Indian Journal of Radio & Space Physics
Vol. 37, June 2008, pp. 221-229

Measurement of complex dielectric constant of soils of Gujarat at X- and C-band microwave frequencies

D H Gadani[1] & A D Vyas[2]

[1]Physics Department, C U Shah Science College, Ashram Road, Ahmedabad 380 014, Gujarat, India
[2]Department of Physics, University School of Sciences, Gujarat University, Ahmedabad 380 009, India
E-mail: dhgadani@yahoo.com

Received 16 February 2006; revised 6 June 2007; accepted 05 May 2008

Dielectric constant and dielectric loss of soils collected from different districts of Gujarat state for various moisture contents have been measured at X- and C-band microwave frequencies. It has been observed that the dielectric constant of soils depend on the moisture content in the soils and frequency of measurement. Dielectric constant of soils increases slowly with increase in the moisture content in the soil up to the transition moisture, after which it increases rapidly with moisture content. The measured values of complex permittivity of dry and wet soils are compared with the values calculated from the empirical models and are found to be in agreement. The observed complex permittivity is used to calculate emissivity of soils for various moisture contents. It has been found that emissivity of soils decreases with increase in moisture content in the soil.

Keywords: Dielectric constant, Microwave frequency, Soil moisture content, Emissivity

PACS No.: 77.22.Gm

1 Introduction

The dielectric constant of a soil is a measure of the response of the soil to an electromagnetic wave. This response is composed of two parts (real and imaginary), which determine the wave velocity and energy losses, respectively. In a non-homogeneous medium such as soil, the bulk dielectric constant (ε_b) is a combination of the individual dielectric constants of its components (i.e. air, water, dry soil, etc.), but is not a weighted average. The large contrast between the dielectric constant of air ($\varepsilon_a \sim 1$), dry soil[1] ($\varepsilon_s \sim 2$ to 4) and water ($\varepsilon_w \sim 80$) in microwave region, result in a range of ε_b from 2 to 40 for a soil-water interface.

From the measured value of dielectric constant, the emissivity and back-scattering coefficient of soil at a given frequency can be calculated. In the passive microwave remote sensing the radiometer measures the emissivity of soil, whereas in active remote sensing the radar measures the back-scattering coefficient of the soil. Thus the knowledge of variation of dielectric constant with moisture content of a soil is useful for the interpretation of data obtained by various sensors for microwave remote sensing applications, e.g. agriculture, hydrology and meteorology. It has been observed by several workers[2-16] that the dielectric constant of dry soil lies between 2 and 4 and increases with increase in moisture content in the soil and hence provides a tool to determine moisture content in the soil. The authors studied[17-22] moisture dependence of complex permittivity for soils collected from Sabarmati river bed, fields of Gandhinagar, Palanpur, Valsad and Amreli district at X-band microwave frequency and found that dielectric constant of these soils increases slowly with moisture content up to transition moisture, after which it increases rapidly with the increase in moisture content in the soil. To gain more information, complex permittivity of dry and wet soils collected from Surendranagar district (Sayla) and Gandhinagar district was measured. The complex permittivity of Surendranagar district soil was measured at X-band, the complex permittivity of Gandhinagar district soil was measured at C-band microwave frequency and the results are presented here. The results of a previous study[17-22] of complex permittivity of soils have also been included in this paper for comparison.

Various empirical[3,4,15] models have been reported in the literature to calculate dielectric constants of moist soil from its texture and frequency of measurement. The determined dielectric constants of soils with various moisture contents at microwave frequencies were also compared with the calculated values obtained from different models.

2 Materials and method

The soil samples were collected from different regions of Gujarat[24] state (Fig. 1). The soil samples were collected from the Sabarmati river bed, fields of Gandhinagar district, Palanpur, Valsad and Amreli districts and from the field of Surendranagar district (Sayla) as well as from the sea bed near Somnath temple. Stones and gravels were removed from the soil samples and then the soil samples were oven dried. Distilled water was added to the soil and allowed to saturate for 24 h. As the days went on, the moisture content in the soil decreased and the measurement of dielectric constant of the soil samples for various moisture contents were carried out. The texture structure of various soil samples was obtained from the KBM Engineering Company, Ahmedabad (shown in Table 1).

The wilting point (WP) and transition moisture (Wt) are calculated using the Wang and Schmugge[3] model as follows:

$$WP = 0.06774 - 0.00064 \times \text{Sand} + 0.00478 \times \text{Clay}$$
$$Wt = 0.49 \times WP + 0.165$$

where, Sand and Clay stand for the sand and clay contents in percent of dry weight of the soil.

The dielectric constant ε′ and dielectric loss ε″ of the soil samples were measured at 5.65 GHz (C-band) and 9.50 GHz (X-band) microwave frequencies, using the two-point method[25]. The reflex Klystron and Gunn diode were used to generate X- and C-band microwave frequencies, respectively. The experimental set up is shown in Fig. 2.

