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A CONDUCTOMETRIC ANALYSIS
OF PORTLAND CEMENT PASTES AND MORTARS
AND SOME OF ITS APPLICATIONS

by

Warren Benefield Boast

A Thesis Submitted to the Graduate Faculty
for the Degree of

DOCTOR OF PHILOSOPHY

Major Subject Electrical Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

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Head of Major Department

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I. INTRODUCTION

A. Purpose of Investigation

Electrical conductometric analyses afford relatively simple means of interpreting and measuring phenomena which may be impossible or difficult of interpretation or measurement by other methods. Many of the problems relating to Portland cement pastes and mortars are of this class. The purpose of this investigation is to develop conductometric methods for several problems dealing with Portland cement pastes and mortars and to correlate the results where possible with the results as obtained by other physical methods.

B. Definition of Terms

The term *conductometric*, although not used extensively in the United States, has been in use in England for several years. Its meaning is self descriptive, being of course, measurement by conductance. The spelling of this term evidently has not been standardized. Glasstone (12) uses *conductimetric*, whereas Britton (5) uses conductometric. The French spelling is *conductométrique*, and the German, *konduktometrische*. In this work the spelling employing the *o* will be used.

The term paste shall be applied to mixtures of Portland cement and water; mortar shall indicate a mixture of Portland cement, sand, and water.

The term internal stratification, or more simply stratification, shall be used in designating the phenomenon of "bleeding", (i.e., the relative movement of water, cement particles, and other constituents of a plastic mass as caused by capillary and gravitational forces).

C. Scope

The problems which have been attacked are: (1) the setting phenomena during the first three hours after gauging a cement paste; (2) the excess water tendency in sand-water mixtures and its possible influence upon internal stratification; (3) internal stratification measurements on cement pastes, and a proposed method of test; and (4) a correlation of the electrical conductivity and the twenty-eight day compressive strength measurements on mortar mixes.

II. REVIEW OF LITERATURE

A study of the literature dealing with the problems of this investigation may be resolved into five classes: (1) conductometric analyses and methods as they have been applied to other problems; (2) the electrochemistry of electrolytes; (3) conductance measurements of electrolytic solutions and conglomerations; (4) the properties of Portland cements, pastes, and mortars; and (5) several aspects of the phenomenon of internal stratification, commonly called "bleeding", of cement pastes and mortars.

A. Conductometric Analyses

The science of conductometric analysis has been developed through the work of many investigations upon the variations of conductivity of solutions of acids, bases, and salts with dilution. A theory of the phenomena has been evolved through the efforts of Kohlrausch, Arrhenius, Ostwald, Debye and Hückel, and others, for dilute solutions. Beyond that point no exact theoretical work has been attempted because of the complexity of the problem. However, by following the electrical conductivity of a solution or plastic mass in which a chemical or physical reaction is occurring, it often is possible to interpret the action through logical deductions. Much of the work of this investigation, as well as those mentioned below, is of this type.

Britton (5) outlines several applications of conductometric analysis; the most important from the viewpoint of electrochemistry being the determination of titration points of solutions.

Industrial applications are numerous. The field of water analysis alone comprises applications to water-softening plants, power-generating plants, testing of sewage pollution of rivers, and many others.

Parker (22) describes the conductometric control as used in the mercerizing industry. Close control of the acid bath, used for neutralizing the caustic carried over in the yarn from the mercerizing bath, is very important. Other applications mentioned by Parker include those of sulfuric acid and sugar manufacture.

The moisture content in wood has been determined by Stamm (28) of the U. S. Forest Products Laboratory at Madison, Wisconsin, through such methods. He found that below the fiber saturation point the logarithm of the electrical resistance decreased directly as the moisture content of the wood increased; but he gives no theoretical reason for this particular function of the resistance.

Kolthoff (18) describes methods of determining titration points for mixtures of acids, particularly those of vinegar.

Kolthoff (17), Krenn, (19), and Coste and Shelbourn (7) have done considerable work on the conductivity of milk. Krenn states that he obtained conductivities as low as 3.506×10^{-3} and as high as 10.508×10^{-3} mhos/cm^3. He states that the conductivity of normal milk should never exceed 4.6 x 10^{-3} mhos/cm^3, and that milks more conducting are always obtained from diseased cows. Coste and Shelbourn, in tests on several hundred samples of normal milk found that the conductivity always fell in the range 4.2 to 4.4 x 10^{-3} mhos/cm^3 at 15°C. They also investigated the effect of dilution of the milk with water upon the conductivity, but arrived at no practical conclusions.

Haines (14), in an addition to the earlier work done by Whitney (29) and his co-workers at the U. S. Bureau of Soils and Deighton (8), correlated the electrical conductivity and the moisture content for five English soils. The variations among soils were considerable as would be anticipated from the possibility of different quantities of mineral salts in soils from several localities.

Sen (25), working on soil suspensions in water at a ratio of 1 part air-dried soil to 5 parts distilled water, investigated the seasonal fluctuations for manured and unmanured plots of land and arrived at his conclusions of soil fertility by such measurements.

Wuerpel (30), through laboratory studies on Missouri River sand was able to determine the moisture content of sand used in the construction of U. S. Twin Locks No. 26 in the Mississippi River at Alton, Illinois, by the conduction current at a given voltage in a given sample container of moist sand. In his conclusions he states that "each project on which this method is adopted requires an individual calibration using the types of sand, water, batch hopper, type of electrodes, and length of leads. . . . ." Again this is to be expected from the very nature of the problem.

The galvanic action in cement mortars, a problem allied to the conductometric analysis of Portland cement pastes or mortars, is discussed by Jesser (15). This work was published in November, 1934, in the magazine Zement, a German publication not carried by the Iowa State College library. It was indexed in the 1935 Engineering Index and was therefore obtained only after the experimental work on this investigation was completed.

Jesser approached the problem of an analysis of cement mortars from an entirely different viewpoint and method than did the author. He reasoned thus: If the cement paste or mortar consists of the more or less inert particles of unhydrated cement together with a solution which exhibits the properties of an electrolyte, and if into this "solution" two metals (he used zinc and silver, and aluminum and silver) are placed, an electromotive force should be produced, the magnitude of which would give a measure of the electrical activity in the cement mortar.

It would be expected that there might be a relationship between the voltages observed by Jesser and the electrical conductivity. This tendency will be discussed later (page 180).

Shimizu (26), working at the Tôhoku Imperial University in Sendai, Japan, presents the only data dealing directly with conductivity measurements as applied to Portland cement pastes which the author has found in a careful survey of the literature.

Shimizu measured the electrical conductivity of cement pastes as they set and hardened at various values of temperature. The curves

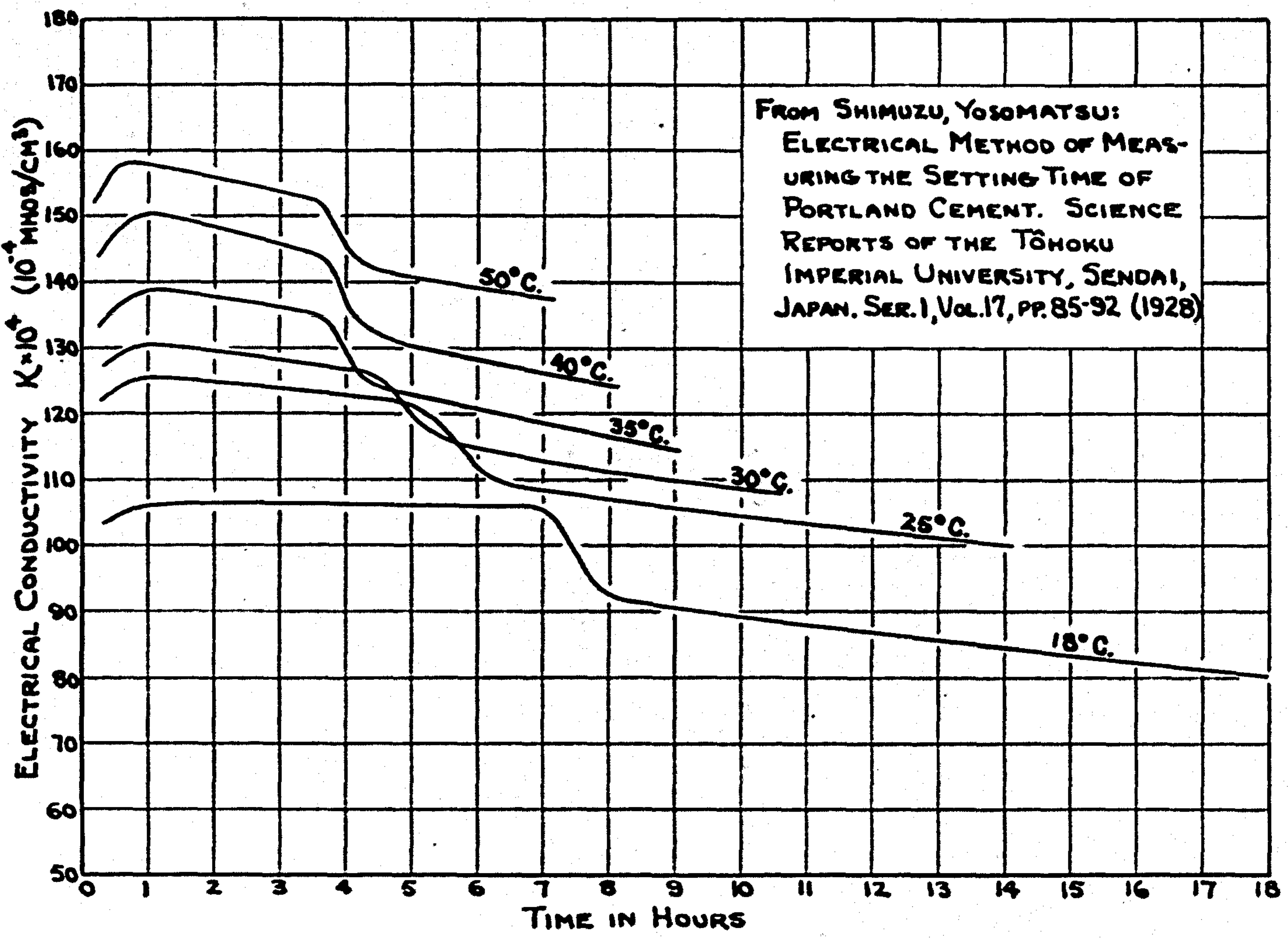

FROM SHIMUZU, YOSOMATSU: ELECTRICAL METHOD OF MEASURING THE SETTING TIME OF PORTLAND CEMENT. SCIENCE REPORTS OF THE TÔHOKU IMPERIAL UNIVERSITY, SENDAI, JAPAN. SER. 1, VOL. 17, PP. 85-92 (1928)

Figure 1

which he presents are shown in Figure 1, page 11. He concluded that electrical measurements gave a much more definite measure of the final set than mechanical methods, but he drew no conclusions concerning the first maximum point in the conductivity versus time curve. His emphasis was placed upon the final set and hardening phenomena, whereas the emphasis of this dissertation is placed upon the initial setting phenomena of cement pastes, that is, the conditions during the first three hours following gauging.

B. Electrochemistry of Electrolytes

The property by which an electrolyte is recognised is the transport of electrically charged matter when an electric field is applied to the substance. Passage of electricity through metals produces no such results. The electricity in this case is considered to be carried by electrons. Electrolytic conductors may therefore be distinguished by the transfer of matter which becomes apparent at points of discontinuity of the electrolyte.

In some of the author's earliest experiments on cement pastes, using direct current and brass electrodes, this electrolytic action at the electrode surfaces was very pronounced. Consequently the electrolytic nature of the cement paste was established. Subsequent investigations into the electrochemistry of solutions were undertaken with this fact in mind.

Glasstone (12) points out that "electricity may be carried through an electrolyte in either one or both of two ways; positive charges may be carried in one direction by cations, or negative charges in the opposite direction by anions". As a result there are three possible ways in which the electricity may be conducted in an electrolyte to produce the final results consistent with Faraday's law of electrochemical equivalents (13).

A development of the theory of the conductance of electricity for a very dilute solution of an electrolyte is given by Newman (21). This development will be reviewed briefly.

In an electrolytic solution containing N molecules per unit volume, assume that each molecule is capable of dissociating into two ions, each of valency ν. If F is the charge on a univalent ion, then each ion carries an equal and opposite charge of $\pm \nu F$. Let u_a and u_c represent the steady-state velocities of the anion and cation, respectively, developed under a unit potential gradient. If E is the potential at any point in the field, then dE/dx is the actual gradient existing in the direction x, where x is taken in the direction of motion of the ions. The force acting upon each ion then is $\nu F\ dE/dx$ and the steady-state velocities of the anions and cations are $u_a\ dE/dx$ and $u_c\ dE/dx$, respectively. If α is the fraction of molecules ionized, then the total number of ions passing across a section, of area A, perpendicular to the direction of flow per unit of time is $\alpha NA\ (u_a + u_c)\ dE/dx$.
As each ion carries a charge $\pm \nu F$, the total charge passing per unit time (or current) is

$$I = \alpha \nu NAF\ (u_a + u_c)\ \frac{dE}{dx} \qquad \text{(Eq. 1)}$$

By Ohm's law the current across the section is

$$I = A \sigma \frac{dE}{dx} \qquad \text{(Eq. 2)}$$

where σ is the specific conductance, or conductivity of the solution. Equating the right-hand sides of equations 1 and 2, and solving for σ

$$\sigma = \alpha N (u_a + u_c) \nu F \qquad \text{(Eq. 3)}$$

Thus, the conductivity is proportional to three items: (1) the concentration of the ions, (αN); (2) the sum of their velocities, ($u_a + u_c$); and (3) the charges which they carry (νF).

It should be remembered that equation 3 applies only to very dilute solutions. As the concentration increases, other factors enter which have been neglected in this derivation, namely inter-ionic (Coulomb) forces and frictional effects due to the increased viscosity of the fluid. Coulomb forces have two effects. First, according to Falkenhagen (9)

> "the ion is surrounded by an oppositely charged ionic atmosphere. The electric field thus causes the solvent to move in the opposite direction to the ion, and gives rise to the effect known as electrophoresis, which increases the ordinary viscosity resistance. In the second place, an ion moving with constant velocity must always be building up the ionic atmosphere in the region to which it moves, while at points behind it the charge distribution is continually returning to a random one..................It gives rise to a retarding force, termed the relaxation force........." (Falkenhagen, page 183, translated by R. P. Bell, 1934)

It would be expected that various brands of Portland cements, each having a different history of manufacture would have different chemical properties; and as a result, different kinds and numbers of ions present for a given water content. Also, the charges on these ions would be again dependent upon the chemical constituents of the cement.

Thus, there is very little that can be predicted in this field by a review of literature.

However, a review of literature dealing with the factors influencing the conductivity for a given electrolyte can be very advantageous.

Assuming a definite water content, the effect of temperature according to Newman (21), Glasstone (12), and Falkenhagen (9), is twofold. First, increasing the temperature of the electrolyte increases the ionic mobility or velocity at which the ions move. If this alone were the only effect the conductivity would continue to increase with increase of temperature. However, the degree of ionization has been found to decrease with increased temperature. Thus it is possible that a maximum conductivity may be reached. Falkenhagen (9) gives a curve for conductivity versus temperature for aqueous solutions of sodium chloride of 0.01, 0.1, and 0.5 normal solutions. The 0.01 normal solution reaches a maximum above 320°C., the 0.1 normal solution at 280°C., and the 0.5 normal solution at 240°C. That is, the maximum occurs at lower temperatures for increasing concentrations, where the Coulomb forces within the electrolyte are stronger.

The effect upon conductivity of increasing the amount of electrolyte in solution is rather complicated. At low dilution an increase in the amount of electrolyte increases the concentration of ions, ($N\alpha$), since N increases faster than α decreases. At higher values this relationship no longer exists, and the conductivity curve reaches a maximum and then decreases. For concentrated solutions, other forces, as previously mentioned, namely Coulomb forces and viscosity effects, also tend to decrease the conductivity with increased ratio of electrolyte to water. Newman (21) gives a set of curves of specific conductance versus concentration (concentration here meaning "gram equivalents per litre of solution") for several electrolytes which bears out this relationship. Solutions in cement pastes are no doubt saturated or nearly saturated solutions. Consequently a decrease in the water-cement ratio would tend to decrease the conductivity. Although this is the tendency observed, the author believes other considerations are much more important than these possible concentration changes (pages 178 and 187).

The derivation previously given (pages 13 and 14) for a dilute solution applied to a stationary or direct field. Because of polarization effects, which will be discussed later (pages 18 and 19), it is not practical to make most measurements with direct currents, but rather with alternating currents. It is only when the frequency becomes sufficiently large so that the time of an oscillation is comparable to the time of relaxation that the forces of relaxation change the value of conductivity. The value of frequency required for such changes to be observed corresponds, according to Falkenhagen (9), to a wave length of the order of magnitude "velocity of light x time of relaxation". At audio frequencies the effect is not measurable. (See Figure 11, page 56, for measurements on a cement paste).

C. Conductivity Measurements of Electrolytes

The methods used in measuring the resistance (or conductance) of an electrolyte may be divided into two classes: (1) those methods in which the effects of polarization at the electrode surfaces are eliminated, and (2) those in which its effects are reduced to a minimum. Polarization as applied to electrolytes signifies concentration changes in the immediate vicinity of the electrodes which give rise to electromotive forces. These forces are in opposition to the applied voltage.

The methods involved in the first class, where polarization effects are eliminated, are, according to Newman (21), usually two in number.

(a) The d. c. resistance of the electrolyte including the polarization effects at the electrodes is first measured by balance of a Wheatstone bridge. The electrodes are then moved closer together and the bridge again balanced by adding a series resistor to the sample arm of the bridge. The value of added resistance gives the resistance of the difference in lengths of the electrolyte sample. Obviously, the electrodes for measurements upon cement pastes and mortars must be fixed. Hence the method could not be applied to this problem.

(b) The second method of this class consists of using auxiliary electrodes, the potential drop being determined by an electrostatic or extremely high resistance voltmeter. This method was employed by Smith and Moss (27) and Haines (14). The choice of auxiliary electrodes for cement pastes and mortars, in which volumetric changes occur as the mixture sets, was a problem undertaken by the author, but not satisfactorily solved. Both of the above investigators used mercury as the contact medium between the electrolyte and the leads. Smith and Moss, working with liquid electrolytes, placed the mercury in cups at the ends of the section of the electrolyte to be measured and allowed the current to flow through the electrolyte past these electrodes to the main current electrodes. The mercury, being more dense than the electrolyte, caused no difficulty as it was firmly supported in the cups. Haines, working with moist soils, molded the soil in the form of a brick with small depressions, or cups, in which the mercury was placed. The soil was so compact that the cup held its form. In cement pastes, especially during the initial period, the paste may be so plastic that the fluidity of the paste and the mercury are approximately the same. As a result, definite contacts between the mercury and leads, and mercury and paste are very nearly impossible. The use of wire auxiliary electrodes is open to the objection of high contact resistance as the paste sets.

The second class of measurements, involving those methods in which the polarization is reduced to a minimum, has become the standard means of determining electrolytic resistance. A modified Wheatstone bridge is usually used with an alternating-current supply. The electrodes and electrolyte in reality form a circuit of resistance and effective capacitance. The term Q, the polarization, is in effect equal to $1/C_1 + 1/C_2$, where C_1 and C_2 are the equivalent capacitances of the electrode-electrolyte inter-surfaces. As a result, the voltage equation of a circuit consisting only of the electrolyte, of resistance R, the electrodes, and a source of alternating-current supply is

$$E \sin \omega t = iR + Q\int i\,dt \qquad \text{(Eq.4)}$$

and the effective impedance of the circuit is shown by Newman (21), page 312, to be

$$Z = R\sqrt{1 + \frac{Q^2}{\omega^2 R^2}} \qquad \text{(Eq.5)}$$

To reduce the effects of polarization, the second term of the radical must be reduced. Since ω (2π times the frequency) appears in the denominator, the effect of polarization may be reduced by increasing the frequency. As a result 1000 cycles has become the standard frequency used in making electrolytic resistance measurements. If capacitance (polarization) is present in the sample branch of a Wheatstone bridge circuit, and, if the variable resistance arm contains pure resistance only, a minimum point may be detected for balance but the phones will never indicate a complete silence. Since the exact determination of the balance point is extremely difficult unless a complete silence is obtained, the capacitance effects of the sample must be balanced by a condenser in the variable resistance branch. A parallel arrangement is usually used. (For a more complete description of the circuit and equipment see page 35 and Figure 2, page 27.)

D. Properties of Portland Cements

The changes which occur when Portland cement is mixed with water are so numerous and complex that they can not be analysed separately with any degree of certainty. Searle (24) describes the phenomena of setting and hardening from a physical viewpoint.

He states that an excess of water used in gauging (the process of mixing water and cement to form a paste) retards the setting process, and that a very dry gauging accelerates it. An increase in temperature also increases the speed of the reactions.

The gain of strength, he believes, has no connection with the setting phenomena, since the causes of setting and hardening are quite different. As the emphasis of this investigation is placed upon the setting rather than upon the hardening phenomena this section of the review of literature will be discussed accordingly. It will be sufficient to state Searle's premise then, regarding the hardening process, that

> "the conversion of the mixture of cement and water into a mass of a hard, stony nature may be due to one or more of the following changes, which may proceed simultaneously:
>
> (a) The formation of a crystalline magma from a supersaturated solution.
>
> (b) The desiccation of a colloidal substance or gel.
>
> (c) The reaction of various substances upon each other, or with water, giving rise to a product which is either crystalline, as in (a), or colloidal, and is later desiccated as in (b)." (Searle, page 89.)

From the chemical viewpoint Searle states that the most probable constituents of cement clinker are tricalcium aluminate and dicalcium and tricalcium silicates. He concludes that tricalcium silicate is the most important constituent of Portland cements because its setting and hardening phenomena appear to be precisely similar to those in the setting of Portland cements; whereas tricalcium aluminate is hydrated in water but does not develop great strength, and dicalcium silicate is not readily hydrated except in the presence of a solution of calcium aluminate and then it forms only a very granular mass of many voids.

An interesting statement, which will be referred to later (page 177) is that

> "When cement is mixed with water, allowed to harden, and then polished and examined under a microscope, it will be found that about half of it consists of the unaltered grains of cement and the remainder of colloidal or gelatinous materials ....Even with the most finely ground cements and the most carefully made mixtures of these with sand, the whole of the cement is never hydrolysed the first time the mixture is gauged with water." (Searle, page 97)

Searle draws a final conclusion that perhaps the setting phenomena is governed largely by the formation of hydrated tricalcium aluminate, and the increase in strength, or the hardening phenomena, by the tricalcium silicate. These conclusions are based upon data of Klein and Phillips (16) and Bates and Klein (4) of the U. S. Bureau of Standards.

