MICROWAVE MEASUREMENTS ON SOME INDIAN COAL SAMPLES

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The relative dielectric constant and the loss tangent values of coal samples from a coal mine at Singarauli, Mirzapur district, U. P., have been measured in the X-band of microwaves. The relative dielectric constant and the loss tangent values are found to average around 1.83 and 0.43 respectively, in the 'dry' state of the coal sample. Both the parameters generally show increasing values with increasing moisture content in the coal sample, as expected. These parameters and their dependence on moisture content and frequency may be very useful as a tool for *in situ* measurements in detecting seepage of water, or for other practical purposes.

INTRODUCTION

ELECTROMAGNETIC wave diagnostic techniques have been extensively used to detect thicknesses and properties of coal seams in open cast coal mines (Lytle, 1974; Ellerbruch & Adams, 1974; Lytle *et al.*, 1974; Scott *et al.*, 1967; Parkhomenko, 1967). The low frequency electromagnetic waves possess the intrinsic potentiality of deeper penetration into the ground and the response of deeper strata of mineral, coal, petroleum and aquifer is capable of providing some valuable remote sensing information. However, for *in situ* measurements in coal and metal mines and the laboratory measurements on chosen natural and moulded samples, microwaves have proven applicability and advantages. The relative dielectric constant and the loss tangent of underground materials completely govern the nature of electromagnetic response and thus determine the qualitative and quantitative diagnostic potentiality of electromagnetic waves. In general, the electromagnetic waves are extensively used in the remote sensing and the safety devices in mines as well. Therefore, the need of detailed and precision laboratory measurements of various physical properties of soil, rock, coal, metal and non-metal at microwave frequencies and their dependence on *in situ* condition and constraint have acquired considerable importance.

The intent of this paper is to report the laboratory measurements of the relative dielectric constant and the loss tangent of various coal samples from the only Indian open cast coal mine at Singarauli, District Mirzapur. The frequency variation of the relative dielectric constant of natural coal samples to-date is rather poorly investigated. Some investigations of powdered and moulded coal blocks have been carried out at microwave frequencies (Groenewege *et al.*,1 975; Miyasita & Higashi, 1957; Balanis *et al.*, 1976). Using the immersion techinque, Groenewege *et al.* (1955) have measured the relative dielectric constant of low grade bituminous coal by making a fine powder and moulding it in the desired shape. The drawbacks of this measurement have been pointed out by Miyasita and Higashi (1957) and the superiority of non-destructive microwave measurement of natural coal samples has been discussed.

The frequency variation of the relative dielectric constant and the loss tangent of natural coal samples in the X-band of microwaves has been studied. The measurements on various coal samples have enabled us to investigate the effect of moisture content on the variation of the relative dielectric constant and the loss tangent. Using these measurements the relative reflected power densities in the X-band have been computed. The intensity of the relative reflected microwave power from the back surface of the coal sample designated by (2,2) is found to change with changing length of the chosen coal samples. Further, it is observed that the reflected microwave power intensity from the surface (2,2) depends significantly on the moisture content of the coal sample.

Measurement of the Relative Dielectric Constant and the Loss Tangent

In the present investigation, one of the most widely used methods of the relative dielectric constant and the loss tangent measurements of solid samples have been used. The block diagram of the experimental set up used for this measurement is shown in Fig. 1. The natural coal samples have been very carefully cut to size and all faces of the coal samples have been gently grounded so that it could be easily inserted in the waveguide. Coal samples, in general, are extremely anisotropic and inhomogeneous. Therefore, samples of nearly the same density have been chosen for the present investigation. All the samples have been cut in the same configuration so that the sedimentation axis of the coal samples (direction of layering) are along the smaller cross-sectional dimension of the waveguide. The coal samples thus prepared are placed between