The sample holders for X-band and C-band measurements were fabricated from the standard waveguides available. At the one end of he sample

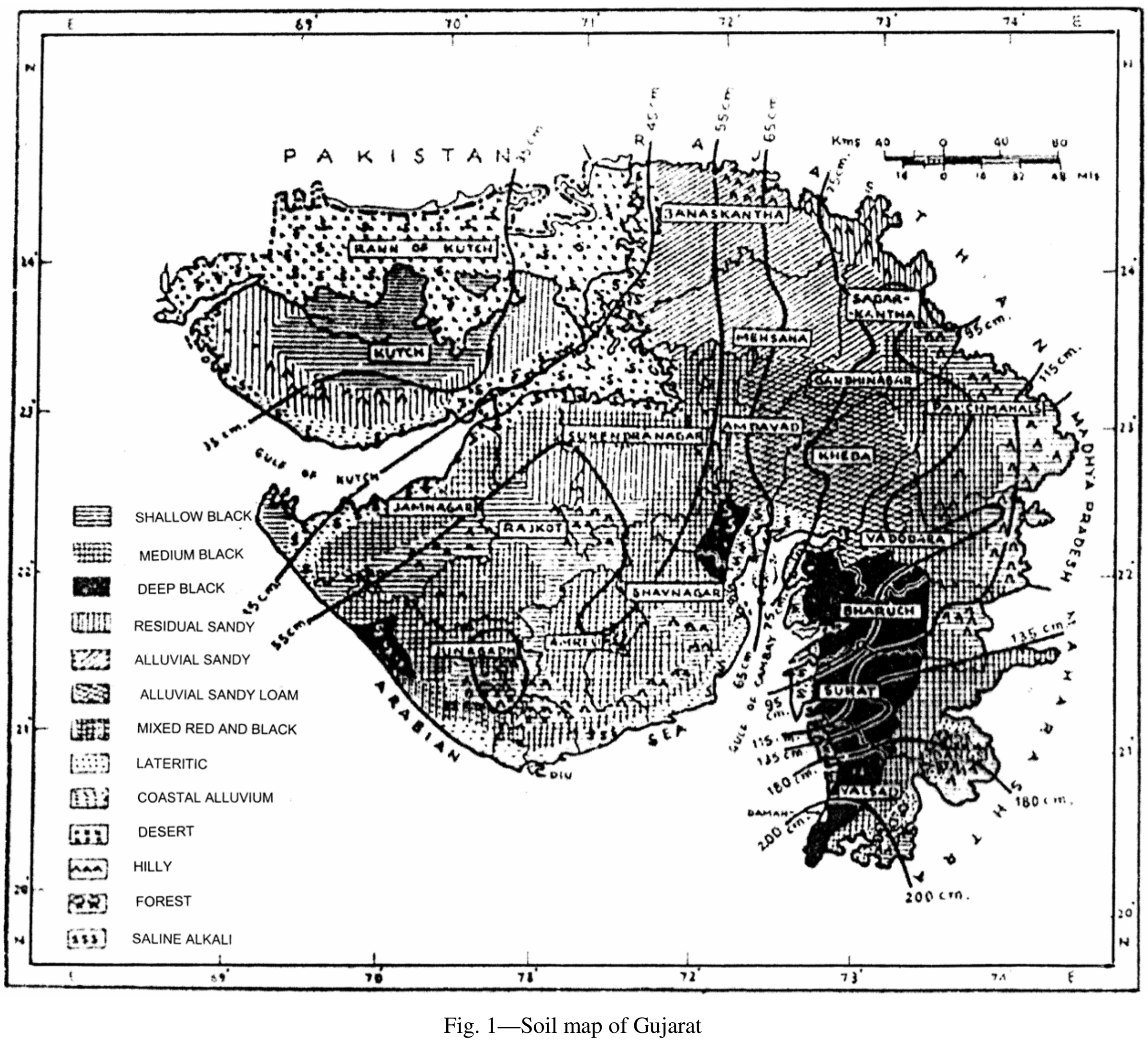

Fig. 1—Soil map of Gujarat

Table 1—The texture structure of soil samples

Location (Region)	Soil texture (%) of			Soil type	Wilting point WP, cm^3/cm^3	Transition moisture Wt, cm^3/cm^3
	Sand	Silt	Clay			
Sea bed near Somnath	96	3.7	0.3	Sand	0.007734	0.16879
Sabarmati river bed (Ahmedabad)	93	6.2	0.8	Sand	0.012	0.1708
Palanpur Dist.	82	16	1	Sand	0.021	0.1698
Surendranagar Dist. (Sayla)	69	29	2	Sandy loam	0.03314	0.18124
Gandhinagar Dist	65	31	4	Sandy loam	0.045	0.1872
Amreli Dist.	11	78	11	Silt loam	0.118	0.2228
Valsad Dist.	7	62	31	Silty clay loam	0.211	0.2686

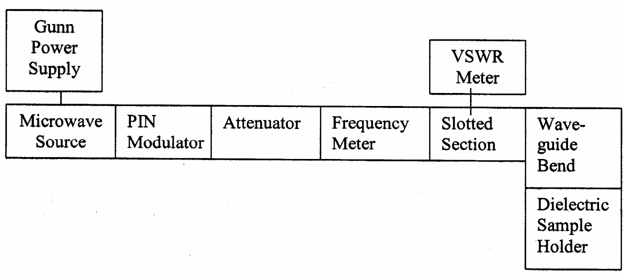

Fig. 2—The experimental set up for the two-point method at X-band microwave frequency

holder a metallic flange was connected, so that it can be connected to the main line and the other end was carefully shorted as shown in Fig. 3. Lengths of the X-band and C-band sample holders are 3 cm and 5 cm, respectively.