A considerable number of investigations have been conducted upon the design of concrete mixes. One of the earliest of these investigations was that of Duff A. Abrams (1) working at Lewis Institute in Chicago, Illinois. The proportion of water was found to be much more important than had been commonly supposed. Abrams found that the strength, as well as many other properties of concrete, made from different proportions of cement and sand was dependent solely upon the ratio of water to cement in the mixture. The only restrictions to this law are that the concrete be plastic and workable and the aggregates clean and made up of sound particles. As the ratio of water to cement increases the strength of the concrete decreases. Abrams, in discussing the curve illustrating this law, states that

> "Values from dry concretes have been omitted. If these were used we should obtain a series of curves dropping downward and to the left. (Author's note: decreasing strength with decreased water-cement ratio) from the curve shown." (Abrams, Bulletin 1, page 3.)

The effect of curing conditions upon the strength of concrete was also investigated by Abrams (2). He found that for moist curing the strength of the concrete was still increasing at the end of four months. The customary period of curing for compressive strength samples is 28 days. The type of curing commonly used is either moist closet curing or immersion in water; the latter being preferred.

E. Internal Stratification in Cement Pastes and Mortars

The tendency for water to rise to the top of cement pastes or mortars soon after being placed is receiving considerable attention at the present time. Powers (23) in a discussion of Weymouth's theory of particle interference states that there are at least two factors which tend to prevent this escape or movement of water. The first is the adhesion force between the liquid and the solid surfaces; the second the friction forces which must be overcome before relative motion can occur.

The first of these forces, the adhesion force, increases with increased curvature of the surface film between two adjacent particles. Consequently the force of adhesion is larger if the particles are of smaller size.

The second factor mentioned, the resistance to relative movements between solid particles and water, may be approximated according to Powers, by Poiseuille's law of capillary flow:

$$V = \frac{H\pi r^4}{8ln} \qquad \text{(Eq. 6)}$$

where V is the volume of fluid flowing per unit of time, r the radius of the capillary, l its length, n the coefficient of viscosity of the liquid, and H the force causing flow. In the case of cement pastes this force is the suspended weight of the particles. The important point to be noted is that the velocity of flow decreases considerably with a decrease in the effective radius of the capillary tube. Thus the flow decreases for particles of smaller size.

Powers, in the same discussion, has also investigated the effect of the thickness of water layers or films upon the loss of strength of concrete. To calculate the thickness of the films it was necessary to know the surface area of sand and cement and the volume of water in the hardened mortar. He found that the reduction in strength became very rapid when the thickness of water film exceeded approximately two microns.

Brown (6), working at the Massachusetts Institute of Technology, made determinations upon the "bleeding tendency" of several cements. His measurements of this tendency consisted of determining the volumes of supernatant water and settled cement paste in test tubes two hours after mixing under uniform conditions. The range of water-cement ratios investigated was 0.7 to 1.0 by weight. These ratios are abnormally high but are necessary because of the nature of the test. As a result the method gives no picture of the distribution of water in a normal mix of cement paste.

III. THE INVESTIGATION

A. Experimental

1. Plan of the investigation

a. Setting phenomena of cement pastes. The setting phenomena for three Portland cement pastes was followed conductometrically for a period of three hours after gauging. The effects of variations in water content (water-cement ratio) and temperature were determined by taking samples at each of four water-cement ratios, 0.25, 0.30, 0.35, and 0.40 by weight, and at temperatures ranging between 20°C. and 30°C. The samples were mixed at or near the temperature (± 2°C.) at which the test was to be made. They were then placed in a thermostatically controlled testing cabinet and held at or near the desired temperature for the period of the test during which time the electrical conductivity measurements were made. For the high early strength cement (designated Cement B in the data) the temperature at two and a half to three hours increased several degrees. Consequently the values of conductivity at lower temperatures for this cement were extrapolated. Four or five samples for each water-cement ratio were necessary to determine the variation of conductivity with temperature.

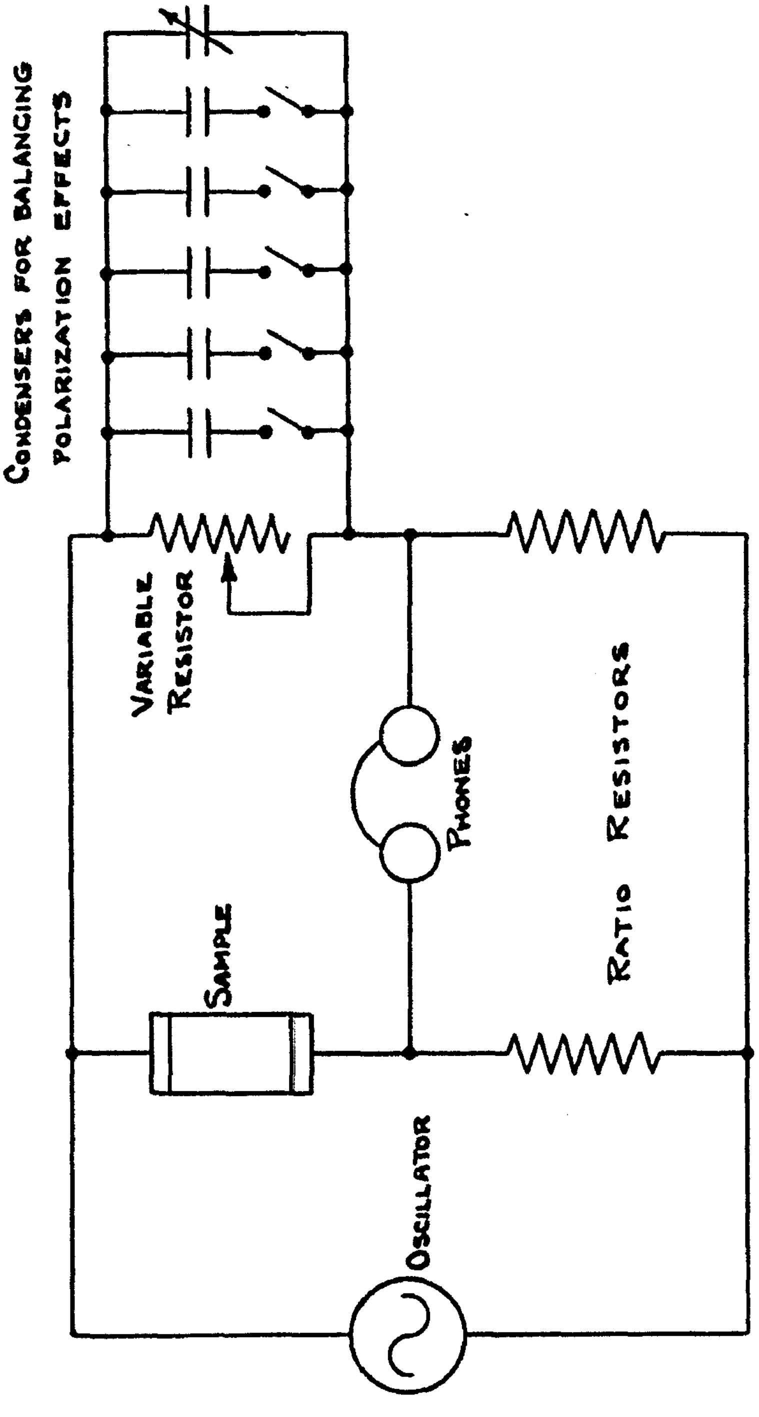
The sample containers for this portion of the investigation were in the form of parallelopipeds with the electrodes covering the entire ends of the sample. The conductivity as measured was therefore the effective conductivity of the entire sample.

Measurements were made using a modified Wheatstone bridge arrangement (Figure 2, page 27).

In plotting the data and drawing the curves a statistical graphic method was employed. This is described in the presentation of results (pages 58 and 59).

b. <u>Excess water tendency in sand-water mixtures</u>. A method of measuring the relative thickness of water film for inert particles was developed. The container and method of electrical measurement were similar to those used in determining the setting phenomena.

It is a well known fact that the percentage of voids in a compacted group of dry particles all of the same size depends upon the shape of the particles but not upon their size. For example, the percentage voids for a compacted mass of sand particles of 1 millimeter average diameter is the same as for particles of 0.2 millimeter average diameter provided the sands have the same configuration. The extreme cases for differences in configuration would be cubes, where the percentage voids for perfect compactness would be 0.0 per cent; and spheres, where the voids for systematic packing would be 47.6 per cent, or for random arrangement approximately 35 per cent (10). In an actual graded sand the particles have upper and lower limits on their dimensions. Since the smaller particles partially fill the voids of the larger ones, the percentage voids may be smaller than 35 per cent.



Modified Wheatstone Bridge Circuit

Figure 2

If now, the spaces between the electrically inert sand particles (carefully washed Ottawa standard silica sand having no appreciable conductance when packed dry) are filled with a conducting medium of known conductivity (tap water, for example), and the conductivity of the combination measured, the ratio of the sand-water conductivity to the water conductivity will give a measure of the percentage of wet voids in the sand.

This ratio will not be the percentage of actual voids for two reasons. First, the current lines through the sand voids, i.e., through the water, are not straight lines from one electrode to the other, and second, the cross sectional areas of water through which the current passes are not uniform in dimensions and hence are not used most effectively. Both of these factors tend to make the ratio as obtained above less than the actual percentage of wet voids. However, the ratio does give a relative measure of the wet voids.

Knowing the dry voids for several sizes or gradings of sands and this relative measure of the wet voids it is possible to determine whether there are differences in the tendency for water films to separate the sand particles. The author believes this tendency may be most easily expressed as a ratio of the relative measure of wet voids to the actual measure of dry voids. This new ratio is termed the "excess water tendency", since an increase in the number indicates an increase in the excess of water above that necessary to fill only the dry voids. A discussion of this "tendency" for the sands investigated will be made later (pages 181 and 182).

Two designs for grading of sand were tested: one a straight line grading, and the other a grading employing Weymouth's theory of particle mixtures (23).

The straight line grading, for the three sizes of sand particles used, was obtained by using 4/7, 2/7, and 1/7 absolute volumes (or weights) of the large, medium, and small sizes, respectively. The larger size particles, having an upper limit on the diameter of twice that of the medium, and likewise for the medium to the small, the resulting grading, using the above proportions, gave a straight line relationship. This is illustrated in Figure 24, page 112.

The Weymouth grading consisted of finding the proportions of space available to each size group and then filling the space with particles to produce the desired concentration, or relative density, d_a, relative to the dry rodded bulk density, d_o.

The first step was to select the spacing of the particles. This, for the Tyler series of sieves, can best be selected as the diameter of the next smaller size particles. Then, using Weymouth's results, $d_a = 0.296\ d_o$, where there is no group of particles missing.

/Powers (23): A Discussion of C. A. G. Weymouth's Theory of Particle Interference, page 4./

The calculations for the design of this mix are discussed more completely on page 48.

c. Internal stratification in cement pastes. The method used for determining the change in water content in lateral sections of a sample consisted essentially of measuring the electrical conductance of those sections of the sample. A diagram of the electric circuit is shown in Figure 3, page 31. If a straight line relationship existed (see page 183), between the electrical conductivity and the water-cement ratio these measurements would give direct measures of the water contents of the layers, and relative changes in the water contents would be evidenced by relative changes in the conductances.

The sample container used for these measurements was a container of six inches depth in which electrode pairs were placed at different levels throughout the vertical height of the sample. By maintaining the same voltage on all the electrode pairs, the sample was sectionalized electrically into lateral layers. The currents flowing through each of the layers were determined from voltage-drop measurements, using a vacuum-tube voltmeter, across low resistance shunts placed in each electrode circuit.

d. Correlation of electrical conductivity and compressive strength of cement mortars. Mortar mixes of various proportions of sand, cement, and water were measured for electrical conductivity at fifteen minutes after gauging, and for compressive strength at twenty-eight days. Standard 20/30 Ottawa silica sand was used for all mortar mixes.

The containers and methods used for the electrical conductivity measurements were identical with those for determining the setting phenomena of cement pastes.

The compressive-strength tests were made upon two-inch cubes. These cubes were cured by immersion in water held at 25°C. by means of thermostatic control.

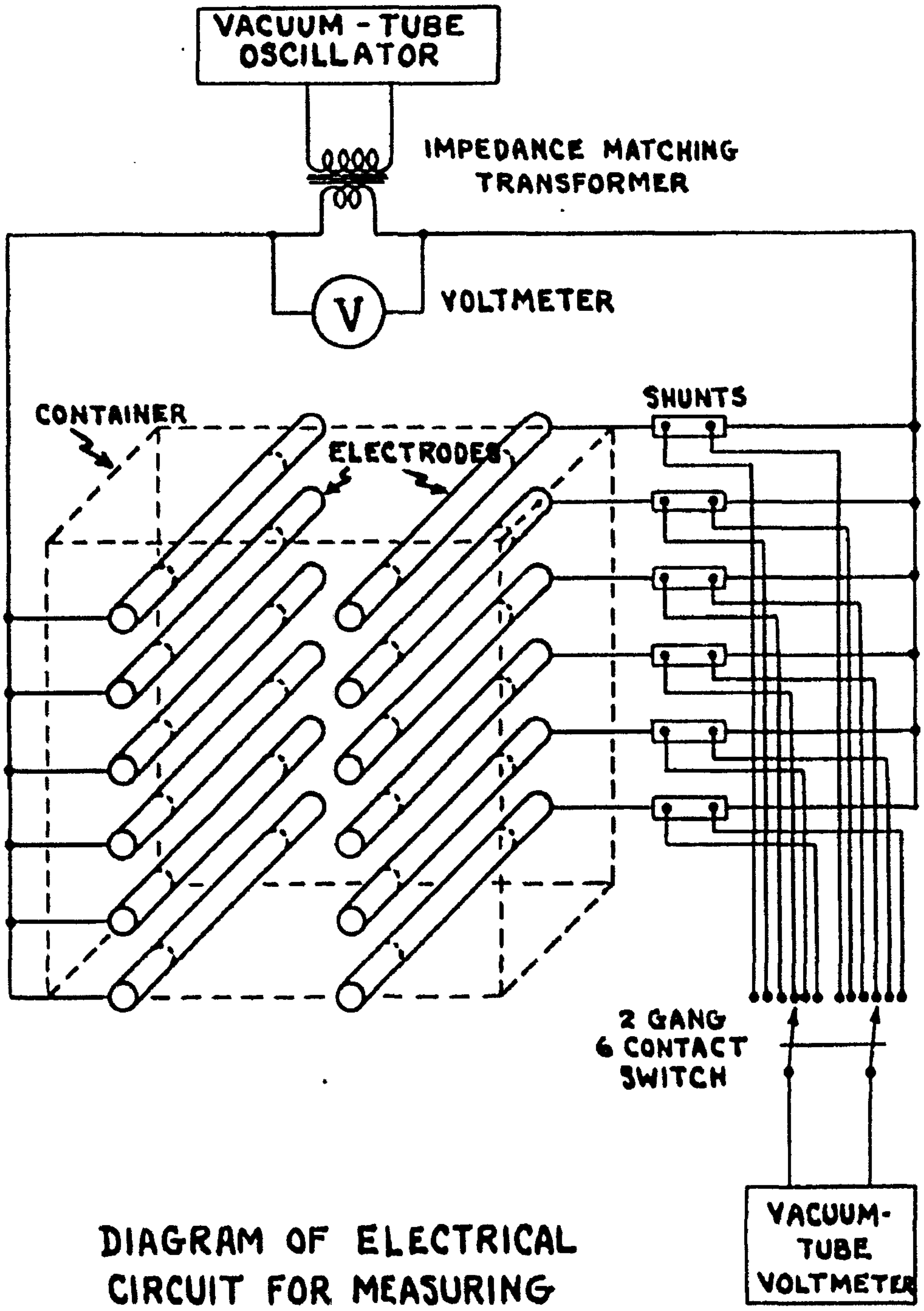


DIAGRAM OF ELECTRICAL CIRCUIT FOR MEASURING THE INTERNAL STRATIFICATION (BLEEDING) OF PORTLAND CEMENT PASTES

WBB

Figure 3

2. Description of apparatus

a. Oscillator. The source of supply used in all measurements of electrical conductivity, or conductance, consisted of a vacuum-tube, low frequency oscillator, type 377-B, manufactured by the General Radio Company of Cambridge, Massachusetts. A frequency of 1000 cycles per second was used in all determinations except one (page 176).

b. Sample containers for conductivity measurements of cement pastes and mortars. The sample containers consisted of four paraffined, wooden containers of approximate inside dimensions: 12.5 cm. by 2.5 cm. by 2.5 cm. These containers are shown in Figure 4, page 33. The material of the electrodes consisted of molded graphite brushes manufactured by the National Carbon Company. These brushes, approximately 1.2 cm. thick, were cut to fit the 2.5 cm. by 2.5 cm. dimensions of the container. The head of a 1 1/4 - inch brass machine screw was then anchored into the carbon block. The screw extended through the end of the container, and the assembly of the electrode was made rigid by suitable washers and nuts on the outside of the end of the container.

The electrodes were sandpapered before each sample was packed; and the containers, with electrodes removed, were frequently boiled in paraffin. The resistance of one of these containers when damp varied from 10,000 to 25,000 ohms. The corresponding conductance amounted to from 0.2 per cent to 3 per cent of the conductance of the sample, depending upon the sample. No doubt most of this conductance was a surface phenomenon. The larger errors were introduced only upon

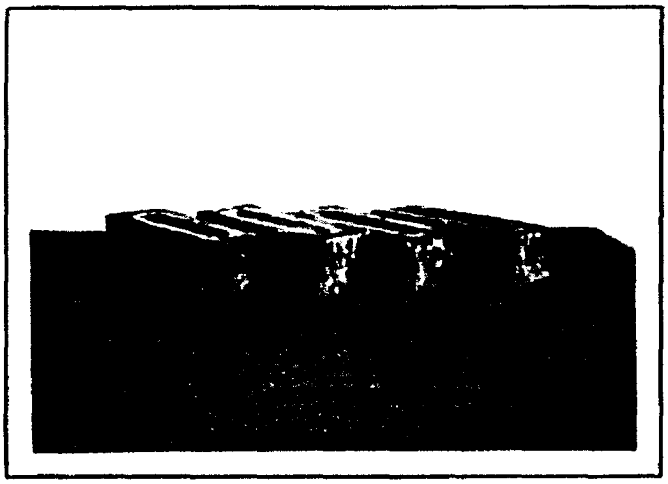


Figure 4. Photograph of Sample Containers for Conductivity Measurements of Cement Pastes and Mortars

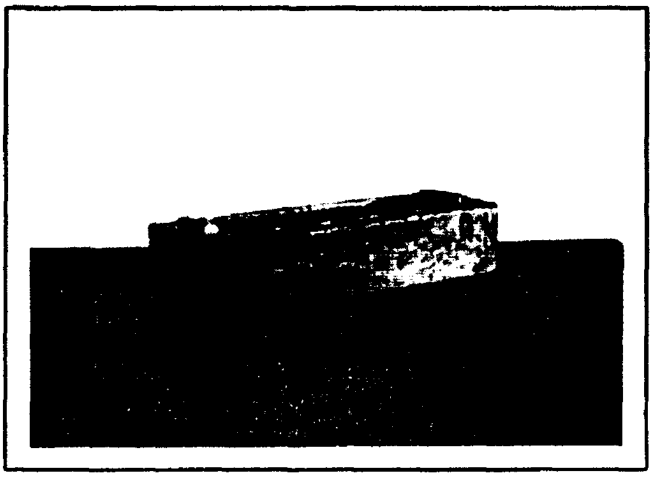


Figure 5. Photograph of Sample Container for Conductivity Measurements of Sand-Water Mixtures

measurements of cement mortars, where the conductance of the sample was much lower than that for cement pastes. For the pastes the container conductance seldom exceeded 1.5 per cent of the sample conductance. No attempt was made to correct for this error because it varied considerably during a single test, and there was no means of knowing its value at any definite time. As the sample set the surface water of the container was absorbed slightly by the sample, thus decreasing the error.

Thermometer wells were constructed in one side wall of each container so that the thermometer bulb came in contact with the cement paste or mortar but was not placed in the path of current flow.

Connections to the container were made with Number 27 Universal test clips.

c. Sample container for sand-water conductivity measurements. The sample container, Figure 5, page 33, for the determination of the excess water tendency in saturated sand-water mixtures was the same type as that used for cement pastes and mortars. The dimensions of this container, however, were approximately 26.0 cm. by 6.4 cm. by 5.1 cm. The form of the electrodes were identical to those previously described.

The resistance of the container when damp was in excess of 200,000 ohms. The container conductance was thus less than 2.5 per cent of the conductance of any sample used in it. Again no attempt was made for a correction.

d. Sample container for stratification measurements. The container, Figure 6, page 36, consisted of a paraffined, wooden box, with paraffin-sealed joints, of the following dimensions: height, 15.2 cm. (6 inches); width, 10.2 cm. (4 inches); and length, 15.2 cm. (6 inches). The two sides of the container (15.2 by 15.2 cm. dimensions) were drilled as shown in Figure 53, page 195. A sheet of 3.2 mm. (1/8 inch) sheet rubber, drilled with 1.1 cm. (7/16 inch) diameter holes was cemented over the outside surface of the container.

The electrodes, placed as shown in the figures referred to above, consisted of twelve graphite carbons of 1.1 cm. (7/16 inch) diameter approximately 18 cm. (7 inches) in length.

