., 1972)

EXPERIMENTAL SET-UP AND PROCEDURE

The schematic diagram of the experimental set up is as shown in Figure 4. The microwave generated by the klystron travels along the waveguide and passes through the sample. When it passes through the sample it suffers attenuation. At the end of the waveguide it gets reflected. Standing wave pattern forms when the reflected wave superimposes on the incoming wave. The voltage of the standing wave was measured by the V.S.W.R. meter. For taking up the readings, initially, the variable attenuator was set as 0 dB and the empty sample holder attached to the end of the slotted section. The V.S.W.R. meter was adjusted to provide a mid-scale or higher reading on the V.S.W.R. meter when the probe is positioned at the voltage minimum. The V.S.W.R. readings were noted and the precision attenuator was adjusted to the required dB levels, for the measurement of node width. The V.S.W.R. meter readings will drop as the attenuation is increased. The probe is then moved carefully to bring back the V.S.W.R. reading to the noted readings on both sides of the voltage minimum. The two air node positions were recorded along with the frequency and the dB level employed.

This similar procedure was followed when the specimen was placed in contact with the short-circuited end of the waveguide.

PREPARATION OF SAMPLE

The rock specimens were cut into rectangular blocs with dimensions approximately 3.0x2.3x1.02 cm^3. The blocks were polished on the sides to fit the

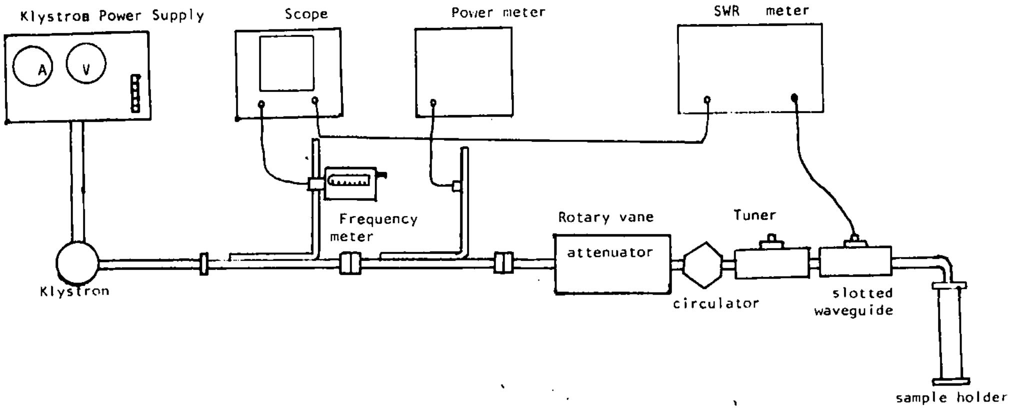

Fig. 4. Schematic diagram of the experimental set-up for short-circuited waveguide measurement of dielectric properties.

