DIELECTRIC PROPERTIES OF INDIAN SOILS AT HIGH AND MEDIUM RADIO-FREQUENCIES

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(Plate VI)

ABSTRACT. The dielectric properties of fifteen Indian soils on medium and high radio-frequencies have been determined under different controlled conditions. Measurements of the effective dielectric constant and the electrical conductivity have been made by the differential transformer method and the oscillographic method. From these data the true dielectric constants have been evaluated. Samples of soil are taken from Dacca, Calcutta, Lucknow, Delhi, Lahore, Peshawar, Bombay, Calicut, Trichinopoly, Ranchi, Cuttack, Bangalore, Madura, Vizagapatam and Trivandrum. The following studies have been made :

(1) The effect of packing.
(2) Variations of the soil constants with moisture-contents.
(3) Variations of the soil constants with frequency
(4) The effect of temperature.
(5) Comparison of the electrical properties of soils from different places.

A general interpretation of all the experimentantal results has been given in the paper.

INTRODUCTION

Apart from the chemical composition, the physical structure and the nature of the soil, there are *three* main factors on which the electrical constants are found to depend : (1) the amount of moisture present in the soil, (2) the degree of packing and (3) the frequency of the alternating field. The first is of great importance, since the variations of the soil constants with moisture-content are indeed, considerable. The experimental study of such variations engaged the attention of various workers for a long time. The dependence of the soil constants on the frequency of the measuring field was also studied by various workers on the subject. Little work has, however, been done on the effect of packing on the soil constants. Besides the three main factors which affect the dielectric properties of the soil considerably the effect of temperature, which is only slight, may also be mentioned.

PREVIOUS WORK ON THE DIRECT DETERMINATION OF THE SOIL-CONSTANTS

It was Bairsto (1912) who, for the first time, made some high frequency measurements of the effective dielectric constant and the electrical conductivity of the two principal constituents of the earth's crust, *viz.*, slate and marble. It had been known from the work of earlier investigators that for very low frequencies within the audio-frequency range, say, up to 5 Kc/s, the electrical

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conductivity of several dielectrics like ebonite, glass and sulphur, was, in general, *linear* function of the frequencies. The main results of Bairsto's investigations with slate and marble, as also with other dielectrics, *viz.*, dry blotting paper, glass, gutta-percha, vulcanised India rubber, over a wide range of frequencies are as follows :

(1) It was shown that in all cases there were present two independent sources of loss. The first, a hysteris loss, was usually the one that was important in the audio-frequency range. The second, a 'viscous' loss, had more influence at higher frequencies.

(2) The linear law found for audio-frequencies connecting the electrical conductivity with frequency was not obeyed at high frequencies. The electrical conductivity gradually rose to a maximum which remained constant for marble and slate over a considerable range of frequencies. With the other dielectrics, the conductivity was found to decrease steadily after attaining the maximum value, as the frequency was further increased. The dielectric constant, on the other hand, dropped rapidly at low frequencies and then decreased gradually with the increase of frequency.

The maximum range of frequencies employed in Bairsto's investigation was from 920 c/s to 2.65 Mc/s and the method of measurement was based on the resonance of a leaky condenser.

Long after Bairsto, Ratcliffe and White (1930) made some direct determinations of the electrical constants of some specimens of English soils by the method of resonance and the oscillographic method using medium radio frequency fields. Their study of the variation of the effective dielectric constant of the soil showed a rapid decrease followed by a gradual one, as the frequency was increased. The electrical conductivity, on the other hand, was found to increase and after attaining a peak value, was found to decrease gradually with the increase of frequency. White (1931) tried to interpret the results of Ratcliffe and White in the light of Debye's theory of di-polar molecules.

Smith-Rose (1938) studied in an elaborate manner the effect of moisture-content and of frequency variation for medium radio-frequency fields on the electrical constants of some specimens of English soils by a resonance method. With all the specimens, it was found that both the conductivity and the effective dielectric constant of the soil increased very rapidly as the moisture-content increased gradually. The effect of frequency variation showed that the electrical conductivity increased slowly with the increase of frequency, whereas the effective dielectric constant was found to decrease continuously with the increase of frequency. There was no peak in the conductivity-frequency curve as had been observed in some dielectrics by Bairsto and also by Ratcliffe and White in their soil measurements in the wide range of frequencies from 1000 c/s to 10 Mc/s employed by Smith-Rose.

In India, Khastgir and Sen Gupta (1936) directly determined the electrical constants of some specimens of Dacca soil by a resonance method for various values of moisture-contents and for varying frequencies from 0·135 Mc/s to 2.7 Mc/s (*i.e.* from about 2000 metres to about 110 metres). The values of the soil constants were distinctly lower than those obtained by Smith-Rose with specimens of English soil, whereas they were of the same nature as those obtained by Ratcliffe and and White. The variation of the effective dielectric constant and the electrical conductivity with temperature was studied by Joshi (1938) in the medium radio-frequency range. Ansari, Toshniwal and Toshniwal (1940) also measured the electrical constants of the Allahabad soil for various values of the moisture-content at three different medium radio frequencies. Recently a study of the dielectric properties of soils from different parts of India was made by Rahman and Muhi (1944) in this laboratory. The soil-constants were measured by the differential transformer method for different medium radio frequencies and also with different moisture-contents.

In the ultra-high frequency range Smith-Rose and McPetrie (1932, 1933) determined the electrical conductivity of English soils. In India Khastgir and Chakravarty (1938) carried out similar observations with Dacca soil for a range of frequencies from 70 to 90 Mc/s. Banerjee and Joshi (1937) also did similar work with Benares soil for varying moisture-contents from 50 to 70 Mc/s. Prasad, Singh and Sinha (1940) also measured the electrical constants of the Patna soil using ultra-high frequencies.

SCOPE OF THE PRESENT INVESTIGATION

In most of the experiments, hitherto performed, on the direct determinations of the soil constants, no special attention was, however, paid to the degree packing. The soil specimen, under examination, was placed inside a container and the packing was made roughly the same, by eye-estimation, as what prevails in fields. It was only in the work of Smith-Rose, that the effect of packing was considered. He found that as the soil was packed more and more tightly the soil constants increased gradually attaining maximum values inside the cylindrical container in his experiment. Smith-Rose's determination of the electrical constants of the soils were claimed to have been obtained under the "desirable condition simulating soil in a well-rolled field or unploughed meadow." In view of the great importance of the effect of packing on the soil constants, it was thought desirable to undertake measurements of the maximum values of the electrical constants of the different Indian soils under optimum condition of packing. The measurements of the maximum values of dielectric constant and electrical conductivity of fifteen different soils taken from the various parts of India were accordingly made on high and medium radio frequencies under various controlled conditions.

From the electrical conductivity data, the *true* dielectric constants were evaluated. No attempt had so far been made of obtaining the true value of the dielectric constant, except in the measurements with ultra-high frequencies. The correction due to the conductivity of the soil makes the value of the *true* dielectric constant substantially different from the effective value as obtained from the capacity-values of the experimental condenser with and without the soil in it. This is specially so, in the case of medium radio-frequency measuring fields and for the high-conductivity values of the soil.

The soil samples were taken from the following places: (1) Dacca, (2) Calcutta (Dum-Dum), (3) Delhi, (4) Lucknow, (5) Lahore, (6) Bombay, (7) Trichinopoly, (8) Peshawar, (9) Calicut (Madras Presidency), (10) Cuttack, (11) Ranchi, (12) Madura, (13) Vizagapatam, (14) Bangalore and (15) Trivandrum. There are transmitting stations of the All India Radio at the first eight places. In the cases of Calicut, Bombay, Madura, Vizagapatam, Bangalore, Trivandrum, Cuttack, Ranchi and Dacca, the specimens were taken from the soil profiles at a depth of 6″ – 3′6″ from the ground surface. At the remaining places, the specimens used for investigation were surface soils within 6″ from the earth's surface.

Measurements were made of the dielectric constant and electrical conductivity of the different soils with special reference to the following:

(1) *The Effect of Packing:* For ordinary packing, a 'packometer' was devised to obtain a reliable measure of the degree of packing of the soil specimens. Alternatively, a load placed on a compressor pressing the soil contained in the intervening space between two co-axial metal cylinders was taken as a measure of the degree of packing. For high packing a hydraulic press with a pressure-gauge was employed. The variation of the soil constants with the degree of packing was thus studied for medium and high radio frequency fields, the temperature and moisture-content remaining the same.

(2) *The Effect of Moisture:* Variation of the soil constants with various values of moisture-contents was studied, keeping temperature and packing the same.

(3) *The Effect of Frequency of the Measuring Field:* Variation of the soil-constants with the variation of frequency in the high and medium radio-frequency ranges was studied, keeping packing, moisture-content and temperature the same.

(4) *The Effect of Temperature:* The variation of the soil constants with the variation of temperature was studied with dry soil having the same packing, for high and medium radio frequencies.

(5) *The Maximum values of Soil Constants:* The maximum values of the electrical constants of the soils from fifteen different places of India for 15% moisture content in all cases and for 20% moisture content in some cases, and for dry soils in a few cases, on high and medium radio-frequency fields were determined.

The soil measurements, for this comparative study were made in each case on 5 Mc/s and on the respective medium radio frequency of the A. I. R. transmitter located in each station from where the soil was taken. The medium frequency measurements with soils from (1) Cuttack, (2) Ranchi, (3) Bangalore, (4) Madras, (5) Vizagapatam and (6) Trivandrum, where there are no transmitting stations, were made at 1 Mc/s.

METHODS OF MEASUREMENT

Two methods of measurements were adopted in the present investigation : (1) the differential transformer method and (2) the oscillographic method. In most of the studies on medium radio frequencies the differential transformer method was followed. In the studies on high radio-frequencies, the oscillographic method was adopted.