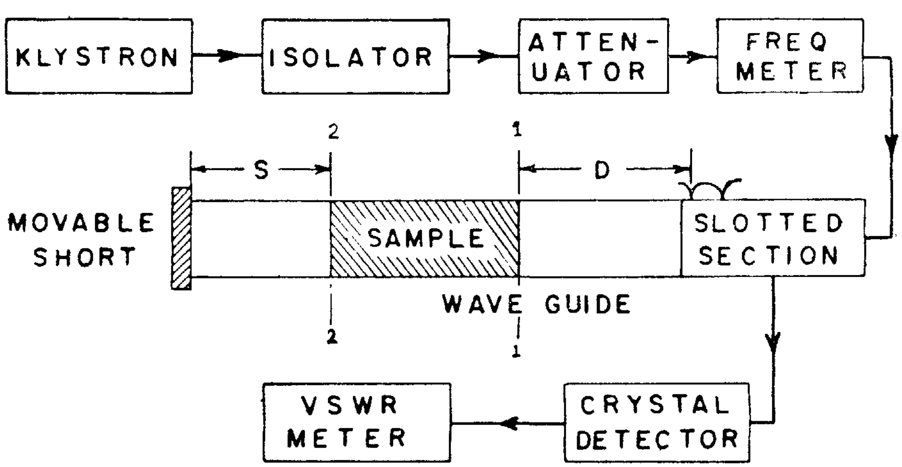

FIG. 1. Schematic diagram of the experiment.

the slotted waveguide and the short circuit termination. For each position of samples in the waveguide, the corresponding position of the first voltage minimum has been accurately determined on the slotted line using double minium method (Sucher & Fox, 1963). The distance from the front face (surface 1,1) of the coal samples to the voltage minimum in the slotted line is denoted by D_1 and the distance from the back face (surface 2,2) of the coal sample to the short circuit termination is denoted by S_1. The voltage standing wave ratio (VSWR) corresponding to D_1 and S_1 has been measured carefully and is denoted by R_1. By changing the position of the sample in the waveguide a different set of experimental data D_2, S_2 and R_2 have been obtained. The microwave signal incident at the front surface (1,1) of the coal sample is partly reflected and partly transmitted. The attenuation and velocity of the microwave signals propagating through the coal samples interposed in the waveguide have been computed which exhibits very little change from one sample to another sample.

The exponential attenuation of the microwave signal propagating through the coal sample is generally expressed as

$$E = E_0 \exp(-\alpha x), \qquad \ldots (1)$$

where E_0 is the magnitude of the incident microwave field intensity and E is the strength of the microwave field after traversing a thickness x into the sample. The attenuation factor (α) is a function of the relative dielectric constant (ϵ_r) and the loss tangent ($\tan \delta$) which is written as

$$\alpha = \omega(\mu_0 \epsilon_0 \epsilon_r)^{1/2} [1/2 \{ (1+ \tan^2\delta)^{1/2} - 1\}]^{1/2}, \qquad \ldots (2)$$

where ω is the angular frequency of the microwave signal, μ_0 is the permeability and ϵ_0 is the permittivity of the free space. The attenuation of the microwave signal through the coal sample is able to depict the thickness of a given sample.

In terms of lumped waveguide parameters of the interposed coal sample and its measured response to microwaves, the relative dielectric constant and the loss tangent are written as

$$\epsilon_r = \frac{\gamma_{er} + \left(\frac{\lambda_g}{\lambda_c}\right)^2}{\left[1 + \left(\frac{\lambda_g}{\lambda_c}\right)^2\right]}. \qquad \ldots (3)$$

$$\tan \delta = -\frac{\gamma_{ex}}{\left[\gamma_{er} + \left(\frac{\lambda_g}{\lambda_c}\right)^2\right]} \qquad \ldots (4)$$

The critical wavelength of the waveguide $\lambda_c = 2a$, 'a' being the largest cross sectional dimension of the waveguide. The λ_g, also related with the wave vector $\mathbf{k}$ as $\mathbf{k} = \frac{2\pi}{\lambda_g}$, is the wavelength of microwaves in the region of the waveguide not occupied by the coal and can be written as

$$\lambda_g = \lambda_0 \left[1 - \left(\frac{\lambda_0}{\lambda_c}\right)^2\right]^{-1/2}$$

where λ_0 is the wavelength in air. The determinant of admittance representation which is, in general, complex and written (in the rectangular form) as

