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MEASUREMENTS OF THE ELECTRICAL CAPACITY AND CONDUCTIVITY OF SOIL BLOCKS.

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(With Six Text-figures.)

INTRODUCTION.

On account of the influence of moisture content on the physical properties of soil, many laboratory studies have been made on the variation with moisture of those of importance in cultural operations, or in such problems as the movement and distribution of water in soils. Matters are complicated by the fact that soil properties depend not only on the moisture content but also on previous moisture changes, as any given moisture may be approached from a higher or lower value: for example, volume changes of soil are not reversible on drying and rewetting if the soil has been dried out below a certain limit. In laboratory work it is most convenient to obtain a series of moisture contents by starting with a wet soil and allowing it to dry out to varying extents, but even under these conditions the results of different investigations often disagree, some suggesting that the variation with moisture content is continuous, others that the variation is essentially a discontinuous process.

Atterberg(1) examined the behaviour of soils over wide ranges of moisture content and divided the moisture range for each soil into six main parts. In any particular moisture region the soil exhibits a definite "consistency" or behaviour towards outside forces such as gravity and pressure, and each consistency is distinguished from the others by the different effects on the soil of these forces, or by the "feel" of the soil. Atterberg's work implies that changes in the properties of soils occur at well-defined moistures, and in recent years some of these have been used by soil workers as "single value" constants, in an attempt to classify the general characteristics of a soil by a single number.

From the point of view of the work to be described, the three most important of Atterberg's limits are the sticky point (die Klebegrenze), the lower plastic limit (die Ausrollgrenze), and the moisture content at

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which air enters the soil pores (die Schwindungsgrenze). The sticky point is determined by first mixing the soil with water until it is definitely wet and will stick to a nickel spatula. The soil is then kneaded by hand until the point is reached when it no longer adheres to the spatula when the latter is drawn across or through it. The lower plastic limit is defined as the moisture content below which the soil can no longer be rolled into a fine wire under the finger without crumbling. Below this limit the soil crumbs will adhere when pressed lightly together, and will shrink on drying without entry of air into the soil pores. When, however, enough water has evaporated the film breaks between the soil particles, the colour changes, and shrinkage ceases. Atterberg (2) also obtained a break in the cohesion-moisture curve at this limit. For lower moistures the soil crumbs will not adhere when pressed lightly together, but if the soil has been moulded when wet and allowed to dry out below this limit, then the force required to crush or break the soil may be considerable.

Haines (3, 4) confirmed the slowing down in the rate of shrinkage, but could find no discontinuity in his cohesion measurements, although he used the same type of apparatus and essentially the same method. The cohesion measurements entail the preparation of a series of test blocks, and as it is impossible to obtain them identically alike the errors in this type of experiment are large: for this reason it is difficult to detect a small change in the variation of cohesion with moisture on the entry of air into the soil, should such a change occur. In order to obtain more accurate data on soil moisture relationships, some type of experiment in which one sample of soil can be used throughout was obviously required, and for this purpose an electrical method is most convenient. Measurements can be made comparatively accurately, and it is reasonable to suppose that any changes, depending on moisture, in the mechanical properties of soils will be reflected in some way in their electrical properties.

PREVIOUS CONDUCTIVITY MEASUREMENTS.

Conductivity determinations have been used chiefly in attempts to develop methods of measuring either moisture or salt contents under field conditions. Laboratory measurements on the change of conductivity with moisture content have been made by Whitney and Means (5), Deighton (6) and Haines (7).

Whitney and Means measured the specific resistance of their soils in a hard rubber cell with brass electrodes, the soils being mixed with water and packed into the cell for each determination. Deighton's method was similar except that for electrodes he used carbon, which is self-depo-

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larising to some extent owing to its ability to absorb gases. As Haines pointed out, these workers were probably altering the degree of packing and the contact with the electrodes for each measurement as well as the moisture content. Consequently, Haines measured the change in resistance taking place, as a block of soil, moulded at the sticky point, was allowed to dry out, and used mercury electrodes to improve the soil-electrode contact. There is one criticism which may be advanced against this technique and that is the possibility of ageing effects.

The results of Whitney and Means gave straight lines or very slightly bent smooth curves for a moisture range of 6 to 18 per cent., the resistance varying inversely as the square of the moisture content. Deighton confirmed the latter law for moistures above 10 per cent., but below this value his results gave one and possibly two discontinuities. Deighton suggested that these might be due to some process analogous to the coagulation of soaps, as Laing and McBain had found that the specific conductivity of soap curds was lower than that of either the sol or gel.

Haines found that for natural soils the conductivity curves were smooth and more or less concave to the moisture axis, with no indication as to when air entered the soil. Some heavy clays and a sample of kaolin, however, formed an exception. The conductivity remained constant for a considerable range of moisture content, and only began to fall when entry of air into the soil took place. The constancy of conductivity when the pore space was filled with water seems remarkable if the conductivity is regarded simply as the usual electrolytic conductivity of a solution: for it might be expected that the shrinkage of the soil would give rise to a mechanical obstruction to the movement of the ions and so cause a decrease in conductivity. It is known, however, that the ions present in the soil solution are attracted towards the soil water interface, their concentration decreasing with distance from the interface. On the application of an alternating field, the ions move over the surface of the soil particle, and since the force of attraction to the interface varies for different ions, their response will depend on the restoring force, the applied field and its frequency. The net effect of their movement will be similar to the passage of an alternating current through a condenser, and will give rise to a difference in phase between the applied E.M.F. and the current flowing. When measuring the conductivity of such a system by a bridge method it is necessary to introduce a compensating capacity either in series or in parallel with the variable arm of the bridge. In the experiments described below the values of the parallel capacity required for balance were measured.