Connections to the electrodes were made with Number 27 Universal test clips.

e. Wheatstone bridge apparatus. The modified Wheatstone bridge circuit used in determining the resistance of samples of paste, mortar, and sand-water mixtures is shown in Figure 2, page 27. The ratio resistors were obtained from a plug-type Leeds and Northrup bridge, number 56642; and the variable resistor from a Leeds and Northrup student type potentiometer, number 30180. The variable condenser was an air condenser of approximately 0.005 microfarad maximum capacitance manufactured by the General Radio Company, type 246 P, number 477; and the fixed condensers, Western Electric paper condensers of 0.005, 0.01, 0.02, 0.02, and 0.05 microfarads. The paper condensers were tested for phase angle using a cathode-ray oscillograph and found that the effective series resistance was extremely low. The phones consisted of Western Electric signal corps phones, type P11.

f. Vacuum-tube voltmeter. The vacuum-tube voltmeter used in measuring the voltage drops across the shunts for the stratification

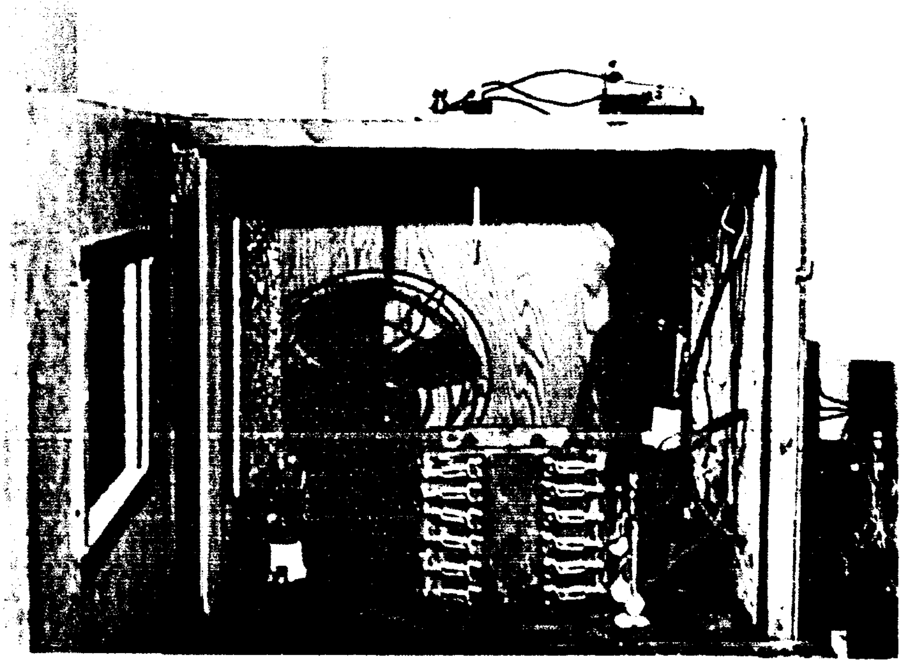


Figure 6. Photograph of Testing Cabinet with Container for Stratification Measurements in Place

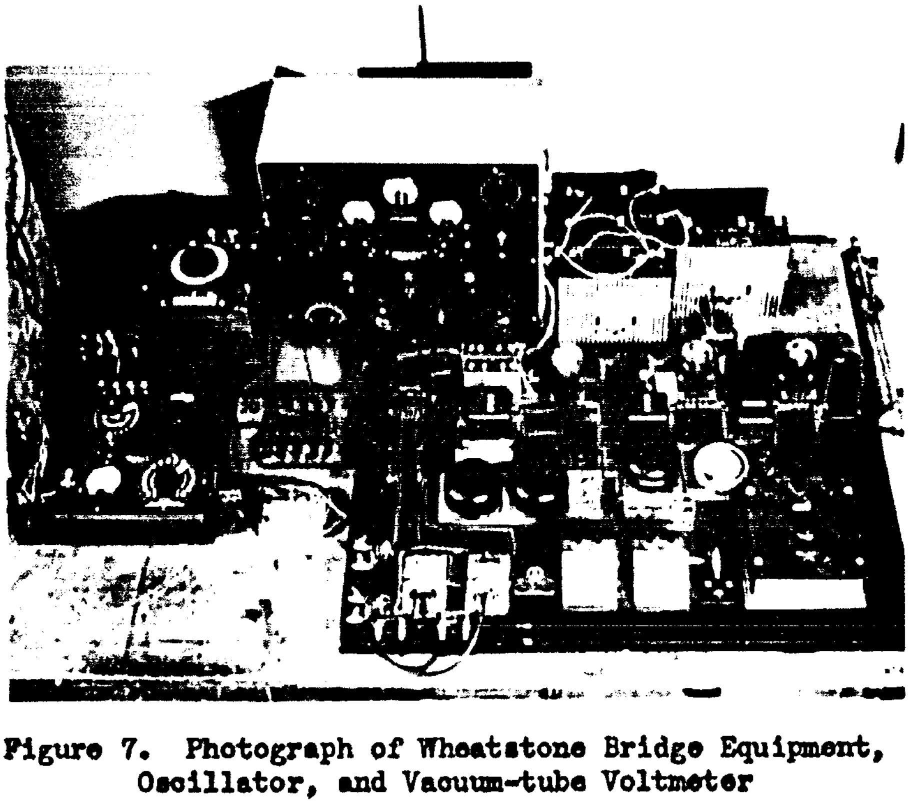
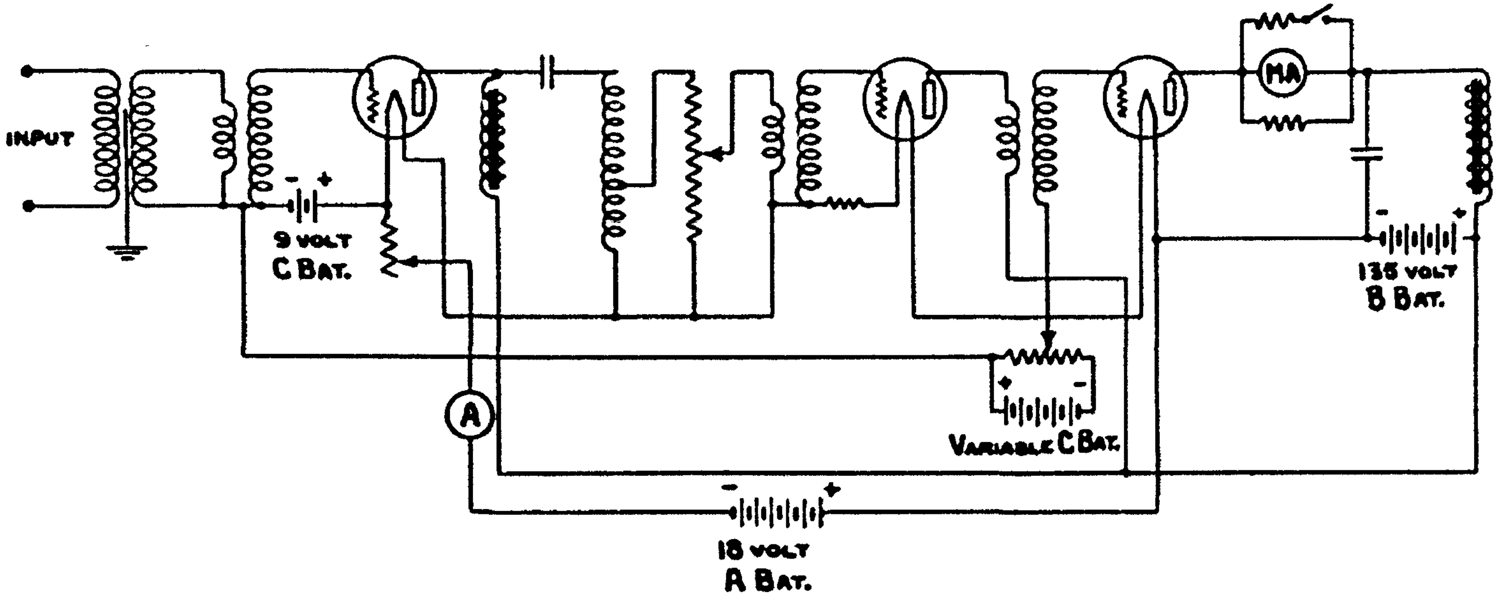


Figure 7. Photograph of Wheatstone Bridge Equipment, Oscillator, and Vacuum-tube Voltmeter



SCHEMATIC DIAGRAM OF VACUUM-TUBE VOLTMETER

Figure 8

measurements was a laboratory model manufactured by the American Telephone and Telegraph Company.

A photograph of the equipment is shown in Figure 7, page 36. The circuit of the voltmeter is shown schematically in Figure 8, page 37.

The voltmeter consisted essentially of the following elements:

(1) A vacuum-tube amplifier

(2) A vacuum-tube detector to rectify the alternating current so that a sensitive direct-current meter could be used to indicate the magnitudes of applied voltages

(3) A calibrated potentiometer used to indicate the ratio of the magnitudes of the voltages impressed on the input of the amplifier.

The operation of the meter consisted of adjusting, by means of the potentiometer, the input to the amplifier for the various applied voltages so that the output meter deflection was maintained constant. The potentiometer readings being inversely proportional to the applied voltages furnished the means of comparison.

For example, assume an applied voltage of 20 millivolts and a potentiometer reading of 250 for a normal output current of 1 milliampere. Now, if a voltage of 10 millivolts be applied, instead of that of 20 millivolts, the potentiometer must be adjusted to twice its original value, or 500, to maintain the same input to the amplifier and thus maintain the output of 1 milliampere.

The range of the meter was adjustable by varying the grid bias of the last tube of the amplifier. For a given grid bias the meter could be calibrated by applying a known voltage to the input and noting the potentiometer reading for normal output.

g. Electrical testing cabinet. The testing cabinet, of double-wall construction, approximately 60 cm. by 50 cm. by 45 cm., was thermostatically controlled (± 1°C.) for holding samples at or near a given temperature for periods of three hours. The terminology "at or near a given temperature" is used to signify that it was not always possible to hold a sample of paste or mortar in which thermal reactions were occurring at a given temperature. The cabinet is evident in the photograph, Figure 6, page 36.

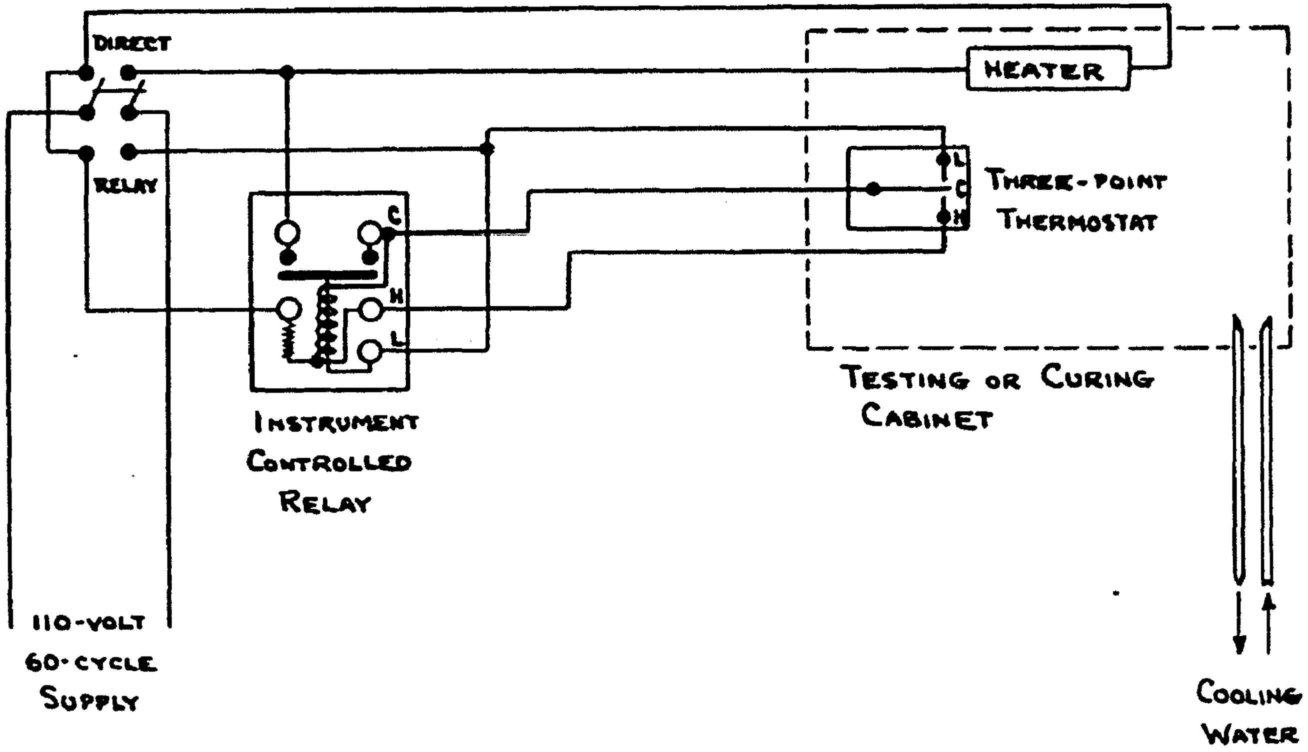
The temperature of the cabinet, with no heating applied, was first maintained below the desired temperature by means of a cold-water radiator and slow speed fan system, as may be seen in the photograph. When desirable the temperature of the cabinet could be maintained more or less below room temperature by this means, the amount below depending upon the cooling water (tap water) temperature and room temperature. For example, at a room temperature of 30°C. and tap water of 15°C. the cabinet could be maintained at approximately 22°C. The temperature was then boosted to the desired temperature by thermostatically controlled lamps.

The thermostat, constructed by the author, was of the three-point variety, the motivating element being a bi-metal strip of zinc and copper.

The relay used in conjunction with the thermostat was manufactured by Struthers Dunn, Incorporated, type ABYT8PO.

The control circuit for the cabinet is shown in Figure 9, page 40.

h. Curing cabinet. The curing cabinet consisted of a plywood



Control Circuit for Testing Cabinet or Curing Cabinet

Figure 9

box lined with galvanized sheet steel made water tight by soldering. The dimensions of the box were approximately 60 cm. by 50 cm. by 45 cm. with an overflow drain at the 35 cm. level.

Sufficient tap water was allowed to flow into the box to maintain the temperature of the water several degrees below 25°C., the temperature at which the samples were cured. The temperature was then boosted to 25°C. by means of thermostatic control on an immersed heating element of nichrome wire.

The thermostatic control equipment was identical with that as described for the testing cabinet (Figure 9, page 40).

i. Compression testing machine. The equipment used in testing the cured mortar cubes for compressive strength was a Southwark-Emery 75,000-pound machine manufactured by the Baldwin-Southwark Corporation, Philadelphia, Pennsylvania, number 56810, under license from Emery-Tatnall Company.

3. Methods of procedure

a. Setting phenomena of cement pastes. Two hundred fifty (250) grams of cement and a sufficient quantity of distilled water (conductivity less than 1×10^{-4} mhos/cm^3), measured in c.c., to produce the desired water-cement ratio were placed in the testing cabinet and allowed to come to the temperature at which the test was to be made.

The cement was then placed on a non-absorbent flat surface and cratered. As the water was poured into the crater a stop watch was started. One-half minute was allowed to turn the cement into the water with a trowel. The paste was then mixed thoroughly for one and one-half minutes. Mixing of the drier samples was done with the hands, protected by rubber gloves so as to absorb no moisture.

The paste was then placed in the sample container, whose dimensions were accurately measured, having the thermometer well of the container filled with a solid rod. The paste, for the drier samples, was compacted with the thumbs, so that the total applied pressure was approximately 10 to 15 pounds.

The top of the sample was then smoothed off with a trowel and the surface sealed with a thin layer of melted paraffin. This was immediately cooled by placing the sample under a stream of cool water for several minutes. This seal was found necessary to protect the sample from cracking and consequently producing erroneous measurements of resistance. The rod was removed from the thermometer well and replaced by a thermometer.

The sample was then placed in the testing cabinet which was maintained at the desired temperature. Readings of sample resistance and temperature were made at 15, 30, 45, 60, 90, 120, 150, and 180 minutes. The resistance was measured by the modified Wheatstone bridge described on page 37.

So that the cements could be compared at the same consistencies as regarded water content, tests with the Vicat Needle were made for normal consistency. The method of procedure of the American Society of Testing Materials, C 77-30 (3) was followed.

b. Excess water tendency in sand-water mixtures. In these conductivity tests, as in others, small temperature variations (several degrees Centigrade) were found to produce considerable variations in the electrical conductivity. As a result 25°C. was chosen as the most desirable temperature for these tests, and all measurements were made within 5°C. of this temperature, the value being noted.

First, samples of tap water were tested for its electrical resistance at temperatures in the above range by filling the container so that the meniscus of the water was level with the top surface of the container.

Samples of the desired sizes and gradings of sand were then tested according to the following method: The container was filled approximately one-half full of tap water. The washed, wet sand was then allowed to settle through the water to the bottom of the container. This procedure was followed to eliminate air bubbles. With the container full the mixture was rodded, and the sides of the container struck sharply with a trowel to produce dense packing. The surface of the mixture was then carefully leveled making certain there was neither an excess or deficiency of water. This accomplished, a reading of the resistance was made using the Wheatstone bridge; and the temperature of the mixture was determined immediately by inserting a thermometer.

Measurements of the dry voids were made by compacting the sand by rodding and tapping the 50 c.c. graduate in which it was placed until no change in volume was noted. The volume of sand thus compacted was recorded. Using a 500 c.c. graduate a volume of water of approximately 200 cc. was measured and recorded. The sand was then poured slowly into the water and the combined volume measured. Three determinations for each size or grading of sand were made.

c. Internal stratification in cement pastes. The vacuum-tube voltmeter was calibrated by measuring a known voltage drop calculated from a measured current flow through a standard non-inductively wound resistor of known resistance.

The container and shunts were calibrated for variations with the container filled with a 0.3 normal solution of sodium chloride. This concentration was found to have a conductivity of the same order of magnitude as most Portland cement pastes of 0.35 or 0.40 water-cement ratio. Three to five sets of relative readings of current flow at a constant impressed voltage were made for this calibration.

The test upon a sample of cement paste was made according to the following procedure.

The container, 5000 grams of cement, and sufficient distilled water to give the proper water-cement ratio were brought to a temperature of 25°C. in the thermostatically controlled testing cabinet.

The cement was then placed upon a non-absorbent flat surface and cratered. The water was poured into the crater and a stop watch started. One minute was allowed for turning the cement into the water with a trowel. The sample was then mixed thoroughly for five minutes.

At the expiration of that time the sample was placed in the container and rodded ten times in the region between the electrodes and five times in each region behind the electrodes. The surface of the sample was smoothed with as little agitation as possible. The container and sample were then placed in the testing cabinet, and the leads to the electrodes made with test clips.

Two sets of readings of current flow through the six circuits were made each five minutes, beginning at ten minutes, for the first sixty minutes. For the remainder of the one hundred eighty minutes of the test, two sets of readings were made each ten minutes. The temperature of the sample was measured with a thermometer placed in the cement paste just behind the common circuit electrodes. Readings of the temperature of the paste and the levels of the water and cement at the center of the top surface were made each ten minutes.

Inasmuch as water collected on the top of the sample for some cements during a portion of the test, and as the cement also underwent a shrinkage as it set, corrections for conductance measurements on the top section of the sample were necessary.

One sample of each cement for which water collected on the surface was used in determining the conductance of this surface water. At a time when the amount of water on top was a maximum, as determined from a previous test, a reading was made and then this water was poured or absorbed from the surface and the reading repeated.

d. Correlation of electrical conductivity and compressive strength of cement mortars. The constituents of the mortar (sand, cement, and distilled water) were measured and brought to a temperature of 25°C in the testing cabinet.

The sand and cement were placed on a non-absorbent, flat surface, mixed thoroughly, and then cratered. The water was then poured into the crater and a stop watch started. One-half minute was allowed for turning the cement and sand into the water. The constituents were then mixed thoroughly for one and one-half minutes by kneading with the hands. During this operation the hands were protected by rubber gloves.

At the expiration of this time two sample containers for electrical measurements were filled and packed as is described for the drier samples of cement paste (page 42), except that no paraffin seal was used. The samples were then placed in the testing cabinet.

Immediately following, oiled brass molds for two-inch cubes, placed on oiled flat glass plates, were filled with the mortar and packed in the same manner. These molds were then covered with damp cloths and allowed to stand twenty to twenty-four hours.

Fifteen minutes after the samples were mixed the electrical resistance and temperature of the conductivity samples were measured.

Twenty to twenty-four hours later the molds were carefully removed from the compressive strength samples. The samples were then numbered with water-proof black paint and immersed in the curing cabinet where the water temperature was held at 25°C. by thermostatic control.

At the end of twenty-eight days the samples were removed and immediately tested for compressive strength.

Additional samples for the electrical conductivity at temperatures over the range of 20°C. to 30°C. were made according to the above procedure to determine the correction factor for temperature variations.

B. Calculations

The importance of the calculations as a logical step between the experimental work and the presentation of data makes this section of the dissertation a necessity. In several divisions of the investigation the calculations were quite simple; in others, quite involved.

1. Setting phenomena of cement pastes.

The calculations of electrical conductivity were made according to the relationship

$$\sigma = l/RA \qquad \text{(Eq. 7)}$$

where σ is the electrical conductivity, l the length of the sample, A its cross sectional area, and R the measured resistance.

2. Excess water tendency in sand-water mixtures.

The percentage of dry voids was calculated from

$$k_d = \frac{V_s + V_w - V_c}{V_s} \times 100\% \qquad \text{(Eq. 8)}$$

where k_d is the percentage of dry voids, V_s the volume of compacted dry sand, V_w the volume of water, and V_c their combined volume after the sand was poured into the water. The calculations are tabulated in Table XI, page 108.

The relative measure of the wet voids was calculated from the ratio of the conductance of the sand-water mixture to the conductance of the water alone. Thus

$$k_w = \frac{1/R_{sw}}{1/R_w} = \frac{R_w}{R_{sw}} \qquad \text{(Eq. 9)}$$

where k_w is the relative measure of wet voids, R_{sw} the resistance of the sand-water mixture, and R_w the resistance of the water alone.

The "excess water tendency", λ, was obtained from the ratio of k_w to k_d,

$$\lambda = \frac{k_w}{k_d} \qquad \text{(Eq. 10)}$$

with all terms expressed as pure numbers.

The results of these calculations are shown in Table XIII, page 110.

The calculations for the Weymouth grading of sand followed the plan as outlined on pages 26 and 28. The larger size particles, lying between Tylor sieves numbers 14 and 28, were spaced throughout the entire unit volume. d_o, the dry bulk density (percentage of solids), was determined from the dry voids measurements by

$$d_o = 1 - k_d \qquad \text{(Eq. 11)}$$

where k_d was the fraction of dry voids. Thus, for the largest size particles (#14 - #28), where k_d was 36.3%, $d_o = 1 - 0.363 = 0.637$. Then $d_a = 0.296\ d_o = 0.188$. Thus the absolute volume per unit volume for the largest size was $0.188 \times 1.000 = 0.188$.

The space available of unit volume for the next size group (#28 - #48) was $1.000 - 0.188 = 0.812$. d_o was 0.611, giving a d_a of 0.181, and $0.181 \times 0.812 = 0.147$ the absolute volume per unit volume for this size.

Likewise for the smallest size group (#48 - #100), the absolute volume was found to be 0.118 per unit volume.

Assuming constant specific gravity for all the particles (the variation was found to be less than 1%), the percentage weights were found by adding the absolute volumes and taking percentage ratios.

The tabular results of these calculations are shown in Table X, page 107. The grading, as compared to the straight-line grading, is shown in Figure 24, page 112.