First, with no dielectric in the short-circuited line, the position of the first minimum D_R in the slotted line was measured. Now the soil sample of certain length (l_ε) having certain moisture content was placed in the sample holder, such that the sample touches the short-circuited end. Now the position of the first minimum D on the slotted line and the corresponding VSWR, r were measured. This procedure was repeated for another soil sample of same moisture content for another soil sample length (l_ε').

Now the propagation constant (in the empty wave-guide) is calculated as

$$k = \frac{2\pi}{\lambda_g} \quad \dots (1)$$

where, $\lambda_g = 2 \times$ (distance between successive minima with empty short circuited wave-guide sample holder)

The complex number $C\angle - \Psi$ is calculated using the equation

$$C\angle - \Psi = \frac{1}{jkl_\varepsilon} * \frac{1-|\Gamma| * \exp(j\phi)}{1+|\Gamma| * \exp(j\phi)} \quad \dots (2)$$

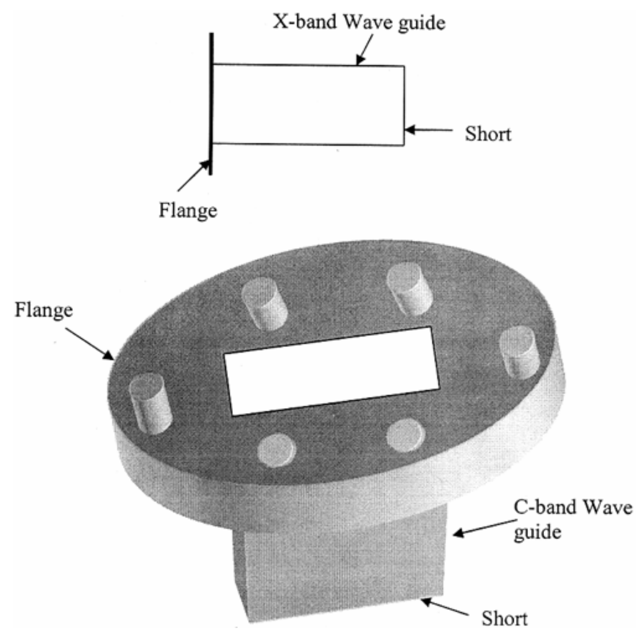

Fig. 3—Construction of the sample holder for X-band and C-band microwave bench

where

$$\phi = 2k*(D - D_R - l_\varepsilon) \quad \dots (3)$$

and

$$|\Gamma| = \frac{r-1}{r+1} \quad \dots (4)$$

The solution of the complex transcendental equation

$$C\angle - \Psi = \frac{\tanh(T\angle\tau)}{T\angle\tau} \quad \dots (5)$$

was obtained[25] to get conductance G_E and susceptance S_E. The dielectric constant ε' and the dielectric loss ε'' of the soil sample were then calculated as

$$\varepsilon' = \frac{G_E + \left(\lambda_g / 2a\right)^2}{1 + \left(\lambda_g / 2a\right)^2} \quad \ldots (6)$$

and

$$\varepsilon'' = \frac{-S_E}{1 + \left(\lambda_g / 2a\right)^2} \quad \ldots (7)$$

where, a = width of the waveguide.

For more accurate results, the length of the sample should be kept near $\lambda_{g\varepsilon}/4$, one-quarter of the wavelength in the dielectric field waveguide. For estimation of $\lambda_{g\varepsilon}/4$, dielectric constant of dry soil as 2.5 was assumed and $\lambda_{g\varepsilon}$ was calculated using the relation[25]

$$\frac{2\pi}{\lambda}\sqrt{\varepsilon_r \mu_r - \left(\lambda / \lambda_c\right)^2} = \frac{2\pi}{\lambda_{g\varepsilon}}$$

where, λ = free space wavelength of microwave signal, $\lambda_c = 2a$, for the dominant mode propagating in the rectangular waveguide and $\mu_r = 1$.

Taking this value as a reference value, measurements were carried out for many samples whose lengths are nearly $\lambda_{g\varepsilon}/4$, till the same values of conductance G_E and susceptance S_E were obtained for the two samples. These values of G_E and S_E were used for further calculations of the dielectric constant ε' and the dielectric loss ε''. As the moisture in the soil increased the sample length were reduced and similar exercise was done for other wet samples.

In order to ascertain the validity of our measurements the complex permittivity of carbon tetrachloride and 1-propyl alcohol were measured at X-band and C-band microwave frequencies at 25° and were compared with the literature values of complex permittivity of these solvents (Table 2). They are fairly in agreement with the literature values. The measurement of complex permittivity of dry and wet soils was done at room temperature (which was around 30°C).

The gravimetric moisture content as weight percent of the soil sample was found by the relation

Percent moisture content Wm
= [(weight of the wet soil – weight of the dry soil)/(weight of the dry soil)] × 100%

Table 2—The comparison of measured values of complex permittivity of carbon tetra chloride and 1-propyl alcohol measured at X-band and C-band microwave frequencies at 25°C, with the literature[27-29] values

Measurement frequency, GHz	Liquid	Measured values		Literature values	
		ε'	ε''	ε'	ε''
9.50	CCl_4	2.26	0.06	2.23	0.0
5.65	CCl_4	2.20	0.08	2.24	0.0
9.50 (X-band)	1-Propyl Alcohol	3.71	0.86	3.53	1.16
5.65 (C-band)	1-Propyl Alcohol	4.03	1.26	3.87	1.48

Hence the volumetric moisture content in the soil sample is calculated as

Wv = Wm × (bulk density of the dry soil sample)

From the measured values of the dielectric constant ε' and the dielectric loss ε'' of the Sabarmati sand and Gandhinager sandy loam soils, at X- and C-band microwave frequencies, the emissivity of the soils for normal incidence were calculated using the relation[10]

$$e = 1 - \left|\frac{1-(\varepsilon)^{1/2}}{1+(\varepsilon)^{1/2}}\right|^2 \quad \ldots (8)$$

where, ε = the dielectric constant of the soil.