DIFFERENTIAL TRANSFORMER METHOD

(a) Experimental Arrangement

The experimental arrangement is shown in Fig. 1. The differential

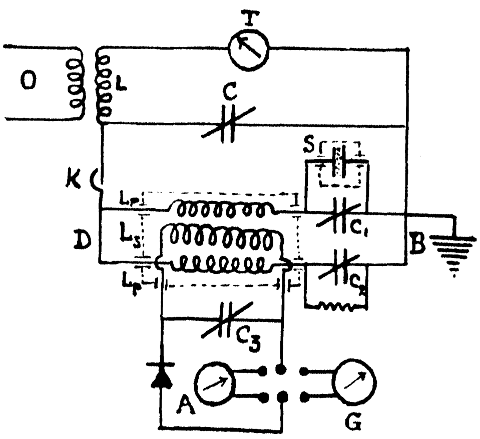


FIG. 1

transformer coils were wound on a wooden former. The number of turns in one primary branch was made exactly equal to that of the other primary branch and the directions of winding in the two cases were opposite, so that the voltage induced on the secondary by one would be neutralised by the voltage induced by the other. The soil condenser S was connected in parallel to a variable condenser C_1 which was in series with one primary branch of inductance L_p and a decade resistance box was connected in parallel (sometimes in series) with another variable condenser C_2 in series with the other primary branch of the same inductance L_p. The two ends of each branch were connected with one another as shown in the diagram and they were further connected by a key K to the main tuning circuit consisting of a suitable coil L, a variable candenser C and a R. F. thermal milliammeter T. When the high frequency voltage from a Hartley oscillator was induced through L into the L–C circuit, the latter could be tuned to the required frequency with the key K closed. The tuning positions of the condenser C were not, however, the same when tuning was done with the key K open and closed. The secondary L_s was tuned to the frequency of the main primary circuit by a suitable variable condenser C_3 and the resonance current in the secondary was detected by means of a galvanometer G after having been rectified by a crystal detector. For larger currents, resonance was obtained with the help of a D. C. milliammeter A which was put into the secondary circuit by means of a throw-over switch.

THEORY OF THE METHOD

Let C_0 and C_s be the capacities of the soil condenser with air and soil in it respectively. When there is no current in the secondary, as is indicated by no-deflection in the galvanometer, the currents and also the impedances in both the primary branches are equal. With the empty soil condenser, let C_1 ond C_2 be the capacities of the two variable air condensers in the two branches under this balanced condition. The total capacity in one branch is equal to the total capacity in the other.

$$\therefore \quad C_2 = C_1 + C_0 \qquad \text{... (1)}$$

When soil is introduced in the soil condenser, the balance is lost and can be restored by changing C_2 to a new value C'_2 and by adjusting a suitable resistance R in series or in parallel with C_2. The capacity change compensates for the increase in capacity in the other branch due to the dielectric property of the soil, and the introduction of a resistance in the same branch due to the electrical conductivity of the soil is made up by the resistance R. We can thus write—

$$C'_2 = C_1 + C_s \qquad \text{... (2)}$$

From (1) and (2) we get

$$C_s = C'_2 - C_2 + C_0$$

Now if the effective dielectric constant of the soil is denoted by ϵ_{eff}, we have,

$$\epsilon_{eff.} = \frac{C_s}{C_0} = \frac{C'_2 - C_2 + C_0}{C_0} \qquad (3)$$

The parallel resistance R used to compensate for the conductivity effect of the soil is given by

$$R = \frac{1}{4\pi\sigma C_0} \qquad \text{... (4)}$$

where σ is the electrical conductivity of the soil.

Hence

$$\sigma = \frac{1}{4\pi R C_0} \qquad \text{... (5)}$$

When a resistance r is used in series with the soil condenser, then this resistance is equivalent to a parallel resistance R which is given by

$$R=\frac{1}{\omega^2 C'^2_2\, r} \quad \cdots \quad (6)$$

where ω is the angular frequency of the measuring field.

In view of (5), we have then in the case of a series-resistance r

$$\sigma=\frac{\omega^2 C'^2_2\, r}{4}=\pi f^2 C'^2_2\, r \quad \cdots \quad (7)$$

where f is the frequency of the field.

Thus the electrical conductivity and the effective dielectric constant of the soil can be calculated from (3) and (5) or (7).

EXPERIMENTAL PROCEDURE

The procedure followed is explained here with reference to the diagram given in Fig. 1. The entire system LTBD consisting of the inductance L and the capacity C placed in parallel to the two primary branches was first tuned to the oscillator, keeping the capacity value of C_1 and C_2 almost equal. The tuning was observed by varying the condenser C in the main circuit by observing the maximum current in the thermal R. F. milliammeter T placed in the circuit. Next the empty soil condenser was placed in parallel to the condenser C_1. Now the tuning of the circuit was restored by varying the condenser C, if at all the tuning was disturbed on inserting the empty soil condenser. Then the current was observed in the secondary circuit which was already tuned to the oscillator. The condenser C_2 was then turned to bring the milliammeter current to the zero position. For more sensitive no-current adjustment, the current was passed through a sensitive galvanometer by means of a double throw-over switch and the zero position of the galvanometer was restored as far as possible by varying the capacity C_2. The zero position was, however, not quite restored by the adjustment of C_2 only. Some resistance had to be included in the circuit to get the exact zero position of the galvanometer.

Next the experimental condenser was filled with the desired degree of packing. The tuning of the system was again made afresh. The no-deflection position of the galvanometer was again obtained by varying C_2 to some new value C'_2 and by inserting either a parallel resistance R or a series resistance r from the decade resistance box. All the requisite data were thus obtained for determining the effective dielectric constant and the electrical conductivity of the soil inside the condenser. The differential transformer was shielded properly, to eliminate stray fields. The oscillator was placed at some distance to avoid its direct effect on the arrangement. The connecting link between the coupling coil and the tuning condenser was also shielded.

THE OSCILLOGRAPHIC METHOD

(a) Theory of the method

When an alternating current I_0 passes through a soil condenser C, placed in series with a perfect condenser C_p, the vector diagram can be represented by the diagram in Fig. 2. The e.m.f. E_s across the soil condenser is in phase with resistance component of the current I_r but lags behind the total current

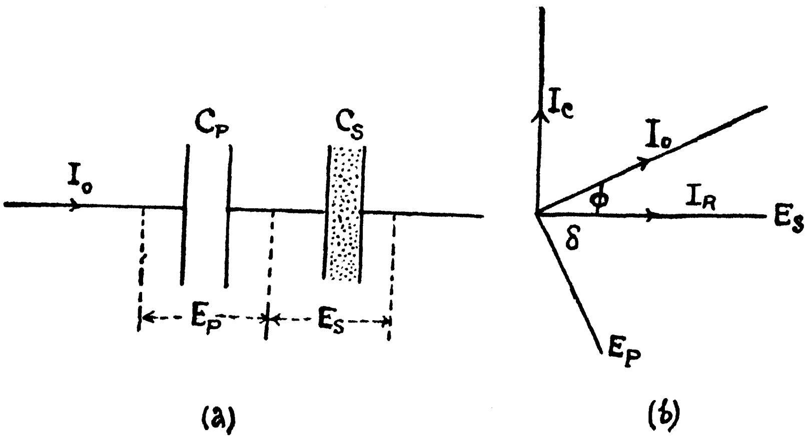


FIG. 2

I_0 by an angle ϕ. The e.m.f. E_p across the perfect condenser will be 90° behind I_0 and will lag behind E_s by an angle δ which is also the angle between the total current I_0 and the capacity component I_c of the latter. The angle δ can be found by measuring the phase-difference between the e.m.f. across the soil condenser and that across the perfect condenser.

Thus if ω is the angular frequency of the alternating current we have

$$\tan\phi=\frac{I_c}{I_r}=\frac{R}{1/\omega C_s}=R\omega C_s,$$

where R is the shunt resistance of the soil due to its conductivity. Assuming a parallel plate condenser, we have

$$R=\frac{1}{4\pi\sigma C_0},$$

where C_0 is the capacity of the empty soil condenser and since

$$\frac{C_s}{C_0}=\epsilon_{eff}.$$

by definition, we have

$$\tan\phi=\frac{\omega C_s}{4\pi\sigma C_0}=\frac{\epsilon_{eff}\omega}{4\pi\sigma}$$

Hence

$$\epsilon_{eff}=\frac{4\pi\sigma\tan\phi}{\omega}=\frac{2\sigma\cot\delta}{f} \quad \ldots \quad (8)$$

Here

$$\phi=\frac{\pi}{2}-\delta$$

Again

$$R=\frac{E_s}{I_r}=\frac{E_s}{I_0\sin\delta}=\frac{1}{4\pi\sigma C_0},$$

whence we get

$$\sigma = \frac{I_0 \sin \delta}{4\pi C_0 E_s} \qquad \dots \quad (9)$$

Since $\dfrac{E_p}{I_0} = \dfrac{1}{\omega C_p}$ and $R = \dfrac{E_s}{I_0 \sin \delta}$, we get $\dfrac{E_s}{E_p} = \omega R C_p \sin \delta$

Therefore

$$\sigma = \frac{1}{4\pi C_0 R} = \frac{\omega C_p \sin \delta}{4\pi C_0} \frac{E_p}{E_s} = \frac{f}{2} \frac{C_p}{C_0} \sin \delta \frac{E_p}{E_s} \qquad \dots \quad (10)$$

and

$$\epsilon_{eff} = \frac{4\pi\sigma \cot \delta}{\omega} = \frac{C_p}{C_0} \cos \delta \frac{E_p}{E_s} \qquad \dots \quad (11)$$

In these expressions the values of C_p and C_0 are known, the values of E_s and E_p can be found in terms of the linear displacements in the x and y directions on the fluorescent screen due to the voltages E_s and E_p applied one after another to the x and y deflecting plates respectively, and the phase-difference δ between the voltages E_s and E_p can be easily obtained from the ellipse pattern on the oscillograph. Thus the electrical conductivity and the effective dielectric constant of the soil can be found from (10) and (11).