3. Internal stratification in cement pastes.

The voltmeter, with the grid bias of the last tube adjusted so the desired range of voltages was obtained, was calibrated as described on page 38. If

I_0 = current through the standard resistor during the calibration

R_0 = resistance of the resistor

P_0 = potentiometer setting of vacuum-tube voltmeter during calibration

P = potentiometer setting of voltmeter for any reading

I = current corresponding to reading P

R_{si} = resistance of the shunt used for reading P,

then, since the readings of the potentiometer are inversely proportional to the voltage drops measured,

$$IR_{si} = I_0R_0 \frac{P_0}{P} \qquad \text{(Eq. 12)}$$

The calibration for variations in R_{si} of the various shunts and in the electrode spacings was made as described on page 44. Let

P_i $(i = 1, 2, \ldots\ldots 6)$ = average readings for the six electrode circuits during the calibration with the NaCl solution

$P_a = 1/6 \sum_{i=1}^{6} P_i$ = grand average of NaCl calibration readings

$F_i = P_a/P_i$ = factor by which readings of the potentiometer, when the voltmeter is connected across shunt i, must be multiplied to refer all readings to the same level of measurement.

This level of measurement is fixed if the average value of R_{si} is assumed to be exactly one ohm. The shunts were wound from the manufacturer's data of resistance per foot of wire.

Then

$$R_s = \frac{E \times F_i \times P}{I_o \times R_o \times P_o} - R_{si} \qquad \text{(Eq. 13)}$$

where R_s is the sample resistance and E the voltage applied.

Converting to conductance

$$G_s = 1/R_s \qquad \text{(Eq. 14)}$$

where G_s is the conductance of the sample.

The calculations of the corrections for surface conditions, discussed on page 45, were made as follows. If

G_w = conductance of the top section with the water

G_g = conductance of the top section without the water

d_w = depth of water during reading of G_w

d = depth of water during any reading for which the conductance is G_s.

then the corrected value of G_s' was

$$G_s' = G_s \left[1 - d/d_w \, (G_w - G_s)\right] \qquad \text{(Eq. 15)}$$

assuming that the water had the same conductivity during both readings.

The corrections for shrinkage of the paste were made on a volumetric basis. If d_c was the distance from the top level of the container to the cement level, measured in inches, then the completely corrected value of G_s'' was

$$G_s'' = G_s' \, / \, (1 - d_c) \qquad \text{(Eq. 16)}$$

The 1 entered because the normal thickness of the section was one inch.

The data of the stratification measurements (potentiometer readings, P) were plotted against time, as shown in Figures 26 to 36, pages 148 to 158, inclusive, and the preceding calculations were applied to the values at 15, 30, 45, 60, 90, 120, 150, and 180 minutes as obtained from the smooth curves thus obtained. The results of these calculations are tabulated in Tables XXVIII to XXXVIII, pages 129 to 147, inclusive.

The two corrections applied to the top section of the sample rendered it open to considerable error. Consequently any basis of percentage which included these readings would likewise admit an uncertainty to all the readings. If section one were excluded from the basis, then only the percentage conductance of section one would be in error and not those of the remaining sections. If

G_i = conductance of section i (i = 1, 2, ...6)

$$G_a = 1/5 \sum_{i=1}^{5} G_{si} = \text{average basic conductance}$$

then the percentage conductance, M_i, of any section i, based upon sections 2 to 6, is

$$M_i = G_i/G_a \times 100 \text{ per cent}$$

4. Correlation of electrical conductivity and compressive strength of cement mortars.

The calculations of electrical conductivity were identical with those described for cement pastes, page 47.

The compressive strength for the 2-inch cube samples was obtained from

$$s_c = \frac{W}{A} \qquad \text{(Eq. 17)}$$

where s_c was the compressive strength, W the total maximum load required to crush the sample, and A the cross sectional area (4 sq. in.).

Calculations of correction factors to be applied to the electrical conductivity measurements to correct them to 25°C. were made according to the following formula

$$\mu = \frac{G_s'}{G_s} \qquad \text{(Eq. 18)}$$

where μ is the factor by which the conductivity at any temperature must be multiplied to correct it to 25°C., G_s' is the conductivity at 25°C. in the test and G_s is the conductivity at the temperature under investigation.

C. Presentation of Results

1. Preliminary results.

Samples of cement paste were tested for the effects of variations of the magnitude of applied voltage and of frequency upon the electrical resistance, or conductance. The results of these investigations are tabulated in Tables I and II, pages 54 and 55, respectively, and shown graphically in Figures 10 and 11, page 56.

TABLE I

VOLTAGE-CURRENT RELATIONS

Cement C
Sample Number 227
Water/cement 0.300
Time 150 to 180 minutes

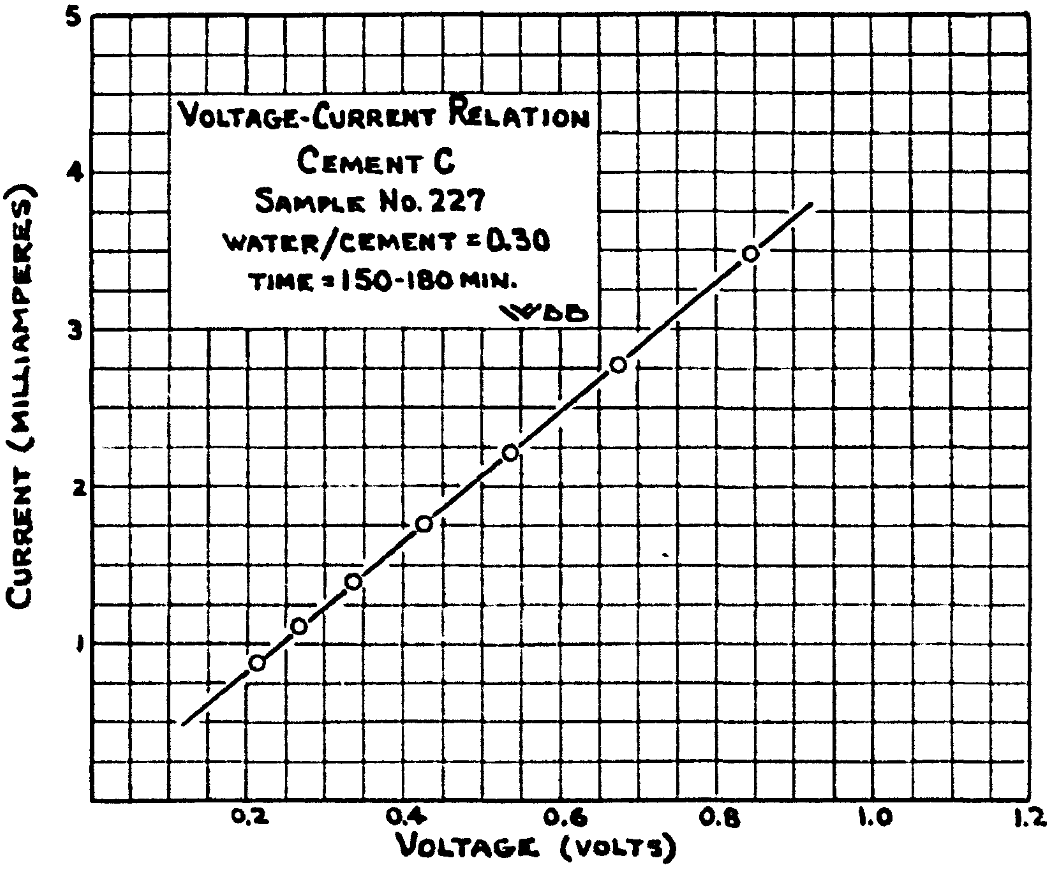
Total Resistance (ohms)	Total Voltage (volts)	Current (m.a.)	Voltage across Standard Resistance (volts)	Sample Voltage (volts)
1243.0	1.09	0.877	0.877	0.213
1242.9	1.37	1.102	1.102	0.268
1242.5	1.73	1.392	1.392	0.538
1242.8	1.73	1.392	1.392	0.338
1242.5	2.18	1.755	1.755	0.426
1243.1	2.75	2.212	2.212	0.538
1243.0	3.45	2.775	2.775	0.674
1243.3	4.32	3.475	3.475	0.845

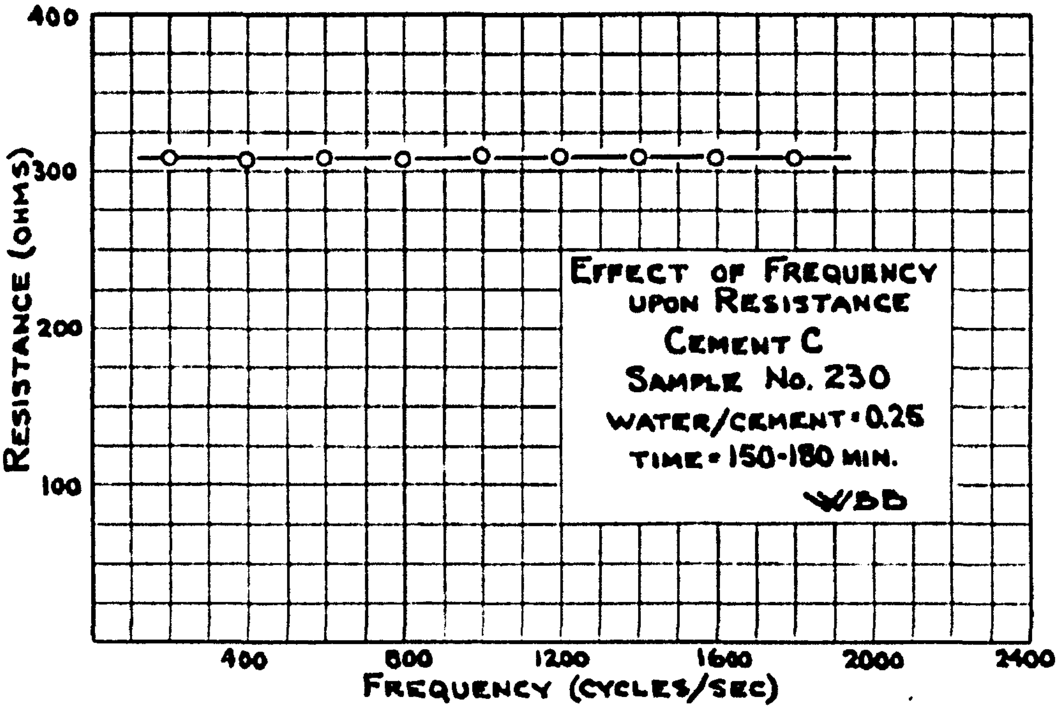
TABLE II

EFFECT OF FREQUENCY UPON RESISTANCE

Cement C
Sample Number 250
Water/cement 0.250
Time 150 to 180 minutes

Frequency (cycles/sec.)	Resistance (ohms)
200	318.4
400	317.5
600	317.7
800	317.4
1000	318.1
1200	318.3
1400	318.5
1600	318.4
1800	318.3





Figures 10 & 11

2. Setting phenomena of cement pastes.

The data for the variations of electrical conductivity of three cements with time, temperature, and water-cement ratio are presented in Tables III, IV, and V, pages 60 to 70, inclusive, and plotted in Figures 12, 13, and 14, pages 75 to 98, inclusive.

The data are presented in two manners as may be noted by referring to the a, b, c, d, e, f, g, and h figures of each series and comparing these with the i, j, k, l, m, n, o, and p figures of the same series. The first of those are plotted for increments of water-cement ratio, the second for increments of time. Thus, each curve appears twice in the entire series, once on each of the above sets and must agree with each of these families of curves. This suggests a means of checking the accuracy of the smooth curves drawn from the data.

The best estimates of the curves were first drawn and then checked one by one, compromises being reached between the two families of curves when necessary. As a result the accuracy of the locations and shapes of the smooth curves was increased immensely.

After the curves were plotted on the cross-section paper from which the grid tracings were made, the errors were calculated, and an upper limit on the error which would be allowed in the final plot was arbitrarily fixed. This limit was set at twice the average negative error. The negative errors were chosen as the basis because they were always larger than the positive errors. A discussion of the errors may be found in Appendix B, page 215. All the data are tabulated in the tables, but those marked * are not plotted.

Tabulations of the results of these curves for increments of temperature, water-cement ratio, and time are listed in Tables VI, VII, and VIII, pages 71, 72, and 73.

To condense these data into three single diagrams, a method suggested by Mackey (20) was used. The method was applied by him to a very simple problem where all the variations of the three independent variables were straight-line functions with respect to the fourth variable, and had no effect upon each other. None of the variations encountered in this problem followed an exact straight-line relationship, but the method is illustrated, at least approximately, by Figures 15, 16, and 17, pages 99 to 101, inclusive.

The form of the function varied for various temperatures and water-cement ratios, and, as these functions must overlap somewhat when applying the above graphs, the approximation was encountered. However, the forms of the functions for all values, except 0.250 water-cement ratio below 25° C., were nearly the same, and the approximation, except as noted, was less than the uncertainty of the data.

To plot these two families of curves, both of which in general were curved lines involving all four variables, a method was devised by the author. This method consisted of plotting the points for conductivity against time on strips of paper approximately 1/5 inch in width, one strip for each increment of temperature and water-cement ratio, and labeled accordingly. These strips were then laid out on a drawing board for increments of temperature at a constant water-cement ratio, so that corresponding values of conductivity at the various values of time formed smooth curves. Then the other families of strips were fitted to those already placed until corresponding points on both families fitted smooth curves. Using this method it was possible to make adjustments of points without erasing perhaps half of the graph. This is not an exaggeration, since an attempt to change the plot often produced accumulative results.

The effects of variations involving any one or any combination of the variables may be determined from these three graphs. Some of these effects are shown in Figures 19, 20, 21, and 22, pages 103 to 105, inclusive.

The results of the Vicat needle test for normal consistency are tabulated in Table IX, page 74, and plotted in Figure 18, page 102.

TABLE III

CONDUCTIVITY OF CEMENT A

Water/cement 0.250 April, 1936

Time (min)	Sample Number	Temperature (^{o}C)	Conductivity (10^{-3} mhos/cm^{3})	Time (min)	Sample Number	Temperature (^{o}C)	Conductivity (10^{-3} mhos/cm^{3})
15	96	23.6	8.10	90	96	22.1	8.28
	106	20.9	8.03		106	20.2	8.28
	115	26.8	8.97		115	24.7	8.70
	184	28.3	9.22		184	26.3	9.12
	188	30.6	9.62		188	30.4	9.68
30	96	22.1	7.92	120	96	22.1	8.10
	106	20.1	8.05		106	21.2	8.26
	115	25.7	8.85		115	25.4	8.58
	184	27.6	9.40		184	26.9	8.98
	188	30.7	9.85		188	30.4	9.50
45	96	22.3	8.31	150	96	22.3	7.97
	106	19.4	8.06		106	21.7	8.17
	115	24.6	8.81		115	25.1	8.36
	184	27.0	9.44		184	27.8	8.81
	188	30.0	9.96		188	31.0	9.13
60	96	22.3	8.46	180	96	22.3	7.76
	106	18.9	8.07		106	22.2	8.04
	115	23.9	8.66		115	25.0	8.04
	184	26.7	9.46		184	27.8	8.48
	188	30.7	9.88		188	31.1	8.61

TABLE III (continued)

Water/cement 0.300

Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)	Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
15	98	23.2	9.20	90	98	21.8	9.75
	108	20.1	8.82		108	20.7	9.58
	117	25.1	9.31		117	25.1	9.49 *
	185	27.1	10.19		185	25.6	10.21
	189	28.7	10.33		189	31.1	10.80
30	98	21.3	9.19	120	98	22.0	9.59
	108	19.8	9.05		108	21.1	9.50
	117	24.0	9.16 *		117	24.6	9.27 *
	185	26.6	10.39		185	25.8	10.06
	189	28.9	10.66		189	31.1	10.64
45	98	22.1	9.72	150	98	22.1	9.43
	108	19.0	9.06		108	21.3	9.43
	117	25.0	9.60 *		117	25.0	9.05 *
	185	26.1	10.51		185	26.0	9.90
	189	29.4	10.90		189	31.2	10.42
60	98	22.1	9.92	180	98	25.1	9.24
	108	20.4	9.65		108	21.3	9.29
	117	25.1	9.74		117	24.6	8.65 *
	185	25.8	10.59		185	26.2	9.62
	189	30.0	11.08		189	31.2	9.76

* indicates an error of more than 5.58 per cent. See Appendix B.

TABLE III (continued)

Water/cement 0.350

Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
15	102	27.0	10.38
	110	21.6	9.22
	186	26.9	10.36
	190	28.0	10.76
30	102	26.1	10.83
	110	20.4	9.58
	186	26.4	10.72
	190	28.7	11.15
45	102	24.7	10.93
	110	19.3	8.90
	186	26.0	10.89
	190	28.9	11.52
60	102	23.8	11.04
	110	19.2	9.13
	186	25.6	11.01
	190	29.3	11.76
90	102	22.4	10.03
	110	21.0	8.47 *
	186	25.4	10.84
	190	29.6	11.43
120	102	23.3	10.67
	110	21.6	8.16 *
	186	25.6	10.64
	190	29.9	11.31
150	102	22.8	10.43
	110	21.8	7.83 *
	186	25.6	10.39
	190	30.3	11.10
180	102	22.3	10.24 *
	110	22.2	9.00
	186	25.7	9.66
	190	30.1	10.11

Water/cement 0.400

Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
15	104	19.7	8.34 *
	112	20.4	8.74
	187	26.4	10.40
	191	28.3	10.78
30	104	19.3	8.83
	112	19.7	9.21
	187	25.6	10.69
	191	29.0	11.13
45	104	20.6	9.88
	112	19.0	9.27
	187	25.1	10.91
	191	29.0	11.32
60	104	20.9	10.28
	112	20.3	10.00
	187	25.0	11.14
	191	29.3	11.43
90	104	22.1	10.36
	112	20.1	10.16
	187	25.1	11.16
	191	29.3	11.06
120	104	21.6	10.14
	112	21.2	9.99
	187	25.2	10.90
	191	29.7	10.78
150	104	21.4	9.96
	112	21.3	9.84
	187	25.1	10.70
	191	29.4	10.44
180	104	21.3	9.77
	112	21.6	9.54
	187	25.6	9.48
	191	28.9	9.48 *

* indicates an error of more than 5.58 per cent. See Appendix B.

TABLE IV

CONDUCTIVITY OF CEMENT B

Water/cement 0.250 June, 1936

Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)	Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
15	214	26.3	14.0	90	214	25.4	15.0
	222	24.6	13.9		222	23.5	15.0
	242	28.2	15.3		242	26.9	15.5
	246	31.2	13.7 *		246	29.0	13.2 *
	250	27.4	14.2		250	28.9	15.3
30	214	26.5	14.6	120	214	25.5	14.6
	222	24.3	14.5		222	23.8	14.7
	242	27.7	15.6		242	27.0	15.1
	246	30.7	13.7 *		246	29.0	12.7 *
	250	28.3	15.0		250	29.0	14.9
45	214	25.7	16.0	150	214	25.5	14.1
	222	23.8	14.8		222	24.1	14.4
	242	27.2	16.7		242	27.6	14.4
	246	29.9	13.8 *		246	29.6	12.0 *
	250	28.6	15.4		250	30.0	14.1
60	214	26.6	15.2	180	214	26.3	13.6
	222	23.7	15.0		222	24.9	13.9
	242	27.0	15.9		242	28.2	13.5
	246	29.4	13.8 *		246	30.9	11.0 *
	250	28.8	15.6		250	31.0	13.0

* indicates an error of more than 7.06 per cent. See Appendix B.

TABLE IV (continued)

Water/cement 0.300

Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)	Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
15	215	23.6	14.4	90	215	23.9	15.9
	223	23.8	14.3		223	23.3	15.5
	243	27.4	16.2 *		243	26.6	16.5
	247	27.4	16.3 *		247	27.9	16.8
	251	30.6	16.6		251	28.9	16.9
30	215	23.8	15.3	120	215	24.4	15.6
	223	23.2	14.8		223	23.5	15.3
	243	27.0	16.4		243	26.9	16.3
	247	27.8	16.7		247	28.5	16.5
	251	29.4	17.0		251	29.2	16.5
45	215	23.8	15.6	150	215	24.7	15.4
	223	23.3	15.2		223	23.9	15.1
	243	26.8	16.7		243	27.6	15.7
	247	27.8	17.0		247	29.4	15.8
	251	28.9	17.2		251	30.0	15.8
60	215	23.9	15.9	180	215	25.6	14.9
	223	23.3	15.4		223	24.3	14.7
	243	26.7	17.0		243	28.1	15.1
	247	27.7	17.2		247	31.0	15.0
	251	28.9	17.3		251	31.3	14.6

* indicates an error of more than 7.06 per cent. See Appendix B.

