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*PROGRESS REPORT NO. 1
THE FEASIBILITY OF MEASURING
THE MOISTURE GRADIENTS IN
CONCRETE PAVEMENT SLABS*

*JANUARY, 1959
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*Joint
Highway
Research
Project*

by
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*PURDUE UNIVERSITY
LAFAYETTE INDIANA*

Progress Report

THE FEASIBILITY OF MEASURING THE MOISTURE GRADIENTS
IN CONCRETE PAVEMENT SLABS

TO: E. B. Woods, Director
Joint Highway Research Project
January 29, 1959

FROM: H. L. Michael, Assistant Director
Joint Highway Research Project
File: 9-7-3
Project: C-36-83C

Attached is Progress Report No. 1 of the research project entitled, "The Feasibility of Measuring the Moisture Gradients in Concrete Pavement Slabs." This report has been prepared by J. R. Bell, Research Assistant on our staff, under the supervision of Dr. G. A. Leonards.

This is a summary report of the activities on the preliminary study for this project from the initiation of the project until the end of 1958. The preliminary study is continuing under the extension approved by the Advisory Board, the State Highway Department of Indiana, and the Bureau of Public Roads. It is anticipated that a second progress report will be prepared within a few months, which will include recommendations concerning the continuance of this study.

The report is presented for the record and will be forwarded to the State Highway Department and the Bureau of Public Roads as an attachment to the monthly Progress Report #10 for their information and review.

Respectfully submitted,

H. L. Michael
H. L. Michael, Secretary

HLM:ac

Attachment

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Progress Report

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IN CONCRETE PAVEMENT SLABS

by

J. R. Bell, Research Assistant

Joint Highway Research Project

Project No: C-36-63C

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Purdue University
Lafayette, Indiana

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SUMMARY

The purposes of this preliminary study were: 1) to conduct a comprehensive literature search to evaluate the available methods of measuring the moisture content of porous media, 2) to conduct limited laboratory investigation of the more promising of these methods, and 3) to select the most promising methods for intensive investigation in the second phase of the study. The first phase of the study has been completed.

The study was divided into two parts: 1) a literature search and 2) a preliminary laboratory investigation of the dielectric constant (or capacitance) method, which on the basis of the literature survey appeared most feasible.

The laboratory tests consisted, for the most part, of measuring the capacitance of a thin mortar disk at various water contents in a parallel plate capacitor by means of a low frequency AC capacitance bridge. The results show these measurements to be very sensitive to changes in water content at low values of water content. However, in the higher water content range the method lacked sensitivity. Companion volume-water content tests indicate that significant volume changes occur in the range of water content above the sensitive range of these tests. Therefore, from the standpoint of obtaining an absolute measure of water content, or of developing an indirect procedure for measuring volume changes by capacitance measurements, the results show an apparent lack of sensitivity at higher water contents.

The literature survey, and careful study of the theory of capacitance measurements, have not indicated any serious inherent limitations to the capacitance measurement method. From this standpoint, the basic method still appears promising. It is believed, therefore, that the difficulties encountered are the result of instrumentation problems, the investigation of which were beyond the scope of the initial study.

For the most part, the instrumentation problems stem from the fact that the apparent dielectric constant as indicated by capacitance measurements is not a true constant. It is a function not only of the material being tested, but also of the test conditions. The two most important factors are boundary conditions and the electrical frequency at which the test instruments are operated. The most troublesome boundary condition is that of obtaining good contact between the capacitor plates and the dielectric material being tested. Poor contact lowers the sensitivity of the measurements. The problems associated with frequency of operation are more complex. The test frequency controls the effects of such factors as conductance, polarization, anomalous dispersion, and force fields acting on the water molecules. The influences of conductance and polarization are reduced as frequency is increased, but the other two factors tend to reduce the sensitivity at high frequencies. The problem, therefore, is to balance the physical size and shape of the capacitor and the frequency and sensitivity of the measuring instrument to the electrical properties of the dielectric - in this case, moist concrete.

It should be pointed out that, considering the relatively crude test procedures used, the data are very consistent not only for a given sample, but from sample to sample. Also, the shape of the curves is not entirely

discouraging when compared with curves obtained using high frequencies. Data by other investigators, for soils and other materials, show curves for low frequency tests of the same general shape as those obtained in this study; but, for tests performed at higher frequencies, the published curves exhibit much steeper slopes at the higher water contents.

For the reasons previously cited, the results of this study are inconclusive from the standpoint of the purpose of the study - namely, to determine whether or not the method is worthy of a detailed study to develop the necessary instruments and methods for field moisture determinations. The capacitance method still appears promising, in spite of the laboratory test results, because these tests have not evaluated instrumentation effects. The present state of our knowledge permits three possible courses of action: 1) to reject a method which might actually be a very valuable research tool on the basis of inconclusive tests; 2) initiate a comparatively elaborate and expensive research program to investigate a method which may have no real merit with respect to the desired application; and 3) extend the present preliminary laboratory studies to incorporate limited refinements of techniques and instrumentation and thereby obtain conclusive data on the basis of which a final decision can be made. This latter course of action is recommended.

INTRODUCTION

A knowledge of the moisture content of hardened portland-cement concrete is of importance in a number of practical problems. Of particular interest to the present study is the effect of moisture gradients on the warping of concrete pavement slabs.

Experimental work has clearly demonstrated the significance of warping both on the development of stresses in the slab (1, 2)* and on the interpretation of pavement deflection data due to loads (3). Earlier theoretical studies (4, 5) appear to be of limited value, due to the assumption that the slab maintains contact with its support at all points and at all times. In a study conducted at Purdue University (6a, 6b), a new theory has been developed that allows for the possibility of a portion of the slab losing contact with its support. In the solution of the resulting equations, length changes due to both temperature and moisture gradients were combined by the use of an equivalent gradient and coefficient of expansion. Accordingly, while this theory appears promising, experimental verification of the computed deflections and stresses is of paramount importance. At the present time, such experimental studies are hampered by the lack of suitable instrumentation for measuring the moisture content, or more specifically, the moisture gradient in concrete slabs. Precision instruments for other necessary measurements - deflection, temperature gradient, strain, and the like - are currently available.

The water content of concrete is, by definition, referenced to the oven-dry condition of the concrete. Therefore, a direct gravimetric

* The numbers in parenthesis refer to the bibliography at the end of this paper.

determination of moisture gradients in concrete slabs is not feasible. Clearly, non-destructive tests are predicated on the measurement of some other characteristic (for example, relative humidity) that is a function of water content. To obtain the water content, the quantity measured must be correlated with the water content, as determined by destructive test methods. However, in the problem of measuring the differential length changes resulting from moisture migration, it may be that some other characteristic; such as, relative humidity or dielectric constant, is an equally good index of these length changes as the water content itself. If such is the case, this characteristic can be measured directly, and correlations with water content for the specific concrete mix can be eliminated.