(*b*) *Measurement of δ from the elliptic oscillogram.*

The circuit arrangement in the oscillograph method is shown in Fig. 3.

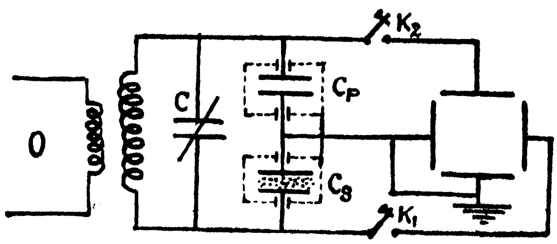


FIG. 3

The radio-frequency current from an oscillator was included into a circuit containing the variable air condenser C_p and the soil condenser C_s and a suitable coupling coil of inductance L. The voltages E_p and E_s across the condensers C_p and C_s were then applied to the y-and x-plates respectively of the oscillograph. Precautions were taken to eliminate stray effects by keeping the leads to the oscillograph as short as possible and by placing the coupling coils at a sufficient distance to prevent magnetic deflexion of the cathode ray beam. All connections were properly shielded by using insulated wires inside earthed metal tubes or inside glass sleeves covered by earthed tin foils. The soil condenser C_s and the air condenser C_p were both enclosed in an earthed tin box in two separate chambers. The key K_1 when switched on, gave the voltage E_s across the soil condenser to the x-plates and similarly with the key K_2 switched on and the key K_1 off, the voltage E_p across the pure condenser was applied to the y-plates. With both keys on, an ellipse was observed on the fluorescent screen. The phase-difference δ between the two voltages E_s and E_p was given by

$$\text{Sin } \delta = \frac{lw}{A_x . A_y} \qquad \dots \quad (14)$$

where l = major axis of the ellipse.
w = minor axis of the ellipse.
A_x = double the amplitude corresponding to E_s.
and A_y = double the amplitude corresponding to E_p.

THE TRUE VALUE OF THE DIELECTRIC CONSTANT OF A CONDUCTING MEDIUM

The relation between the effective dielectric constant $\epsilon_{eff.}$ and the true dielectric constant ϵ of a conducting medium can be found in the following manner. A 'leaky' condenser can be compared with a pure capacity C_s and a resistance $\mathbf{r}$ in series due to the conductivity of the soil. In such a system, a potential difference $Ve^{j\omega t}$ would cause a current given by

$$i = \frac{Ve^{j\omega t}}{\mathbf{r} + \frac{1}{j\omega C_s}} = j\omega\left[\frac{C_s}{1+\omega^2 C_s^2 \mathbf{r}^2} - \frac{j\omega C_s^2 \mathbf{r}}{1+\omega^2 C_s^2 \mathbf{r}^2}\right] . Ve^{j\omega t} \qquad \dots \quad (12)$$

The complex dielectric constant of a conducting medium is given by

$$\epsilon' = \epsilon - j\frac{2\sigma}{f}$$

In view of this division into real and imaginary parts and remembering that the current through the soil condenser (containing soil) is given by

$$i = \frac{d}{dt}(\epsilon' C_0 V e^{j\omega t}) = j\omega\left((\epsilon - j\frac{2\sigma}{f}\right) C_0 V e^{j\omega t} \qquad \dots \quad (13)$$

we get from (12) and (13) the true value of the dielectric constant, *viz.*

$$\epsilon = \frac{C_s/C_0}{1+\omega^2 \mathbf{r}^2 C_s^2} \qquad \dots \quad (14)$$

If ρ is the parallel resistance, corresponding to the series resistance $\mathbf{r}$, we know

$$\mathbf{r} = \frac{1}{\omega^2 C_s^2 \rho}$$

Again we know that $\rho = 1/4\pi\sigma C_o$, where σ = effective electrical conductivity of the soil. In view of the above two relations and putting $C_s/C_o = \epsilon_{eff.}$ = effective dielectric constant, we get

$$\epsilon = \frac{\epsilon_{eff}}{1 + \frac{4\sigma^2}{f^2 . \epsilon_{eff.}^2}} \qquad \dots \quad (15)$$

The true dielectric constant of soil can thus be obtained from (15), when the values of $\epsilon_{eff.}$ and σ are already known by direct measurements.

EXPERIMENTAL RESULTS

(i) Study of the variation of the electrical constants of some soils with the degree of packing, the temperature and moisture-content remaining the same, on high and medium radio frequencies

A 'packometer' was devised to have a reliable measure of the degree of packing in a soil specimen when the packing was not of a high order.

The instrument consisted of a spring balance which was held fixed in a vertical position by a clamp which could be raised or lowered. From the bottom of the spring balance was suspended a small scale pan as shown in Fig 4. A sharp blade, with a stout brass rod attached to the middle of the

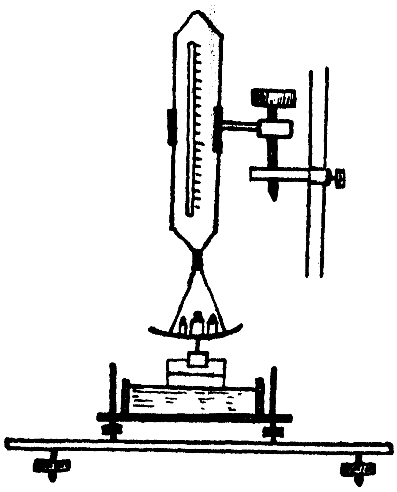
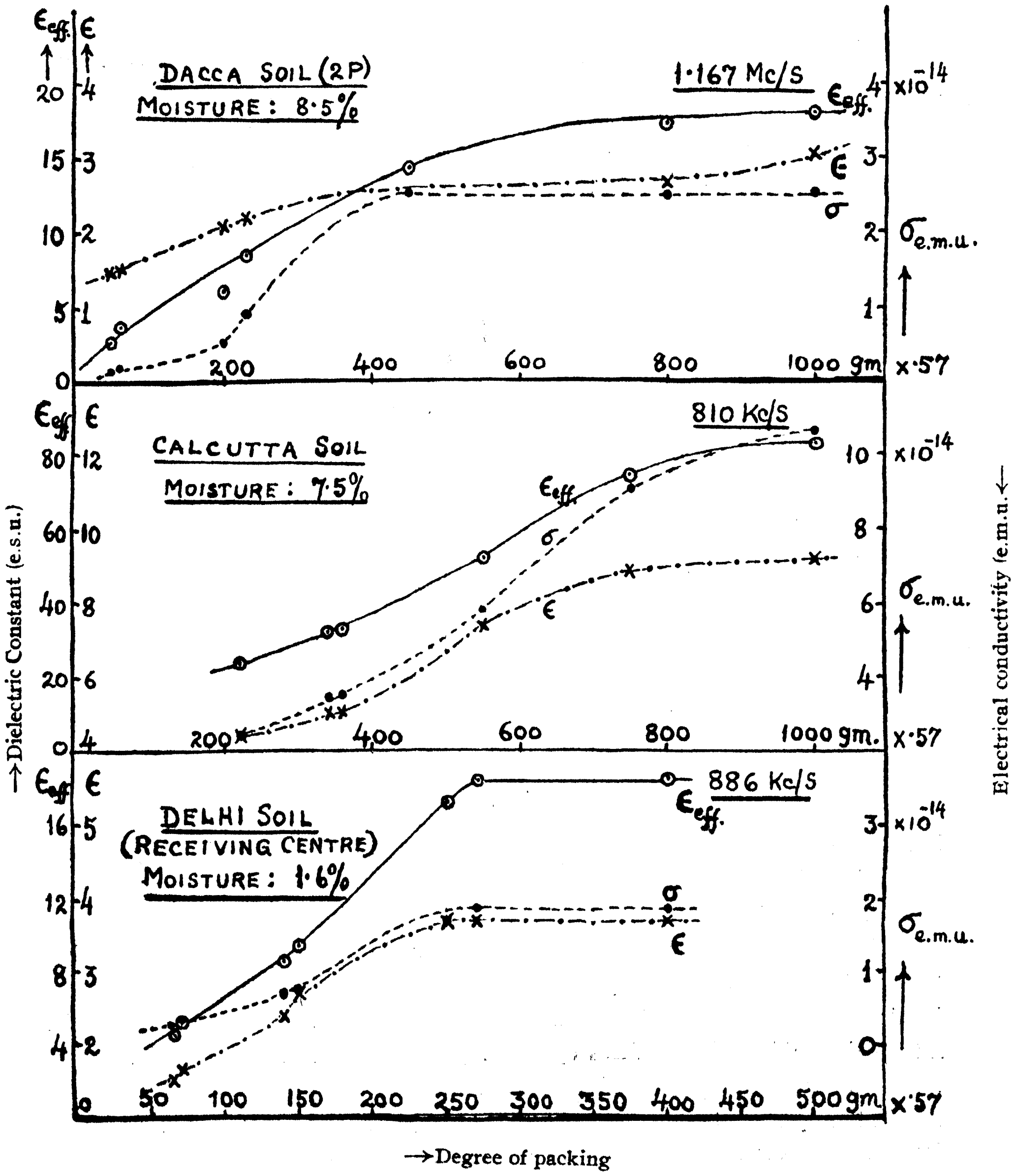


FIG. 4

blunt side in the plane of the blade, was held with its plane vertical by fixing the rod rigidly to the centre of the underside of the pan. The entire system had a free play in the vertical direction.