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EXPERIMENTAL.

The technique of preparation of the soil blocks was the same as that employed by Haines. After passing the soil through a sieve with 100 meshes to the inch, distilled water was added until the moisture content was approximately that of the sticky point. After thorough mixing, rectangular blocks of soil were made by means of brass moulds and the electrodes inserted. For purposes of comparison both carbon and mercury electrodes were used. Ideally the electrodes should be of the same cross-section as the block, but, owing to shrinkage, it is not possible to maintain a constant contact, and the carbon electrodes employed were cylindrical rods of approximately 1·5 mm. diameter. The system is complex in the sense that besides the resistance and capacity of the soil there are resistance and capacity associated with the electrode-soil interface. The measurements taken, *i.e.* the parallel capacity and resistance, give the equivalent electrical circuit of the soil and interface effects combined. An attempt was made to separate them by using three electrodes at different distances apart, for, assuming that each electrode introduces the same impedance, it should be possible to calculate the phase angle of the current in the soil.

In a preliminary series of measurements the soils were allowed to dry out slowly, the experiments lasting approximately 4 weeks so that the moisture distribution in the block should remain as uniform as possible. In his paper on the shrinkage of soils Haines has shown that under such conditions the difference in moisture for the inside and the outside layers is small.

The apparatus consisted of a valve oscillator, a Cambridge Scientific Instrument Company bridge, and a variable condenser, earphones being used as detector. One corner of the bridge was earthed. The condenser was made from a series of T.C.C. mica condensers ranging in value from 0·0001 to 1·0 μF and an Ormond 0·001 μF variable condenser. Each fixed condenser could be connected in parallel with the Ormond, and all were calibrated in terms of one of them chosen as standard. With this apparatus sharp minima of sound could be obtained in the earphones, but the method of earthing the bridge was unsatisfactory, and at low moistures the current flowing through the soil block was large enough to produce slight heating effects as the measurements were being made.

Consequently, in the second series of experiments the oscillator was modified to give a smaller output, and a two-stage amplifier was employed to provide the necessary sensitivity. The technique was further improved by earthing the bridge in the manner described by Jones and Josephs(8).

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This method ensures that the telephone is kept at earth potential when in balance, and also eliminates errors due to unsymmetrical capacitance from the oscillator or oscillator leads to earth. The final form of the apparatus is shown in Fig. 1. The input balancing device consists of a series of resistances approximately equal to those of the ratio arms of the bridge, and a variable condenser K. Any pair of these resistances could be joined in series with the slide wire CC', and either input lead connected to earth through the condenser K by means of a switch (S_1). In this apparatus K was a Ton-a-cap variable condenser and the resistances were of manganin wire wound non-inductively on ebonite plates.

In using the bridge, one end of the telephones is first connected to earth by a switch (S_2), and the point B of the main bridge brought to earth potential by adjusting the position of the contact on the slide wire and the setting of the condenser K. When a balance has been obtained, S_2 is reversed, connecting the telephones across the main bridge, which is then balanced. The setting of the balancing system is checked, and, if necessary, the readings on the bridge corrected.

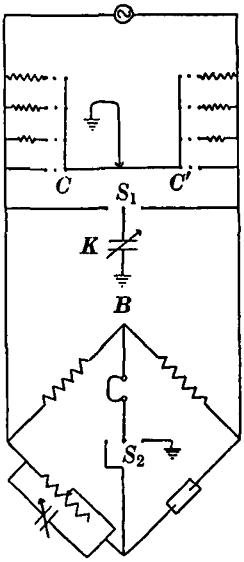

Fig. 1.

In a second series of measurements, the range of the experiment was extended to prove the presence, or absence, of ageing effects by allowing half the number of blocks for each soil to dry out at a faster rate than the remainder.

Experimental results.

Before describing the results obtained for soil, capacity effects observed in the measurement of the resistance of electrolytes will be considered. When, for example, a current is passed between platinum electrodes immersed in dilute sulphuric acid, a back electromotive force is set up and the electrodes are said to be polarised. For alternating current the system can be represented by a resistance R in series with a capacity K, where R is the resistance of the electrolyte and K is the capacity of the polarised electrode. The vector impedance of the system for an alternating current of frequency $\frac{\omega}{2\pi}$ is given by

$$z = R + \frac{1}{j\omega K},$$

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and the current leads the E.M.F. by a phase angle $\tan\theta = \frac{1}{\omega RK}$. Thus the effective resistance is R and the reactance $-\frac{1}{\omega K}$.

In bridge measurements the compensating capacity is usually placed in parallel with the variable arm of the bridge, and the vector impedance of a resistance S in parallel with a capacity C is given by

$$z = \left(\frac{1}{S} + \frac{1}{\frac{1}{j\omega C}}\right)^{-1} = \frac{S - j\omega S^2 C}{1 + \omega^2 S^2 C^2},$$

so that for this system the phase angle is given by $\tan\theta = \omega SC$, and the effective resistance and reactance by

$$\frac{S}{1 + \omega^2 S^2 C^2} \quad \text{and} \quad -\frac{\omega S^2 C}{1 + \omega^2 S^2 C^2}$$

respectively.