If a non-destructive test method for measuring the moisture content (or its effects) in hardened concrete can be developed, the method can be applied to the solution of many other problems. For example, the investigation of stresses and deflections resulting from moisture gradients in structural units as well as in pavement slabs, and studies of moisture movements through walls and floor slabs. It is also possible that the method could be modified and applied to other porous materials such as soil, wood, and rock.

REVIEW OF LITERATURE

Moisture-Volume Relationships of Concrete

There is a great deal of literature on the water in concrete and its effect on the properties of concrete; however, much of the published information is qualitative rather than quantitative because reliable methods of measuring water content in non-destructive tests have not been available (1, 2). The published data are difficult to interpret because in many cases the description of test conditions are incomplete. This has resulted in many apparent discrepancies; however, there are a few general trends, which are discussed below.

Menzel (7) states: "With all of the different types of concrete, whether rich or lean, dense or porous, etc., significant shrinkage begins at a moisture content corresponding roughly to the equilibrium value that would ultimately be attained with exposure to a 99 to 100 per cent relative humidity". Therefore, much of the water may be removed before appreciable shrinkage occurs. This limits the moisture content range of interest in this study to relatively low water contents. This statement is borne out by tests on masonry blocks by Shideler (8) and Kalcousek (9). A plot of shrinkage vs. water content prepared from Shideler's data is shown on Figure 1. This curve shows that nearly all volume change occurred at water contents below 2 to 3 per cent by dry weight. This same general trend is shown by Yoshida (10) for cement paste; however, in the absence of aggregates, the shrinkage begins at somewhat higher water contents. See also the shrinkage data in this study (Figures 8 and 9).

The above data are not for concrete mixes used in highway pavements; however, they consistently show that nearly all shrinkage occurs at mois-

FIG.1.- SHRINKAGE vs. WATER CONTENT
FOR CONCRETE MASONRY UNITS.

ture contents lower than that corresponding to about 40 per cent of total absorption as determined by ASTM Designation C140-52. The results of tests by Blackman (11) show that total absorption for highway pavements would almost certainly correspond to water contents of less than 10 per cent by dry weight. This indicates that the critical moisture content range is below 4 per cent by dry weight. Teller and Sutherland (2) found by gravimetric tests the average moisture content of a slab at the Arlington Test Road to be 3.5 per cent in the summer and 3.8 per cent in the winter.

Theoretical considerations by Harr (6) indicate that it is desirable, with respect to slab warping studies, to measure the water content with sufficient accuracy to indicate length changes resulting from moisture variations equivalent to a temperature change of about 5°F. Rveem (12) has shown that changes in the moisture content of 30 oven-dried thin concrete disks, sawed from cores from pavements, which were soaked for seven days resulted (for 2/3 of the specimens) in length changes greater than those resulting from a 90°F. temperature increase. Also, a study of Shideler's data (Figure 1) shows that in the critical range a 2 per cent moisture increase results in a volume increase equivalent to a temperature increase of 30°F. or more.

Many factors influence the volume-water content relationship of concrete other than just water content. Some of these factors are age, curing, mix design, type and size of aggregate, cycles of wetting drying, carbonation, and others. (7. 8. 9. 10. 13).

Moisture Measuring Methods - General

Literature on the subject of moisture measuring techniques is extensive and there are several general reviews and bibliographies available (14, 15, 16). Most of the methods have been applied to concrete, soils, and a variety of other materials with widely varying degrees of success. The literature is very confusing, as one author will report a method to be very reliable while another reports it as less than worthless. Therefore, in this discussion an attempt is made to evaluate the various methods on their relative inherent advantages and disadvantages and not solely on their reported reliabilities.

The definition of water content, as used throughout this paper, is the ratio of the weight of water lost upon drying to constant weight at 105°C to the weight of solids at this temperature. Direct determination of water content is unsatisfactory for the purposes of this study because it generally requires destruction of the concrete slab during testing. A possible modification would be to construct the slab with removable segments which would periodically be weighed, oven dried, weighed and returned to the slab. This would cause discontinuities in the slab, could provide avenues for the entrance of water, would not give a continuous record because a long time delay would be required before equilibrium was re-established after the segment was replaced, and the oven drying would alter the structure of the segment so that it would not remain the same as the rest of the slab.

Indirect methods measure some property of the concrete which is a function of water content and can be used for in-place, non-destructive measurements. These methods all present similar problems of range and

sensitivity, the necessity of calibration, the speed of response to moisture changes, the effective zone of influence, determination of just what water the device actually measures, the effect of changes other than moisture (i. e., changes in density, temperature, structure, and salt concentration), degree of contact between the sensing element and the material being measured, requiring some object or cavity to be placed in the concrete, and in some cases, the necessity for a hygroscopic material surrounding the sensing element which is supposedly in moisture equilibrium with the material being tested.

The more promising indirect methods are discussed in the following section.

Moisture Measuring Methods - Discussion of Methods

Resistance Method - In this method, the resistance of the material to the flow of an electric current is measured. An A. C. current must be used to prevent polarization in the vicinity of the electrodes. The electrical resistance is a function of both the structure of the solids and the composition and quantity of the pore water; therefore, it varies with changes in water content. The equipment and procedures required are simple but have the important disadvantages that the resistance is a function of the composition of the pore water. The resistance varies considerably with changes in salt concentration as well as changes in water content; therefore, variations in the measured resistance may not indicate corresponding changes in the water content. Spencer (17) reports that leaching may increase the resistance by 40 per cent in concrete.

Several moisture cells have been manufactured using this principle. In these cells the electrodes are embedded in some porous medium, usually plaster-of-paris (18) or wrapped in a nylon or fiber-glass fabric (19, 20). In using these cells, the whole cell is embedded in the material for which the water content is desired. The cell absorbs water of varying amounts depending on the water content of the surrounding material and the resistance of the cell is measured as an indication of the water content of the material in question. This requires that the resistance of the cell be calibrated with respect to the water content of the particular specimen being tested. These cells are subject to the same disadvantages stated above except that dissolved gypsum in the plaster-of-paris block acts as a buffer and reduces the effect of variations in salt concentrations in

the pore water of the material being tested. An additional problem is that there may be a time lag between the change in the water content of the concrete and the corresponding change of the moisture content of the hydrophilic material of the cell. This delay, if long enough, would be a serious problem when the moisture gradient must be measured under non-steady state conditions. Also the nature of the hygroscopic material limits the range of moisture content the cell can absorb and measure.

A recent modification of the resistance method worthy of special note is the Ionic Barrier Moisture Meter (21, 22). In this meter, the electrodes are surrounded by an ionic membrane which filters the ions from the water before it reaches the electrodes, thereby freeing the method from the disadvantage of being susceptible to changes in pore water composition. This method, in its present form, still has the disadvantage of measuring the resistance of a hydrophilic material (in this case the ionic membrane) instead of the concrete directly. Also, at this time the life of the ionic membranes is not known, but this modification seems deserving of special consideration.