$$\gamma_\epsilon = \gamma_{\epsilon r} + j\,\gamma_{\epsilon x} = \frac{\gamma_{i1}\,\gamma_{01}\,(\gamma_{i2} - \gamma_{02}) - \gamma_{i2}\,\gamma_{02}\,(\gamma_{i1}\,\gamma_{01})}{(\gamma_{i2} - \gamma_{02}) - (\gamma_{i1} - \gamma_{02})},$$

where $\gamma_{\epsilon r}$ and $\gamma_{\epsilon x}$ are the real and imaginary parts of γ_ϵ. The letter suffixes '*i*' and '*o*' signify the input and output admittances, whereas the numeral suffixes '1' and '2' following the letter suffixes signify the admittance corresponding to the two positions of coal sample in the waveguide. In terms of measured response parameters, the input and the output admittances corresponding to the two positions of the short circuit termination are written as

$$\gamma_{im} = \frac{1 + |\,\Gamma_{in}|_m \exp(2\,j\,\mathbf{k}D_m)}{1 - |\,\Gamma_{in}|_m \exp(2\,j\mathbf{k}D_m)}.$$

and

$$\gamma_{om} = -\,j \cot(\mathbf{k}S_m).$$

The two positions of the short circuit termination correspond to $m = 1$ and $m = 2$. The corresponding voltage reflection coefficient $|\,\Gamma_{in}|_m$ for two positions of the short circuit termination are written as

$$|\,\Gamma_{in}|_m = \frac{R_m - 1}{R_m + 1},$$

where R_m are the values of VSWR corresponding to the two positions of the short circuit termination. The measurements on 'dry' and 'wet' coal samples have been made in the variable frequency range of the klystron operating in X-band of microwave. The coal sample slowly heated to 110°C and cooled down to the room temperature have been said to be 'dry' whereas the coal samples dipped in water and surface dried by wiping off the water have been said to be 'wet' samples in the present experiment. The difference in the weight of the 'wet' and 'dry' coal samples have been used to calculate the moisture content. The percentage of the moisture content is expressed as

$$M_w = \frac{W_w - W_d}{W_d} \times 100,$$

where W_w is the weight of the 'wet' sample and W_d is the weight of the 'dry' sample. The samples from the top seam of the open cast coal mine used for the present measurement is characterized by the following average parameters

Moisture content	9.1%
Volatile matter	28.5%
Ash content	22.5%
Fix carbon	39.5%

The coal samples have been graded on the basis of ash and moisture content and rated as grade III.

Results and Discussion

Using the measured parameters, the relative dielectric constant and the loss tangent have been computed in the X-band of the microwave. All precautions and care have been taken to maintain the integrity of the coal sample during the investigation. Several measurements on each sample have been made and the consistent observations have been used to compute the relative dielectric constant and the loss tangent. The relative dielectric constant is seen to decrease slowly with frequency as shown in Fig. 2. The measurements at high frequency end of the the X-band show a tendency to increase slightly with increasing frequency; although, the increasing tendency is consistently seen but its physical significance is not obvious. It is unlikely that the sample itself would exhibit such a narrow band effect and it is quite likely that this may also result as an artifact of the experimental set-up, sample preparation or measurement procedure. The error bars are seen to increase with increasing microwave frequency. Almost similar frequency variations are shown by the 'wet' and the 'dry' samples. The moisture and volatile substances in the coal samples are not able to dissolve or interact with the coal content so as to change its dispersion feature drastically from that shown by the 'dry' sample. The variations of the loss tangent with frequency for 'dry' and 'wet' coal samples are shown in Fig. 3. The relative dielectric constant values and the loss tangent of coal samples from other coal mines and their frequency variations are not available at present for comparison. However, these results are comparable with the reported data available for Japanese and European coal samples. The relative dielectric constant values for the coal samples measured have been found to be somewhat smaller whereas the loss tangent values have been found to be slightly more, than the Japanese and European coal samples.