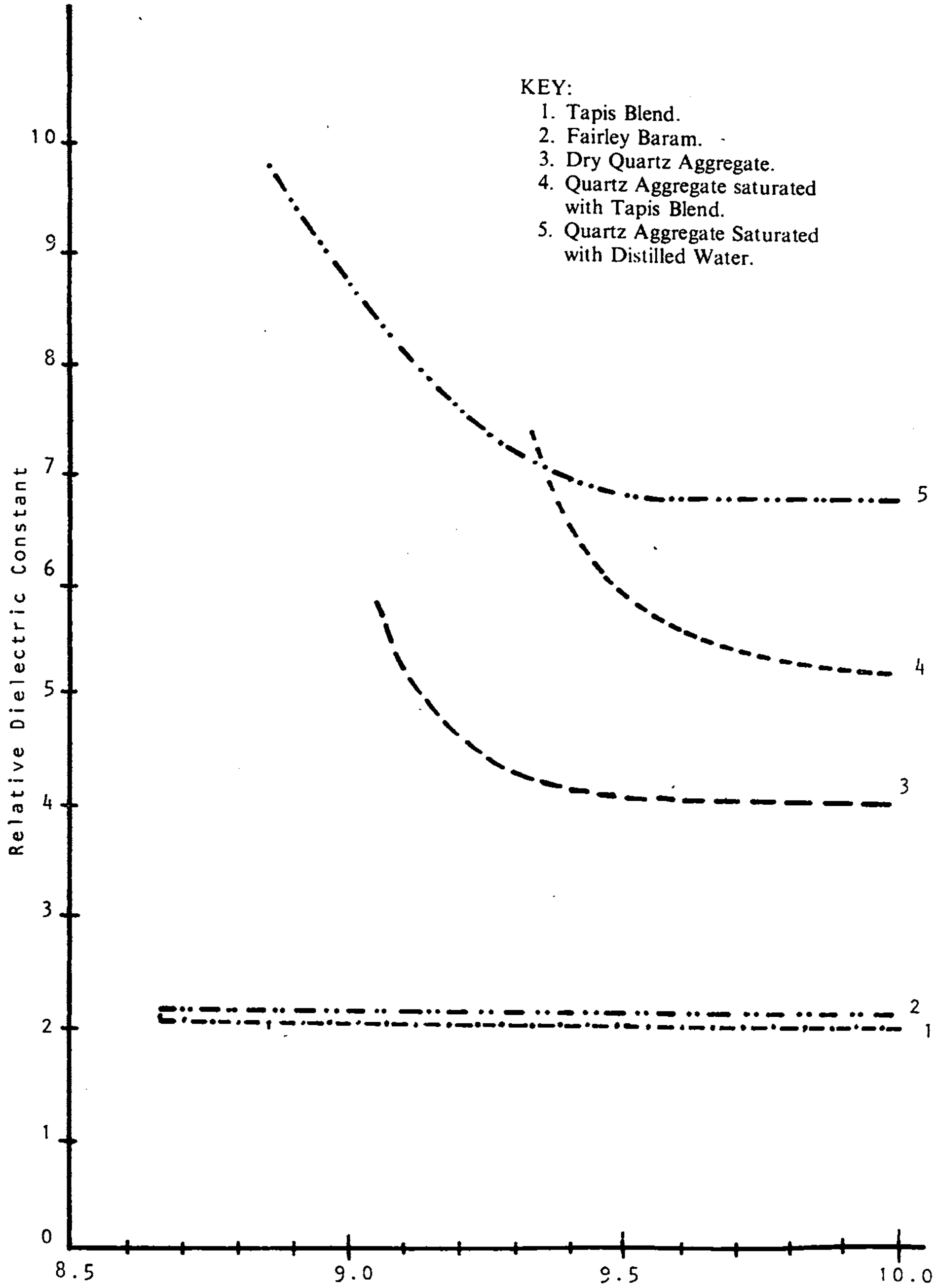

Fig. 5. Variation of Relative Dielectric Constant against the frequency of incident microwave.

internal dimensions of the waveguide which are 22.86 mm x 10.16 mm. The specimens were saturated with distilled water or crude oil for 16 hours before the measurements were performed. The degree of saturation of the samples were determined by comparing the weight of the dry samples and the saturated samples.

RESULT AND DISCUSSION

There is only a limited number of work carried out on the determination of dielectric properties of rocks at microwave frequencies. However, numerous references exist in the values of dielectric properties of rocks and other materials at lower frequencies. This may be due to the fact that waves with higher frequencies suffer severe attenuation when passing through a solid medium such as rock.

The present study, involved the relative dielectric permittivity of rocks at microwave frequency and the effect of saturating the rocks with water and crude oil. Table 1, 2, 3, 4 and 5 shows the results obtained. These results are depicted in graphical form in Figure 5.