When the bridge has been balanced the two circuits are equivalent and the corresponding quantities are identical. The effective resistances must be equal, *i.e.*

$$R = \frac{S}{1 + \omega^2 S^2 C^2},$$

or, since the same phase angles are the same,

$$R\left(1 + \frac{1}{\omega^2 R^2 K^2}\right) = S.$$

From the latter equation it is seen that the measured resistance differs from the true resistance R, and that for any given frequency the difference is larger, the smaller the product RK. The correction required may be made negligible by increasing RK to a suitable value, and, when small values of R are being measured, K should be made as large as possible. In practice this condition is realised by platinisation which produces a mass of spongy platinum and greatly increases the effective area of the electrode. For such electrodes the capacity may be of the order of thousands of microfarads per square centimetre, while for bright platinum it is twenty-five to thirty times less. The actual value depends on the concentration of the solution and decreases with increasing frequency. In the case of mercury, the value of the capacity, as calculated from capillary electrometer measurements (*i.e.* for static conditions), is about 30 microfarads per square centimetre, so that for alternating current the value will be somewhat smaller.

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Consequently, in the present work with soil, it would be expected that the small series capacity associated with the mercury electrode would require a comparatively large parallel capacity for balance, and that most of the measured parallel capacity would be due to the electrodes. Carbon, being porous, would present a greater surface area, and for this electrode the capacity should be larger and require a smaller balancing capacity. The experimental results show that the parallel capacity measured for the soil blocks with mercury electrodes was always greater than for the soil with carbon electrodes.

For mercury electrodes in the first series of experiments, the general result for falling moisture is an increase in parallel resistance, an initial decrease in parallel capacity followed by a sharp rise to a maximum, after which it falls again, showing two changes in direction at lower moistures. The parallel capacity-moisture curve for a Punjab soil is shown in Fig. 2.

In view of the preceding discussion on electrode effects the parallel capacity has been converted into the equivalent series capacity by means of the equation

$$K = C\left(1 + \frac{1}{\omega^2 S^2 C^2}\right),$$

assuming that the electrode capacity is responsible for the whole of the reactance. The series capacity-moisture curves for the Punjab soil and a Long Newton clay are given in Fig. 2, both curves exhibiting a striking drop in series capacity which is steepest when air begins to enter the soil pores. For the Punjab soil this occurs between moistures of 20 and 18 per cent. The curve also shows that the series capacity decreases over the moisture range of 23 to 20 per cent., while at still higher moistures there is a marked fall, to which reference will be made in a later part of the paper. For high moistures, a calculation from the data for the electrodes at different distances apart shows that the parallel capacity due to the soil is not negligible compared with that due to the electrode, so that the series capacities given are less than those actually existing at the electrode. At the beginning of the experiment, the true series capacities are of the order of 15 microfarads per square centimetre, a value comparable with that found for the capillary electrometer.

Below a moisture of 18 per cent. the series capacity remains comparatively constant, until at 6 per cent. it again decreases rapidly. If plotted on a larger scale, this portion of the curve shows that the capacity is decreasing with decreasing moisture and that a change in its variation with moisture occurs at 13 per cent. This is shown for the second series of

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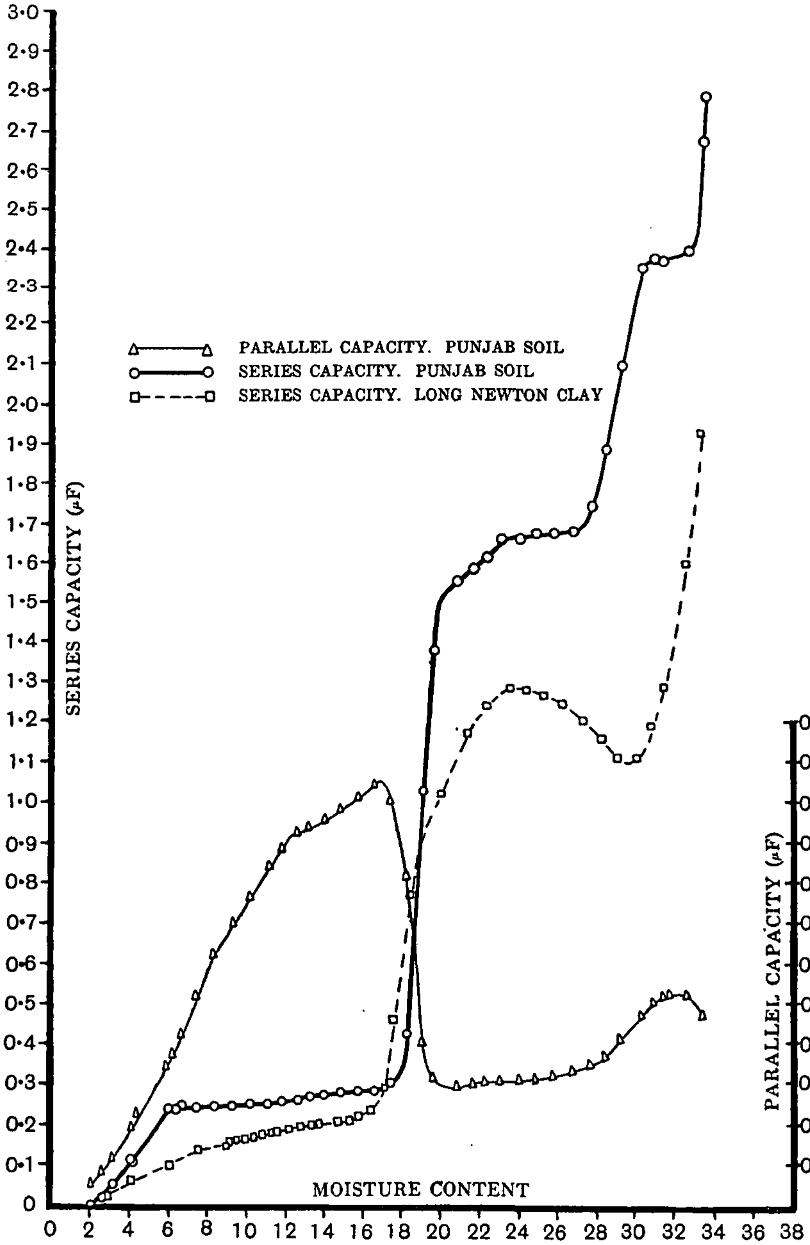

Fig. 2.