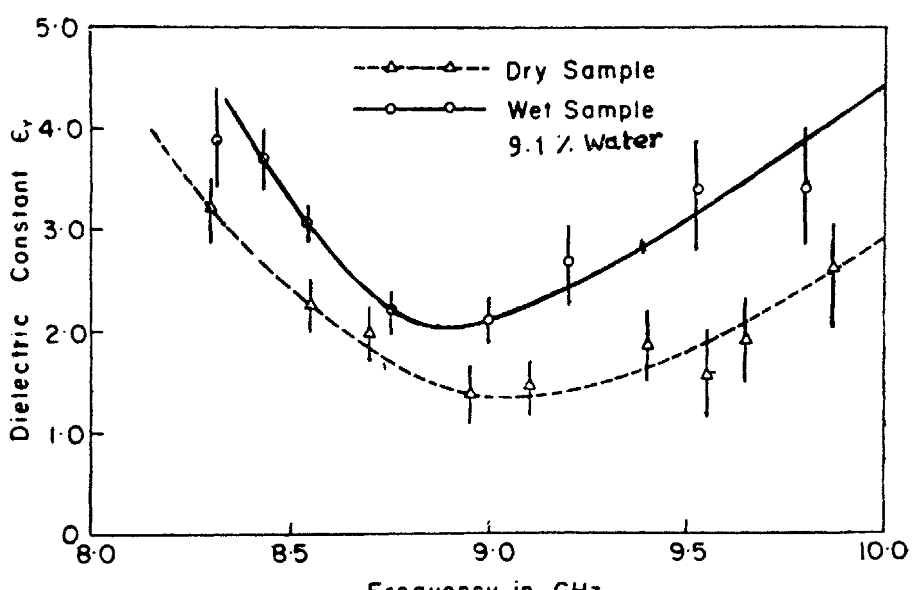

FIG. 2. Variation of the relative dielectric constant with frequency.

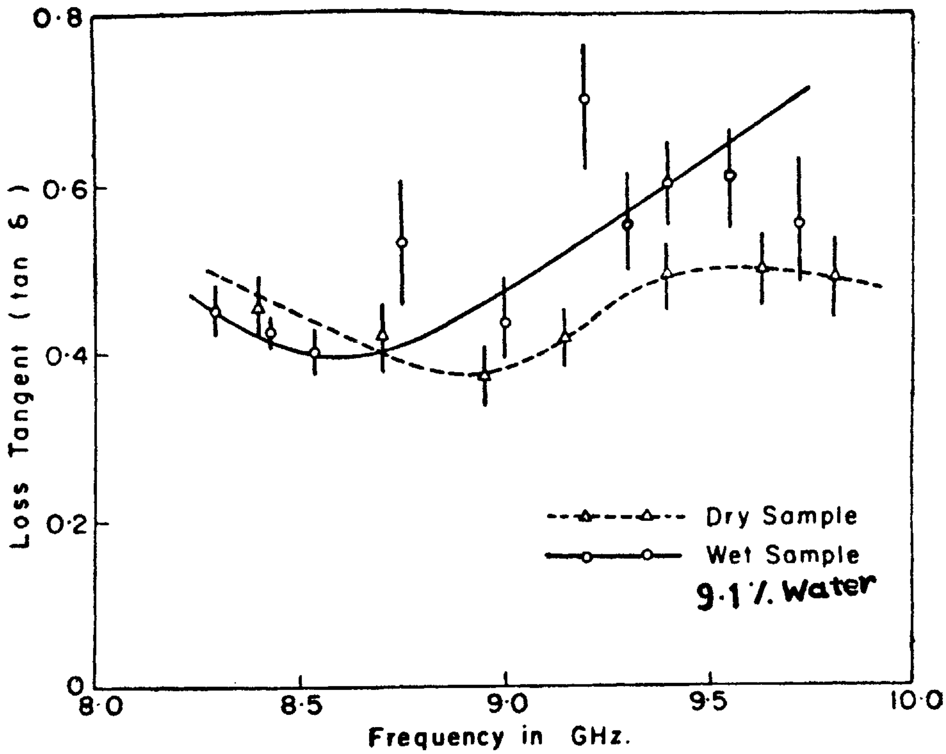

FIG. 3. Variation of the loss tangent with frequency.