Relative Humidity and Suction Methods - These methods measure factors which may prove to be better indices of the volume changes of concrete associated with moisture changes than water content per se (7). They can be related one to the other once and for all, and then, within certain limitations, related to water content for any given specimen (23). Relative humidity as used here is the ratio of vapor pressure at the surface of the water held in the porous material to the vapor pressure of a free water surface at the same temperature expressed as a percentage. Suction is the negative pressure (tension) of the water in the porous medium. Both are functions

of water content, structure, and to a limited extent composition of pore water.

The principal inherent problems associated with the use of these characteristics as measures of volume-water content relationships are: 1) the difficulty of finding one method that will measure these quantities over the full range of interest and 2) at high water contents, a relatively large change in water content results in only a very small change in relative humidity or suction. The advantage of using one of these quantities as an indicator of volume changes resulting from moisture changes would be that the equipment could be calibrated to read relative humidity (or suction directly). This would eliminate the necessity of calibrating the equipment for the specific specimen being studied. However, a relationship between humidity and the moisture coefficient of expansion of the concrete would still probably be required for the specific mix.

Relative humidity can be measured in a number of ways but the method which appears most logical for this study is the electric hygrometer method (24). The electric hygrometer measures relative humidity by measuring the electrical resistance of the air in the pores of the material. The resistance of the air depends on its water content. This may be measured either directly or indirectly by measuring the resistance of a hygroscopic material in equilibrium with the air.

Suction may be determined directly by measuring the force required to remove water from the porous material or indirectly by calculation from relative humidity. A vacuum method (25) is most frequently used for direct determinations but this method could not be used in this study because at the low water contents of interest the suction is greater than can be measured by vacuum methods.

The main advantage to these methods is that they are relatively free from effects of changes in pore water composition.

The problems of installing the hygrometers would be severe. They would have to be installed in cavities or they would simply be a modification of the resistance method and as such subject to all of the disadvantages of that method. The cavities themselves would be difficult to form and maintain without changing the moisture conditions in their immediate vicinity from that of the slab in general.

Radiation Methods - Radiations of all kinds through a porous material are affected by the presence of water in the pores. There are three kinds of radiation which might lend themselves to the purpose of this study; neutron, radio wave, and sonic radiations.

The neutron moderating moisture meter consists basically of a source of neutrons emitted into the material being tested and a detector which counts the number of slow neutrons reaching it. As the neutron moves through the material it is constantly colliding with the nuclei of the atoms in the material. Each collision slows the neutron. The magnitude of the reduction in velocity is a function of the relative sizes of neutron and the nucleus. The smaller the nucleus the slower the neutrons velocity after the collision. The hydrogen atom has a nucleus of mass equal to that of the neutron; therefore, the neutron is slowed much more by a collision with a hydrogen nucleus than by any other atom. Since almost all hydrogens in concrete are contained in the water the number of slow neutrons reaching the detector would be a function of water content. Neutron scattering indicates all water present-chemically combined water as well as evaporable water. This method has been studied by several investigators for moisture determination purposes (26)²²

²² Contains a very extensive bibliography.

The one probe neutron method which has the radiation source and the detector in the same probe probably could not be used because the volume of the zone of influence is too large to measure moisture gradients in thin slabs. If two probes, one with the neutron source and one with the detector, are used, the method is very sensitive to small changes in the distance between the probes unless the spacing is large. To control the size of the zone of influence the spacing would have to be quite small. Additional problems in maintaining the spacing of the probes would be encountered because, due to their high cost, the probes should be free to be moved from test point to test point. This presents the problem of forming and maintaining the cavities in the slab. Small, accurate spacing might make it necessary to embed the probes in the concrete, which would be very expensive. There are also the problems of designing a very small probe, danger in handling radioactive materials, and complex and expensive equipment.

The propagation of radio waves through a medium depends primarily upon the conductivity and dielectric constant of the material (27). Since both of these are functions of water content radio wave propagation is also a function of water content; however, this method simply combines all of the disadvantages of both the resistance and capacitance method without offering any special advantages.

The sonic method, which has been used to measure physical properties of concrete (i.e., Young's modulus, strength, etc.) (28, 29), measures the velocity of wave propagation through a material. The velocity of the wave disturbance is a function of the elasticity of the material which in turn is, among other things, influenced by water content; however, the precision required in measuring the velocity over the very

short distance necessary to establish moisture gradients in thin slabs would be very difficult if not impossible to obtain. Also, the changes in wave velocity resulting from factors other than moisture changes, such as deterioration of the concrete, would be much larger than the velocity variations from changing water content.

Heat Transfer Methods - Because of the high heat capacity of water, the heat transfer properties of porous materials are highly dependent on their water content. However, a serious problem confronting any effort to determine water content from measurement of heat properties is that, when a heat source is placed in a material such as concrete, thermal gradients are established which cause moisture migration thereby altering the moisture gradients as they are being measured (30). Further studies may show that these moisture movements occur so slowly in concrete that this problem may not be prohibitive. Aldous and Lowton (31) tested more than 50 moisture cells of this type in connection with soils. Spencer (17) also discusses unsuccessful attempts to use this method with concrete. Another problem relates to the contact established with the material being tested and extreme sensitivity to minor variations in density and structure. There is also the problem of restricting the zone of influence to determine the gradient in a relatively thin slab. These cells, however, are relatively free from the influence of salts in the water (32).

Dielectric Constant or Capacitance Method - This method is very similar to the resistance method except that the dielectric constant of the material rather than its resistance is measured. Two plates forming a capacitor with the porous medium as the dielectric are embedded in the material to be tested. The dielectric constant of concrete varies with water content. The sensitivity of this method to slight changes in

moisture content may prove to be very high as the value of the dielectric constant of water is of the order of ten times that of mineral aggregates (33, 34). This method has an additional advantage in that the dielectric constant of water is only moderately susceptible to relatively large changes in salt content of the pore fluid.

Reference to the use of this method with concrete could not be found in the literature searched, but it has been used to measure the moisture content of soils (35, 36, 37, 38, 39), soybeans (40), wheat (41), cotton (42), gelatin and paper pulp (43), and others.

The apparent disadvantages to this method are mainly problems of instrumentation stemming from the fact that while the true dielectric constant of the material is a constant the apparent dielectric constant (the dielectric constant indicated by capacitance measurements) is a function of the frequency of the electrical current used to measure it. The problem, then, is to balance the physical size, shape, and spacing of capacitor plates and the electrical frequency of operation of the measuring instruments to the electrical and chemical properties of the concrete to give the desired sensitivity over the moisture range of interest. If all factors can be properly balanced, the size of the zone of influence can also be controlled.

The one apparent inherent disadvantage is that the dielectric constant of water is also a function of the force fields acting on the water molecules; therefore, the capacitance - water content relationship may show a hysteresis loop in the wetting and drying cycle and may also drift as the structure changes with continued hydration of the cement. It is, however, interesting to note that Andersen (35) found water content-capacitance curves of almost identical shape for five different granular

soils, indicating that possibly density and structure (except as it effects the force fields) may not have a large effect on dielectric constant of the water solids mixture.