From Figure 5, it can be seen that the relative dielectric permittivity of Fairley Baram (a crude oil sample from Sabah) is slightly higher than that of the Tapis Blend (a crude oil sample from off coast, Trengganu). Both crude oils maintain a constant relative dielectric permittivity throughout the frequency range employed in this experiment. The dielectric permittivity of the quartz aggregate, both dry and oil or water saturated, decreases with frequency, even though the values of the relative dielectric permittivity differs in the three cases. The values of the dielectric permittivity appears to be constant at the higher end of the frequency spectrum.

Saturating the rock specimens with oil or water seems to have an additive effect on the relative dielectric permittivity. This is to be expected. The same effect occurs in the lower frequency range.

TABLE 1

SHORT-CIRCUITED WAVEGUIDE MEASUREMENT FOR DIELECTRIC PROPERTIES

Sample	Frequency GHz	Air node readings mm		Sample node readings mm		Sample length mm	dB level		Relative dielectric constant
							Air	Sample	
Tapis Blend	8.85	105.3	100.8	105.4	104.3	30	9.6	0.6	2.066
	8.90	99.5	98.0	101.8	99.3	30	9.4	0.5	2.073
	8.95	95.4	93.5	96.9	96.0	30	9.5	6.8	2.070
	9.00	92.3	87.9	94.2	90.5	30	9.4	9.6	1.903
	9.30	68.6	67.6	70.3	69.2	30	9.3	8.1	2.047
	9.35	64.8	64.6	67.0	65.8	30	2.0	6.8	2.020
	9.775	61.2	60.5	62.1	61.3	30	8.3	4.5	2.023
	9.8	58.8	58.0	59.2	58.5	30	9.5	2.3	2.011
	9.95	50.3	48.8	49.9	48.7	30	9.0	6.3	2.001
	10.00	47.2	46.4	46.9	46.1	30	9.4	4.1	2.009

TABLE 2

SHORT-CIRCUITED WAVEGUIDE MEASUREMENT FOR DIELECTRIC PROPERTIES

Sample	Frequency GHz	Air node readings mm		Sample node readings mm		Sample length mm	db level		Relative dielectric constant
							Air	Sample	
Fairley	8.95	95.4	93.5	96.4	95.5	30	9.5	6.9	2.116
Baram	9.00	92.3	87.9	93.5	89.5	30	9.4	8.8	1.971
	9.30	68.6	67.6	69.3	68.3	30	9.3	4.6	2.115
	9.35	64.8	64.6	66.4	64.4	30	2.0	9.2	2.112
	9.40	62.0	60.6	62.2	61.3	30	9.4	4.3	2.113
	9.45	58.7	57.0	59.0	57.5	30	9.6	5.7	2.102
	9.50	55.2	53.7	55.1	54.0	30	9.5	4.5	2.097
	9.775	61.2	60.5	60.8	58.2	30	8.3	9.5	2.157
	9.80	58.8	58.0	57.1	55.9	30	9.5	4.4	2.118
	9.90	53.7	51.3	50.8	49.1	30	9.6	6.5	2.121
	9.95	50.3	48.8	47.5	46.4	30	9.0	4.6	2.121
	10.00	47.2	46.4	45.2	42.9	30	9.4	8.2	2.120

TABLE 3

SHORT-CIRCUITED WAVEGUIDE MEASUREMENT FOR DIELECTRIC PROPERTIES

Sample	Frequency GHz	Air node readings mm		sample node readings mm		Sample length mm	dB level		Relative Dielectric Constant
							Air	Sample	
Quartz	8.90	99.5	98.0	112.1	107.3	35.3	9.4	9.5	4.076
aggregate	9.05	80.3	80.1	95.1	94.6	35.3	9.5	9.0	5.369
(dry)	9.15	80.0	79.7	93.6	93.0	35.3	9.3	9.0	5.501
	9.30	68.6	67.6	79.8	78.4	35.3	9.3	6.6	4.137
	9.35	64.8	64.6	76.4	74.9	35.3	2.0	8.5	4.136
	9.40	62.0	60.6	72.6	71.8	35.3	9.4	5.6	4.131
	9.50	55.2	53.7	66.8	65.1	35.3	9.5	8.5	4.025
	9.775	61.2	60.5	69.1	66.9	35.3	8.3	5.7	4.177
	9.980	58.8	58.0	66.8	65.7	35.3	9.5	3.0	4.128
	9.85	56.6	54.6	64.0	61.5	35.3	9.6	6.6	4.125
	9.90	53.7		59.7	58.4	35.3	9.6	2.1	4.113
	9.95	50.3	48.8	56.3	54.1	35.3	9.0	4.3	4.098