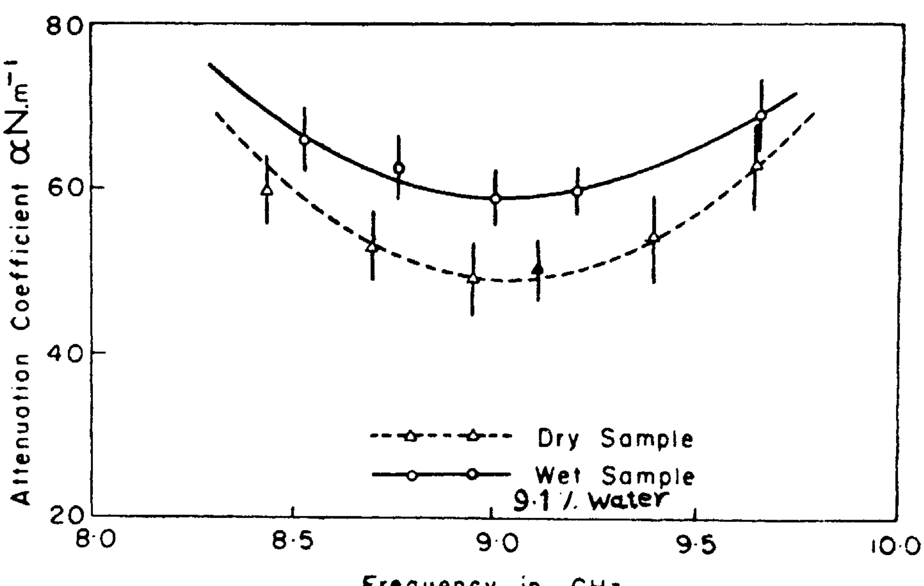

FIG. 4. Variation of attenuation coefficient with frequency.

Using eqn. (2), the frequency variation of the attenuation coefficient of the coal sample has been computed and is shown in Fig. 4. The attenuation coefficient of the coal sample is found to vary slightly within the frequency range of measurement. For coal samples used in the present investigation, the attenuation coefficient is found to be minimum at the central frequency of the band. On either side of this frequency, the attenuation coefficient of the signal is found to increase, both for 'wet' and 'dry' samples of the coal. The attenuation coefficient is more in the case of the wet samples as expected. Using the measured impedances of the coal sample to the incident microwave, an estimate of the normalized reflected microwave power from the front and the back surface have been made. The expressions for the normalized reflected powers from the front surface (1,1) of the coal sample and the corresponding normalized reflected power from the back surface (2,2) after transmission backward through the sample and emerging from surface (1,1) are written as

$$\frac{P_1}{P_i} = \left| \frac{\eta_i - \eta_0}{\eta_1 + \eta_0} \right|^2 \qquad \dots (5)$$