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experiments (when more readings were taken for the lower moistures) in Fig. 5. It will be seen that the final fall in series capacity commences at a moisture between 7 and 8 per cent.

Similarly for the Long Newton Clay the series capacity decreases for moistures below 25 per cent., the rate of change being greatest from 18 to 16 per cent. when entry of air begins. Again, there are two further moistures, 13 and 7 per cent. approximately, where changes in its variation with moisture take place.

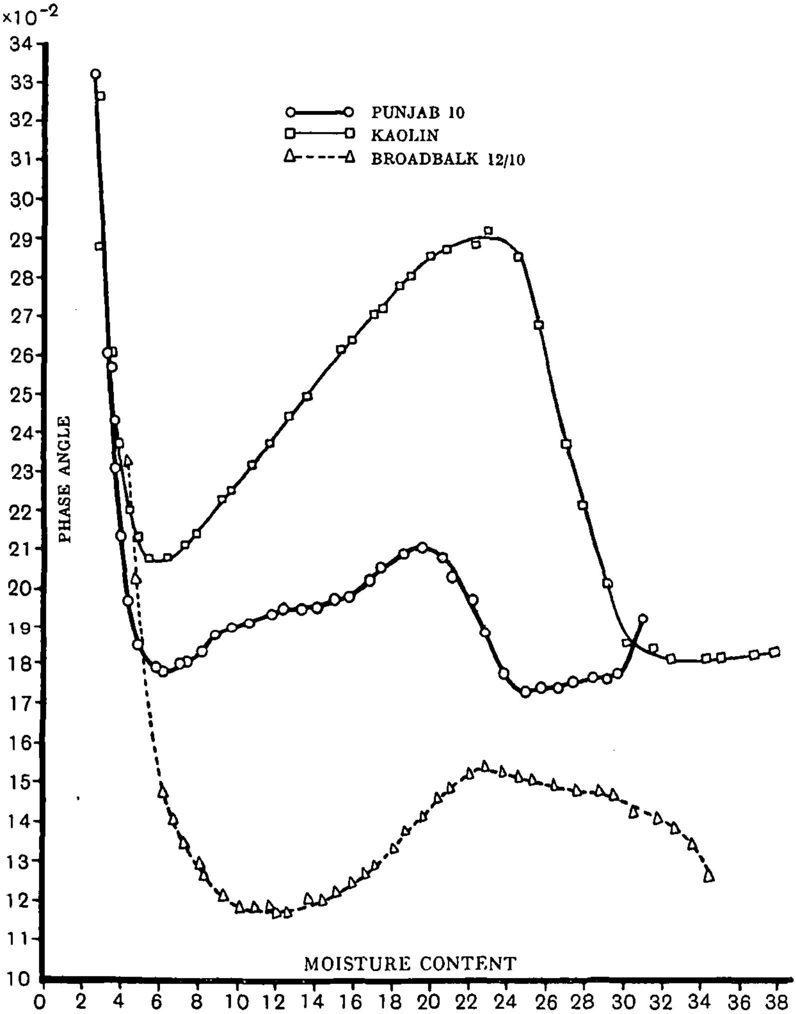

Fig. 3.

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For carbon electrodes in the first series of experiments the general result for falling moisture is an increase in parallel capacity. This is true for a series of soils and a sample of kaolin, the only exception being the heavy Long Newton clay, for which the parallel capacity rises to a maximum at an intermediate moisture and afterwards falls rapidly. The soils are perhaps best compared by considering the variation of the phase angle with moisture content, shown in Fig. 3, for two soils and the kaolin. All the curves exhibit a maximum at a moisture content which is approximately that at which air enters the pores, and at lower moistures the phase angle passes through a minimum, after which it rises rapidly. The curve for the Punjab soil shows changes at 12 and 8·5 per cent. corresponding to those observed in the measurements with the mercury electrodes. For this soil and the kaolin the minimum occurs at 6 per cent., while for the heavier Broadbalk soil the phase angle rises for moistures lower than 12 per cent. On the other hand, the phase angle for the still heavier Long Newton clay rises for most of the moisture range, the curve showing discontinuities at moistures of 26, 19, 12 and 7 per cent. approximately.

The second series of experiments with the improved technique gave similar results in all cases where carbon electrodes were used. With mercury electrodes the results are the same except for the Long Newton clay: the parallel capacity required was extremely large and showed a curious reversal in its variation with moisture content. In this series a decrease occurred on the entry of air, whereas in the first there was an increase. Consequently the series capacity rises from a value of 0·3 microfarads per square centimetre to a value of 0·6 microfarads after air had entered the soil pores.