TABLE IV (continued)

Water/cement 0.350

Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
15	216	23.0	13.5
	224	23.2	14.2
	244	27.1	15.8
	248	28.5	15.5
	252	29.3	15.5
30	216	23.2	14.2
	224	23.3	14.9
	244	26.9	16.3
	248	28.2	15.8
	252	29.0	16.0
45	216	23.3	14.7
	224	23.3	15.3
	244	26.8	16.6
	248	28.2	16.2
	252	28.9	16.3
60	216	23.5	15.0
	224	23.3	15.5
	244	26.7	16.9
	248	28.2	16.5
	252	28.9	16.6
90	216	23.8	15.1
	224	23.3	15.8
	244	26.8	16.6
	248	28.5	16.2
	252	28.9	16.3
120	216	24.2	14.9
	224	23.7	15.5
	244	26.8	16.4
	248	28.9	16.0
	252	29.1	16.0
150	216	24.6	14.7
	224	24.2	15.3
	244	27.2	16.0
	248	29.9	15.8
	252	30.0	15.6
180	216	25.2	14.4
	224	24.9	15.1
	244	27.8	15.5
	248	31.0	15.4
	252	30.9	15.1

TABLE IV (continued)

Water/cement 0.400

Time (min)	Sample Number	Temperature ($^{\circ}C$)	Conductivity (10^{-3} mhos/cm^3)	Time (min)	Sample Number	Temperature ($^{\circ}C$)	Conductivity (10^{-3} mhos/cm^3)
15	217	23.1	14.2	90	217	23.6	16.0
	225	22.1	13.6		225	22.9	15.4
	245	26.7	16.0		245	26.5	17.1
	249	27.1	15.3		249	27.8	16.3
	253	29.9	16.6		253	28.9	17.3
30	217	23.3	16.0	120	217	23.8	15.7
	225	22.2	14.3		225	23.2	15.1
	245	26.7	16.6		245	26.5	16.7
	249	27.5	15.8		249	28.5	16.1
	253	29.3	17.2		253	28.9	17.1
45	217	23.5	15.4	150	217	24.3	15.4
	225	22.5	14.7		225	24.3	15.0
	245	26.7	16.9		245	26.7	16.4
	249	27.5	16.1		249	29.3	16.0
	253	29.0	17.5		253	29.4	16.6
60	217	23.5	15.7	180	217	24.9	15.3
	225	22.5	15.1		225	24.7	14.7
	245	26.6	17.2		245	27.4	16.0
	249	27.6	16.3		249	30.7	15.8
	253	28.9	17.6		253	30.5	16.1

TABLE V

CONDUCTIVITY OF CEMENT C

Water/cement 0.250 June, 1936

Time (min)	Sample Number	Temperature ($^{\circ}C$)	Conductivity (10^{-3} mhos/cm^3)	Time (min)	Sample Number	Temperature ($^{\circ}C$)	Conductivity (10^{-3} mhos/cm^3)
15	218	26.7	4.49	90	218	25.2	4.87
	226	27.7	4.80		226	25.8	5.29
	230	22.9	4.12		230	23.2	4.61
	234	30.0	4.69		234	29.3	5.10
	238	30.3	4.87		238	27.9	5.21
30	218	26.6	4.71	120	218	24.9	4.83
	226	26.8	5.00		226	25.7	5.27
	230	22.9	4.31		230	23.2	4.61
	234	29.9	4.85		234	29.6	5.09
	238	29.3	5.12		238	27.9	5.18
45	218	26.0	4.85	150	218	24.6	4.82
	226	26.5	5.21		226	25.7	5.31 *
	230	23.1	4.51		230	23.5	4.59
	234	29.3	5.05		234	29.9	5.09
	238	29.0	5.29		238	27.8	5.14
60	218	25.6	5.00	180	218	24.7	4.80
	226	26.8	5.41		226	25.8	5.25 *
	230	23.2	4.83		230	23.7	4.61
	234	29.3	5.05		234	30.2	5.00
	238	28.5	5.27		238	28.0	5.05

* indicates an error of more than 7.96 per cent. See Appendix B.

TABLE V (continued)

Water/cement 0.300

Time (min)	Sample Number	Temperature ($^{\circ}$C)	Conductivity (10^{-3} mhos/cm^3)
15	219	22.6	4.60
	227	26.9	5.21
	231	23.2	4.74
	235	29.2	5.29
	239	30.0	5.52
30	219	23.2	4.89
	227	26.3	5.48
	231	23.3	5.10
	235	28.0	5.52
	239	29.3	5.79
45	219	23.2	5.14
	227	25.7	5.72
	231	23.3	5.33
	235	28.8	5.77
	239	28.9	6.01
60	219	23.3	5.41
	227	25.6	5.91
	231	23.3	5.54
	235	28.7	5.84
	239	28.3	6.14
90	219	23.7	5.31
	227	25.6	5.81
	231	23.3	5.46
	235	28.8	5.74
	239	27.9	5.89
120	219	23.9	5.29
	227	25.6	5.79
	231	23.5	5.43
	235	29.0	5.79
	239	28.0	5.89
150	219	24.2	5.31
	227	25.8	5.81
	231	23.8	5.43
	235	29.6	5.72
	239	28.0	5.84
180	219	24.4	5.29
	227	26.0	5.81
	231	24.1	5.46
	235	30.0	5.79
	239	28.0	5.79

TABLE V (continued)

Water/cement 0.350

Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)	Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
15	220	25.3	5.29	90	220	24.3	6.17
	228	24.0	5.74 *		228	25.0	6.50
	232	22.0	4.79		232	22.7	5.74
	236	30.4	4.97 *		236	29.3	5.44 *
	230	25.4	5.08		230	26.7	5.86
30	220	25.0	5.63	120	220	24.2	6.05
	228	24.6	6.09 *		228	25.3	6.50
	232	22.1	5.02		232	23.2	5.55
	236	30.2	5.11 *		236	29.9	5.42 *
	240	26.3	5.44		240	26.9	5.82
45	220	24.6	5.89	150	220	24.2	6.02
	228	24.7	6.46 *		228	25.5	6.50
	232	22.2	5.20		232	23.3	5.55
	236	29.6	5.27 *		236	30.0	5.38 *
	240	28.3	5.69		240	27.1	5.82
60	220	24.4	6.07	180	220	24.3	6.00
	228	24.8	6.61 *		228	25.5	6.50
	232	22.4	5.44		232	23.6	5.57
	236	29.3	5.45 *		236	30.0	5.38 *
	240	26.3	5.98		240	27.7	5.78

* indicates an error of more than 7.96 per cent. See Appendix B.

TABLE V (continued)

Water/cement 0.400

Time (min)	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
15	221	24.0	5.41
	229	27.7	5.86
	233	22.6	5.62
	237	30.2	5.46
	241	28.6	6.30 *
30	221	24.0	5.80
	229	26.8	6.18
	233	22.5	5.95
	237	29.6	5.74 *
	241	27.9	6.69 *
45	221	24.0	6.06
	229	26.5	6.40
	233	22.5	6.11
	237	29.3	5.82 *
	241	27.4	6.84
60	221	23.9	6.27
	229	25.9	6.58
	233	22.5	6.45
	237	29.1	6.08 *
	241	27.1	7.04
90	221	23.8	6.40
	229	25.6	6.80
	233	22.6	6.30
	237	29.0	6.22 *
	241	26.8	6.83
120	221	23.9	6.25
	229	25.5	6.58
	233	29.4	6.30
	237	29.4	6.04 *
	241	26.9	6.80
150	221	24.0	6.25
	229	25.5	6.58
	233	23.1	6.25
	237	29.8	5.97 *
	241	26.9	6.77
180	221	24.2	6.25
	229	25.5	6.58
	233	23.3	6.27
	237	29.9	5.99 *
	241	27.2	6.69

* indicates an error of more than 7.96 per cent. See Appendix B.

TABLE VI

SUMMARY OF
VARIATION OF CONDUCTIVITY WITH TEMPERATURE, WATER-CEMENT RATIO, AND TIME

Cement A

Water/cement	Time (min)	Conductivity (10^{-3} mhos/cm^3) at Temperature of 22°C.	24°C.	26°C.	28°C.	30°C.
0.250	15	8.10	8.41	8.75	9.12	9.50
	30	8.32	8.64	8.98	9.34	9.71
	45	8.48	8.80	9.14	9.50	9.88
	60	8.58	8.89	9.23	9.59	9.97
	90	8.49	8.77	9.08	9.41	9.78
	120	8.26	8.55	8.85	9.14	9.45
	150	8.01	8.29	8.55	8.80	9.20
	180	7.75	8.00	8.25	8.49	8.69
0.300	15	8.91	9.31	9.73	10.15	10.56
	30	9.27	9.69	10.09	10.50	10.90
	45	9.60	10.00	10.40	10.79	11.14
	60	9.75	10.14	10.51	10.87	11.21
	90	9.75	10.08	10.40	10.70	11.00
	120	9.58	9.85	10.10	10.36	10.58
	150	9.36	9.60	9.83	10.04	10.21
	180	9.00	9.21	9.40	9.58	9.74
0.350	15	9.20	9.65	10.10	10.54	10.98
	30	9.70	10.19	10.64	11.02	11.40
	45	10.05	10.51	10.95	11.36	11.72
	60	10.20	10.66	11.08	11.48	11.81
	90	10.29	10.62	10.96	11.28	11.55
	120	10.08	10.40	10.67	10.92	11.15
	150	9.85	10.10	10.30	10.50	10.70
	180	9.37	9.58	9.78	9.96	10.13
0.400	15	9.35	9.80	10.24	10.70	11.10
	30	9.88	10.35	10.80	11.21	11.60
	45	10.16	10.64	11.10	11.50	11.87
	60	10.40	10.84	11.25	11.65	12.00
	90	10.47	10.81	11.15	11.46	11.75
	120	10.25	10.58	10.85	11.11	11.33
	150	9.94	10.21	10.46	10.69	10.85
	180	9.53	9.75	9.96	10.15	10.32

TABLE VII

SUMMARY OF
VARIATION OF CONDUCTIVITY WITH TEMPERATURE, WATER-CEMENT RATIO, AND TIME

Cement B

Water/cement	Time (min)	Conductivity (10^{-3} mhos/cm^3) at Temperature of 22°C.	24°C.	26°C.	28°C.	30°C.
0.250	15	13.4	13.8	14.1	14.4	14.6
	30	14.0	14.4	14.8	15.1	15.4
	45	14.4	14.8	15.2	15.6	15.9
	60	14.6	15.1	15.6	16.1	16.5
	90	14.5	14.9	15.3	15.5	15.8
	120	14.3	14.6	14.9	15.2	15.4
	150	13.9	14.1	14.3	14.5	14.6
	180	13.3	13.4	13.5	13.6	13.7
0.300	15	13.7	14.2	14.7	15.2	15.6
	30	14.3	15.0	15.6	16.1	16.6
	45	14.8	15.4	16.0	16.6	17.1
	60	15.1	15.8	16.4	17.1	17.7
	90	15.1	15.6	16.1	16.6	17.0
	120	14.8	15.3	15.8	16.2	16.6
	150	14.4	14.9	15.3	15.6	15.9
	180	14.0	14.6	14.8	15.0	15.1
0.350	15	13.9	14.5	15.1	15.6	16.1
	30	14.6	15.3	15.9	16.5	17.1
	45	15.0	15.7	16.3	17.0	17.5
	60	15.3	16.0	16.7	17.3	17.9
	90	15.3	15.9	16.5	17.0	17.5
	120	15.0	15.6	16.1	16.5	16.9
	150	14.8	15.2	16.1	16.5	16.9
	180	14.5	14.8	15.1	15.4	15.7
0.400	15	14.1	14.8	15.4	16.0	16.6
	30	14.8	15.5	16.2	16.8	17.4
	45	15.2	15.9	16.6	17.2	17.8
	60	15.5	16.2	16.9	17.5	18.1
	90	15.6	16.2	16.7	17.3	17.8
	120	15.3	15.8	16.3	16.8	17.2
	150	15.0	15.4	15.8	16.2	16.5
	180	14.7	15.0	15.3	15.6	15.9

TABLE VIII

SUMMARY OF VARIATION OF CONDUCTIVITY WITH TEMPERATURE, WATER-CEMENT RATIO, AND TIME

Cement C

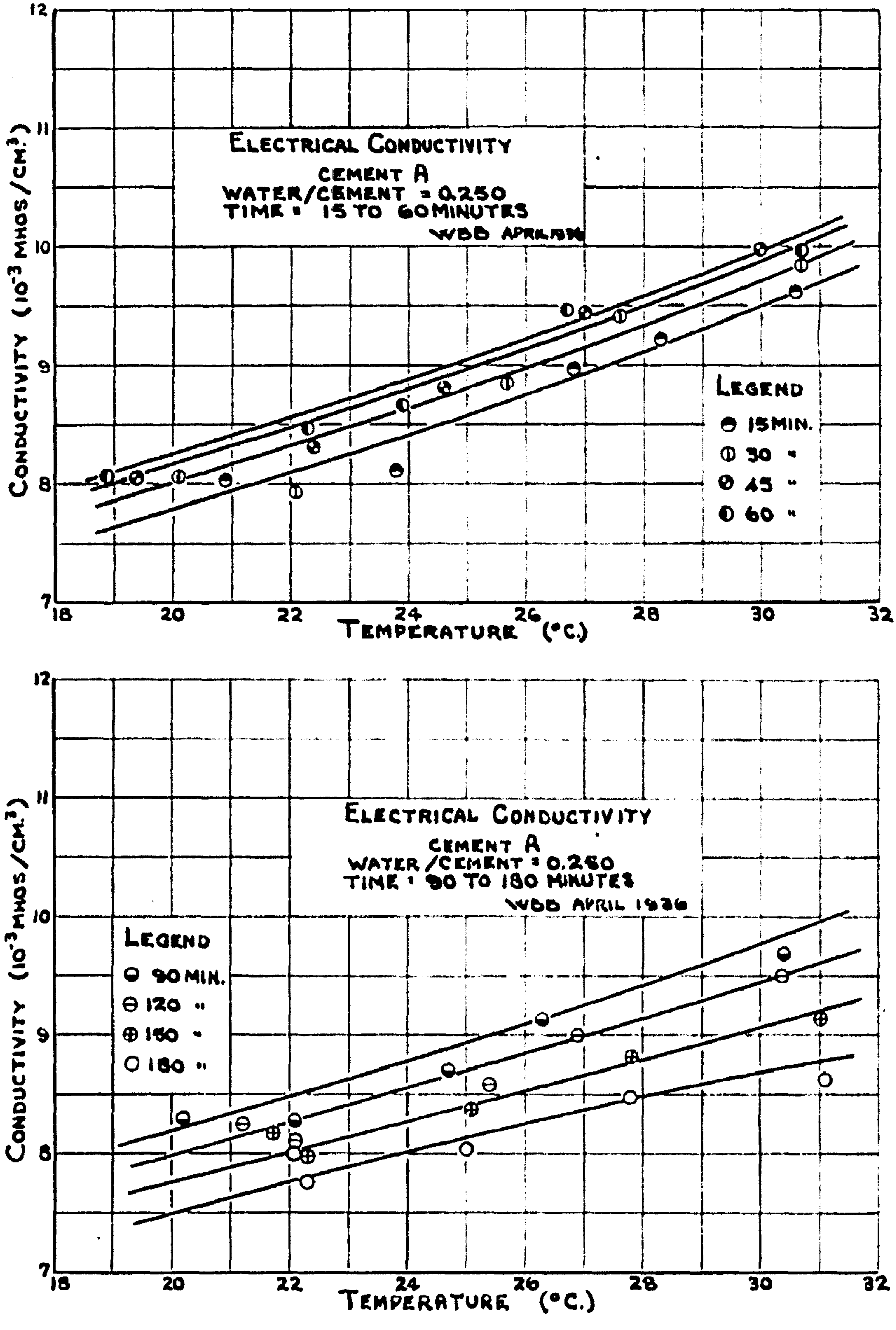
Water/cement	Time (min)	Conductivity (10^{-3} mhos/cm^3) at Temperature of 22°C.	24°C.	26°C.	28°C.	30°C.
0.250	15	4.05	4.26	4.47	4.66	4.80
	30	4.26	4.50	4.70	4.89	5.03
	45	4.46	4.71	4.91	5.09	5.20
	60	4.60	4.82	5.04	5.20	5.34
	90	4.58	4.78	4.98	5.15	5.28
	120	4.51	4.72	4.90	5.08	5.20
	150	4.47	4.66	4.82	5.01	5.15
	180	4.42	4.62	4.79	4.96	5.09
0.300	15	4.56	4.79	5.00	5.19	5.38
	30	4.84	5.10	5.30	5.50	5.70
	45	5.12	5.36	5.55	5.75	5.95
	60	5.36	5.57	5.79	5.96	6.11
	90	5.32	5.51	5.70	5.87	6.01
	120	5.29	5.46	5.63	5.80	5.92
	150	5.23	5.42	5.59	5.75	5.88
	180	5.20	5.38	5.53	5.69	5.82
0.350	15	4.90	5.09	5.29	5.46	5.60
	30	5.29	5.49	5.68	5.87	6.05
	45	5.58	5.78	5.97	6.15	6.31
	60	5.76	5.98	6.15	6.30	6.46
	90	5.81	6.03	6.19	6.34	6.51
	120	5.80	6.00	6.16	6.31	6.43
	150	5.76	5.94	6.10	6.27	6.40
	180	5.68	5.86	6.05	6.21	6.36
0.400	15	5.28	5.46	5.60	5.74	5.88
	30	5.69	5.88	6.05	6.19	6.31
	45	6.04	6.21	6.40	6.51	6.64
	60	6.21	6.41	6.60	6.71	6.85
	90	6.31	6.51	6.69	6.84	6.97
	120	6.25	6.47	6.67	6.80	6.94
	150	6.19	6.40	6.57	6.72	6.86
	180	6.14	6.31	6.49	6.65	6.80

TABLE IX

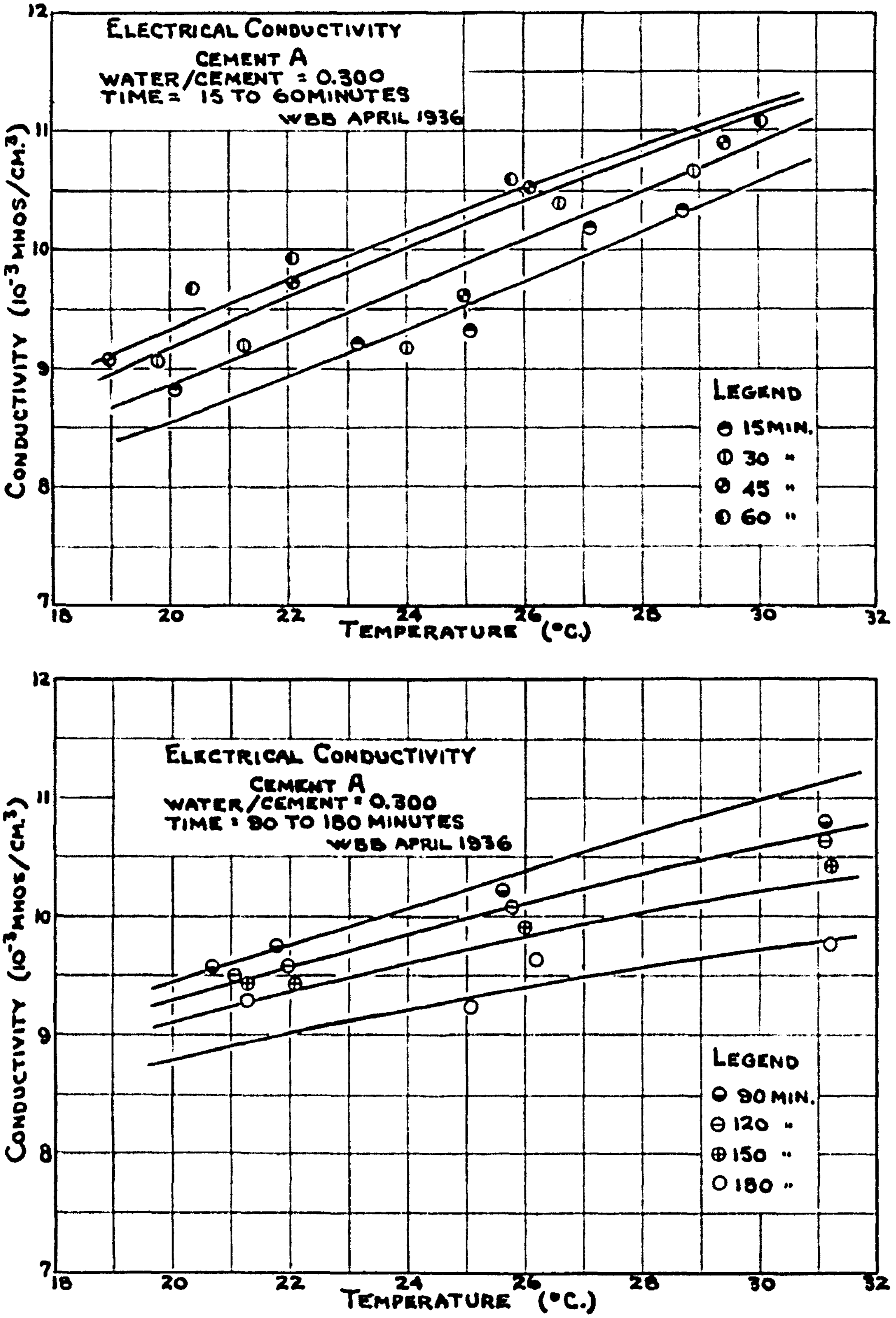
VICAT NEEDLE TEST FOR NORMAL CONSISTENCY

April 14, 1936

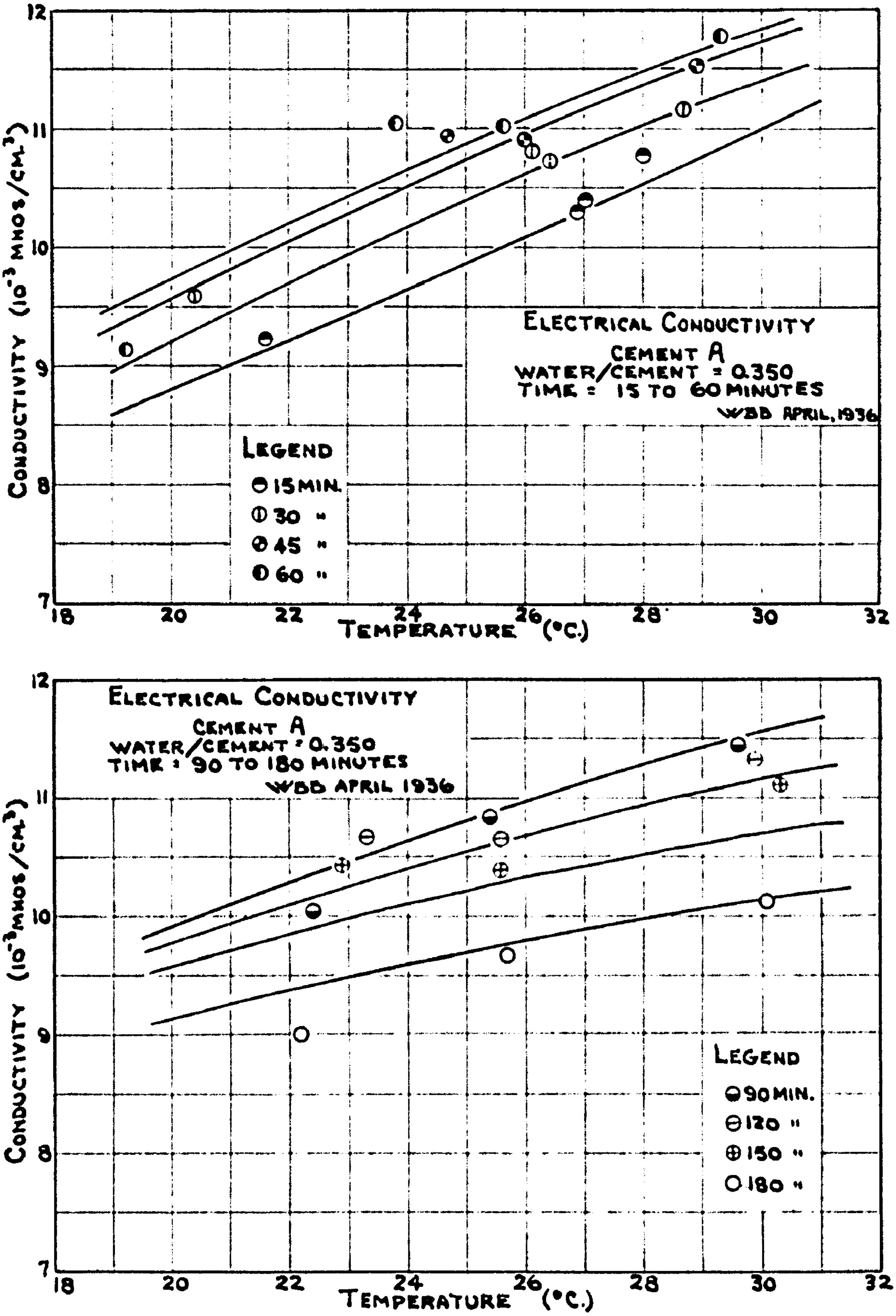
Cement	Sample Number	Water / cement	Initial Reading (mm)	Final Reading (mm)	Net Distance (mm)
A	124	0.280	3	21	18
	125	0.268	6	10	4
	126	0.274	6	12	6
	127	0.275	6	16	10
	128	0.283	4	16	12
	129	0.278	5	16	11
B	135	0.270	4	10	6
	136	0.279	5	15	10
	137	0.286	5	40	35
	138	0.276	4	14	10
	139	0.272	6	15	9
	140	0.283	3	21	18
C	130	0.270	4	35	31
	131	0.260	5	24	19
	132	0.250	5	17	12
	133	0.240	6	11	5
	134	0.247	5	14	9