3 Results

The measured values of the dielectric constant ε' and dielectric loss ε'' at X-band microwave frequency for different soil samples were plotted against various values of moisture content. The plots are shown in Fig. 4.

The dielectric constant ε' and the dielectric loss ε'' of soils increase with the increase in moisture content for all the soil samples. Further, dielectric constant ε' increases slowly up to the transition moisture for all soil samples, after which it increases rapidly, but the dielectric loss ε'' increases linearly with the moisture content Wv. The variation of ε' with moisture content is almost similar for all the soil samples up to the transition moisture. For the moisture content above transition moisture the increase in the dielectric constant ε' of sandy soils is more as compared to that of the high clay content soils.

Figures 5(a) and 5(b) show the variation of dielectric constant ε' and dielectric loss ε'' respectively, as a function of sand content in the soils

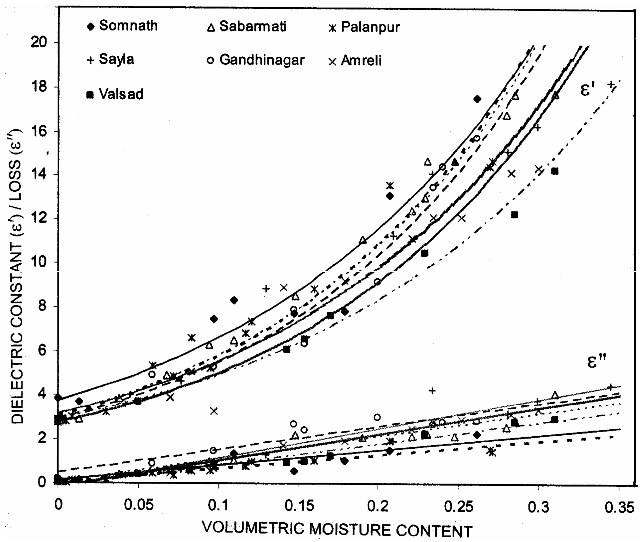

Fig. 4—The measured values of the dielectric constant ε′ and dielectric loss ε″ at X-band microwave frequency for different soil samples plotted against moisture content

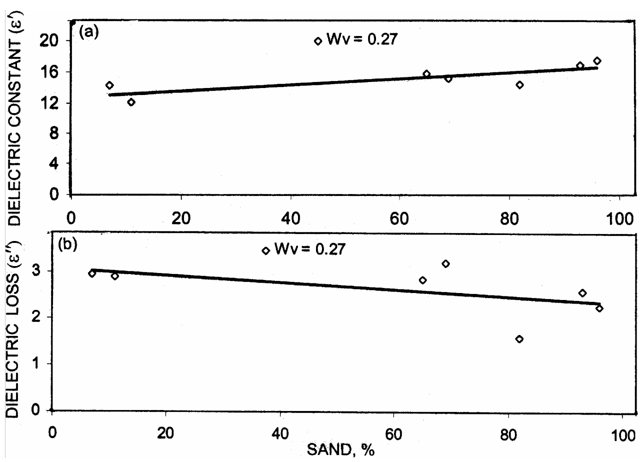

Fig. 5—The variation of (a) dielectric constant ε′ and (b) dielectric loss ε″ as a function of sand content in the soils at X-band microwave frequency

for $Wv \approx 0.27$ at X-band microwave frequency. It is evident from the figure that, the value of ε′ increases with increase in sand content in the soils. Thus at X-band microwave frequency, at higher moisture contents above transition moisture

$$\varepsilon'_{Sand} > \varepsilon'_{Sandy\ loam} > \varepsilon'_{Silt\ loam} > \varepsilon'_{Silty\ clay\ loam}$$

From Fig. 5(b) it is evident that for wet soil ($Wv \approx 0.27$) the value of ε″ decreases with increase in sand content at X-band microwave frequency.

The dielectric constant ε′ and the dielectric loss ε″ of various soil samples were calculated using the empirical models based on the texture structure of the soil, moisture content in the soil and the frequency of measurement[3,4,15]. Some typical results of comparison of measured values of the dielectric constant ε′ and the dielectric loss ε″ of the soil samples with the values calculated using the empirical models are shown in Fig. 6(a) and Fig. 6(b) for sandy loam and silty clay loam soils. It is evident from Fig. 6 that the measured values of ε′ are in good agreement with the values calculated using the three empirical models, for various moisture contents. The values of ε″ are