The data obtained shows that the variation of the electrical properties of the soil blocks with decreasing moisture is not continuous, the mercury electrodes being most suitable for detecting these effects, and giving the same general type of result for widely varying soils. The changes observed in the series capacity can only be caused by changes in the contact between the soil and the electrode, and these in turn must depend on the manner in which the moisture is held by the soil: a determination of the lower plastic limit by the rolling technique gives a value of between 22 and 23 per cent. for the Punjab soil, and a fall in series capacity occurs at 23 per cent. Similarly, a shrinkage experiment shows that air begins to enter the soil at 19·5 per cent. moisture, and the main drop in series capacity commences at approximately 20 per cent. This decrease is practically complete in the moisture range 20 to 18 per cent. and, since only a small fraction of the water in the soil has been replaced by air, it can only be

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explained by the spreading of a film of air between the soil and the mercury. Contact occurs over a small area of the soil particles, and if this area remains approximately constant the small change in series capacity for a considerable moisture range below 18 per cent. is explained. Similarly, such a decrease in contact area should cause an increase in the resistance between the soil and the electrode: a marked fall in conductivity does occur on the entry of air, as shown in Fig. 5, for the slow rate of drying. The series capacity finally falls as the moisture is removed from the surface of the soil particles. The slight change at 12 per cent. is probably due to a series of larger capillaries having filled with air, this moisture marking the extension of the process to the finer ones in the soil. This suggestion is borne out by a more rapid change in the slope of the conductivity curve at this point.

Similar reasoning applies to the Long Newton Clay, where the results for the series capacity are confirmed by the phase-angle curves for the blocks with carbon electrodes. The lower plastic limit occurs at a moisture of 26 per cent. and entry of air at 18 per cent. At present only a tentative explanation can be advanced for the anomalous behaviour in the second experiment when the series capacity increased. The explanation for the decrease generally observed is based on a decreased area of contact between the soil and the electrode. On the same hypothesis, an increase in series capacity could only be caused by an effective increase in the area of contact. This might arise if the surface of the soil were originally contaminated by a film of conducting grease which was drawn into the soil pores. The conductivity did not show the sudden decrease observed in the first experiment, which is in keeping with the above suggestion that the effective contact area was not, at any rate, decreased.

With carbon electrodes the results obtained vary more with the type of soil than is the case with mercury. Since carbon can absorb water the demarcation between the soil and the electrode is less distinct than with mercury, and possibly exceptional moisture conditions may arise near the electrodes. These would depend on the texture of the soil, and may account for the difference in the phase-angle curves for the Punjab soil and the Long Newton clay. As recorded in the experimental section, an attempt was made to separate the soil and electrode effects by using three electrodes in each soil block at different distances apart. The phase angles were always greater for the electrodes closer together, showing that the electrodes do introduce some impedance. When the phase angle of the current in the Punjab soil was calculated from the two sets of readings, the variation with moisture was similar to that for the phase angles

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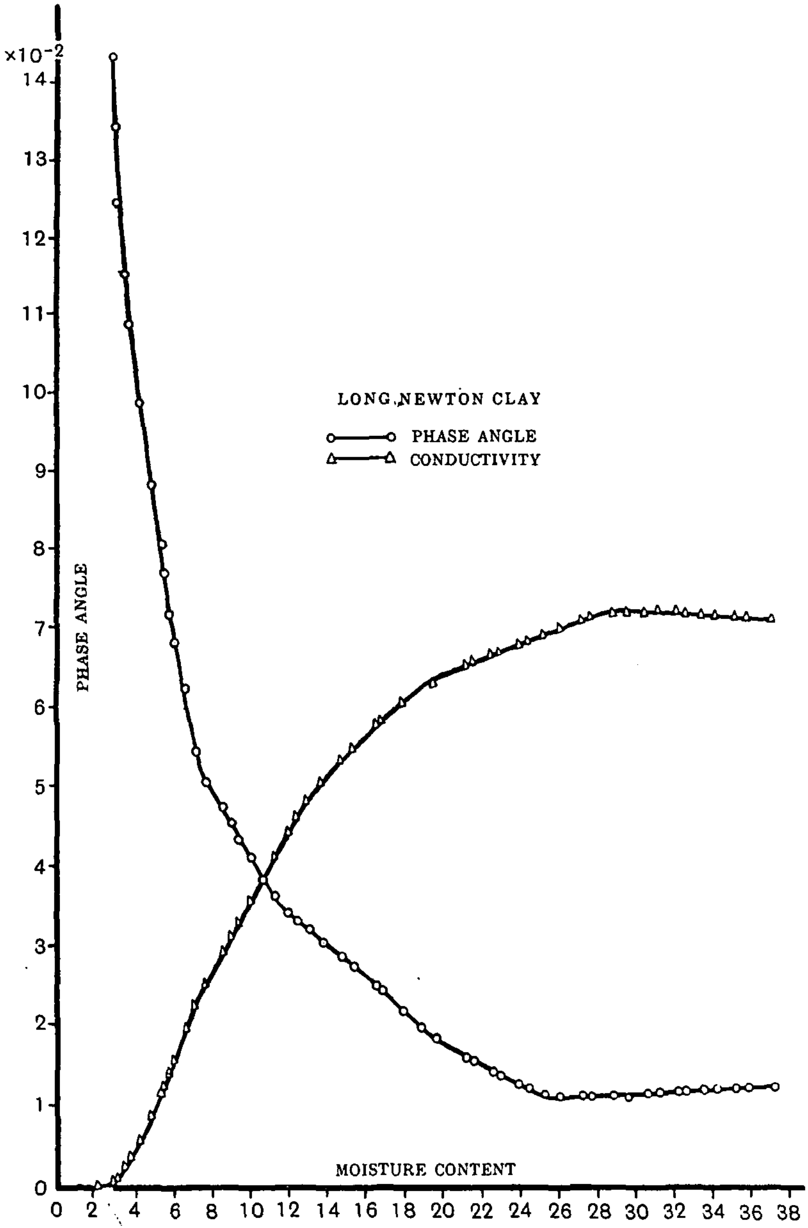

Fig. 4.