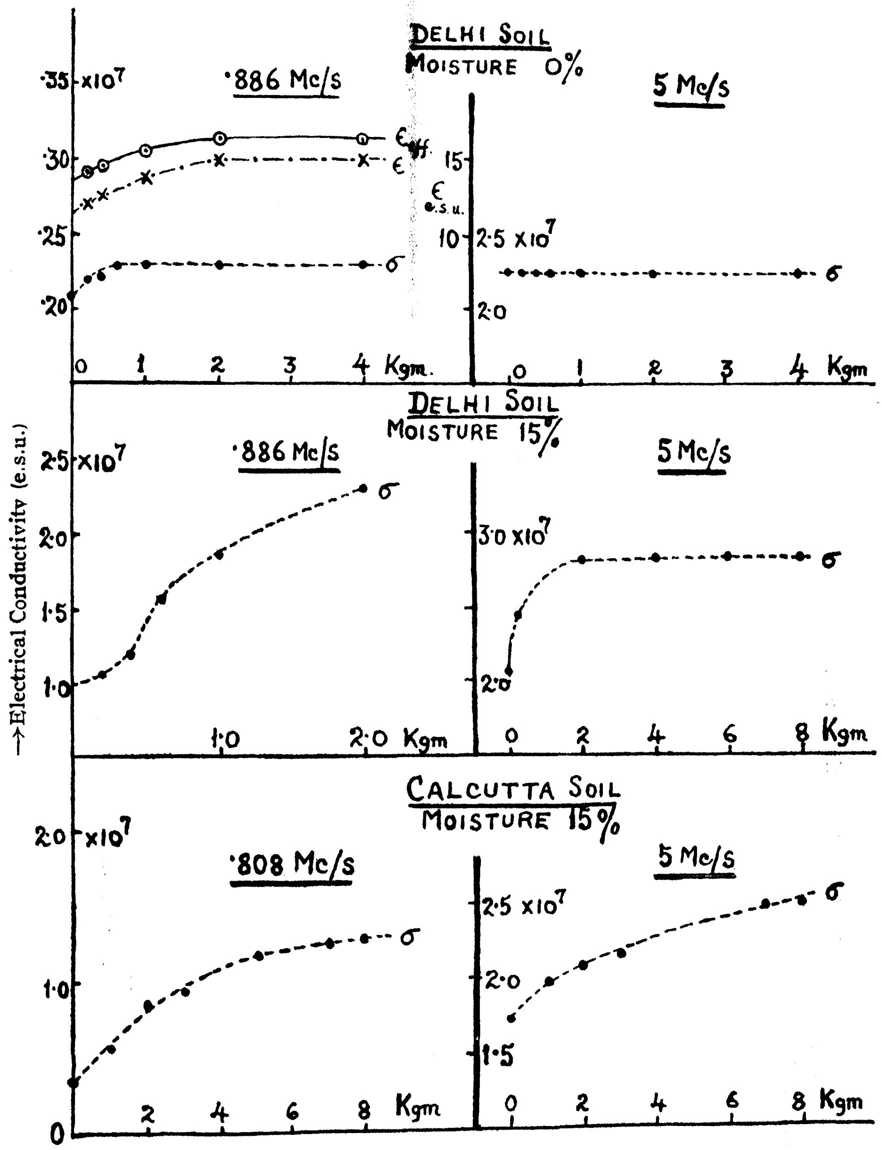
Usually for measurements of soil constants for low orders of packing this instrument was employed. The soil under examination was then taken inside a parallel plate condenser inside an ebonite container with an ebonite lid which could be tightly fixed by binding screws. After having taken the usual measurements, the lid of the container was carefully opened and the soil in the open container was placed on a glass slab provided with three levelling screws. The glass slab with the soil inside the container was brought under the blade of the packometer. By adjusting the top screw in the clamp, the spring balance was lowered gradually till the sharp edge of the blade just touched the soil surface. It was, however, necessary to level the glass slab during the above procedure. An index line, provided by a paper strip (parallel to the edge) pasted on the upper part of the blade, was arbitrarily chosen. Weights on the pan were then carefully placed till the blade went down vertically up to the index line, cutting through the soil. If the weights totalled M gms., the degree of packing was given by M/A gms. per unit area, where A= surface area of the blade in contact with the soil.



—•—•—•— Electrical conductivity (e.m.u.)
—⊙—⊙—⊙— Effective dielectric constant (e.s.u.)
— × — × — × — True dielectric constant (e.s.u.)

FIG. 5

For high degrees of packing a hydraulic press with a pressure-gauge was used. The soil condenser in this case consisted of two hollow concentric brass cylinders of the same length, one inside another with their ends fixed on a thick ebonite base. A hollow ebonite cylinder fitting tightly on to the outer surface of the outer brass cylinder was of sufficient length to project well beyond the brass cylinders. The soil specimen was rammed into the



→Load in Kgm.

—•—•—•— Electrical conductivity (e.s.u.)
—⊙—⊙—⊙— Effective dielectric constant (e.s.u.)
—×—×—×— True dielectric constant (e.s.u.)

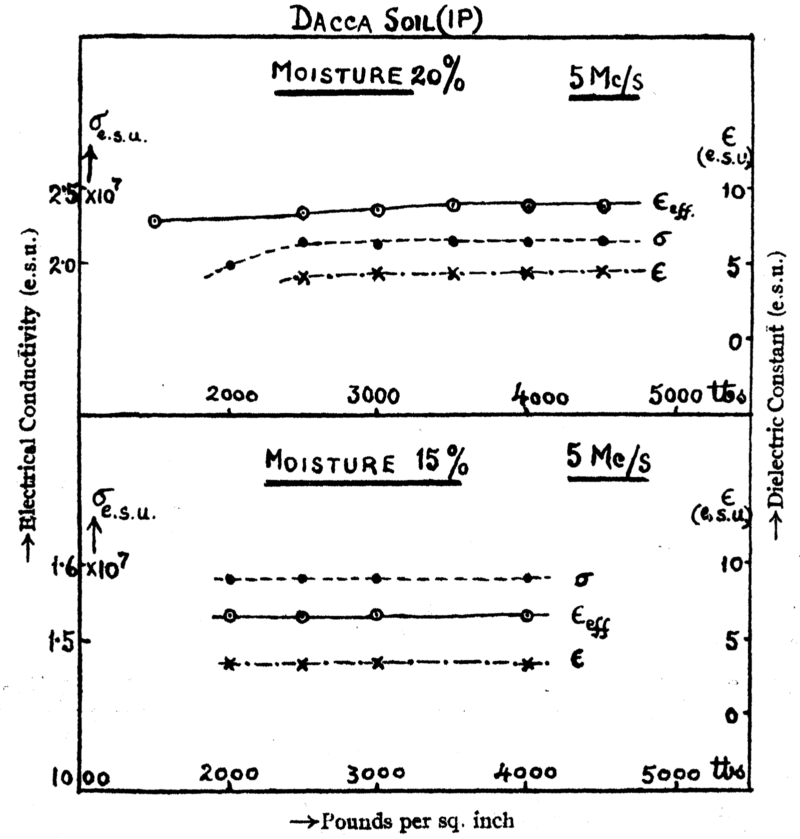
FIG. 6

space between the two concentric brass cylinders and was made to fill a portion of the outer ebonite cylinder above the top level of the brass cylinders. A solid wooden cylinder held vertically and loosely fitting into the ebonite cylinder was inserted in it above the soil. The ebonite base of the soil condenser was placed on the lower moving platform of the hydraulic press and the top surface of the wooden cylinder was made to press against the upper fixed platform of the press.

The same soil condenser was also used occasionally for measurements with soils of low orders of packing. In such cases, loads were placed on the top of the wooden cylinder pressing the soil in the cylinder system.

Typical experimental results by the differential transformer method with Dacca, Calcutta and Delhi soils on 1167Kc/s (257. m), 808 Kc/s (370.4 m.) and 886 Kc/s (338 m) respectively are shown in Fig. 5. The values of the electrical conductivity, effective and true dielectric constants are here plotted against various degrees of packing as indicated by the packometer. It is evident that all the values tended to approach saturation values.

Typical experimental results by the oscillographic method using cylindrical soil condensers with Calcutta and Delhi soils on high and medium radio frequencies are illustrated in Fig. 6.



→Pounds per sq. inch

FIG. 7

For high degrees of packing obtained by using a hydraulic press the values of the soil constants were also measured by the oscillographic method and found practically constant from a pressure of 20000 lbs. per sq. in. to a maximum pressure of 45000 lbs. per sq. in. which the soil condenser was able to stand. These results for high packing with Dacca soil are shown in Fig. 7.

(ii) Study of the variation of the electrical constants of the Dacca soil with moisture content variation, for various degrees of packing (temperature remaining the same) on medium radio frequency

In preparing soil of a definite moisture content, the following procedure was adopted : the soil was heated in a double-walled air bath to a little over 100° C for about 12 hours and it was then considered as completely dry. Required quantity of this dry soil was then cooled inside a desiccator. Requisite quantity of distilled water was then added to the soil from a burette to make the moisture content percentage equal to some desired value.