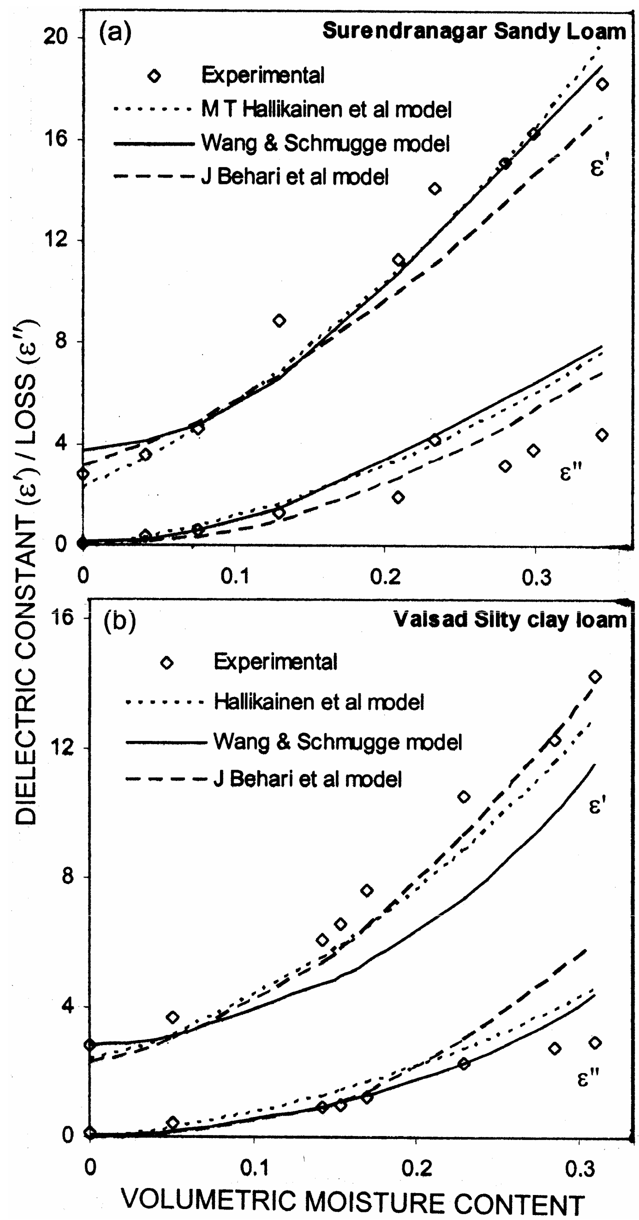

Fig. 6—Comparison of measured values of the dielectric constant ε′ and the dielectric loss ε″ of the soil samples of (a) Surendranagar sandy loam and (b) Valsad silty clay loam with the values calculated using the empirical models

also in good agreement with the empirical models up to the transition moisture, after which the calculated values using the empirical models are higher than the measured values.

Figure 7 shows the graph of experimentally measured values of the dielectric constant ε′ and the dielectric loss ε″ for the Sabarmati river sand and Gandhinagar district sandy loam soils for various moisture contents at C-band microwave frequency. Again it is seen that the dielectric constant increases with increase in moisture content in the soils. For the moisture contents up to the transition moisture the value of ε′ increases slowly initially, and after transition moisture it increases rapidly.

The value of dielectric loss ε″ increases linearly with increase in moisture content for the sand and sandy loam soils. Above transition moisture the value of ε″ for sand is slightly higher than that of the sandy loam.

For a comparison, C- and X-band measured values of the dielectric constant ε′ and the dielectric loss ε″ for Sabarmati sand and Gandhinager sandy loam soils plotted against various moisture contents are shown in Figs 8(a) and 8(b). It is seen that the value of ε′ decreases with increase in frequency from 5.65 GHz to 9.5 GHz for both the soils. The value of ε″ slightly increases with increase in frequency from C- to X-band range for Sabarmati sand, but for Gandhinagar sandy loam ε″ slightly decreases with increase in frequency. Similar results were obtained by other workers[5,8].

Figures 9(a) and 9(b) show comparison of experimentally measured values of ε′ and ε″, at C-band microwave frequency, for Sabarmati sand and Gandhinager sandy loam soils, with the calculated values using the empirical models[3,4,15]. It is seen that the measured values of ε′ for both soils are in good agreement with the calculated values using the empirical models. The measured values of ε″ for both

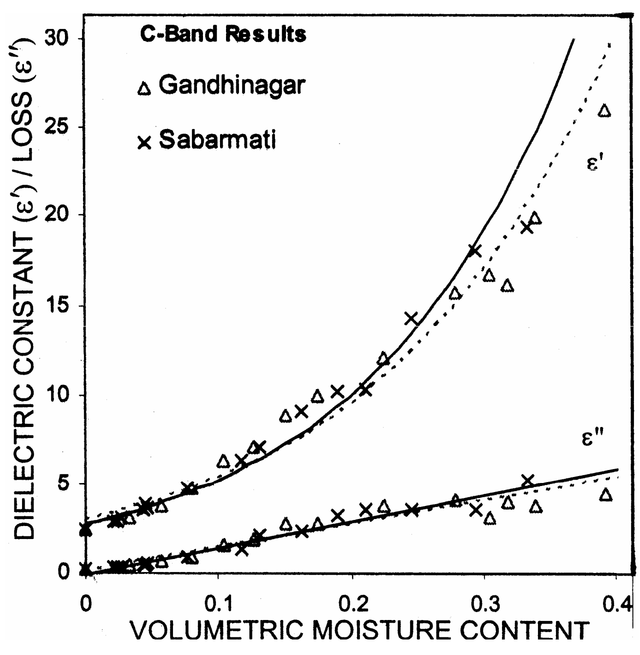

Fig. 7—Measured values of the dielectric constant ε′ and the dielectric loss ε″ for the Sabarmati river sand and Gandhinagar district sandy loam soils for various moisture contents at C-band microwave frequency