SELECTION OF MOISTURE MEASURING METHOD

All of the indirect moisture measuring methods are to a greater or lesser extent subject to the same general problems and in addition some of the methods present special problems. In comparing the various methods, to select the most promising methods for laboratory testing, the following factors were considered:

1. Range and sensitivity
2. Calibration procedures
3. Response time
4. Size and shape of the zone of influence
5. What water is actually measured
6. The effect of factors other than amount of water present (temperature, density, structure, composition of water, and special)
7. Dependence upon degree of contact between sensing element and porous material
8. Effect of installation upon moisture distribution in a concrete slab
9. Expense and complexity of equipment and operation
10. Special inherent problems
11. Special instrumentation problems

The more important moisture measuring methods are listed and their more important advantages and disadvantages are outlined in Table 1. As most of the methods are subject to similar difficulties, a factor is listed only if it is relatively a serious disadvantage or an important advantage. For example, most of the methods are simple and inexpensive; therefore,

this item is not mentioned except in the case of the neutron radiation method where the comparatively complex and expensive equipment is disadvantageous, and in the case of the resistance method which is the simplest and least expensive method of all.

The resistance method was eliminated from consideration for laboratory tests because of its susceptibility to changes in pore water composition which may cause larger resistance variations than relatively large changes in water content.

The relative humidity and suction method, radiation methods, and heat transfer methods were rejected because while they offer no special advantages over the ionic barrier resistance method or the dielectric constant method they suffer from a wide variety of additional disadvantages. At first the ionic barrier method appears to be the most promising method; however, while this method is considered to be deserving of additional study, the capacitance method was judged superior for three reasons: 1) the ionic barrier requires a hygroscopic material surrounding the electrodes which increases its response time, 2) the useful life of the ionic barrier is unknown and 3) while the dependence of the measured capacitance upon the electrical frequency of measurement presents special instrumentation problems it also gives the capacitance method a degree of flexibility which none of the other methods possess. The factors which present problems at one frequency are not problems at some higher or lower frequency and it is believed that there is some combination of frequency and capacitor geometry which will properly balance all of the factors involved to give a satisfactory sensitivity over the moisture range of interest and still provide freedom from the effects of small changes in

TABLE 1 - COMPARISON OF MOISTURE MEASURING METHODS

Method	Disadvantages	Advantages
Resistance Method	<ol style="list-style-type: none"> 1. Subject to variations in composition of pore water 2. Some methods require hygroscopic materials which increase response time and limits range 	<ol style="list-style-type: none"> 1. Very simple and inexpensive
Ionic Barrier Resistance Method	<ol style="list-style-type: none"> 1. Hygroscopic material required 2. Life of ionic membranes unknown 	<ol style="list-style-type: none"> 1. Free of effects of pore water composition. 2. Range of sensitivity may be controlled.
Relative Humidity and Suction Methods	<ol style="list-style-type: none"> 1. Range limited to very low water contents 2. Cavities required in concrete slab 3. Some methods require hygroscopic materials 	<ol style="list-style-type: none"> 1. Relatively free of effects of changes in pore water composition 2. Simple calibration procedure
Neutron Radiation Method	<ol style="list-style-type: none"> 1. Detects all water present-combined and evaporable water 2. Zone of influence large 3. Cavities required in concrete 4. Complex expensive equipment 5. Special instrumentation problems of designing special small probes and of maintaining critical probe spacing 	<ol style="list-style-type: none"> 1. Free of effects of changing pore water composition 2. Wide range 3. Relatively free of problems of contact between probes and material being tested

TABLE 1 (cont.) - COMPARISON OF MOISTURE MEASURING METHODS

Method	Disadvantages	Advantages
R. F. Radiation Method	1. Combines disadvantages of both the resistance and the capacitance methods	1. No special advantages
Ionic Radiation Method	1. Extreme precision of measurement required 2. Very sensitive to changes in structure (deterioration of the concrete)	1. Free of effects of changing salt concentration of pore fluid
Heat Transfer Method	1. Serious problems of contact between sensing element and porous material 2. Sensitive to changes in structure and density 3. Measurements cause moisture migration 4. Large zone of influence	1. Free of effects of changing pore water composition
Dielectric Constant (capacitance) Method	1. What water measured - dielectric constant of water a function of the forces holding it in the concrete 2. Sensitive to degree of contact between the sensing elements and the material being tested 3. Special instrumentation problems - the measured dielectric constant is a function of the electrical frequency of the measuring instruments.	1. Relatively free from effects of small changes in composition of pore fluid 2. Rapid response to changes in water content. 3. Small zone of influence - well adapted to measurement of moisture gradients

composition of the pore fluid and the structure of the porous medium.

The capacitance method was chosen as the most promising because, although it presents instrumentation problems, it does not appear to be restricted by serious inherent limitations.

THEORY OF DIELECTRIC HYGROSCOPY

The following discussion of the dielectric constant is generally qualitative rather than quantitative because, while some of the factors influencing the dielectric constant can be expressed quantitatively, the interaction of all the contributing factors is so complex as to render the quantitative approach impractical. Therefore, only a general development of the theory will be attempted. The following discussions are based upon the works of MacInnes (44), Terman (45), Borsey (33), and Hartshorn (46) except where otherwise noted.

The dielectric constant (D) of a substance is defined by Coulomb's Law:

$$F = \frac{q_1 q_2}{Dr^2} \text{ ----- 1}$$

where F is the force exerted between two electrostatic charges q_1 and q_2 separated by a distance r in the substance. The dielectric constant of a vacuum is by definition equal to one; therefore, the dielectric constant of a material is equal to the ratio of the force (F_0) in a vacuum to force (F) in the material, all other factors being equal.

$$D = \frac{F_0}{F} \text{ ----- 2}$$

Dielectric constant is a dimensionless quantity with values equal to or greater than unity.

Substances composed of polar molecules possess high dielectric constants because in the presence of an electric field the polar molecules become oriented in such a manner as to oppose the field and, thereby, reduce the force F in equation 2. Molecules may be distorted by the electric field. This displaces the centers of their positive and negative charges

and produces an "induced" dipole; therefore, non-polar substances may also have dielectric constants greater than unity. The dielectric constants of non-polar substances are, however, usually lower than the dielectric constants of polar materials.

Water molecules are very strongly polar giving water an abnormally high dielectric constant of about 80. The dielectric constants of most earth materials, which comprise the bulk of concrete, range from about 3 to 10. Therefore, the dielectric constant of a concrete is highly dependent upon its water content.

The dielectric constant of a material is a function not only of the magnitude of the polar moment (permanent and induced) of its molecules but also of the freedom of the molecules to be orientated by the applied electric field. If the molecules are already orientated and held by an existing field or are at a high energy level it will be more difficult for the applied field to orient them and the dielectric constant of the substance will be low. Therefore, the dielectric constant of a material is not truly a constant but is a function of temperature which influences the energy of the molecules (increasing temperature reduces the dielectric constant) and for polar substances such as water the dielectric constant is reduced in the vicinity of charged particles (i.e. ions and colloids).