The soil with a particular percentage of moisture was then packed inside the soil condenser to gradually increasing extent and the soil constants

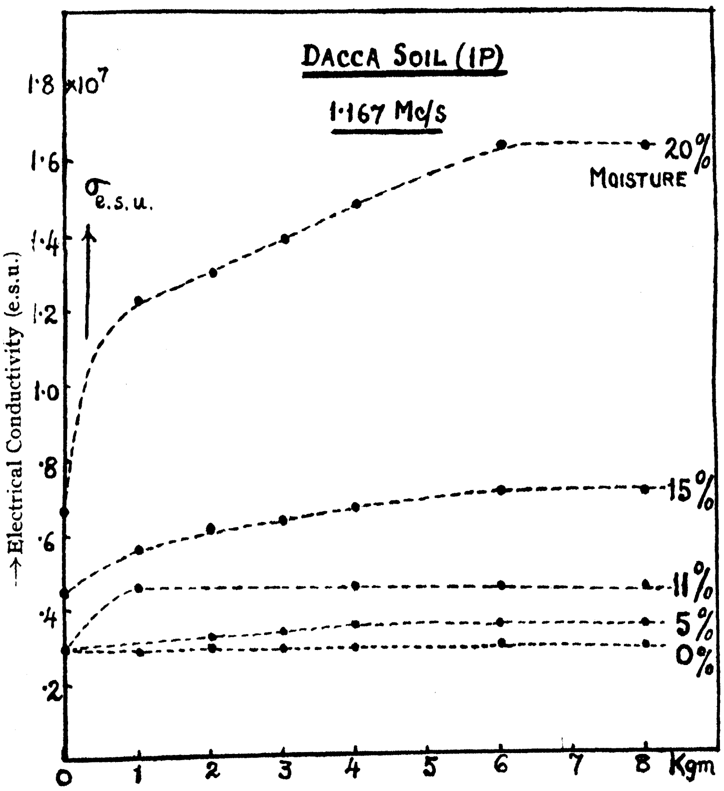


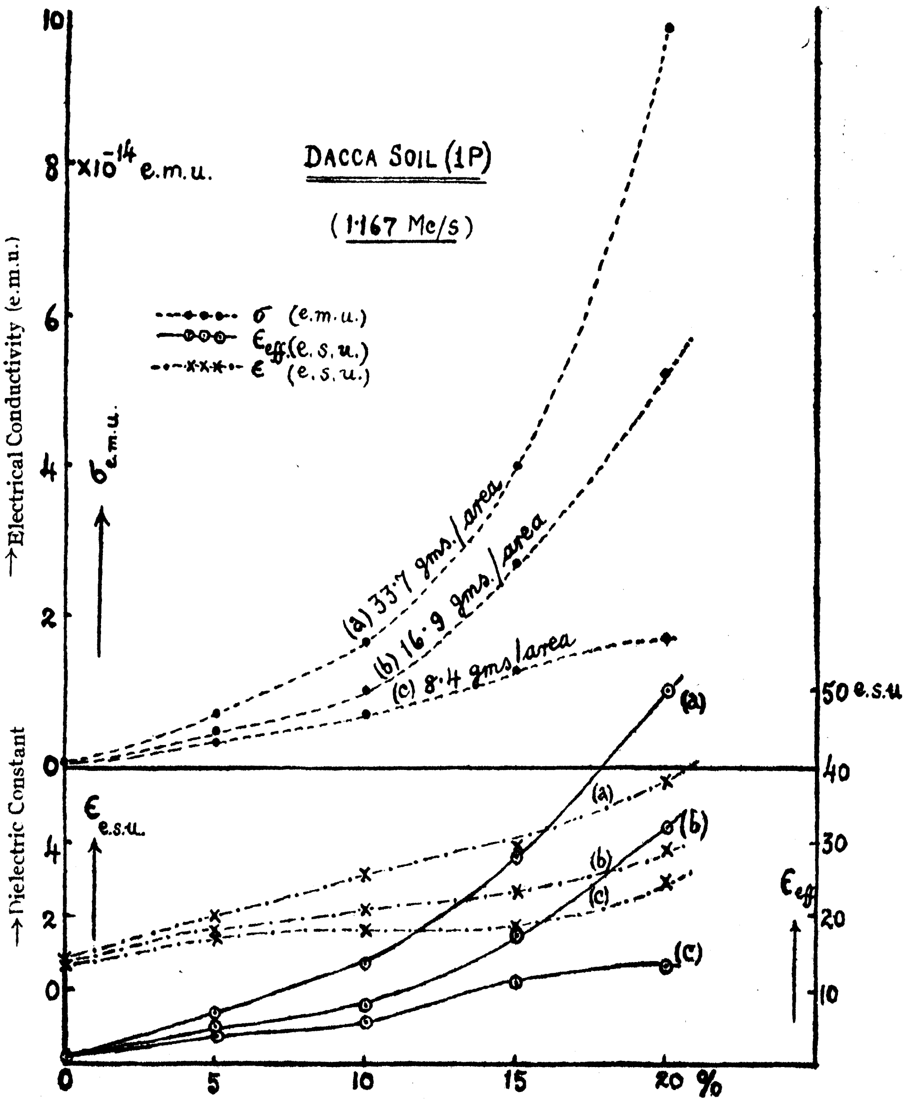
FIG. 8

measured on medium radio-frequencies by the differential transformer method. Different sets of similar measurements were made for moisture contents ranging from 0 to 20%.

The experimental results with the Dacca soil (1P) on 1167 Kc/s (the frequency of the Dacca A.I.R. transmitter) are shown in Fig. 8. It is to be noted that the soil constants increased with packing and were found to attain saturation values in most cases.

The variations of the soil constants of the Dacca soil (2P) with moisture content on 1167 Kc/s for three different degrees of packing are graphically shown in Fig. 9.

Same Packing



→Percentage of Moisture

FIG. 9

(iii) Study of the variation of the electrical constants of different soils with frequency (the temperature, packing and moisture content remaining the same) on high and medium radio frequencies for low and high packing

In Fig. 10 are shown the values of electrical conductivity, effective and true dielectric constants of Calcutta, Dacca and Delhi soils obtained by the differential transfomer method for a range of frequencies from 600 Kc/s to 1200 Kc/s. The packing was kept at some fixed value and the moisture was 2-3%. It is to be noted that the electrical conductivity increased with frequency and that both effective and true dielectric constants decreased with the increase of frequency.

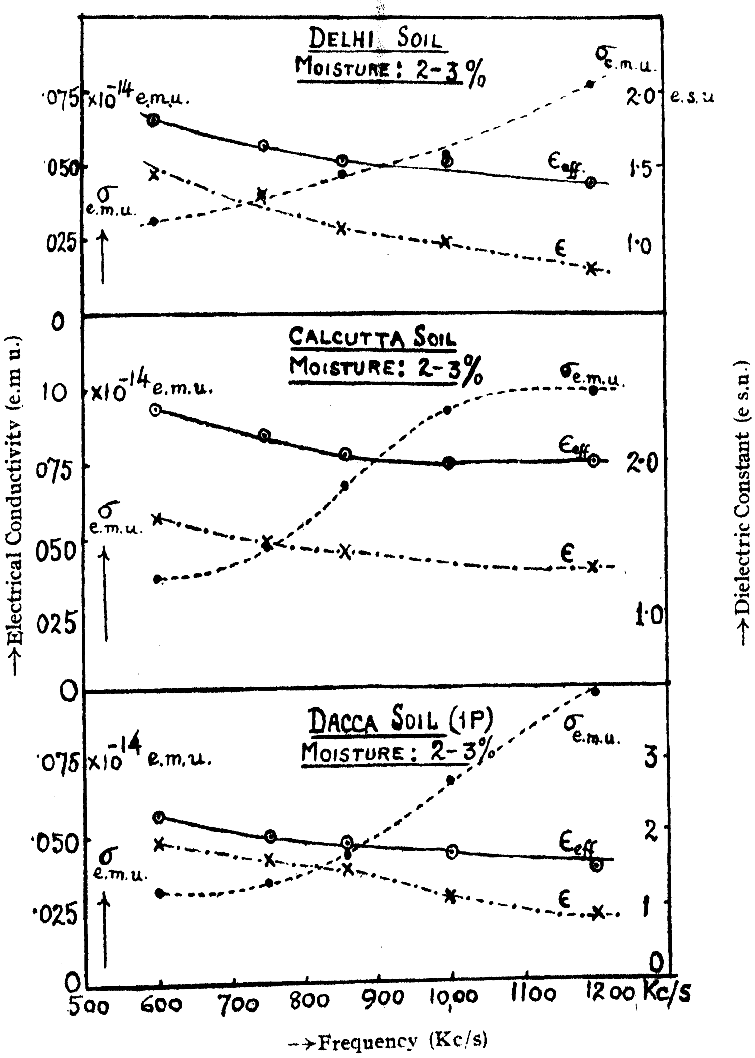
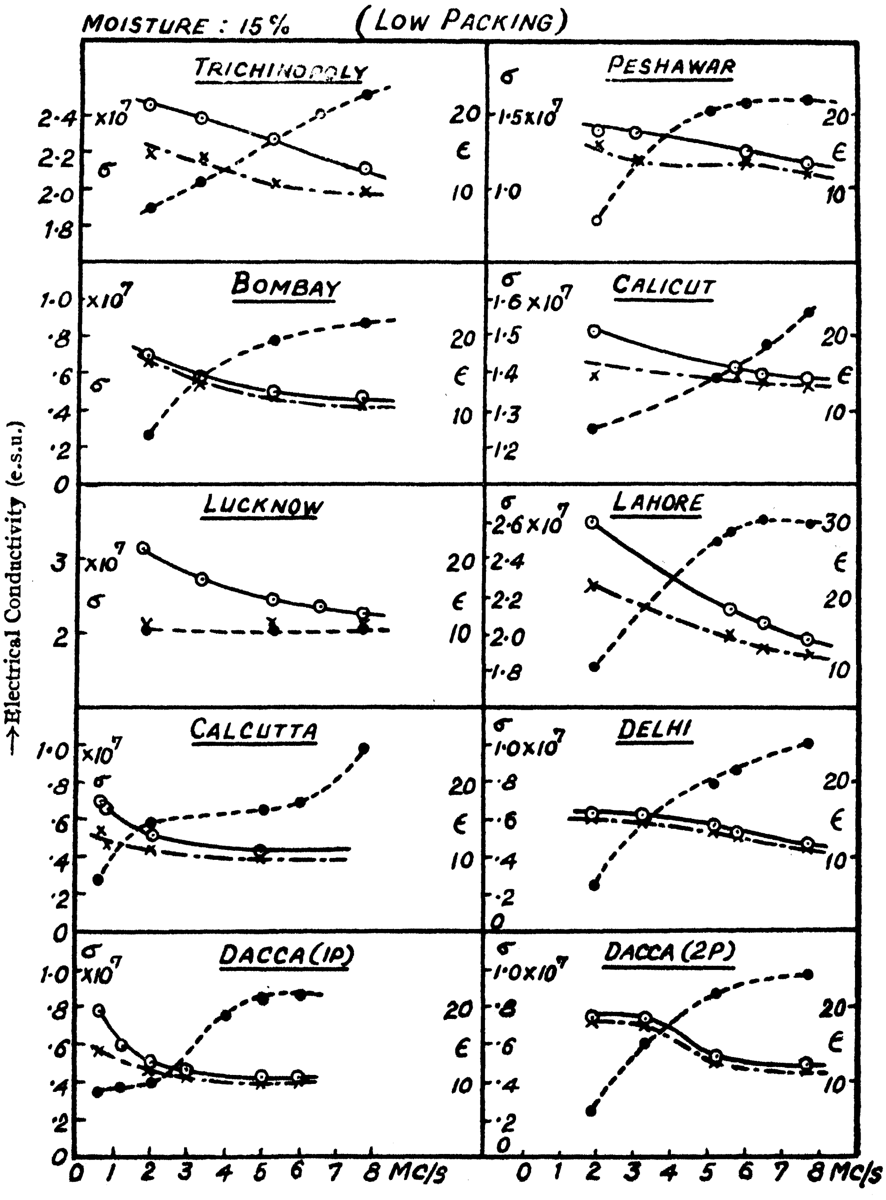