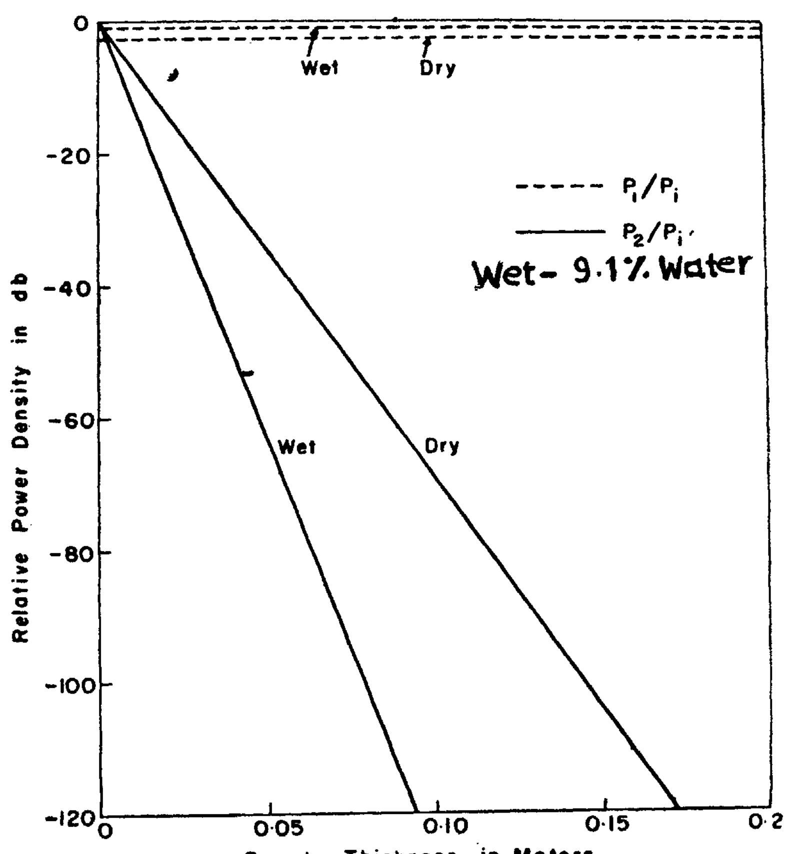

FIG. 5. Variation of relative power density with depth.

and

$$\frac{P_2}{P_i} = \left|\frac{2\eta_0}{\eta_0 + \eta_1}\right|^2 \left|\frac{2\eta_1}{\eta_0 + \eta_1}\right|^2 \exp(-4\alpha x), \quad \ldots (6)$$

where P_i is the incidence power at surface (1,1), P_1 is the reflected power from the surface (1,1) and P_2 is the reflected power from the surface (2,2). The impedances appearing in eqns. (5 and 6) are defined as

$$\eta_0 = \left[\frac{\mu_0}{\epsilon_0}\right]^{1/2} \quad \ldots (7)$$

and

$$\eta_1 = \left[\frac{\mu_0}{\epsilon_0\, \epsilon_r (1 - j \tan \delta)}\right]^{1/2} \quad \ldots (8)$$

The variation of the normalized reflected power from the surface (2,2) with the length of the coal sample has been calculated and shown in Fig. 5. These curves are similar to those reported by Balanis *et al.* (1976) in case of powdered and moulded samples from American coal mines. The dependence of the reflected power from the surface (1,1) is not affected significantly by the 'dry' and 'wet' coal sample, however, the reflected power from the surface (2,2) is affected because of the wave propagation through the 'wet' and 'dry' coal samples of different length. A sensitive measuring device for microwave power reflected from the front surface (1,1) and back surface (2,2) can be used for diagnosing the effect of moisture content in *in situ* measurements and to predict the likely seepage of water in the coal mine.

Conclusion

The estimate of normalised reflected microwave power obtained with the help of precision values of the relative dielectric constant and the loss tangent can be used to detect the seepage of water in coal seams. The information enables issuing of early warning for likely disasters and provides an opportunity for adopting safety measures in coal mines. The variation of normalized reflected microwave power with thickness of the coal seam is capable of depicting the effect of moisture content. The measurements have shown that the penetration depth of microwaves in coal samples is low and is less practical for transmission measurements.

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References

Lytle, R. J. (1974). Measurement of earth medium electrical characteristic : techniques, results and applications. *IEEE Trans. Geosci. Elect.*, **GE-12**, 81–101.

Ellerbruch, D. A., and Adams, J. W. (1974). *Microwave Measurement of Coal Layer Thickness*, NBSIR 74-387. US National Bureau of Standards, Boulder, Colorado.

Lytle, R. J., Laine, E. F., and Lager, D. L. (1974). *Coal Fracture Measurements using in situ Electrical Methods.* UCI-16639, Lawrence Livermore Laboratory, Livermore, California.

Scott, J. H., Carroll, R. D., and Curmingham, D. R. (1967). Dielectric constant and electrical conductivity measurements of moist rock : a new laboratory method. *J. Geophys. Res.,* **72** (20), 5101.

Parkhomenko, E. O. (1967). *Electrical Properties of Rocks.* Pergamon Press, N. Y.

Sucher, M., and Fox, J. (1963). *Handbook of Microwave Measurements* **2**, Ch. 9.Polytechnic, New York

Groenewege, M. P., Schuyer, J., and Van Krevelen, D. W. (1955). Chemical structure and properties of coals. *Fuel,* **34**, 339-344.

Miyasita, I., and Higashi, K. (1957). Dielectric investigations of coals. *Bull. chem. Soc. Japan,,* **30**, No. 1, 513-517.

Balanis, C. A., Rice, W. S. and Smith, N. S. (1976). Microwave measurements of coal. *Radio Sci.,* **11**, No. 4 413–418,