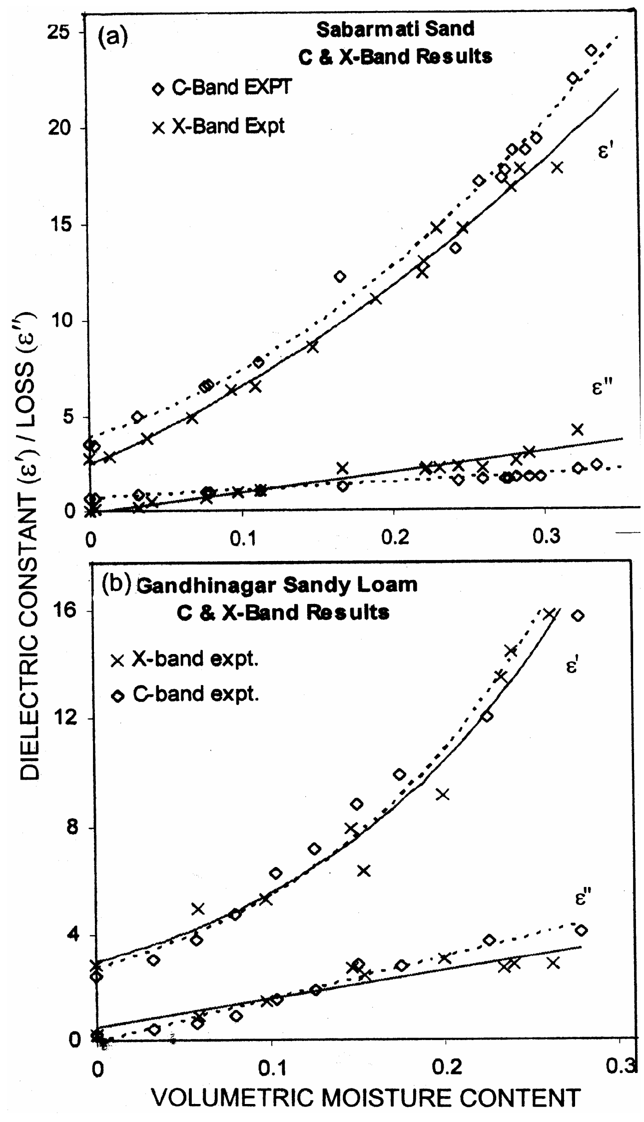

Fig. 8—Comparison of C- and X-band measured values of the dielectric constant ε′ and the dielectric loss ε″ for (a) Sabarmati sand and (b) Gandhinager sandy loam soils plotted against various moisture contents

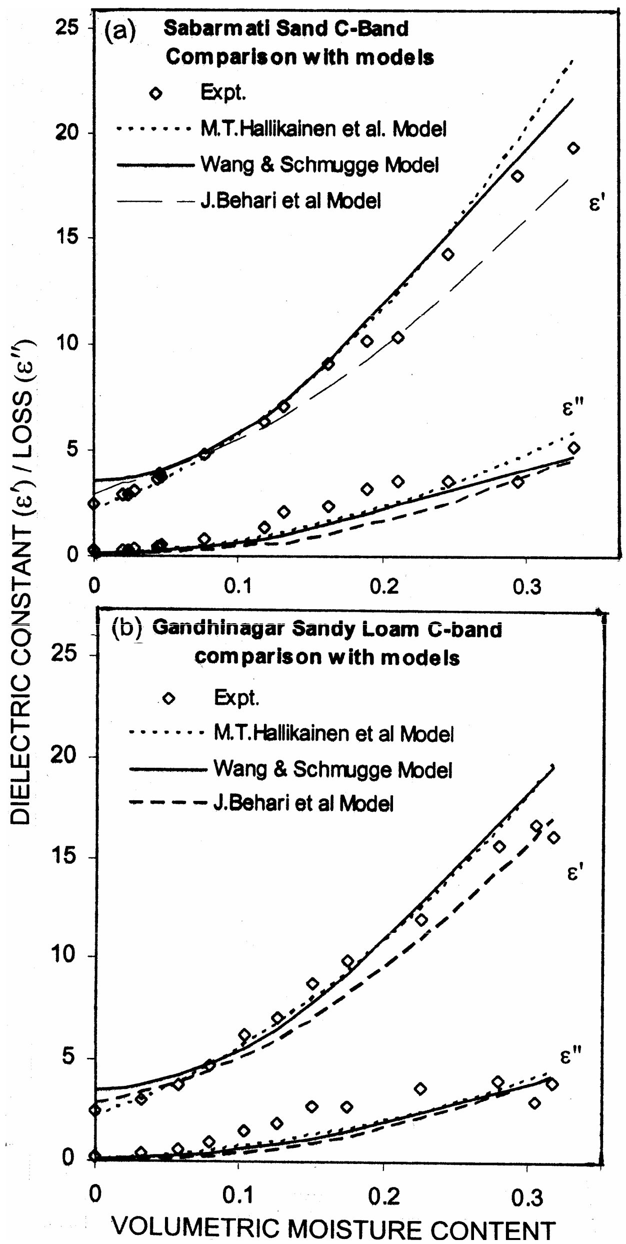

Fig. 9—Comparison of experimentally measured values of ε′ and ε″, at C-band microwave frequency, for (a) Sabarmati sand and (b) Gandhinager sandy loam soils, with the calculated values using the empirical models

the soils are higher than the values calculated using the empirical models.