Several equations have been proposed to permit the calculation of the dielectric constants of materials which are aggregates of substances with different dielectric constants. Most of the equations are based on models which do not truly represent the structure of concrete. The few methods which consider the structure of the material, for example the method developed by Brown (47), require experimentally determined shape

and/or distribution factors and are not applicable to this study. Bruggeman's equation (48), which assumes spheres in a matrix of different dielectric constant lends itself to the study of solid-water-air systems, and does not require prohibitively long calculations. This equation was modified by Cowie and Palmer (37) to consider the effects of force fields acting on the water held very close to the spheres. They found good correlation between calculated values of dielectric constant and measured values for a clay. The solid curve in Figure 2a shows the general shape of the curve obtained by Cowie and Palmer. They considered that the structure expanded as the water content increased and assumed saturation except at very low water contents. This is not the case with concrete. The theory was modified to consider a rigid structure of spheres consisting of a solid core with a water shell and air voids. The curve so obtained is represented by the dashed curve in Figure 2a. Neither of these models is considered to be sufficiently representative of the true structure to warrant quantitative consideration; however, the following theoretical values are given to show order of magnitude. At zero water content D is approximately 5 and for a water content of 20 percent (saturated) the calculated D is approximately 40 if force fields are neglected and about 15 if the effect of force fields as estimated by Cowie and Palmer is considered. This last value appears to be too low. The work of other investigators (49) tends to show that the effect of force fields would be much smaller than that indicated by this value. The actual case for concrete is probably intermediate between the two curves.

If an electrical potential is applied between two conductors separated by a perfect insulating material an electrical charge is built up on the

FIG. 2.- ILLUSTRATIONS OF DIELECTRIC CONSTANT THEORY

FIG. 2a.- THEORETICAL DIELECTRIC CONSTANT vs. WATER CONTENT RELATIONSHIPS

FIG. 2b.- APPARENT DIELECTRIC CONSTANT vs. FREQUENCY FOR POLAR MATERIALS

(i) Perfect Dielectric (ii) Real Dielectric

FIG. 2c.- EQUIVALENT CAPACITOR CIRCUITS

FIG. 2d.- CAPACITANCE vs. FREQUENCY FOR REAL CAPACITORS

conductors. This arrangement of conductors (usually plates) and insulators is called a capacitor and the ratio of the charge to the applied potential is defined as the capacity or capacitance of the capacitor:

$$C = \frac{Q}{E} \text{ ----- 3}$$

where: C = Capacitance in farads (fd.)

Q = Charge on the capacitor plates in coulombs

E = Electric potential in volts

One farad is a very large capacitance; therefore, capacitance is usually expressed in $\mu\text{fd.}$ (10^{-6} farads) or pfd. (10^{-12} farads).

The capacity of a capacitor is a constant dependent only on the size, spacing, and geometry of the plates and the dielectric constant of the insulating material. For parallel plate capacitors, the capacitance is expressed by the following formula.

$$C = K D \frac{A}{d} \text{ ----- 4}$$

where: A = area of the plates

d = distance between the plates

K = a constant selected to give capacitance in farads ($K = 8.84 \times 10^{-14}$ for A and d in square centimeters and centimeters and $K = 22.45 \times 10^{-14}$ for values in square inches and inches).

From the above, it can be seen that the dielectric constant can also be expressed in terms of capacitance.

$$D = \frac{C}{C_0} \text{ ----- 5}$$

where C is the capacitance of a given capacitor with the material of dielectric constant D as the insulator and C_0 is the capacitance of the same capacitor with the dielectric replaced by a vacuum.

Dielectric constant is usually determined from capacitance measurements because of their simplicity. However, this introduces complications because although the dielectric constant of polar materials as defined for electrostatic fields is a constant for given temperature and force fields the apparent dielectric constant determined from capacitance measurements which must be made with alternating currents is not a constant but is a function of the frequency of the current used in the measurements. The symbol ϵ will be used throughout the remainder of this discussion to represent the apparent dielectric constant as indicated by capacitance measurements. The dependence of ϵ upon frequency results from the fact that with each cycle the induced electrical field reverses polarity and the dipole molecules, in order to remain oriented to the field, must rotate through 180° . The surrounding molecules offer a frictional resistance to this rotation and as the frequency increases all of the molecules are not able to change orientation as rapidly as the field reverses. For polar substances the plot of ϵ versus frequency assumes the general shape shown in Figure 2b. At very high frequencies the molecules are nearly stationary and maintain a random orientation so that the permanent dipole moment no longer contributes to the apparent dielectric constant. The induced dipole moment, however, is not interfered with by adjacent molecules and can keep up with the reversals at all frequencies; therefore, at very high frequencies ϵ approaches a constant value called the optical dielectric constant (ϵ_∞). Non-polar substances exhibit an essentially constant ϵ for all frequencies. This phenomenon is referred to as anomalous dispersion. The sharp break in the curve occurs at different frequencies for different substances. For liquid water the break comes at approximately 6×10^8 cycles per sec. and

for solid water (ice) at about 2.5×10^3 cycles per sec. The critical frequency for water very near charged surfaces is probably of the same order of magnitude as the value for ice (50).

The contacts between the capacitor plates and solid dielectrics are never perfect. If a space exists between the plate and the insulating material, the space has a capacitance. The capacitance developed at the contact between the dielectric and the capacitor plate is called the contact capacitance. To account for this contact capacitance a capacitor must be considered as three capacitors in series. This representation is illustrated by Figure 2c(1). In this figure, C_1 is the capacitance of the dielectric and C_A and C_B are the contact capacitances. If the contact capacitances are assumed equal, $C_A = C_B = 2C_c$ where C_c is the total contact capacitance and the capacitor can be treated as two capacitors C_1 and C_c in series. For this condition,

$$C' = \frac{C_1 C_c}{C_1 + C_c} \quad \text{----- 6}$$

where C' is the total capacitance of a capacitor with imperfect contacts indicated by the capacitance measuring instrument. Equation 6 requires that the total capacitance must always be less than the smallest constituent capacitance; therefore, if the contact is very good making C_c very large compared to C_1 the value of C' will approach the value of C_1 and the effect of the contact capacitances can be neglected. On the other hand, if the contact is poor so that C_c is small the measured capacitance will approach a constant value equal to C_c regardless of the value of the dielectric constant of the dielectric. If the purpose of the capacitance measurements is to determine the dielectric constant of the insulator from the

values of C' , the method will be insensitive unless the contacts between the capacitor plates and the dielectric are very good.