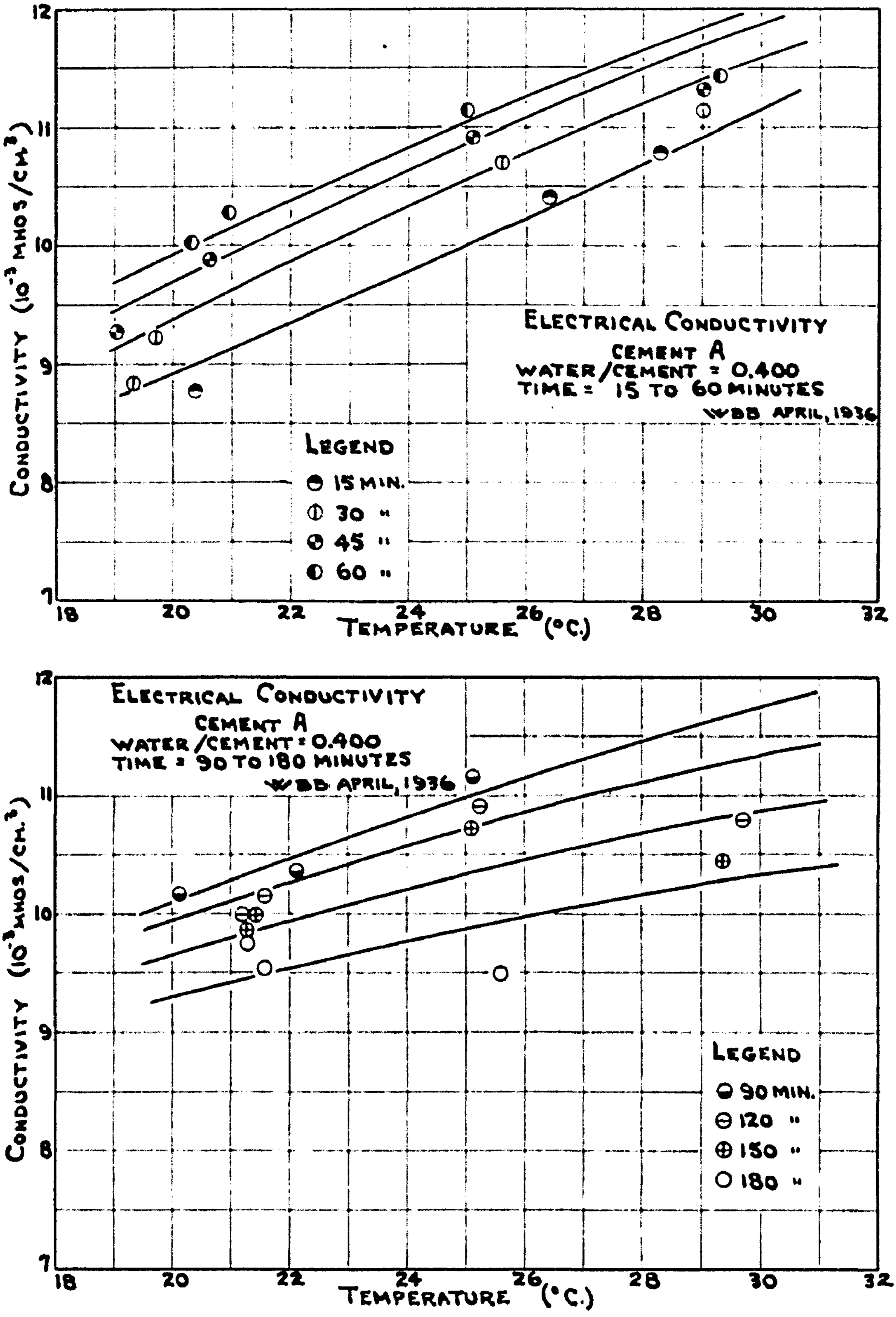
Figures 12 a & b



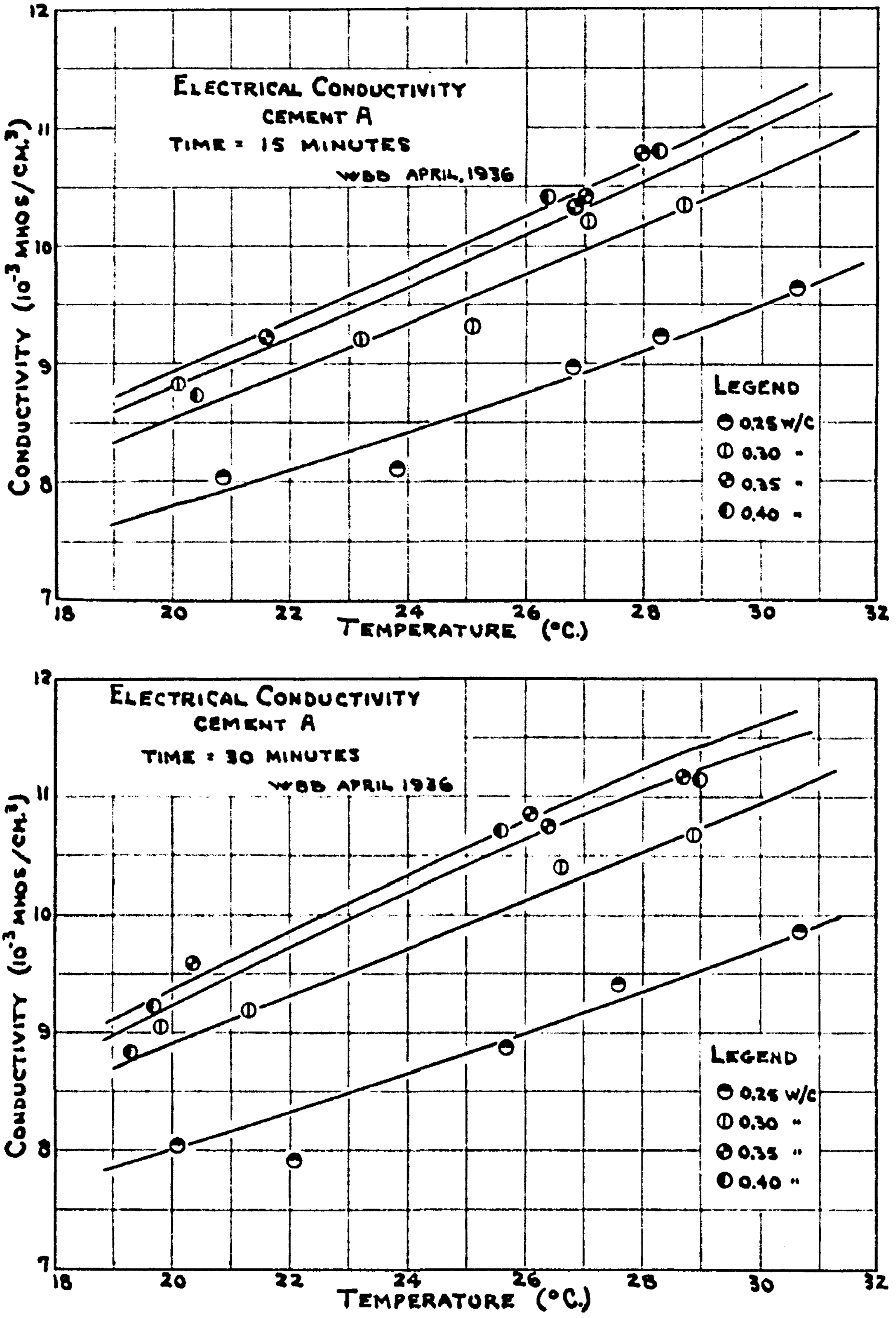
Figures 12 c & d



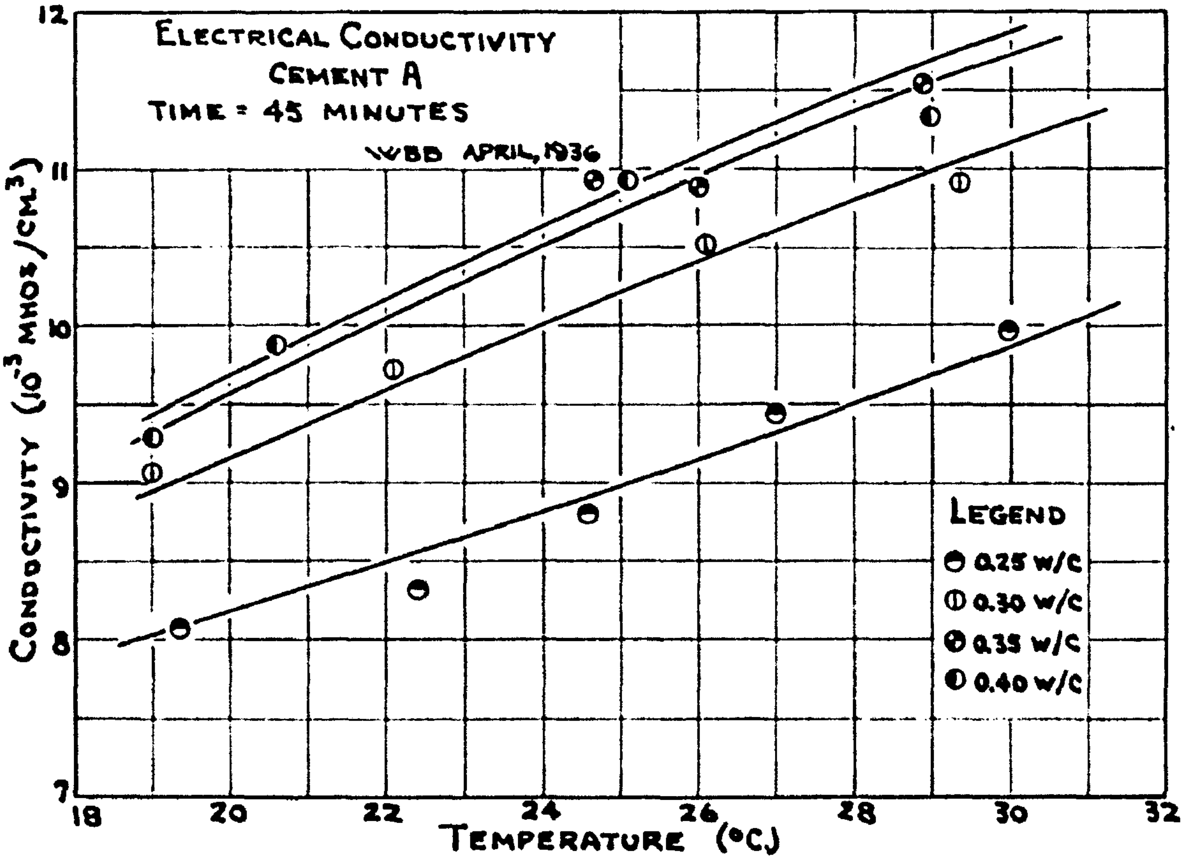
Figures 12 e & f

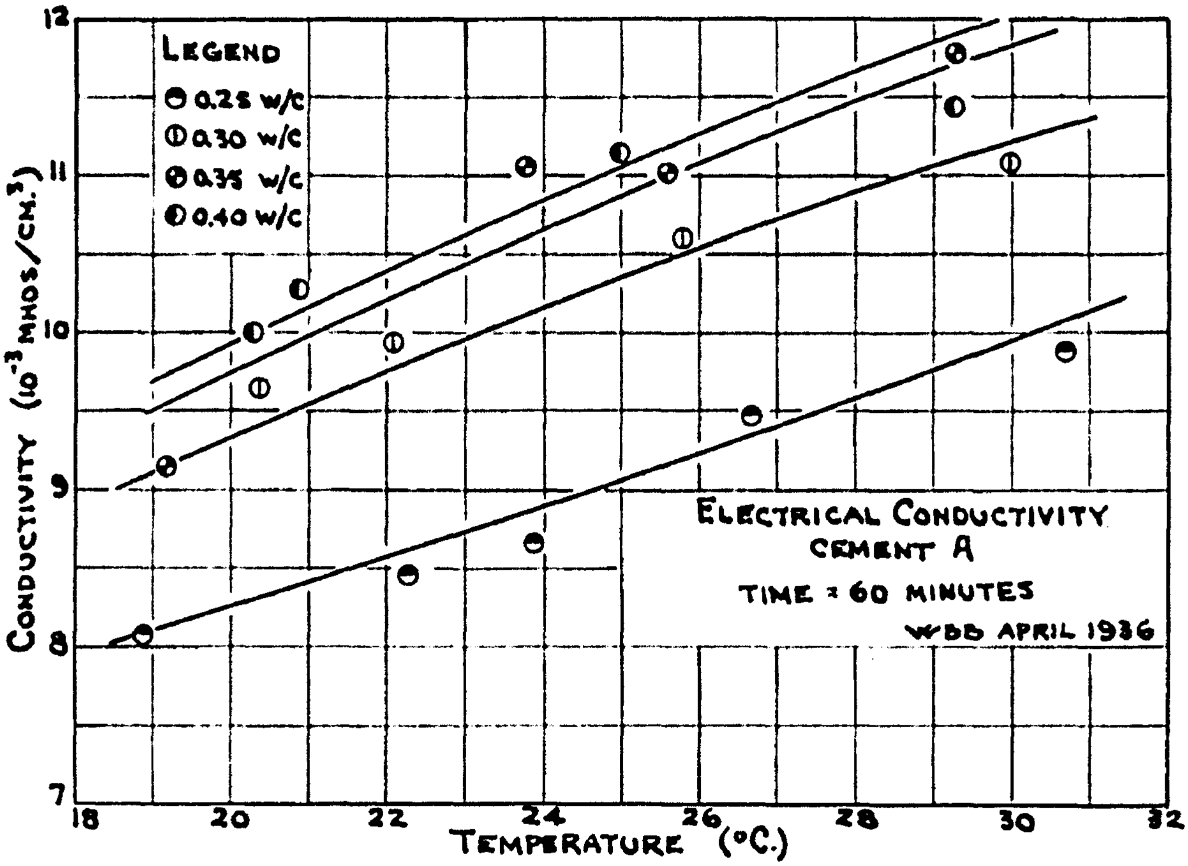


Figures 12 g & h

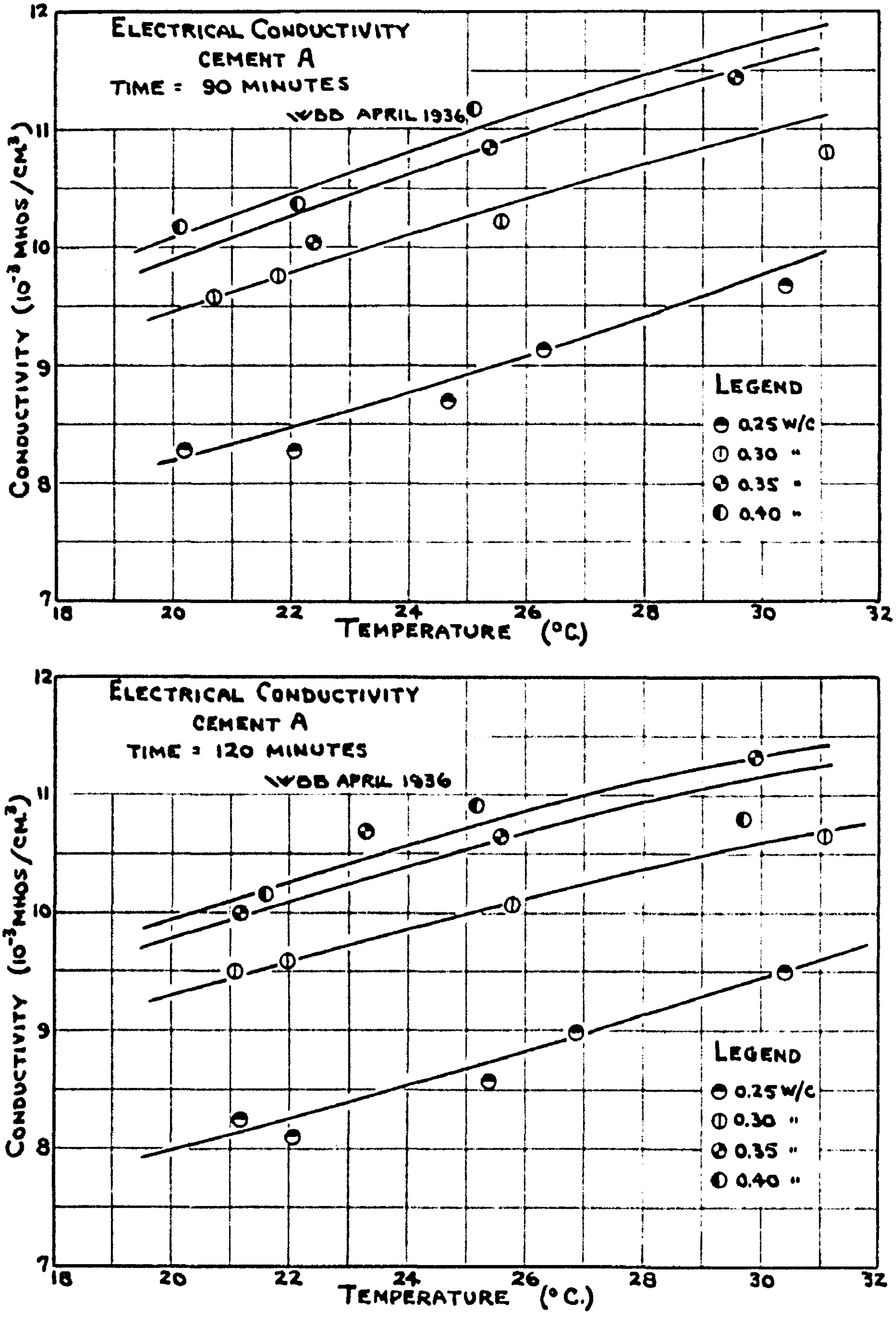


Figures 12 i & j

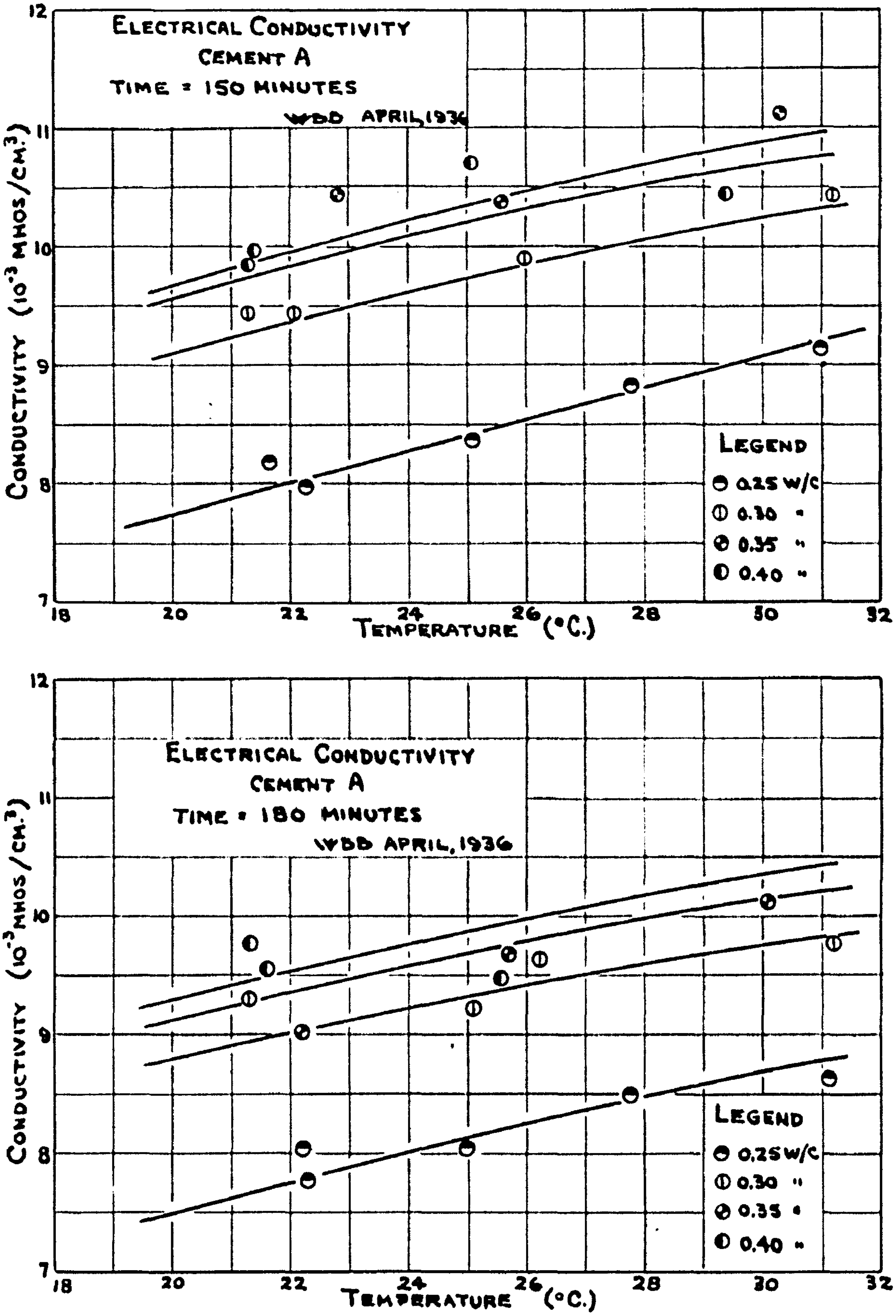




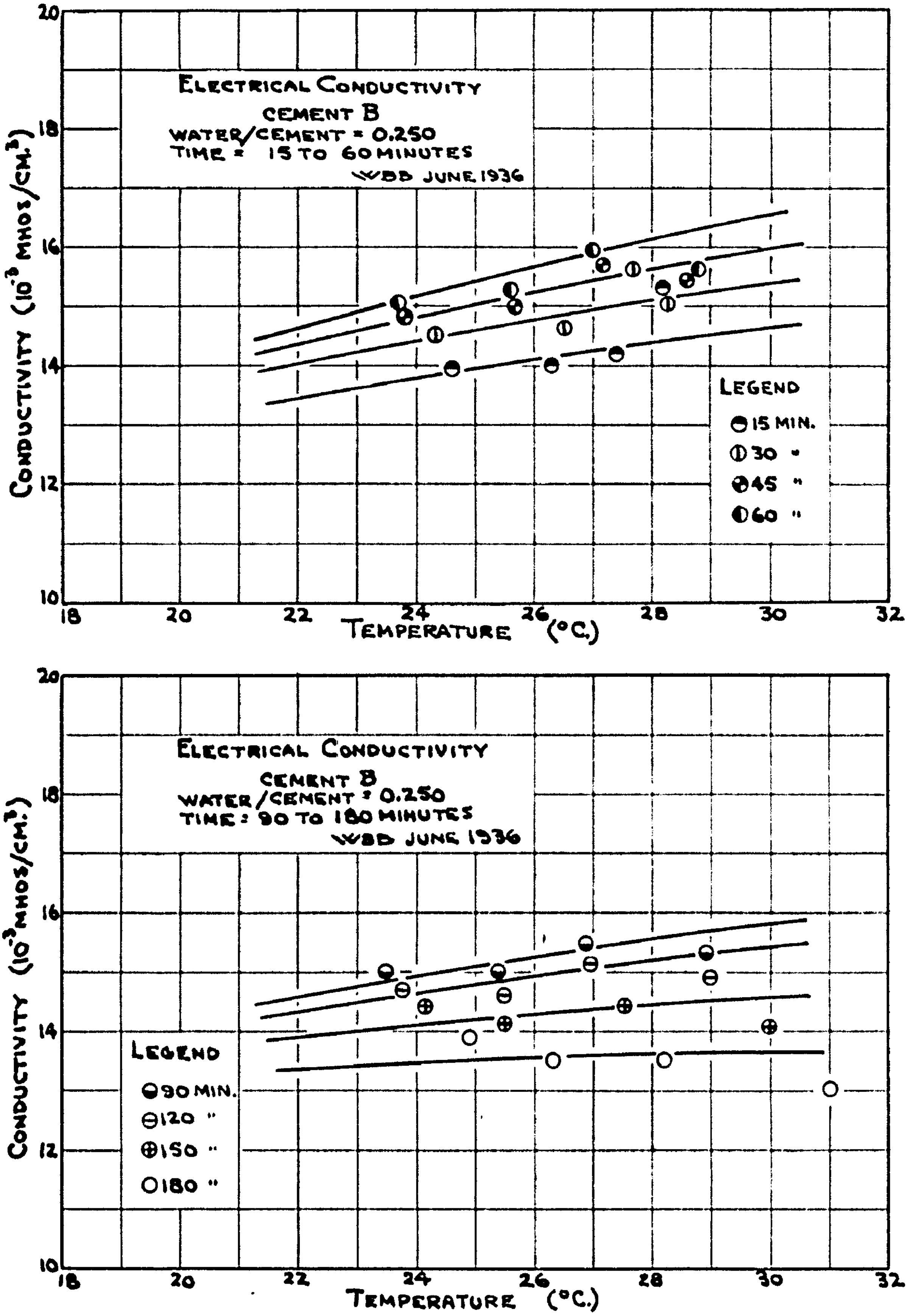