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measured, and in this case it may be assumed that the soil is responsible for the major part of the parallel capacity measured. Similar calculations for the Long Newton clay show that the electrode effect is more marked, especially for the lower moistures. In general, the experimental data suggests that the electrodes cannot be regarded as identical, as it is not always possible to obtain satisfactory derived curves from the readings for different distances apart of the electrodes.

Conductivity curves.

The type of conductivity curve obtained varies with the characteristics of the soil used, and at least, in some cases, on the rate at which the soil is allowed to dry out. In Fig. 4 is shown the conductivity for the Long Newton clay with carbon electrodes for the faster rate of drying. At the beginning of the experiments there is often a rise in conductivity, due most probably to salt dissolving out from the soil, and consequently if loss of water causes the conductivity to decrease there will be two opposing factors in operation. In the curve shown, the conductivity has a maximum at 29 per cent. moisture, but for the slower rate of drying the maximum occurs at 33 per cent. If the conductivities are plotted against time, it is found that both maxima occur after 4 days, and that the curves agree for a period of 8 days; at this stage the drier block has reached a moisture content of 26 per cent. and the curves diverge. After the maximum has been reached the conductivity decreases with decreasing moisture until the point is reached where air enters the soil pores when the conductivity falls more rapidly. The slow change over the saturated region corresponds to Haines' observation on the constancy of the conductivity of this soil over the same moisture region. The fact that his experiments were completed in a shorter time would help to give a flatter appearance to the curve. After the entry of air the curve is more or less concave to the moisture axis, but is not smooth.

The Punjab soil gives an entirely distinct kind of variation with moisture, the results for the slow and fast rates of drying being shown in Fig. 5. As these curves are for mercury electrodes the series capacities are also given. For the slower drying the conductivity first passes through a maximum and then falls rapidly. This fall is peculiar in that it is steepest at a high moisture and gradually slows down until a moisture of 22 per cent. is reached, the shape of the curve suggesting that the conductivity tends to reach a constant value. At 22 per cent. moisture it commences to fall again, until at 19·5 per cent. there is a sharp drop corresponding with the fall in series capacity. Below 17·4 per cent. the curve is concave

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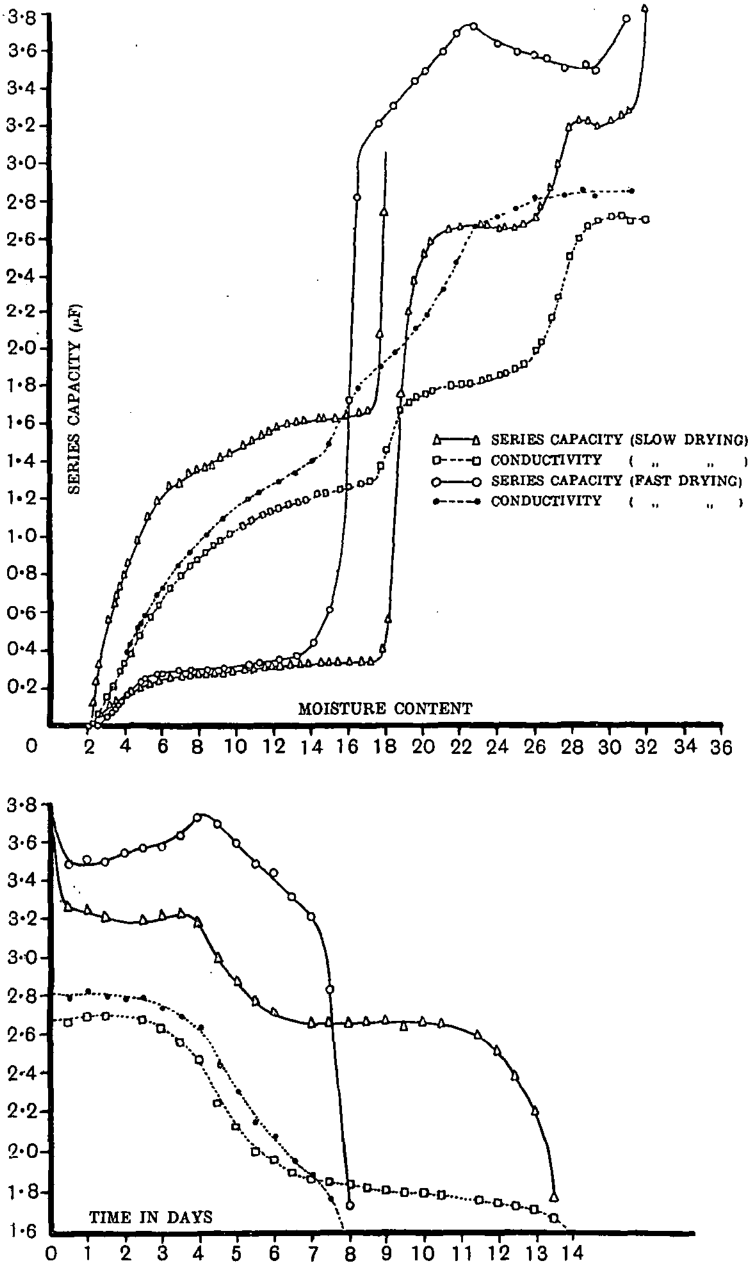

Fig. 5.