The discussions thus far considered ideal capacitors incorporating dielectrics which are perfect insulators. Unfortunately, real dielectrics possess some conductivity, and this conductivity must be taken into account. Real capacitors can be considered as consisting of an ideal capacitor with a shunt resistance. The schematic representation of a real capacitor, considering both contact capacitances and conductivity, is shown in Figure 2c(ii). Assuming the contact capacitances and resistances to be equal $C_A = C_B = 2C_c$ and $R_A = R_B = \frac{R_c}{2}$ and the real capacitor can be represented by two capacitors in series: one with capacitance of C_c and resistance R_c representing the total contacts and the other with capacitance C_1 and resistance R_1 representing the dielectric. It is not possible to write a simple expression for total capacitance similar to equation 6 for this case because current passing through the capacitor is shifted so it is out of phase with the current passing through the resistance making the impedance of the network a complex variable with a real part and an imaginary part, which must be treated as vectors. However, by appropriate applications of the theories of alternating current electricity it is possible to derive the following expression for the total capacitance of a real capacitor (for derivation of equation 7 see Hartshorn (46)).

$$C'' = C' + \Delta C \text{ ----- 7}$$

where: C'' = total measured capacitance of a real capacitor

C' = geometric capacitance determined, for parallel plate capacitors, from equation 6 and 4 by substituting ϵ for D in equation 4

$$\Delta C = \frac{K C'}{1 + \omega^2 T^2}$$

$$\omega = 2 \pi f$$

f = electrical frequency in cycles per second

$$K = \frac{(R_1 C_1 - R_C C_C)^2}{C_1 C_C (R_1 + R_C)^2}$$

$$T = \frac{R_1 R_C (C_1 + C_C)}{R_1 + R_C}$$

From equation 7 the apparent dielectric constant as determined from capacitance measurements is clearly a function of the conductance of the material and of the frequency. A general plot of C'' in terms of frequency is shown in Figure 2d.

As the water content of a porous material such as concrete is increased the apparent dielectric constant increases not only because of the increased ratio of water ($D \approx 80$) to concrete ($D \approx 5$) but also because as the water content increases the conductivity also increases. Therefore, even for a fixed frequency the measured dielectric constant of the water in a porous material is not a constant over the full range of moisture contents. Also, changes in the composition of the pore water will change the conductivity and the apparent dielectric constant. These effects are greatest for low frequencies and, as shown by Figure 2d, are insignificant for frequencies higher than about $4T^{-1}$.

In addition to influencing conductivity, the composition of the water affects the dielectric constant (D) of the water. First, as the salt content of the water is increased the force fields, from the ions in the solution, acting on the water molecules are increased and the dielectric constant is decreased. Data by Hasted, Ritson, and Collie (51) show that the effect of water composition is small except for very concentrated

salt solutions and indicate that the effect on anomalous dispersion is insignificant within the requirements of this study. Second and probably more important is the effect of electrode polarization. When a charged electrode, or capacitor plate, is placed in an electrolytic solution ions of charge opposite to that of the electrode are attracted to the electrode. This sheath of ions sets up a field opposing the field from the capacitor plates and causes an abnormally high value for the apparent dielectric constant of the solution. This problem has been studied by Skiley and Smith (52) and their data show that the apparent dielectric constant may be more than twice the true dielectric constant for low frequency measurements. In alternating current measurements the charge on the plate is constantly changing in sign and the ions are alternately attracted and repelled. At high frequencies there is insufficient time between alternations for the ions to move a significant distance and there is very little accumulation of ions on the plate. Smith-Ross (53) have shown that for frequencies above the low radio frequencies the effect of electrode polarization is very small.

There are several additional factors acting to produce discrepancies between the apparent dielectric constant indicated by capacitance measurements and the true dielectric constant which can not be evaluated. A few of these are heterogeneity of the dielectric, non-uniform moisture distributions, and fringe effects. Fringe effects are the effects of lines of force which do not extend directly across the space between the capacitor plates but loop outside of the zone between the plates. The effects of these factors should be relatively consistent for any given case and the resulting errors should be accountable by calibration.

The effect of all of the factors discussed above is to cause the ϵ - water content curves to deviate from the D - water content curves as shown in Figure 2a. It is impossible to predict what the net effect of all of these factors will be because very little is known about the dielectric properties of concrete or the concrete pore water. The actions and interactions of these several factors are complex but they do not appear to preclude a successful development of a capacitance moisture meter. The development of a successful capacitance moisture meter depends upon instrumentation which will satisfy three conditions. First, the frequency used must balance the effects of anomalous dispersion, force fields, conductivity, and electrode polarization, to give the steepest slope of the ϵ - water content curve in the moisture range of interest, and limit the effects of changing pore water composition. Possibly one frequency will be satisfactory for any given application or it may be desirable to use different frequencies for different moisture content ranges. Second, there must be good contact between the plates of the moisture indicating capacitor and the material being tested to insure consistent measurements and high sensitivity. If insulated capacitor plates are used the capacitance of the insulation must be constant with time and sufficiently high to provide adequate sensitivity at high water contents. Finally, the size and shape of the capacitor must be such as to have a large enough capacitance to permit accurate measurement and a zone of influence both large enough to give a representative water content and restricted enough to limit the measurements to a thin section of concrete so gradients can be determined. The problems involved are complex but a successful solution would provide an extremely flexible moisture measuring method whose range, sensitivity, and zone of influence could be varied to apply specifically to many different applications.

LABORATORY INVESTIGATIONS

Test Procedures

All capacitance measurements were made with a 60 cycle A. C. capacitance test bridge which measured both capacitance and power factor simultaneously. This bridge is similar to a D. C. Wheatstone Bridge except the power source is alternating current and the bridge is balanced by a variable capacitor and a variable resistance instead of only a variable resistance. The output of the bridge is fed into a tuned amplifier which in turn drives an electron-ray indicator tube. The variable capacitor and variable resistance in the bridge are adjusted simultaneously to balance the impedance of the unknown capacitance and null the bridge. A proper adjustment is indicated by a maximum spread on the indicator. The range of this bridge is $5\mu\text{fd}$ to $110\mu\text{fd}$ with a rated accuracy of $\pm 3\mu\text{fd}$ in the range of measurements of interest in this study.

Preliminary Tests

The first tests attempted were capacitance measurements of a parallel wire capacitor, with the wires about 12 inches long spaced about $1/4$ inch apart embedded in two porous materials: plaster of paris and sand. These media were chosen for simplicity. The wires were insulated to keep the power factor within the range of the bridge. The parallel wire capacitor in appearance closely resembled a conventional television antenna lead-in wire. This shape of capacitor was chosen because it would confine the zone of influence to a relatively thin section but would still give capacitances large enough to measure and would also average the moisture content over a fairly large volume. These tests showed significant capacitance

changes with changes in moisture of the porous material; however, it was soon discovered that the insulation on the wire was absorbing water and changing the measured values. It was also apparent that the wire diameter and spacing and the insulation thickness were not suitable for optimum results. It was decided at this time that it was outside the scope of the preliminary study to develop the sensing element. Such tests were therefore abandoned.