A typical plot of emissivity versus moisture content at normal incidence for the soil collected from Gandhinagar district is shown in Fig. 10. It can be seen that at both the frequencies emissivity decreases with increase in moisture content in the soil. Similar results were observed for the soils collected from other regions of Gujarat.

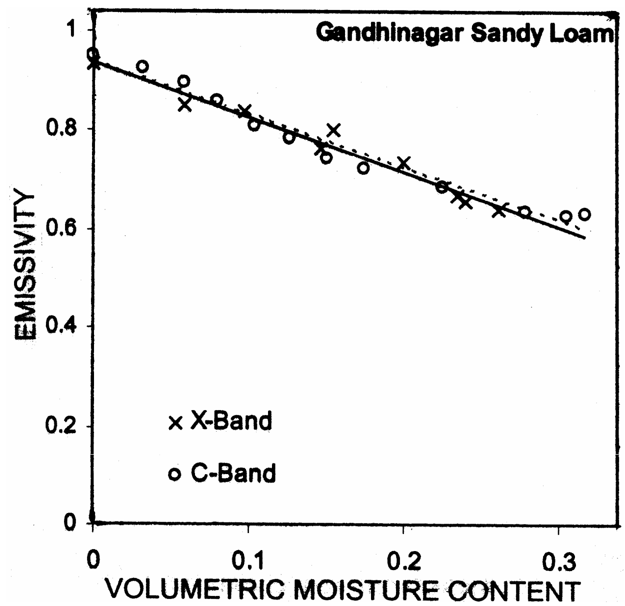

Fig. 10—The variation of emissivity of Gandhinagar sandy loam soil at C-band microwave frequency as compared to that at X-band microwave frequency

4 Discussion

Wet soil is a mixture of soil particles, air voids and liquid water. The high dielectric constant of water (ε_w ~ 80) depends on the molecules' ability to align its dipole moment along an applied field. Anything that hinders the molecule's rotation (e.g. freezing, tight binding to a soil particle, etc.) therefore reduces the dielectric constant of water. The water molecules contained in the first molecular layers surrounding the soil particles are tightly held by the soil particles, due to the influence of matric and osmotic forces, called bound water[3,4]. Hence the dielectric constant of bound water is low. The matric forces acting on a water molecule decrease rapidly with the distance away from the soil particle surface. Hence the water molecules located several molecular layers away from the soil particles are able to move freely within the soil medium, called free water. Thus the dielectric constant of free water is high.

At moisture contents below the transition moisture in the soil there are more bound water molecules as compared to free water molecules. Hence the dielectric constant of soil at lower moisture contents is low. As the moisture content in the soil increases above transition moisture in the soil, the free water molecules increase rapidly in the soil increasing the dielectric constant ε′ rapidly.

The sand has a small surface area per unit volume as compared to that of clay particles. Hence at given moisture content the clay particles are capable of holding more bound water molecules as compared to sand, i.e. there are more free water molecules in sand as compared to that in clay at given moisture content. Hence the increase in the dielectric constant of sandy soils is more as compared to high clay content soils, above the transition moisture.

This is the reason why in Figs 4 and 7 the dielectric constant ε' of the soils increase slowly initially up to the transition moisture and rapidly after the transition moisture, and why the ε' of sandy soils is more as compared to high clay content soils at moisture content above transition moisture.

In Fig. 5(a) for $Wv \approx 0.27$ the dielectric constant ε' increases as sand content increases, due to the lower specific surface area of sand per unit volume.

At given moisture content above Wt, the dielectric constant ε' decreases with increase in frequency for Sabarmati river sand and Gandhinagar sandy loam soil in Fig. 8. But the dielectric loss ε'' for Sabarmati river sand increases with increase in frequency from 5.65 GHz to 9.50 GHz, where as ε'' for Gandhinagar sandy loam soil decreases with increase in frequency. This can be explained by the fact that at any given moisture content and at all frequencies, ε' is found to be roughly proportional to sand content (and inversely proportional to clay content). Thus ε' is soil texture dependent in the same fashion at 5.65 GHz and 9.50 GHz. But between 4 and 6 GHz ε'' is nearly independent of the soil texture[3,4] at all soil moisture conditions. At frequencies above 8 GHz ε' decreases with soil clay fraction[4] (or increase with increase in soil sand fraction).

Acknowledgement

Authors are thankful to the Head, Department of Physics, University School of Sciences, Gujarat University, Ahmedabad, for providing constant encouragement and laboratory facilities.

References

1 Ulaby F T, Moore R K & Fung A K, *Microwave Remote Sensing. Active and passive*, vol.3, (Artech House, Dedham, Massachusetts, USA), 1986.

2 Vyas A D, Complex Permittivity of Sand & Sandy Loam Soils at Microwave Frequency, *Indian J Radio Space Phys*, 2 (1982) 169.

3 Wang J R & Schmugge T J, An empirical model for the complex dielectric permitivity of soils as a function of water content, *IEEE Trans Geosci Remote Sens (USA),* 18 /4 (1980) 288.