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to the moisture axis. With carbon electrodes and the slower rate of drying, the general appearance of the curve is similar except that the change at 22 per cent. moisture is not so marked and the decrease between 19·5 and 17·4 per cent. is absent. This shows that the latter effect is characteristic of the mercury electrode, and suggests that the change at 22 per cent. is also an electrode effect. Both changes disappear in the curve obtained by plotting the reciprocal of the difference in series resistance for the mercury electrodes at different distances apart. The initial rise and fall is still present, and as they also occur with the carbon electrodes, they must be due to the soil.

For the faster rate of evaporation the conductivity does not decrease so rapidly, and from a comparison of the two rates of drying it is obvious that time is again an important factor. The conductivity-time curves and series capacity-time curves agree for a period of 6 days, although the block which was drying the faster had lost one-third of its original moisture content and about twice as much as that lost by the other. Consequently for a considerable range below the sticky point ageing effects are of greater importance than moisture in causing variations in the conductivity and capacity. With the faster rate of drying no change similar to that at 22 per cent. moisture for the slower rate of drying can be detected, because the ageing process is not complete and the apparent variation of conductivity with moisture is still considerable.

There is a second difference between the slow and fast rates of drying in that the moisture content at which air enters the pores is greater for the former. This means that the soil particles are in closer packing for the block which dried the faster, and such a difference in packing might arise if the internal friction, which tends to prevent the relative motion of the particles, became greater the longer the soil is in contact with water. Similar effects were obtained to a less degree with a Broadbalk and a Woburn soil, and in all cases the differences between the initial moistures of the blocks of the same soil were quite small. There is, however, the possibility that the blocks were not in the same state of packing at the beginning of the experiment and, in the absence of density measurements, this possibility cannot definitely be ruled out, although the differences in the conductivities do show that ageing effects are taking place. Before a full explanation of the latter can be given it would be necessary to have a clearer picture of the way in which conduction takes place, since a material like soil will exhibit surface conductance. The relative importance of this as compared with the conductivity of the soil solution in bulk can only be determined by measurements made with different

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concentrations of salt solutions, and a series of measurements with the frequency and voltage of the oscillator varied is desirable.

The bearing of this work on other soil properties will now be considered.

Cohesion, shrinkage and evaporation.

In studies on the forces which bind soil particles together several methods of measurement have been employed: the crushing strength and transverse breaking load of soil cylinders and the resistance offered by soil to the penetration of a wedge have been taken as a measure of soil cohesion. The results depend on the method of preparation of the soil samples and the technique employed, but if the crumb structure of the soil has been destroyed by puddling with water and the soil particles brought into still closer contact by allowing the test samples to dry out, then it is found that the cohesion of most soils increases with decreasing moisture content. This is true of the results obtained by Atterberg and Johansson and by Haines, but, as recorded in the introduction, Atterberg and Johansson's curves were divided into two parts, while those of Haines were continuous. Haines considered his experimental data was never of sufficient accuracy to exclude definitely the possibility of a break, while the deviations in Johansson's values necessitated his using shrinkage data to define its position with greater accuracy. The way in which the wedge of the Atterberg apparatus penetrates any soil block depends on its moisture content, as when wet the soil shows a smoothly cut surface, and when dry breaks irregularly after a very slight penetration by the wedge. It is known that the breaking load for most materials increases with rate of load, and it was thought that a slow and fast rate might have different relative effects on the drier and moister parts of the curve, suggesting that the disagreement between Atterberg's and Haines' results was due, at least in part, to a difference of this kind. Tests were made on soils with rapid and slow rates of load, but in no case was a break of the magnitude of those of Atterberg obtained. For the fast rate of load a smooth curve could be drawn fitting the points with reasonable accuracy, but when the logarithm of the cohesion was plotted against the logarithm of the moisture content, the curve could be divided into three parts. The first break was that of Atterberg, while the second, which could not always be clearly located owing to experimental inaccuracies, occurred at a moisture of 6 to 9 per cent.

Recently a paper has been published by Christensen (9) on the stress-strain relationships for compression tests for soils at varying moisture content. The maximum bearing strength of the samples was also deter-

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mined for varying moisture contents and was found to decrease with increasing moisture. Christensen's own description is as follows: "The results representing the mean of three tests seem to follow a definite trend, suggesting an exponential law of decrease approaching the horizontal axis (*i.e.* moisture axis) asymptotically. The equation $p = p_0 e^{-k\omega}$ was therefore used as a basis for smoothing the data. It was first transformed into the logarithmic form

$$\log p = \log p_0 + \log (e^{-k})\, \omega,$$

and an auxiliary graph was made of the latter equation, which showed in some cases a tendency to break into a pair of straight lines."

Thus Christensen's data tends to give a curve of two parts similar to that of Atterberg, and from the graphs given it would appear that such a curve would fit his experimental points better than the exponential curve he has used. There are not enough points for the lower moistures to show if there is the possibility of a break occurring here.

Haines has shown that the shrinkage curve for a soil can be divided into two main portions. In the first, before air can enter the soil pores the volume decrease is equal to the volume of water lost, while in the second, when air is entering the soil, the rate of decrease with loss of water is much less. Haines records that the latter portion of the curve, which represents the residual shrinkage, bends again before reaching zero. As a rough representation of the actual processes taking place in shrinkage, Haines supposed that the residual shrinkage depends on the presence of colloidal material around the soil particles. This forms small pads between them when they have been brought into contact by the first stage of the shrinkage, and only begins to lose water when air is replacing water in the soil pores.