FIG. 10

The experimental results obtained by the oscillographic method working with various soils of a fixed degree of packing (400 gms/13·3) on high radio frequencies ranging from about 1 to about 8 Mc/s are shown in Fig. 11.



→Frequency (Mc/s)

—•—•—•— Electrical conductivity (e.s.u.)

—⊙—⊙—⊙— Effective dielectric constant (e.s.u.)

—×—×—×— True dielectric constant (e.s.u.)

FIG 11

In all cases the dielectric constant decreased but the electrical conductivity increased with frequency tending in many cases to constant values. Measurements were also made with Calcutta, Dacca and Delhi soils for very high packing (4500 lbs. per sq. in.) on the same range of high radio frequencies. The results are shown in Fig. 12. As contrasted with the experimental results

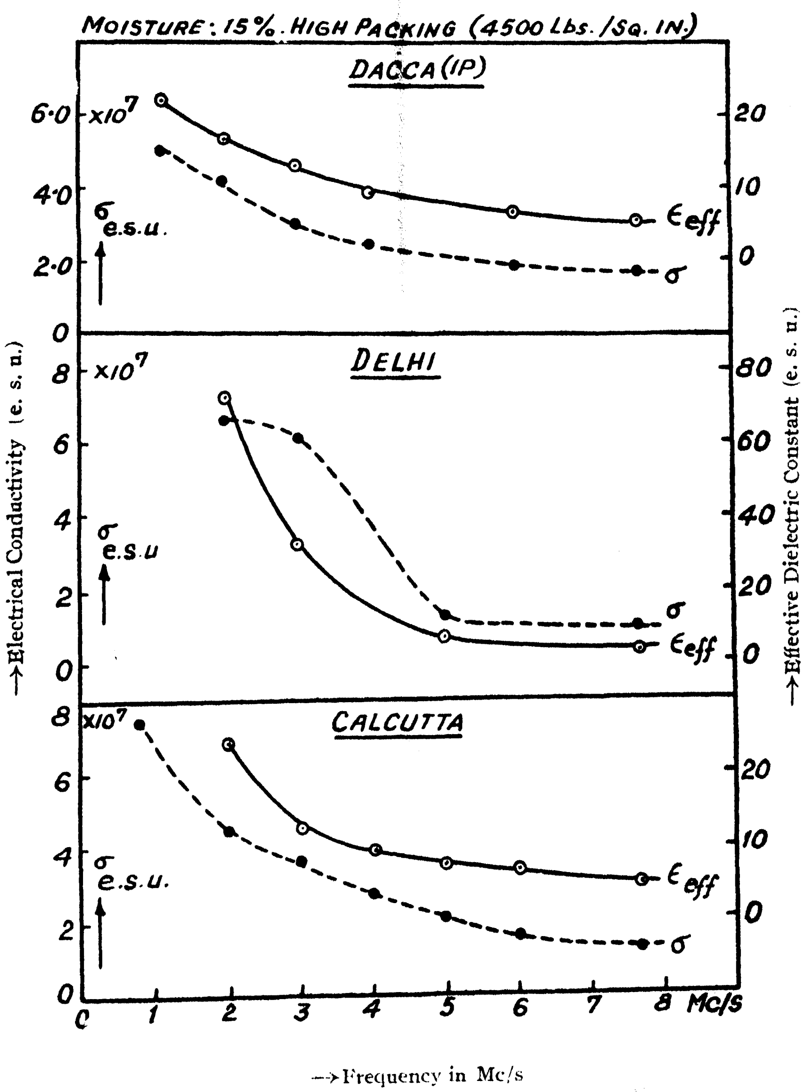


FIG. 12

with low packing, the electrical conductivity was found to diminish steadily with increasing frequency, whereas the effective dielectric constant decreased in the same way with the increase of frequency.

(iv) Study of the variatian of the electrical constants of some dry soils with temperature for fixed values of packing (low and high)

(a) Experiments on medium radio frequency (1167 Kc/s.)

For this study by the differential transformer method on medium frequency, a special glass container with parallel platinum plates rigidly fixed by fusiug platinum connections into the glass was constructed. The soil having been dried was introduced into the container and a thermometer was inserted inside the soil above the platinum plates through a stopper. The glass container with the soil inside and the thermometer, was then fixed inside a glass cylinder with a base so that the container rested on a piece of cork on the base of the outer cylinder. The open end of the outer cylinder at the top was closed with a cork through which the neck of the inner glass container was inserted. The short platinum wire connections from the plates were led out into the outer cylinder.

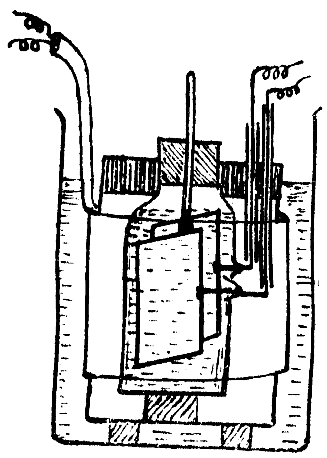


FIG. 13

Thin copper wire leads were then passed through narrow glass sleeves and were taken out as shown in the diagram in Fig. 13. The outer glass cylinder was then fitted inside a heater coil which was enclosed within a metal case in the form of a cylinder. The entire system was then placed inside a calorimeter containing water. On passing current through the heater coil the water in the calorimeter was heated. It was found convenient to increase the temperature of the soil to a high value and then to take measurements of the electrical constants when the temperature was falling. The temperature was noted carefully after stirring the water. With Dacca soil the effect of temperature variation for two frequencies from about 4°C to about 75°C was investigated.

The values of the soil constants for various temperatures are shown in Fig. 14 for each of the two medium frequencies of the Dacca and Calcutta transmitting stations. It is interesting that while the soil conductivity was found to increase with temperature, the effective dielectric constant remained practically constant. The true dielectric constant was found on calculation to decrease with the rise of temperature. It should be noted that the packing of the soil in this experiment was extremely low.

For high packing on the same medium radio frequency the oscillographic method was employed and the cylindrical condenser filled with dry soil and packed with the help of the hydraulic press was used for the purpose. The steel platform of the press could be electrically heated so that there was no difficulty in raising the temperature of the soil. For lower temperatures ice or iced water was used in a vessel surrounding the soil condenser. The lower limit of the temperature was 15°C, as below 15°C there was difficulty in taking