4 Hallikainen M T, Ulaby F T, Dobson M C, El-Rays M A & Lin-Kun Wu, Microwave Dielectric Behaviour of wet Soil-Part 1: Empirical Models and Experimental Observations, *IEEE Trans Geosci Remote Sens (USA)*, 23/1 (1985) 25.

5 Mishra Uma Shankar & Behari Jitendra, In-situ measurement of Dielectric Parameter of Soil at Microwave Frequencies, *J Indian Soc Remote Sens*, 28/1 (2000) 1.

6 Hoekstra P & Delaney A, Dielectric Properties of Soils at UHF and Microwave Frequencies, *J Geophys Res (USA)*, 79/11 (1974) 1699.

7 Pancholi K C, Khameshra S M, Complex dielectric permittivity of some Rajasthan soils at 7.114 GHz, *Indian J Radio Space Phys*, 23 (1994) 201.

8 Calla O P N, Borah M C, Vashishtha P, Mishra R, Bhattacharya A & Purohit S P, "Study of the Properties of dry and wet loamy sand soil at microwave frequencies", *Indian J Radio Space Phys*, 28 (1999) 109.

9 Calla O P N, Ranjan Vivek, Bohra Chetan, Naik Gangadhar L, Hasan Waseem & Bali Harmeet Singh, Estimation of dielectric constant of soil from the given texture at microwave frequency, *Indian J Radio Space Phys*, 33 (2004) 196.

10 Ho W & Hall H F, *J Geophys Res (USA)*, 78 (1973) 603.

11 Ghosh Anirbid, Behari Jitendra & Pyne Supriyo, Dielectric parameters of dry and wet soils at 14.89 GHz, *Indian J Radio Space Phys*, 27 (1998) 130.

12 Njoku Eni G & Kong Jin-Au, Theory for Passive Microwave Remote Sensing of Near-Surface Soil Moisture, *J Geophys Res (USA)*, 82/20 (1977) 3108.

13 Behari J, Sahu S K & Mishra U M, Microwave Dielectric Constants of soil, *Physical Methods of Soil Characterization*, (Narosa, New Delhi), 2001, 25.

14 Behari J, Frequency Dependent Variation of Dielectric Parameters of wet Soil, *Microwave Measurement Technique and Applications*, (Anamaya, New Delhi), 2003, 71.

15 Behari J, *Microwave Dielectric Characterization of Soil in Relation to Agriculture Applications*, DST Sponsored Project, (April 1998- March 2001).

16 Alex Z C & J Behari, Complex dielectric permittivity of soils as a function of frequency, moisture and texture, *Indian J Pure Appl Phys*, 34 (1996) 319.

17 Vyas A D & Gadani D H, Study of Complex Permittivity of Soils of Gujarat at Microwave Frequencies, *Physical Methods of Soil Characterization*, Edited by J Behari (Narosa, New Delhi), 2001, 129.

18 Vyas A D & Gadani D H, Study of Emissivity of Soil of Gujarat at Microwave Frequencies, *Proceedings National Conference on Applications of Radio Techniques for Remote Sensing*, ICRS, Jodhpur, 2002, 23.

19 Vyas A D & Gadani D H, Dielectric Properties of Dry and Wet Soils at Microwave Frequencies, *Microwave Measurement Techniques and Applications*, Edited by J Behari (Anamaya, New Delhi, India), 2003, 80.

20 Gadani D H & Vyas A D, Measurement of Permittivity of Soils at X-band Microwave Frequency, *Proceedings National Conference on Microwaves, Antenna, Propagation and Remote Sensing*, ICRS, Jodhpur, 2002, VIII-5.

21 Gadani D H & Vyas A D, Complex Permittivity of Soil at C- and X-band Microwave Frequencies, *Microwaves and Optoelectronics*, Edited by M D Shirsat, Nawarkhele, G S Raju and Khirade, (Anamaya, New Delhi, India), 2004, 266.

22 Vyas A D & Gadani D H, Microwave Dielectric Constant of Soils in *Topics in Electromagnetic Waves, Devices, Effects and Applications*, Edited by J Behari, (Anamaya, New Delhi, India), 2005, 120.
23 Alex Z C & Behari J, Laboratory evaluation of emissivity of soils*, Int J Remote Sens (UK)*, 19/7 (1998) 1335.
24 Biswas B C, Yadav D S & Maheshwari Satish (Eds), *Soils of India and Their Management* (Published by The Fertilizer Association of India, New Delhi), 1985, 106.
25 Sucher M & Fox J, *Handbook of microwave measurements*, 1963, 504.
26 *Dielectric Materials and Applications*, Edited by Arthur R Von Hippel (The Technology Press, MIT, and John Wiley, New York, USA), 1954.
27 Hill N E, Vaughan W E, Price A H & Davies M, *Dielectric Properties and molecular behaviour* (Van Nostrand-Reinhold, London), 1969.
28 Garg S K & Smyth C P, Microwave Absorption and Molecular Structure in Liquid. LXII. The Three Dielectric Dispersion Region of the Normal Primary Alcohols, *J Phys Chem (USA)*, 69 (1965) 1294.
29 Barthel J & Buchner R, High Frequency Permittivity and its use in the Investigation of Solution Properties, *Pure Appl Chem (UK)*, 63 (1991) 1473.