Figures 12 k & 1



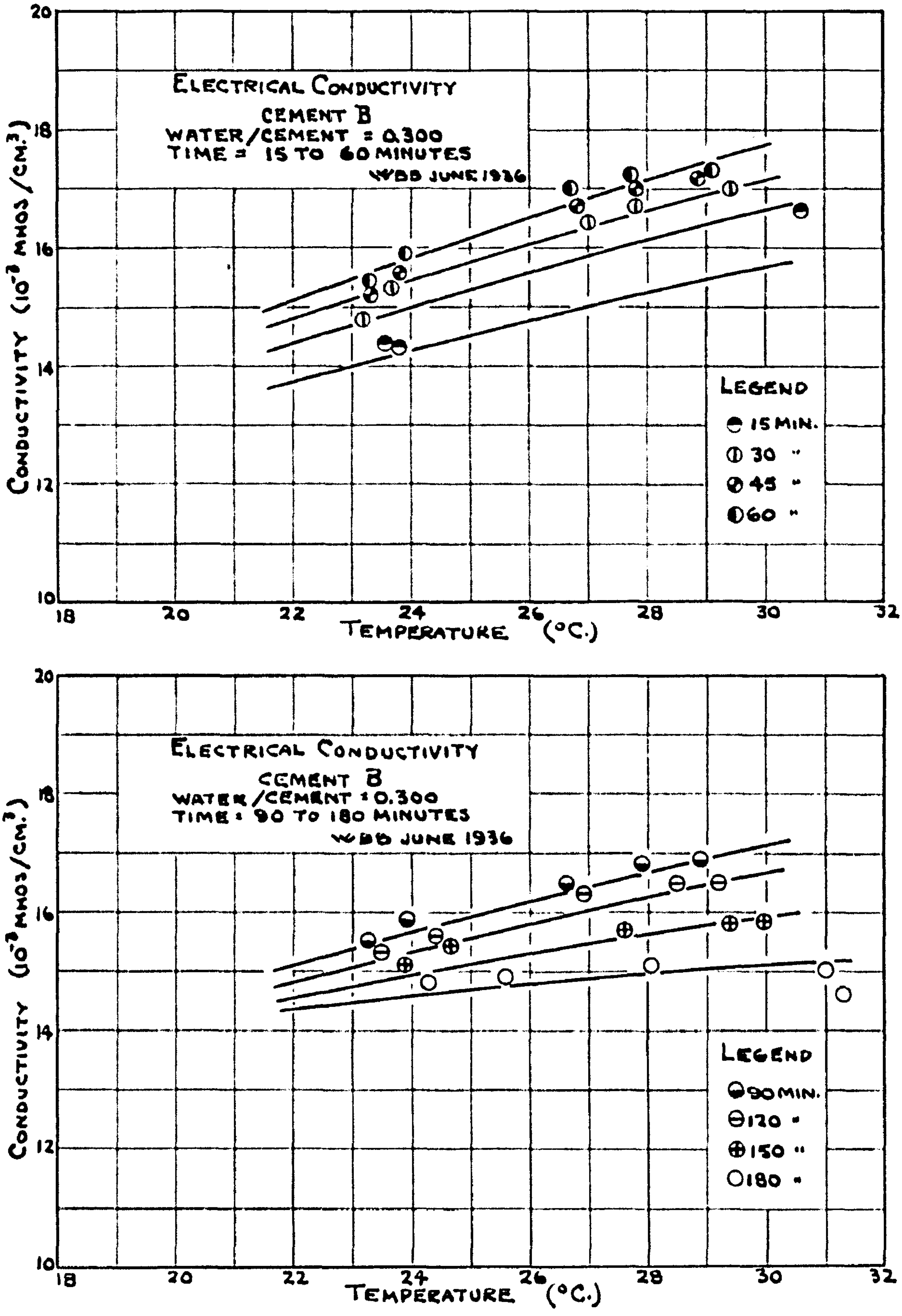
Figures 12 m & n



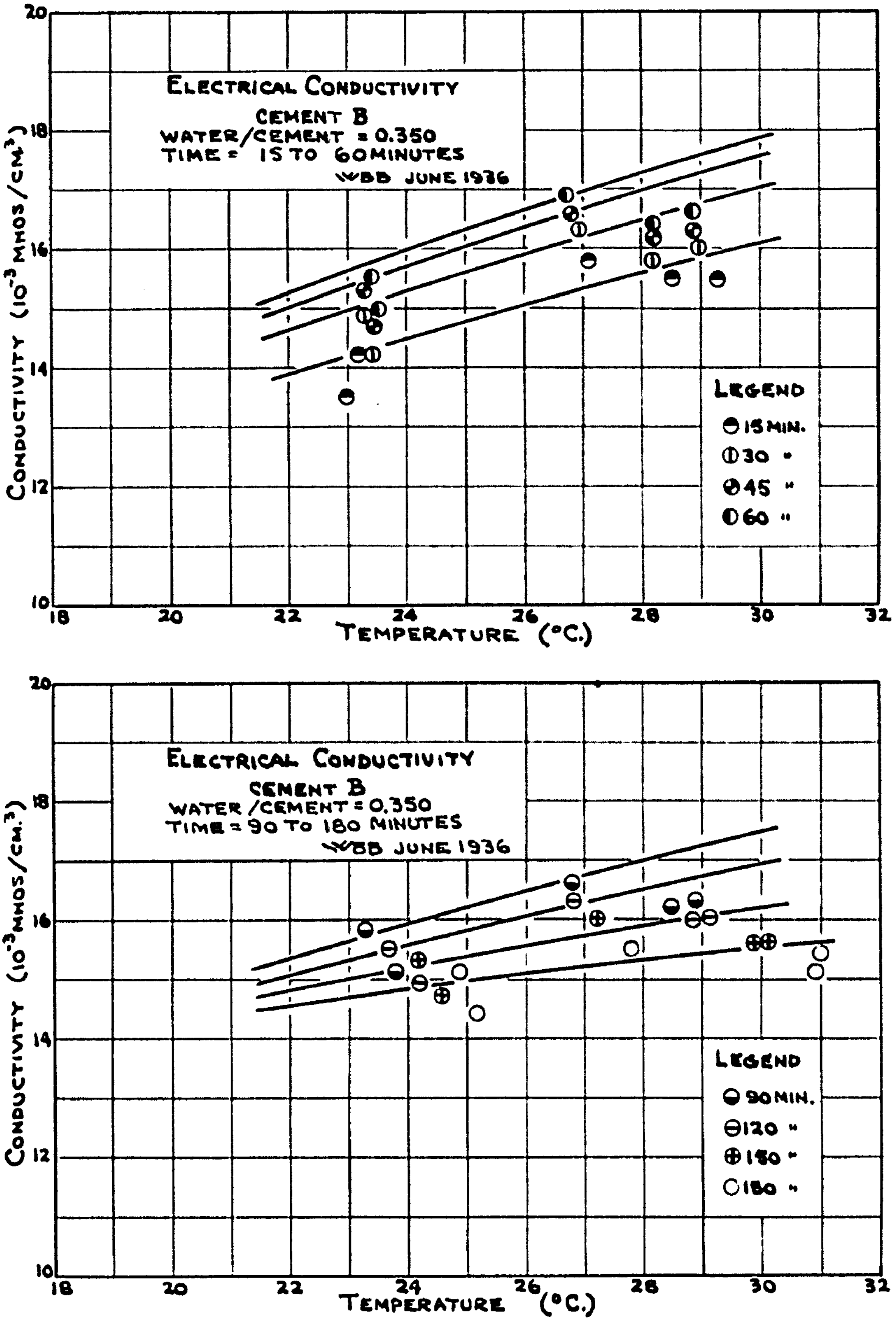
Figures 12 o & p



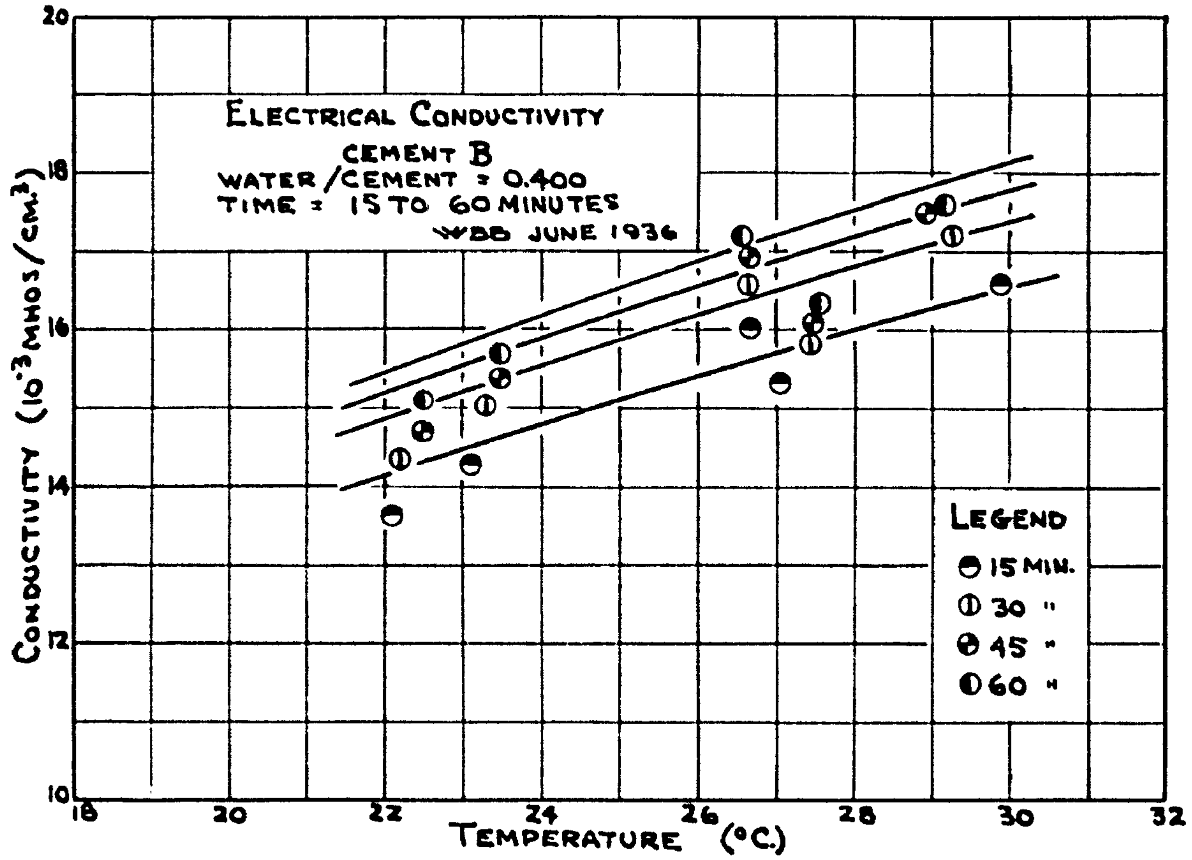
Figures 13 a & b

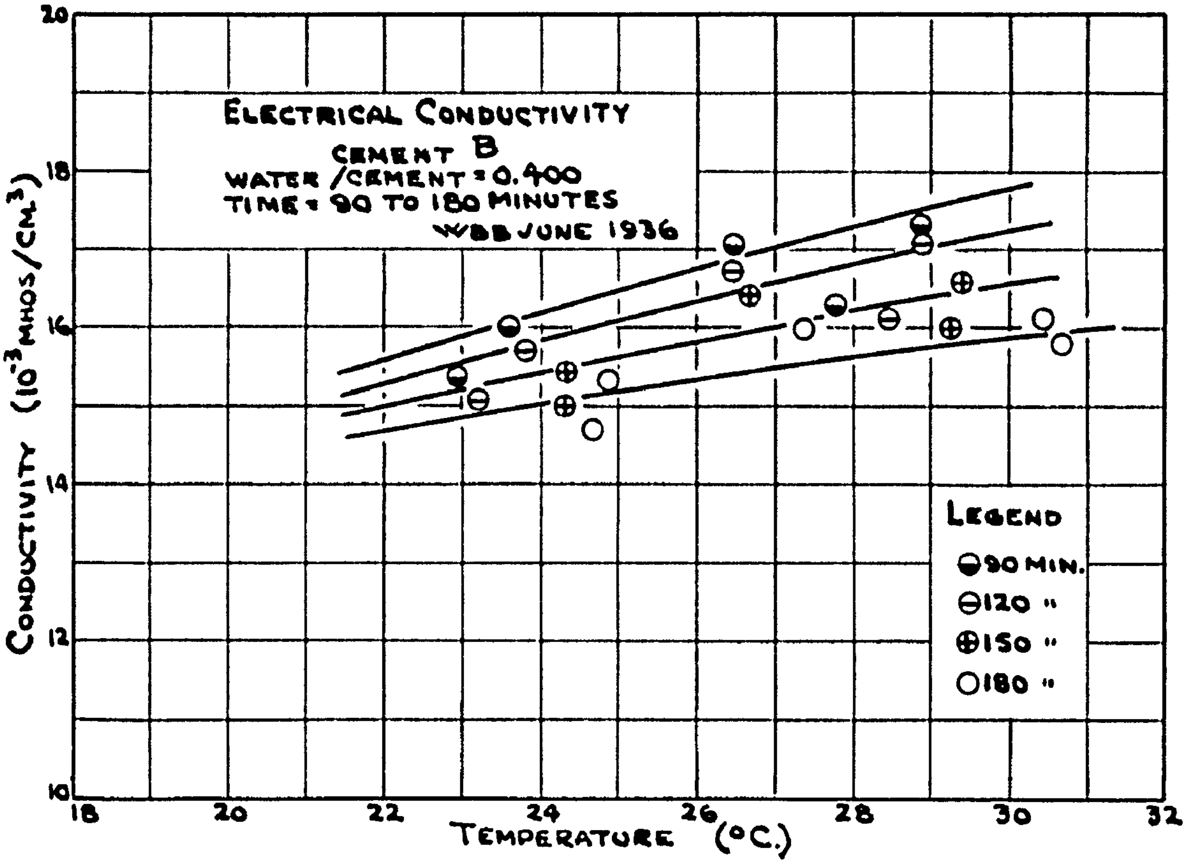


Figures 13 c & d

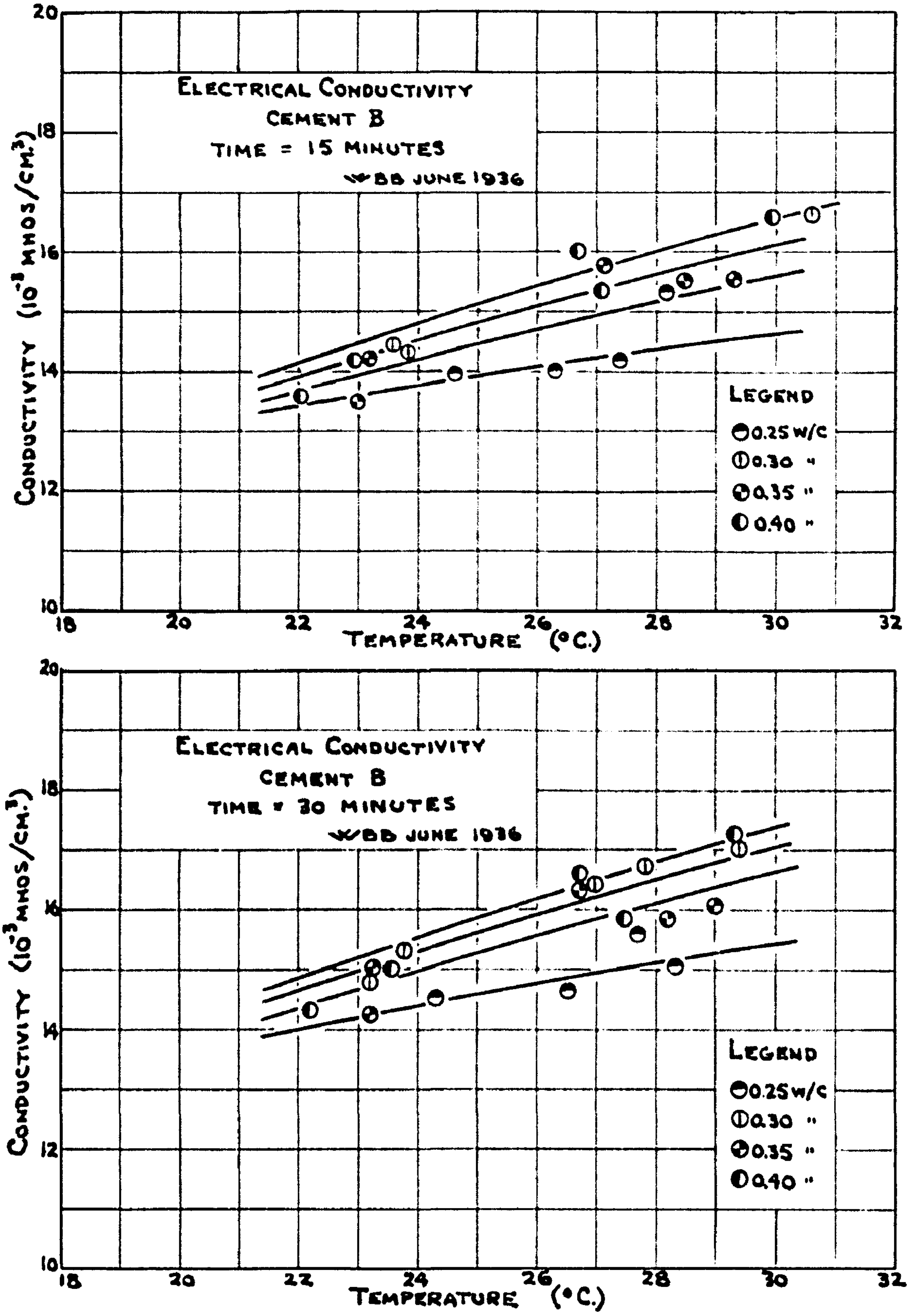


Figures 13 e & f

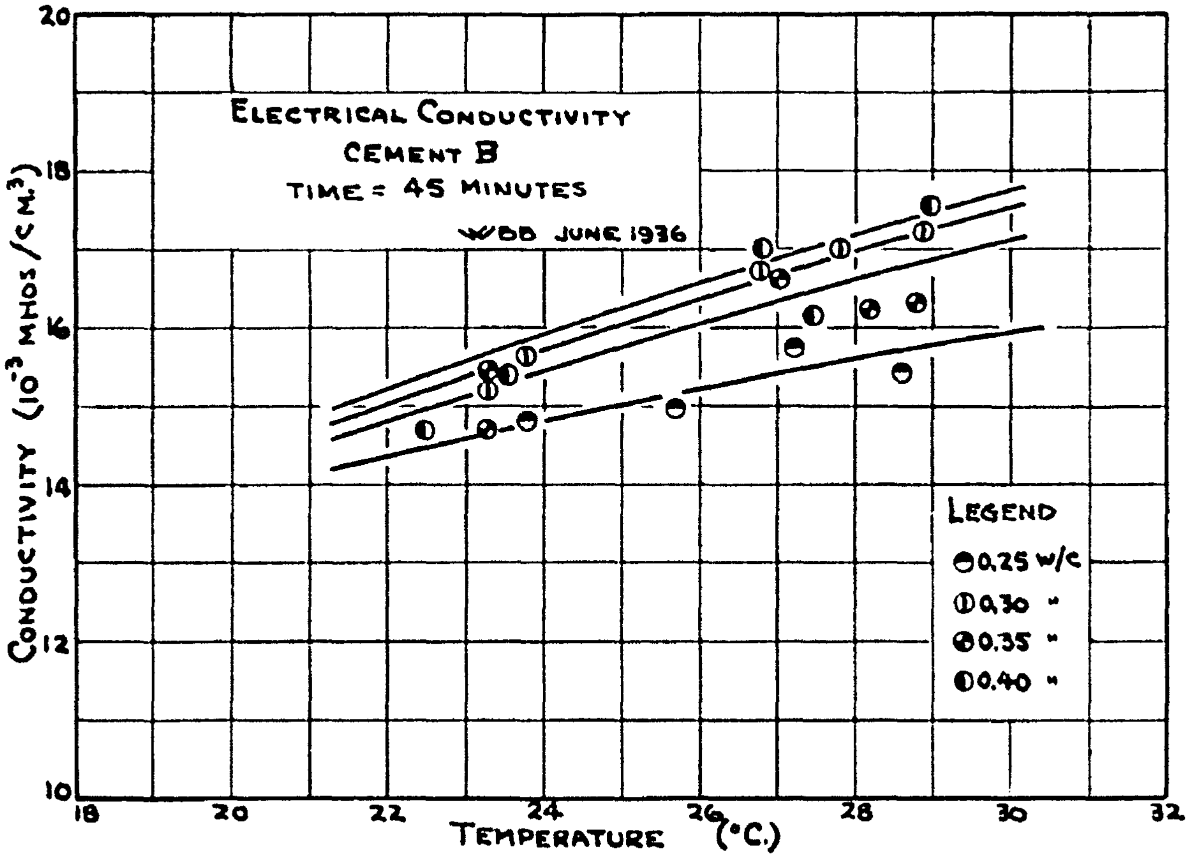