Dry Dacca Soil

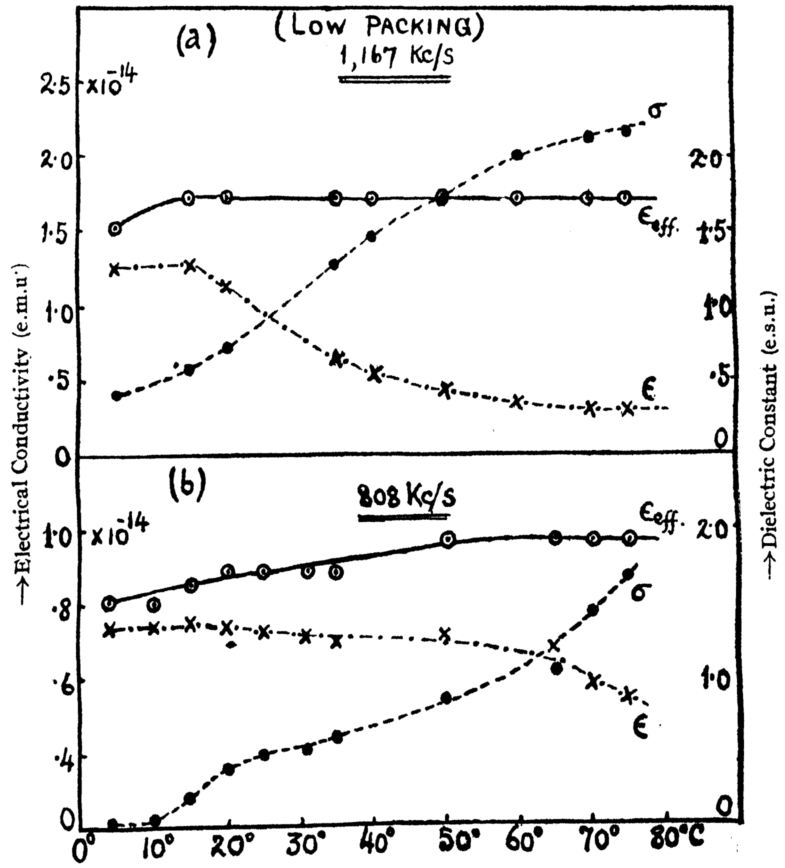
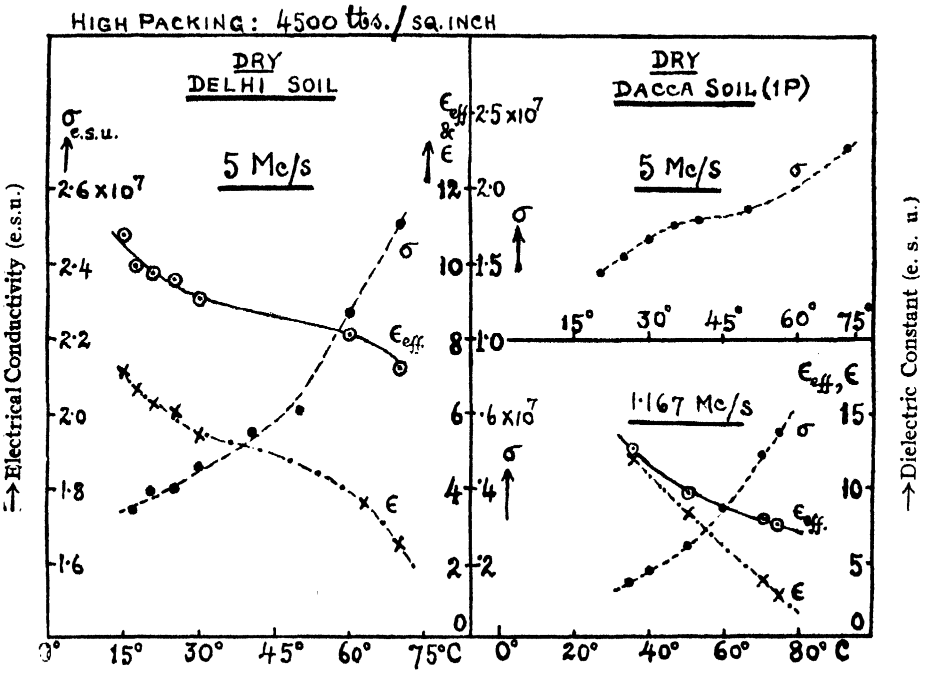


FIG. 14

reliable measurements owing to the wetting of the soil by the dew that was formed in appreciable quantity at such low temperature. The results with such high packing of Dacca soil are illustrated in a part of Fig. 15. The electrical conductivity increased with temperature but the effective dielectric constant was, in this case, found to decrease as the temperature was increased from 35° to 75°C.

(*b*) *Experiments on high radio-frequency* (5 *Mc/s*)

The experimental results on 5 Mc/s obtained by the oscillographic method employing Delhi and Dacca soils packed at a pressure of 4500 lbs. per sq. in.



→Temperature (Centigrade)

FIG. 15

are shown in Fig. 15. The electrical conductivity was found to increase and the dielectric constant to decrease as the temperature was raised from 15°C to 70°C.

In the study of the temperature effect, it was tested carefully that effect was not due to dimensional change of the soil condenser owing to temperature variations.

(*c*) *Comparative study of the maximum values of the electrical constants of the surface soils from fifteen different places on* 5 *Mc/s and on medium frequencies for a few soils for fixed moisture content values.*

A short description of the different soils employed, the depth from which they were obtained and the localities are entered in Table I. The p_H values of the soils are also given there. In Table II are given the maximum values of the electrical conductivity, the effective and the true dielectric constants of the different soils. The frequency of the measuring field and the p_H values are also shown in the same table.

TABLE I

Place and Locality.	Depth.	Description.	Value.
*1. Dacca (1 P)	0″–6″	Grey loamy	5.7
„ (2 P)	6″–2′-3″	Yellowish, heavy loam	
(Agricultural Farm)			
2. Calcutta (Dum Dum Acrodrome) ...	0″–6″	Grey, Clayey	5.8
3. Delhi (A. I. R. Receiving Station) ...	0″–6″	Brownish	6.5
4. Luckuow (A. I. R. Transmitting station) ...	0″–6″	Light brown, clayey	6.8
5. Lahore (A. I. R. Transmitting station) ...	0″–6″	Grey, clayey	6.6
6. Peshawar (A. I. R. Transmitting station)...	0″–6″	Light brown	7.3
7. Trichinopoly (A. I. R. Transmitting station)	0″–6″	Grey, clayey	6.7
*8. Bombay (Kumata)	0″–6″	Red	6.0
*9. Calicut (Madras Presidency)	0″–6″	Red	5.1
*10. Ranchi (Ratu)	0″–1′	Red, clayey	4.8
*11. Cuttack (Tangi)	0″–1′	Grey, gravelly	4.5
*12. Bangalore	0″–3′-6″	Red, Loamy, granular	6.2
*13. Madura (Pasumalai)...	0″–1′-2″	Brownish, red sandy loam granular	6.7
*14. Vizagapatam (Muddilipalayam ...	0″–1′	Brownish, red sandy loam, granular	6.2
*15. Trivandrum (Khoddappanam Kunnu) ..	0″–1′-6″	Light red, gravelly	5.6

* The description of the soil profiles is taken from the records of the Soil Science Section of the Chemistry department, Dacca University.

It will be seen from Table II that there is no connection between the values of the soil constants and the p_H values of the soils. It is also significant that for such high packing the values of both the electrical conductivity and the dielectric constant at 5 Mc/s are decidedly lower than those at medium radio frequencies. This is consistent with the experimental results regarding the variation of the soil constant with frequency for such high degree of packing. (See Fig. 12).

Some typical oscillograms, on high and medium radio-frequencies, are shown in Plate (VI)

TABLE II

(Electrical constants in e. s. u.)

Soils	p_H values	Radio frequency f = 5 Mc/s (λ = 60m)						Medium radio-frequency							
		Moisture 15%			Moisture 20%			Moisture 15%			Moisture 20%			Frequency.	Wave-length
		$\sigma \times 10^{-7}$	ϵ eff.	ϵ	$\sigma \times 10^{-7}$	ϵ eff.	ϵ	$\sigma \times 10^{-7}$	ϵ eff.	ϵ	$\sigma \times 10^{-7}$	ϵ eff.	ϵ	Mc/s	metres
(1) Dacca (1P) ...	5.7	1.58	6.5	—	2.16	8.8	4.5	4.96	22.0	1.4	5.7	34.6	3.9	1.167	257.1
(2) Calcutta (Dum Dum)	5.8	1.52	5.7	2.67	1.69	6.4	3.1	7.5	—	—	14.8	—	—	.808	370.4
(3) Delhi ..	6.5	1.25	7.05	4.75	1.28	7.25	4.9	21.5	—	—	24.2	—	—	.886	338.6
(4) Lucknow ...	6.8	1.52	7.8	4.85	1.65	7.7 ?	4.4	1.01	46.2	39.0	—	—	—	1.022	293.5
(5) Lahore ...	6.6	1.33	5.7	3.05	1.50	5.6	2.6	7.04	70.1	15.85	10.3	—	—	1.086	276
(6) Bombay ...	6.0	1.45	6.7	3.83	2.01	6.4 ?	2.5	—	—	—	—	—	—	1.231	244
(7) Calicut (Madras)	5.1	1.42	6.1	3.27	1.71	4.9 ?	2.0	5.14	34.2	6.3	—	—	—	1.420	211
(8) Trichinopoly ...	6.7	2.68	15.5	10.50	—	—	—	—	—	—	—	—	—	.758	395.8
(9) Peshawar ...	7.3	1.75	9.3	5.94	—	—	—	1.46 ?	40.2	32.5	5.72	—	—	1.500	200
(10) Cuttack ...	4.5	1.71	9.2	5.93	—	—	—	—	—	—	—	—	—	—	—
(11) Ranchi ...	4.8	1.23	8.8	6.7	1.98	6.0	2.2	—	—	—	—	—	—	—	—
(12) Bangalore ...	6.2	1.72	6.7	3.26	1.91	6.2	2.5	—	—	—	—	—	—	—	—
(13) Madura ..	6.7	1.90	8.3	4.51	2.09	—	—	—	—	—	—	—	—	—	—
(14) Vizagapatam ...	6.2	1.76	8.5	5.04	1.93	6.7	2.9	—	—	—	—	—	—	—	—
(15) Trivandrum ...	5.6	1.63	8.1	4.92	1.94	7.35	3.5	—	—	—	—	—	—	—	—

INTERPRETATION OF EXPERIMENTAL RESULTS

(a) *The Effect of Packing*

As the soil is packed, some of the air gaps between soil particles are removed. As the degree of packing is increased, more and more air gaps are closed up resulting in a large values of the electrical conductivity and of the dielectric constant. As density also increases with the increase in the degree of packing, the dielectric constant would also increase with the degree of packing. We would also expect some limiting values of the soil constants for some high value of packing.

The experimental results with regard to the effect of packing are thus explained.

(b) *The Effect of Moisture*

The electrical conductivity and dielectric constant of water are both high. When water is added to dry soil, it gets into the innumerable air gaps among the soil particles. With more water, there is greater penetration and we should expect an increase of dielectric constant and electrical conductivity with the increase of moisture. For higher moisture contents it is also expected that the soil constants would tend to approach saturation values.