The shrinkage and cohesion curves for the Punjab soil are shown in Fig. 6. It will be seen that the shrinkage curve agrees with the results obtained in the present experiments, the change from the main to the residual shrinkage commencing at 19·5 per cent. moisture, and the bend in the residual shrinkage occurring at 8·5 per cent. moisture. The cohesion curve is that for a slow rate of load and gives the Atterberg break at 20 per cent. moisture, and a second break at a moisture of the order of 9 per cent. The three readings for the lower moistures are not accurate, but they definitely lie off the second part of the curve.

There is one other type of experiment in which discontinuities have been observed—the evaporation of water from a puddled soil. When the rate of evaporation is plotted against moisture content, then under cer-

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tain experimental conditions a curve is obtained which consists of three parts, the variation with moisture being nearly linear in each. Fisher (10) suggested that the ease of movement of water from the inside of the soil to the outside was a limiting factor, and that this was the explanation

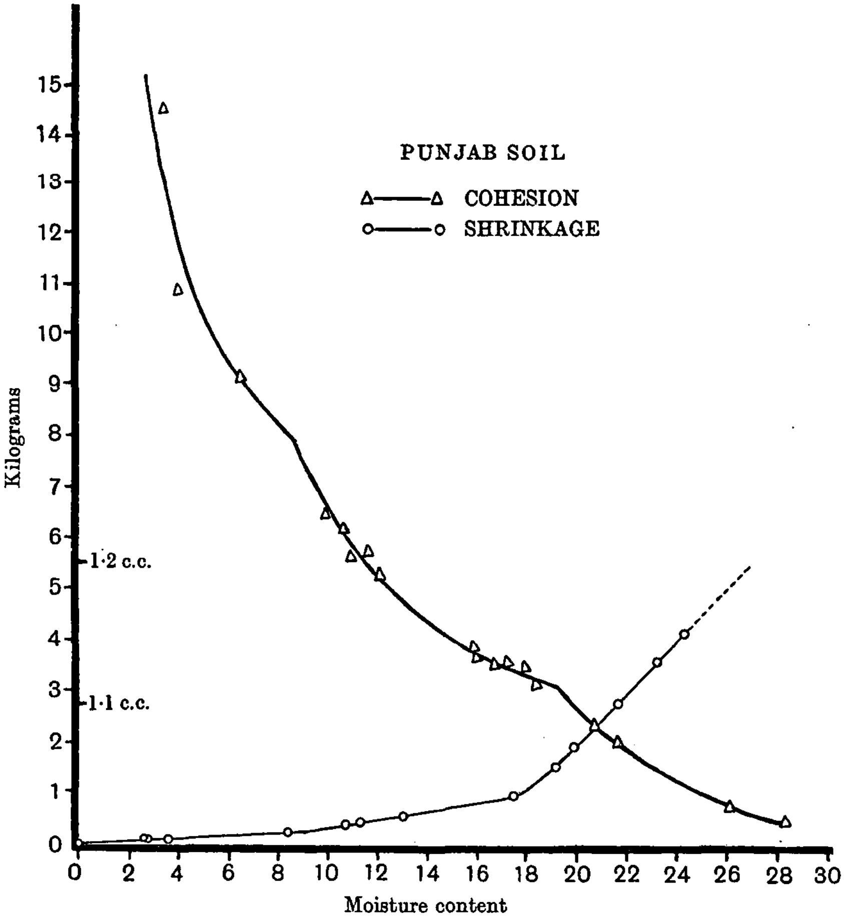

Fig. 6.

for the discontinuous rate curves he usually obtained. The rate of evaporation depends on two main groups of factors, the soil itself and the environmental conditions, and as shown by Keen, Crowther and Coutts (11), the kind of rate variation with moisture obtained depends very largely on their relative importance. With soil in inverted weighing bottles, bulk-air movements were reduced, and the rate of evaporation was low and

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constant down to low moisture contents. What was really being measured was the rate of diffusion of water vapour from the soil surface to that of the acid, and soil factors did not become apparent until low moistures were reached. When the soils were supported below glass plates the curves obtained varied with the area of the plate covered. A rate curve consisting of three nearly linear portions was obtained for the plate completely covered with soil, the authors concluding that this type of curve was the resultant of two dominant and opposing forces, a more rapid evaporation from the outer edges of the plate and the water movements outward by capillary action as water gradients are set up. Thus when the soil tends to become the controlling factor the moisture range is divided into three parts similar to those observed for the other soil properties described in this paper.

SUMMARY.

1. The equivalent parallel capacity and conductance of a series of soil blocks have been measured for decreasing moisture content.

2. The results obtained depend on the electrodes used. With mercury, all soils give curves of the same general type for the variation of the capacity with moisture because the capacity effects associated with the soil electrode interface are large compared with those due to the soil. The electrical properties of the interface have been shown to exhibit marked changes in their variation with moisture at certain moisture contents.

The results obtained with carbon electrodes, though depending on the texture of the soil, generally confirm the changes observed with the mercury electrodes.

3. Of the four characteristic moistures found, the second is readily identified as Atterberg's "Schwindungsgrenze" (the moisture at which air enters the pores), while the first appears to correspond with his "Ausrollgrenze" (the lower plastic limit).

The two lower moistures are hitherto unrecorded, but there are indications that at the lower one changes may occur in the variation with moisture of the shrinkage and cohesion of soil, and the rate of evaporation of water from soil.

In conclusion, I wish to thank Dr R. K. Schofield for much helpful advice during the course of this work.

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