TABLE 4

SHORT-CIRCUITED WAVEGUIDE MEASUREMENT FOR DIELECTRIC PROPERTIES

Sample I.	Frequency GHz	Air node readings mm		Sample node readings mm		Sample length mm	dB level		Relative Dielectric Constant
							Air	Sample	
Quartz	9.35	64.8	64.6	77.3	72.6	29.8	2.0	9.7	6.848
aggregate	9.45	58.7	57.0	70.4	68.1	29.8	9.6	0.6	6.614
withl 1.015%	9.85	56.6	54.6	64.7	60.4	29.8	9.6	7.7	5.212
Tapis Blend	9.90	53.7	51.3	82.1	75.6	29.8	9.6	5.6	5.301
	9.95	50.3	48.8	81.5	71.4	29.8	9.0	4.3	5.185
	10.00	47.2	46.4	79.0	68.0	29.8	9.4	8.0	5.158

TABLE 5

SHORT-CIRCUITED WAVEGUIDE MEASUREMENT FOR DIELECTRIC PROPERTIES

Sample I.	Frequency GHz	Air node readings mm		Sample node readings mm		Sample length mm	dB level		Relative Dielectric Constant
							Air	Sample	
Quartz aggregate with 1.015% moisture	8.85	105.3	100.8	119.8	101.1	29.8	9.6	7.6	9.75
	8.90	99.5	98.0	114.3	97.5	29.8	9.4	6.3	9.72
	9.25	72.2	70.3	70.7	55.5	29.8	9.5	4.4	9.35
	9.30	68.6	67.6	67.6	55.2	29.8	9.3	3.5	7.16
	9.50	55.2	53.7	72.8	68.5	29.8	9.5	3.4	6.96
	9.90	58.8	58.0	54.6	52.4	29.8	9.5	2.0	6.86
	10.00	47.2	46.4	63.8	62.2	29.8	9.4	2.0	6.74

According to Keller and Frischknetch (1977), the relative dielectrive permittivity for water decreases from about 80 at very low frequency range to about 4 at frequencies exceeding 30 MHz. At the microwave frequencies employed in this experiment the relative permittivity of water is expected to be around 4.

From the results of this preliminary investigation, it can be seen that, saturating rock specimen with oil will increase the relative permittivity of the specimen. The increase in the permittivity of the bulk material is about the same as the permittivity of the oil itself. Saturating the quartz aggregate (relative permittivity = 4 at 10 GHz) with 1.02 weight percent of crude oil increases its relative permittivity to about 5.3, whereas saturating the specimen with 1.16 weight percent of water increases the relative permittivity of the sample from about 4(at 10 GHz) to about 6.8. The difference in the values of relative dielectric permittivity is not as much as the permittivity of the saturating fluid itself, but this may be because of the low percentage of fluid present in the rock specimen. Perhaps, if we have rocks with higher porosity, the difference in permittivity between fluid saturated rocks to that of the dry rocks could be the value of the permittivity of the fluid itself. If this is the case, then we might be able to use this information to 'guess whether a rock is water bearing or oil bearing. Further investigations along this line might be useful.

CONCLUSION

In the present preliminary study, it was found that saturating a rock specimen with fluid will increase its relative dielectric permittivity by an amount about equal to the permittivity of the saturating fluid itself. Since the values of relative dielectric permittivity of crude oil and water are different, we might be able to make use of this difference to guess whether a rock contains water or oil.

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