The experimental results showed that the soil constants increased considerably as the percentage moisture was increased from 0 to 20%.

(c) *The Variation of the Soil Constants with Frequency*

So far as the electrical conductivity is concerned, we have to consider the effect of (1) displacement currents in the soil medium, (2) the effect of orientation of dipolar molecules in the soil and (3) the skin-effect. The effect of an ionic space-charge formed in the soil condenser can be left out of consideration, as it is well established that the effect of such ionic charge has practically no effect except at very low audio-frequencies. In the range of audio-frequencies the variation of the electrical conductivity due to the orientation of molecules is of little importance and the major portion of the soil conductivity is due to displacement currents. In the region of high frequencies, however, the effect of orientation of the dipolar molecules, is predominant. The total electrical conductivity of soil at any frequency is, however, given by

$$\sigma = \sigma_0 + \sigma_d + \sigma_p \qquad \dots \quad (16)$$

where, σ_0 = d.c. electrical conductivity ;

σ_d = electrical conductivity due to displacement currents in the dielectric ;

and σ_p = electrical conductivity due to orientation of polar molecules in the electrical field.

It can be shown that the electrical conductivity due to displacement currents is directly proportional to the frequency, so that in audio-frequency range, the variation of the electrical conductivity with frequency f would be of a linear form, *viz.*,

$$\sigma = \sigma_0 + k_1 f, \text{ where } k_1 \text{ is a constant.}$$

Considering, however, the conductivity of soil due to dipolar orientation, it can be shown that in range of radio-frequencies, where the product of angular frequency and relaxation time is very much less than unity, Debye's expression for the electrical conductivity would reduce to a simple square law, *viz.*,

$$\sigma_p = k_2 f^2, \text{ where } k_2 \text{ is a constant.}$$

Thus the expression for the total soil conductivity at any frequency would be given by

$$\sigma = \sigma_0 + {}_1kf + k_2 f^2$$

Bairsto's (*loc.cit.*) work substantiated this relation in the case of marble and slate. It is to be noted here that the d.c. conductivity term σ_0 is indeed a small quantity. When, however, it is high as in the case of tightly packed soil, the skin effect becomes appreciable and the expression for total electrical conductivity would be of the form :—

$$\sigma = \frac{k_0}{\sqrt{f}} + k_1 f + k_2 f^2 \qquad \ldots \quad (17)$$

where k_0 involves the d.c.conductivity.

This relation has been substantiated by our experimental results on the variation of soil conductivity with frequency. For low packing, the d.c. conductivity of soil is very small so that the conductivity terms due to displacement currents and the orientation of dipolar molecules in soil are only effective. For low packing, therefore, the soil conductivity should increase with frequency in accordance with (17). When the packing of soil is very high, the d.c. conductivity term becomes large in comparison with the other terms, and the skin-effect which is predominent determines the variation of the soil conductivity with frequency. Thus for such high packing, the soil conductivity is expected to decrease with frequency. Such results have actually been obtained experimentally.

The variation of the dielectric constant with freqnency, on the other hand, should be attributed solely to the orientation of the dipolar molecules in the soil medium. The experimental results on dielectric constant are in qualitative agreement with Debye's formula.

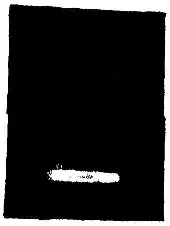
(*d*) *The Effect of Temperature*

As density decreases with the increase of temperature, it is expected that the true dielectric constant would decrease as the temperature is raised. Considering, however, Debye's expression for the dielectric constant, since it is known that the relaxation time decreases as temperature increases, the dielectric constant would gradually increase with the increase of temperature. This increase, however, is more than counter-balanced by the decrease of dielectric constant with temperature due to change in density. Usually, therefore, the true dielectric constant of soil would gradually decrease with the increase of temperature. This is what has been actually observed.

CALCUTTA SOIL

·808 Mc/s

DACCA SOIL



1·167 Mc/s

DELHI SOIL

·886 Mc/s

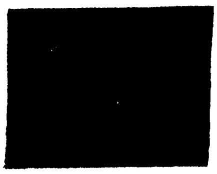
CALCUTTA SOIL

3 Mc/s

CALCUTTA SOIL

5 Mc/s

CALCUTTA SOIL



7·7 Mc/s

Regarding variation of electrical conductivity with temperature, it is evident that the d.c. conductivity part increases with temperature. The conductivity due to orientation of polar molecules would also gradually increase with temperature, since relaxation time decreases as the temperature is raised. The conductivity due to displacement current which is small in the region of radio-frequencies, is proportional to the dielectric constant and would decrease with the increase of temperature. On the whole, therefore, in the region of radio-frequencies, the soil conductivity would steadily increase as the temperature is raised. This is also what has been experimentally found.

Since the effective dielectric constant involves the true dielectric constant and the electrical conductivity, it is evident that its variation with temperature would be determined by the variations of both these quantities. We have seen that the true dielectric constant decreases and that the electrical conductivity increases as the temperature is raised. The latter variation is usually such that the effective dielectric constant of soil would slowly decrease with the increase of temperature. It may also remain constant over a range of temperature. Our experimental results on the effect of temperature on the soil constants are thus interpreted.

SUMMARY

The results of investigations on the dielectric properties of fifteen different soils from the different parts of India on medium and high radio frequencies are given in the paper. Measurements of the effective dielectric constant and the electrical conductivity were made by the differential transformer method or the oscillographic method. From these data, the true dielectric constants were evaluated. The following studies were made:

(*a*) *The Effect of Packing* : The packing effect on the electrical constants of some soils was studied on 5 Mc/s and also on the respective frequencies of the medium wave A. I. R. stations located at the places from where the soils were taken, for specified moisture contents. The packing effect was studied in two stages : (*i*) for low order of packing and (*ii*) for high order of packing as obtained by a hydraulic press. The soil constants were found to increase gradually till in many cases some constant values were attained.

(*b*) *The Effect of Moisture* : The increase of soil constants of the Dacca soil with the increase of moisture content from 0 to 20% was studied for various degrees of packing. Both electrical conductivity and dielectic constant were found to increase rapidly with the increase of moisture content. The degree of packing was kept at the same value for the soils with different moisture contents.

(*c*) *The Variation of the Soil Constants with Frequency* : The experiments were performed for low and high orders of packing. Some soils were studied for low packing in the range of medium radio frequencies, while all the fifteen soils were studied for low packing in the high frequency range from

about 1 or 2 to about 8 Mc/s. A slow *decrease* of dielectric constant and a rapid *increase* of electrical conductivity with the increase of frequency were noted for low packing.

Experiments with some soils with extremely high packing in the same high frequency range, on the other hand, showed a *decrease* of both the electrical conductivity and the effective dieletric constant of the soils with the increase of frequency.

(d) *The Effect of Temperature* : The experiments on the temperature effect with some soils both on medium and high radio frequencies showed an increase of electrical conductivity and a slow decrease of the effective dielectric constant with the rise of temperature for very high packing. For low packing on medium radio frequency the effective dielectric constant of the Dacca soil was found to be constant over a wide range of temperature. The true dielectric constant was found, however, on calculation, to decrease in all cases as the temperature was raised both for low and high packing.

(e) *Comparative study of the maximum values of the soil constants of soils from fifteen different places on 5 Mc/s and on medium radio frequencies for some soils* : The maximum values of the electrical constants of the soils from Dacca, Calcutta (Dum Dum), Delhi, Lucknow, Lahore, Peshawar, Bombay, Trichinopoly, Calicut, Ranchi, Vizagapatam, Cuttack, Bangalore, Madura and Trivandram were measured on 5 Mc/s for 15% and 20% moisture contents.

The maximum values of these constant were also obtained for the soils from Dacca, Calcutta, Delhi, Lahore, Peshawar and Calicut (Madras) on the respective frequencies of the medium wave stations located at these places.

The values of the soil constant do not appear to have any correlation with the p_H-values of the soils.

A general interpretation of all experimental results is given.

ACKNOWLEDGEMENTS

We are indebted to the Soil Science Section of the Chemistry Department of the Dacca University for supplying us with all the soil profiles used in the present investigation. Our sincere thanks are also due to the A. I. R. Station Engineers of some of the stations for kindly sending us the surface soil from the neighbourhood of their transmitters and to Prof. S. K. Mitra, D.Sc., M.B.E., for supplying us with Calcutta soil specimens. We also thank the Head of the Chemistry Department for the use of the Carver Laboratory Hydraulic Press.

Finally we offer our warm thanks to Prof. S. N. Bose for his help and interest in this investigation.

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REFERENCES

Ansari, Toshniwal and Toshniwal, 1940 *Proc. Nat. Inst. Sciences* (India), **6**, 627
Bairsto, 1912, *Proc. Roy. Soc. A.*, **96**, 363.
Banerjee and Joshi, 1937, *Science and Culture*, **2**, 587
Joshi, 1938, *Science and Culture*, **4**, 196
Joshi, 1938, *Ind. Jour. Phys.*, **12**, 1
Prasad, Singh and Sinha, 1940, *Science and Culture*, **6**, 243
Khastgir and Chakravarty, 1938, *Phil Mag.*, **26**, 793
Khastgir and Sen Gupta, 1936, *Phil. Mag.*, **22**, 265
Rahman and Muhi, 1944, *Ind. Jour Phys.*, **18**
Ratcliffe and White, 1930, *Phil Mag.*, **10**, 667
Smith-Rose, 1938, *Proc. Roy. Soc. A.*, **111**, 359
Smith-Rose and McPetrie, 1932, *Proc. Phys Soc.*, **44**, 1933, *Proc. Phys. Soc*, **45**
White, 1931, *Proc Camb. Phil. Soc.*, **27**, 268