A second series of tests was initiated to establish the capacitance-water content relationship of a Portland cement mortar. In these tests, the capacitance of a thin (about 4 mm) mortar disk 3 inches in diameter was measured at various water contents in a parallel plate capacitor (see Figure 3). The plates of the capacitor were insulated with Teflon (plastic) tape which has negligible water absorption.

The mortar disks were one part Type III cement to 2-1/2 parts of 16-100 sand mix at a water cement ratio of 0.65. The mortar was cast in a 3 x 6 inch cylinder cured 1 day in the mold and 3 days in a 100°F water bath. Upon removal from the bath the cylinder was sliced on a concrete saw and a disk was ground to the desired thickness and polished to give good contact with the capacitor plates.

After polishing the disk was vacuum saturated, weighed, and placed in the capacitor. The capacitor plates were adjusted for maximum capacitance reading (indicated best contact between plates and disk). The disk was left in the capacitor until an essentially constant value was obtained. This waiting period allowed the plastic insulation on the plates, which was not rigid, to adjust to the disk and was required to permit the moisture gradient through the disk to become essentially

FIG. 3.- TEST CAPACITOR

Not to scale

uniform. Subsequent experimentation showed that equilibrium was reached after about 1/2 hour. After the waiting period, the capacitance and dissipation factor were recorded and the disk reweighed. All readings were obtained in this manner. The water content was lowered by drying in a vacuum desiccator. When the water content could no longer be lowered appreciably in a reasonable time the disk was dried 16 hours in the oven at 105°C. After drying the disk was cooled in a desiccator, weighed, and the capacitance was measured. All water contents were based on this dry weight. The water content was allowed to increase by absorbing water from the atmosphere and capacitance readings continued. When the disk would no longer absorb water from the laboratory atmosphere it was placed in a humid room and finally vacuum saturated in water.

The water content-capacitance curve obtained by this procedure had the same general shape as the curve shown for disk #8 in Figure 5 except the change in slope began at a slightly higher water content. On the second drying cycle it was observed that the curve had shifted to the right. This suggested some irreversible change upon drying, however, the dry weight at the end of the second cycle was higher than the first, and when the water contents for the second drying curve were recalculated using this higher dry weight the second curve nearly coincided with the first. This development made it impossible to determine whether there was a hysteresis loop in the curve, a general shifting of the curve due to structural changes, or just an apparent change due to increased hydration and carbonation during the period of the test; therefore, this test series was also discontinued.

Test Procedures Adopted

A third series of tests was designed to investigate the effects of continued hydration during the test and the resulting change in the structure of the mortar. For these tests, 15 disks were prepared as before with two exceptions: the disks were never allowed to become air dry before the tests and they were cured in 100°F water for 5 days instead of 3. After curing the disks were kept in water at room temperature except during grinding and polishing operations when they were kept surface wet. In addition, 5 disks were pressure steam cured for 5 days in an autoclave at a pressure of 150 psi.

Capacitance measurements were made on three disks (2 hot water cured and 1 steam cured). The procedure was the same as that outlined above except that the edge of the capacitor was wrapped with a plastic ribbon during the waiting period of the capacitance measurement to maintain a more constant water content in the disk during this period.

Changes in the diameter of two other disks (one autoclaved and one hot water cured) were measured at approximately the time as the capacitance measurements were taken. All disks were treated, with respect to moisture environment, as nearly the same as possible throughout the testing program. The remaining 15 disks were periodically removed from the test one at a time, oven dried, and weighed. The purpose of this procedure was to establish the rate of increase of dry weight during the test so that the true water contents of the capacitance and shrinkage specimens could be computed at any time during the test. As these disks were wet at the beginning of the test the initial dry weight was calculated by breaking each disk, weighing both parts, and drying one segment

in the oven. The water content of the oven dry segment was calculated and, assuming that the initial water contents of both segments were the same, this water content with the wet weight of the other segment was used to calculate the initial dry weight of the wet segment. The dried segment was discarded and the moist segment was placed in the same moisture environment as the disks for capacitance and volume measurements until its time for oven drying. Later dry weights proved that evaporation during the time required for weighing of the wet segments caused appreciable errors in the calculated initial dry weight; therefore, the oven dry weight determined at the end of the first drying cycle was used as the dry weight without correction for the first drying cycle. The plot of the dry weight vs. time is shown on Figure 4. This figure also shows the moisture history of one of the capacitance disks during the testing period.

This third test series was continued through two cycles of wetting and drying.

FIG. 4 - DRY WEIGHT AND WATER CONTENT OF TEST DISKS vs. TIME

Test Results

The results of the capacitance - water content tests for the third test series are shown as Figures 5 through 7 and the shrinkage - water content test results are presented as Figures 8 and 9. The water contents represented on these curves are based on the oven dry weight corrected for the average rate of increase of dry weight to the time of the specific measurement represented. The capacitance values plotted are dial reading values for the total capacitance. These values include the contact capacitance as well as the capacitance of the mortar disk.

The curves show that for the conditions of these tests the method is very sensitive at very low water contents (below about 2% for disk #8) but very insensitive at higher water contents. Comparing the range of sensitivity to the range over which most of the volume change occurs it is seen that about 40% of the volume change occurs in the range of insensitivity (see Figures 10 and 11). Significant volume changes result from moisture changes up to a water content of approximately 5 or 6% after the first drying. This is somewhat higher than the values indicated in the literature for concrete. In concrete, the presence of the relatively inert coarse aggregate moves the volume change - water content curve to the left. In concrete, the capacitance - water content curve would also probably be moved to the left and the two curves would maintain approximately the same relative positions as those obtained in the tests on mortar.

The capacitance curves show a hysteresis loop in the wetting - drying cycle with the re-wetting curve shifted slightly upward and to the left.

FIG. 5.-CAPACITANCE vs. WATER CONTENT - DISK # 8
(100°F water cured)

FIG. 6.- CAPACITANCE vs. WATER CONTENT.- DISK #10

FIG. 7.- CAPACITANCE vs. WATER CONTENT:- DISK # 1
(150 psi steam cured)

FIG. 8 - SHRINKAGE vs. WATER CONTENT - DISK # 9
(100° F water cured)

FIG. 9-SHRINKAGE vs. WATER CONTENT- DISK # 2
(150 psi steam cured)

FIG.10.- CAPACITANCE vs. PERCENT OF SHRINKAGE
PER WETTING OR DRYING PHASE.-DISKS # 8 & 9.
(100°F water cured)

FIG. II.- CAPACITANCE vs. PERCENT OF SHRINKAGE
PER WETTING OR DRYING PHASE.- DISKS #1 & 2.
(150 psi steam cured)

Possibly, this results from the same factors which cause the hysteresis in the sorption curves for concrete (54).

The capacitance curves also show a shift to the right on the second cycle. This shift was also indicated by the tests on the disk in the second series of tests (not plotted). As this disk had been air dried before the start of the test, it is probable that this shifting continues for several cycles. The shrinkage - water content curves also demonstrate a shift on successive cycles; however, a comparison of the capacitance vs. percentage of total shrinkage occurring on a particular wetting or drying curve (Figures 10 and 11) for different cycles reflects the same general shifting of the curves indicating that the factors causing this shift are not necessarily the factors controlling shrinkage.

The capacitance curve for the autoclave cured specimen is of the same general shape as the curves for the hot water cured specimens but moved appreciably to the left. This must be the result of the different structure of the mortar resulting from the pressure steam curing. It is interesting to note that the data for the autoclave specimen shows the same general hysteresis in the capacitance curves and increase of dry weight as the 100°F water cured specimens.

DISCUSSION OF RESULTS

Based only upon the experimental data collected in the laboratory phase of this study the dielectric constant method appears unsatisfactory because it does not adequately cover the moisture range of interest. However, the literature survey has not uncovered any serious inherent disadvantages to the method and it is believed that the difficulties to date are the results of unsatisfactory instrumentation. A detailed instrumentation study was outside the scope of this initial study and the simple tests performed did not have sufficient instrument flexibility to answer all of the questions suggested by the data obtained.

Some aspects of these data are encouraging. First, the total range of capacitance readings is quite wide so that if the range over which the method is sensitive to moisture changes can be expanded without a large loss in sensitivity the accuracy of the method should be satisfactory. Also, the sensitivity of the method is greatest at low moisture contents and to make the method applicable to studies of moisture - volume relationships it is only necessary to expand the range of sensitivity slightly to include somewhat higher water contents. Finally, even with the relatively crude test methods used, the results are reproducible and consistent from sample to sample.

The most serious disadvantage to the method as it was tested is the very narrow range of sensitivity to changes in water content. The curve obtained experimentally does not correspond to the theoretically predicted curve in this respect (see Figure 2a). This is probably because the apparent dielectric constant of the pore water as measured at the electrical

frequency of these tests is different from the true dielectric constant as assumed in the theory. Also the apparent dielectric constant is probably not constant over the full range of moisture contents tested.

There are several possible explanations for these anomalous results obtained. First, at the low frequencies used, polarization films may have developed around the capacitor plates causing apparent dielectric constants higher than the true value for distilled water. Smith - Rose (53) has shown that this effect may be significant at frequencies up to the low R. F. frequencies, which are much higher than the frequencies normally employed to eliminate polarization effects in resistivity measurements and also much higher than the frequency used in this study. At high frequencies the dielectric constant of salt water is very nearly equal to the value for distilled water. Second, changes in conductivity of the dielectric are reflected in the values of the measured apparent dielectric constant. Childs (55) demonstrates that at low frequencies this effect may be large but at high frequencies it is negligible. The data by Blyth (22) and Spencer (17) show that very large changes in the conductivity of concrete accompany small changes in water content below about 3 percent. This is the approximate range over which most of the capacitance change occurred in this study.

If either or both of the above factors are actually the cause of the anomalous results obtained in this study, the capacitance method may be more susceptible to changes in the pore water composition than was anticipated; however, these difficulties may not be insurmountable because an increase in the electrical frequency of the measuring instruments will reduce the effects of both polarization and conductance and tend to smooth

out the abrupt change in the slope of the capacitance - water content curve, and thereby extending the range of sensitivity. If this can be accomplished without too great a sacrifice of sensitivity, the capacitance method may still prove to be a most satisfactory moisture measuring method. Capacitance - water content curves obtained at low frequencies, presented by Anderson (35), are very similar in shape to the curves obtained in this study but curves obtained at higher frequencies for soils (37, 42) and for gelatin and paper pulp (43) exhibit more nearly linear relationships. The data for gelatin and paper pulp were obtained at several frequencies in the low mega-cycle range. These curves become progressively flatter as the frequency is increased. In addition, companion conductivity determinations indicate that at these frequencies the apparent dielectric constant is essentially free of the influence of conductivity. The range of capacitance values obtained in this study for the mortar disks is sufficiently large to permit considerable flattening of the slope in the low moisture range if it results in a corresponding increase in the slope of the capacitance - water content curve for the higher moisture contents.

Difficulty was encountered in obtaining good contact between the mortar disks and the capacitor plates. Poor contact resulting in a low contact capacitance could be a factor contributing to the low sensitivity at the higher capacitance readings.

The anomalous curves obtained in this study are probably the result of a combination of the above factors, and possibly others, which the author is not aware of.

The second disadvantage of the data obtained in this study is the hysteresis in the wetting and drying cycle and the shifting of the capacitance curve to the right on subsequent cycles. These are probably the effects of differences in the forces holding the water in the mortar during wetting and drying and of structural changes in the mortar due to continued hydration and carbonation. The forces acting on the water in the pores would have a strong influence on the polarizability and the conductivity of this water; therefore, reducing the effects of polarization and conductivity by increasing the electrical frequency of the measurements should also reduce the hysteresis effect and tend to prevent shifting of the curves.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the information obtained in the study, it is concluded:

1. To be satisfactory for use in connection with moisture - volume relationship investigations, a moisture meter should be capable of measuring water contents to within about $1/2$ of one percent for the range of water contents below about 4 percent. For mortars and pastes, the range of interest extends to 6 to 8 percent.
2. On the basis of theoretical considerations, the dielectric constant or capacitance moisture meter appears most feasible. The ionic barrier moisture meter is also promising and, in the event that experimentation should prove the capacitance method unsatisfactory, is deserving of additional study.
3. For the low electrical frequencies used in the laboratory phase of this study, the capacitance method is unsatisfactory because of the extremely narrow range of sensitivity to moisture changes; however, theory indicates that at higher frequencies this disadvantage may be eliminated. The capacitance method should not be abandoned before additional instrumentation studies are made because it is very sensitive at low water contents and if the range of sensitivity can be extended to cover the complete moisture range of interest, it may prove to be

a very reliable and sensitive moisture measuring method. Although the capacitance method appears worthy of additional study, a comprehensive instrumentation study to develop field equipment and procedures for insitu moisture measurements is not justified by the data obtained thus far.

In the light of the above conclusions, it is recommended that the preliminary phase of this study be extended to include the following investigations:

- a) An additional series of capacitance vs. water contents tests, similar to those performed in this study, should be made using a capacitance bridge capable of operating at frequencies in the low mega - cycle range to investigate the effects of increasing the measuring frequency on the range and sensitivity of the method. In addition to changing the instrument frequency, certain refinements in capacitor construction and in sample preparation would be incorporated to improve the contact between the mortar disk and the capacitor plates. These refinements would increase the sensitivity of the apparatus and improve the reproducibility of the results.

The above modifications of the test procedure should yield data which would provide a basis for a conclusive evaluation of the merit of the dielectric constant moisture measuring method.

- b. In the event that the dielectric constant method should be proven unsatisfactory, a more detailed investigation of the ionic barrier moisture meter should be conducted to determine whether or not this method fulfills the requirements for measuring moisture gradients in hardened concrete slabs.

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