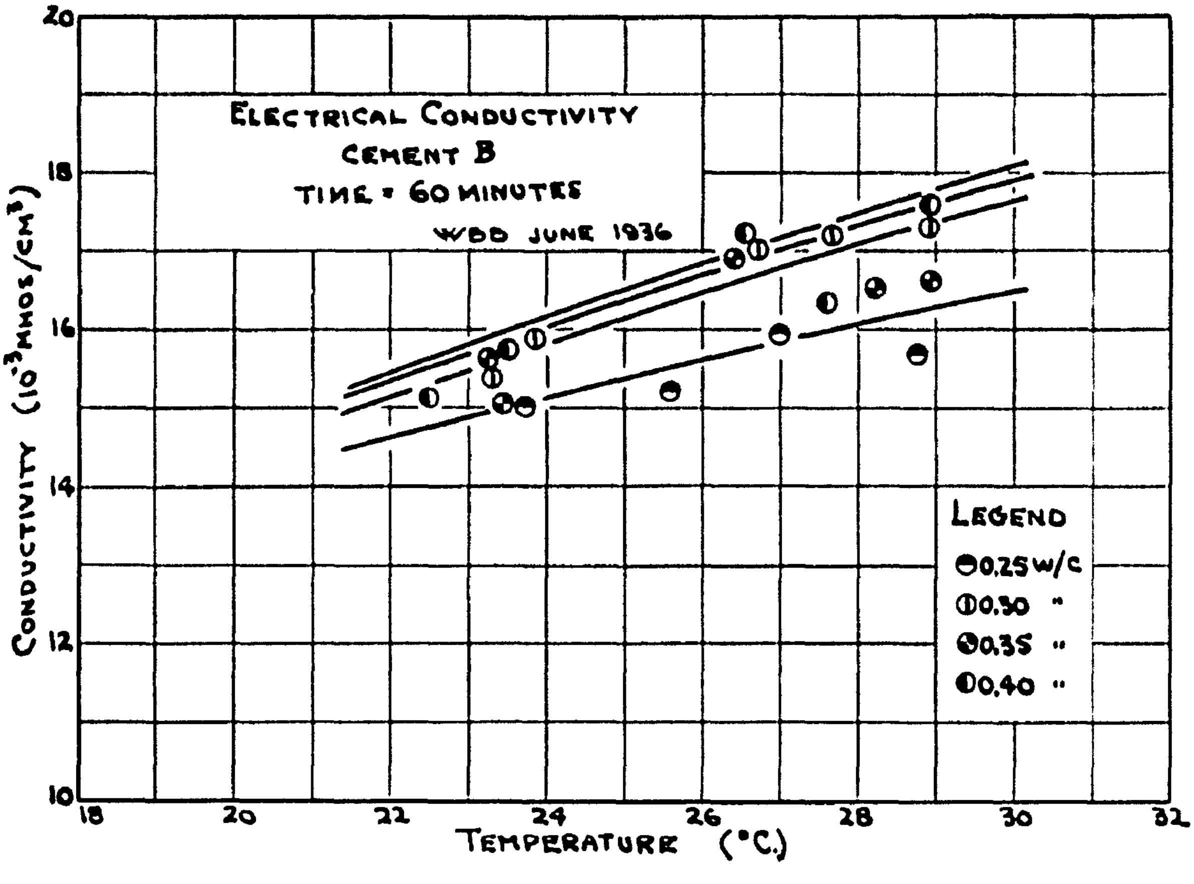


Figures 13 g & h

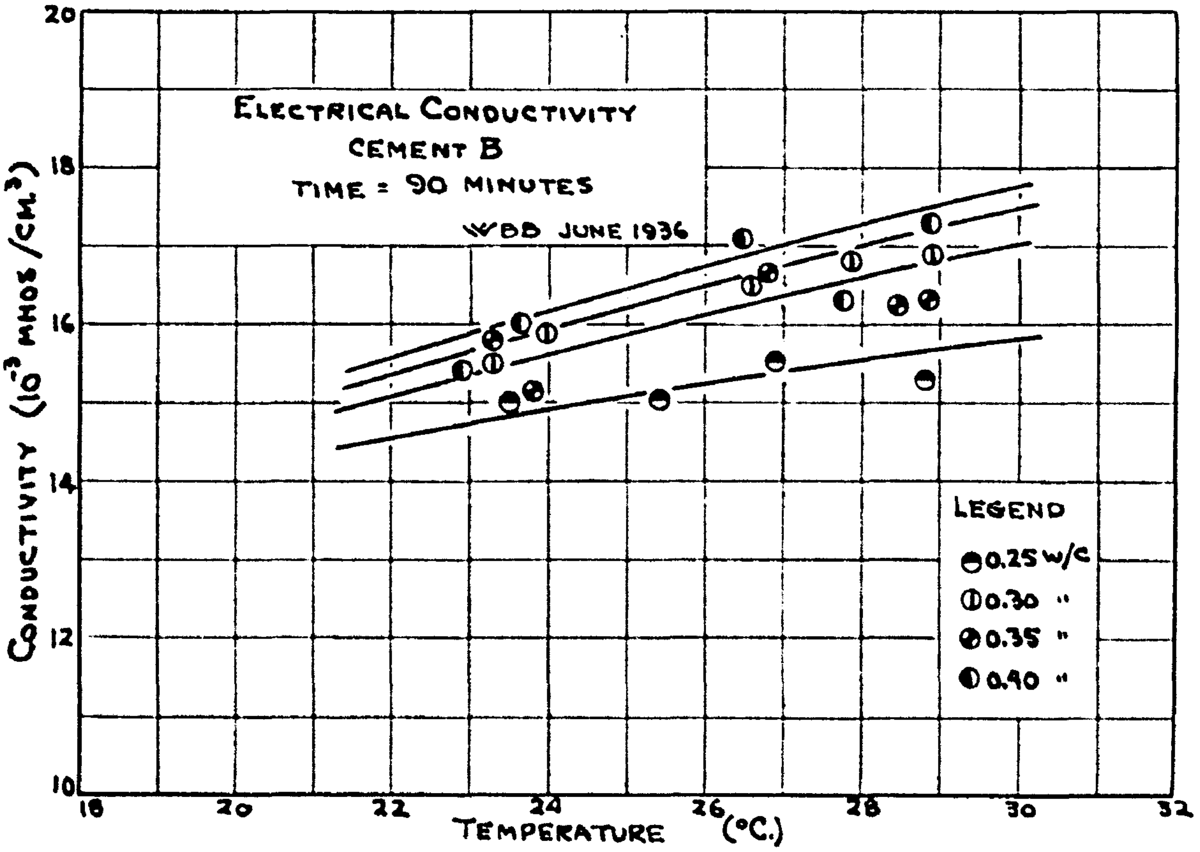


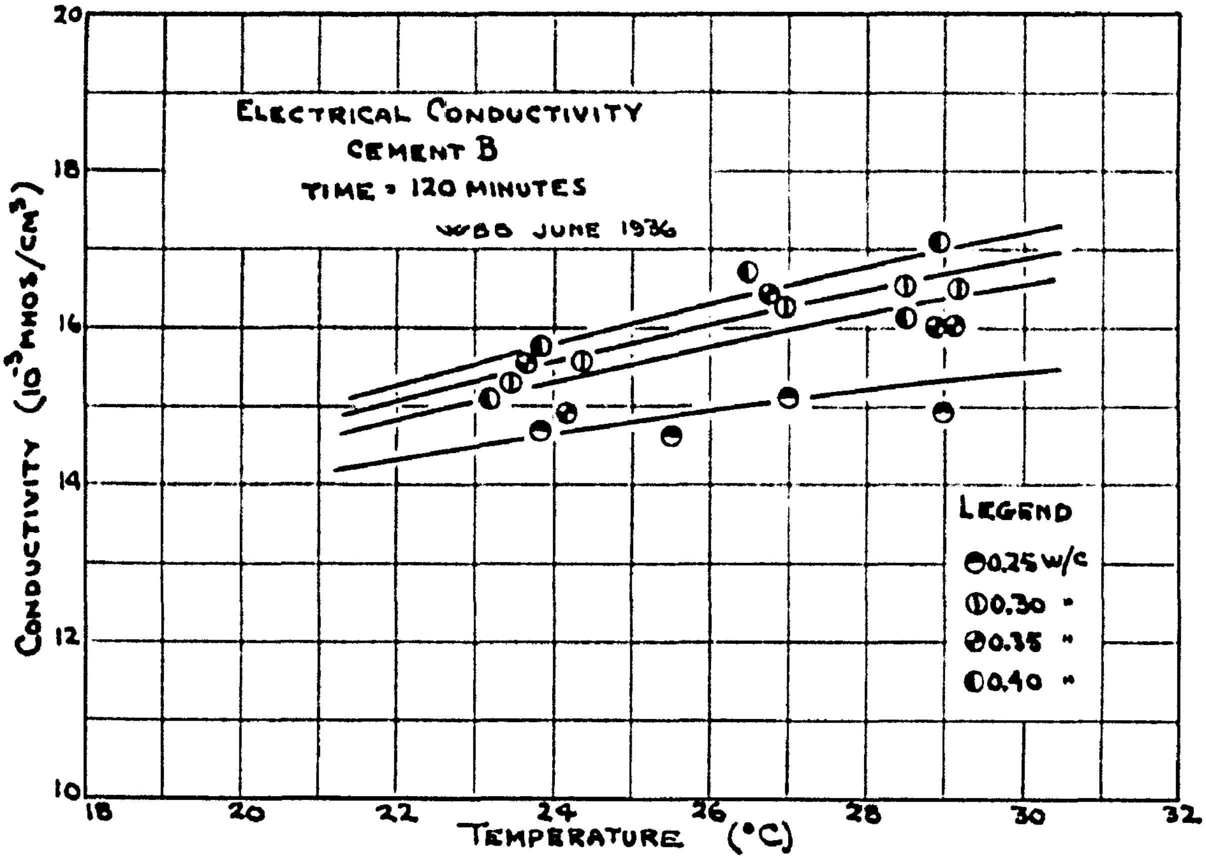
Figures 13 i & j





Figures 13 k & l





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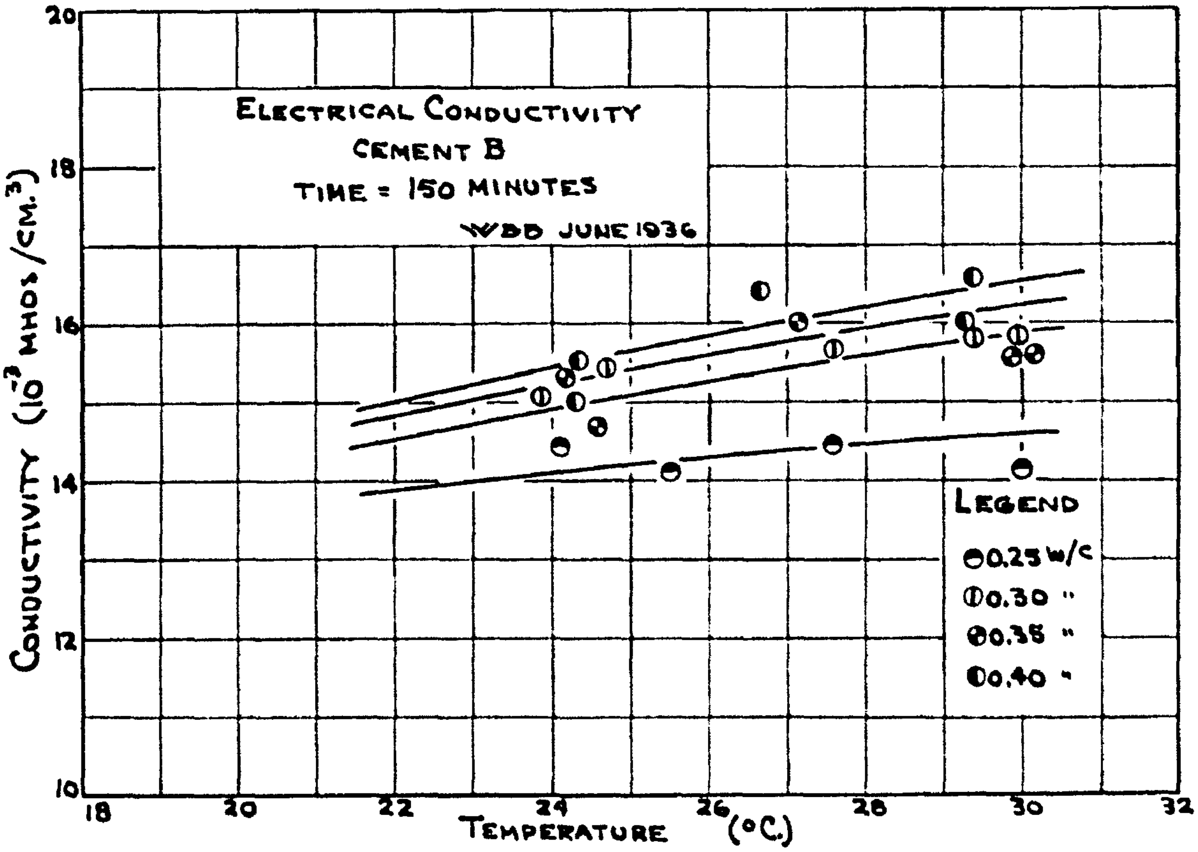
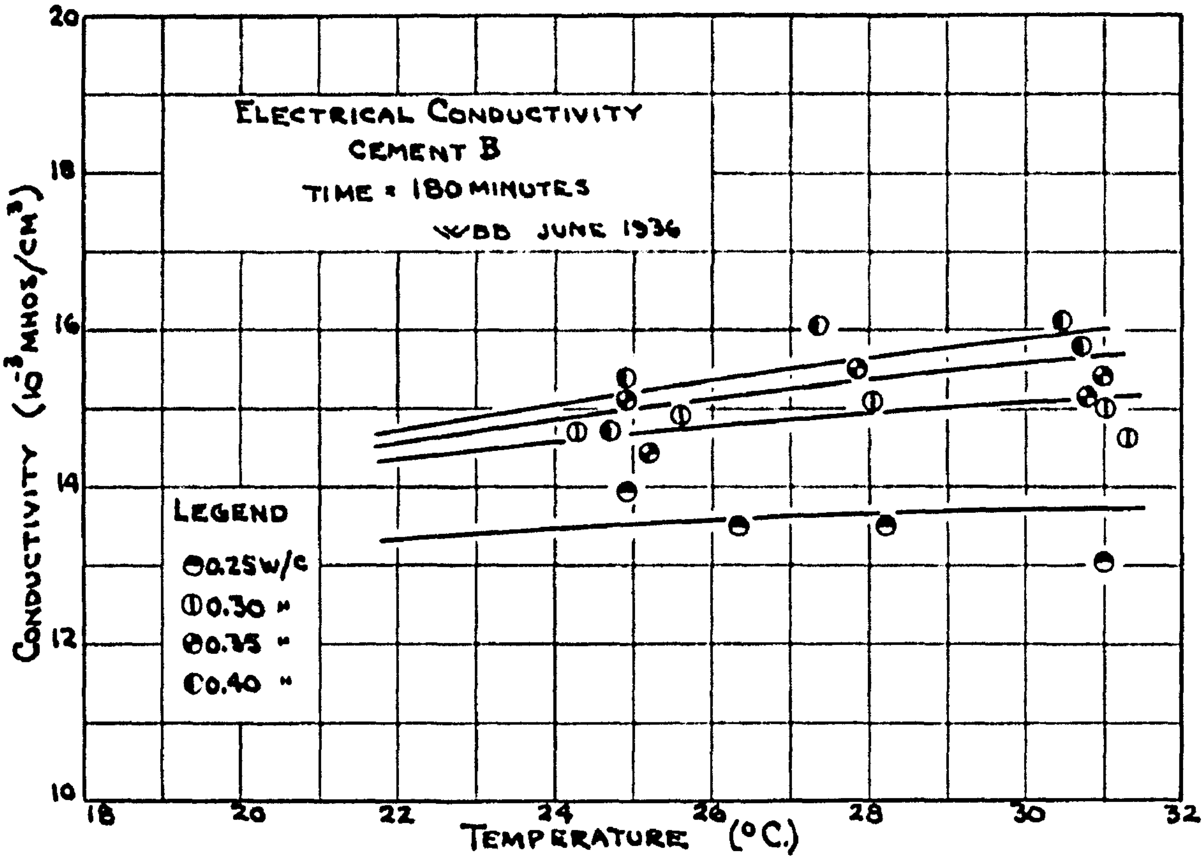
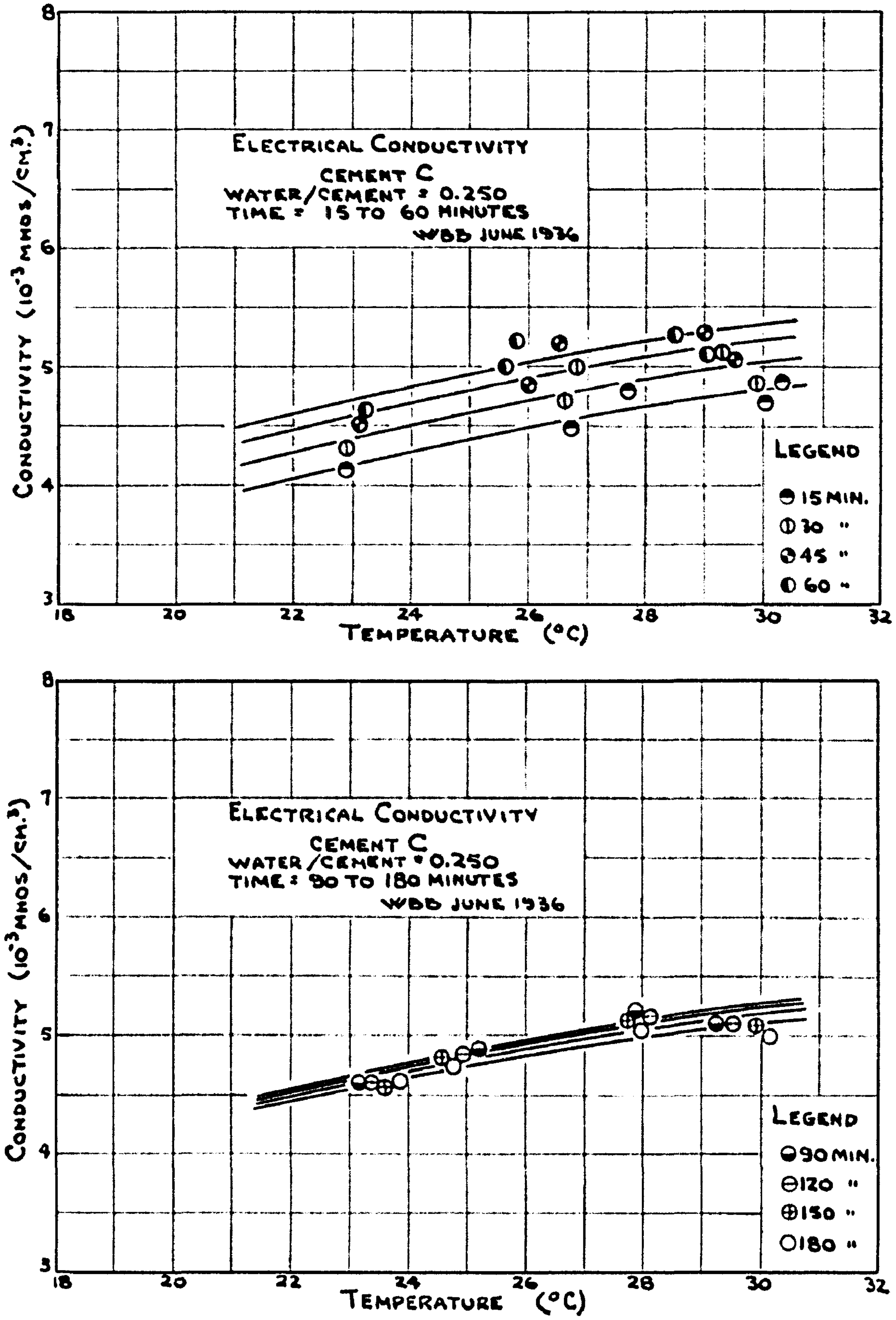
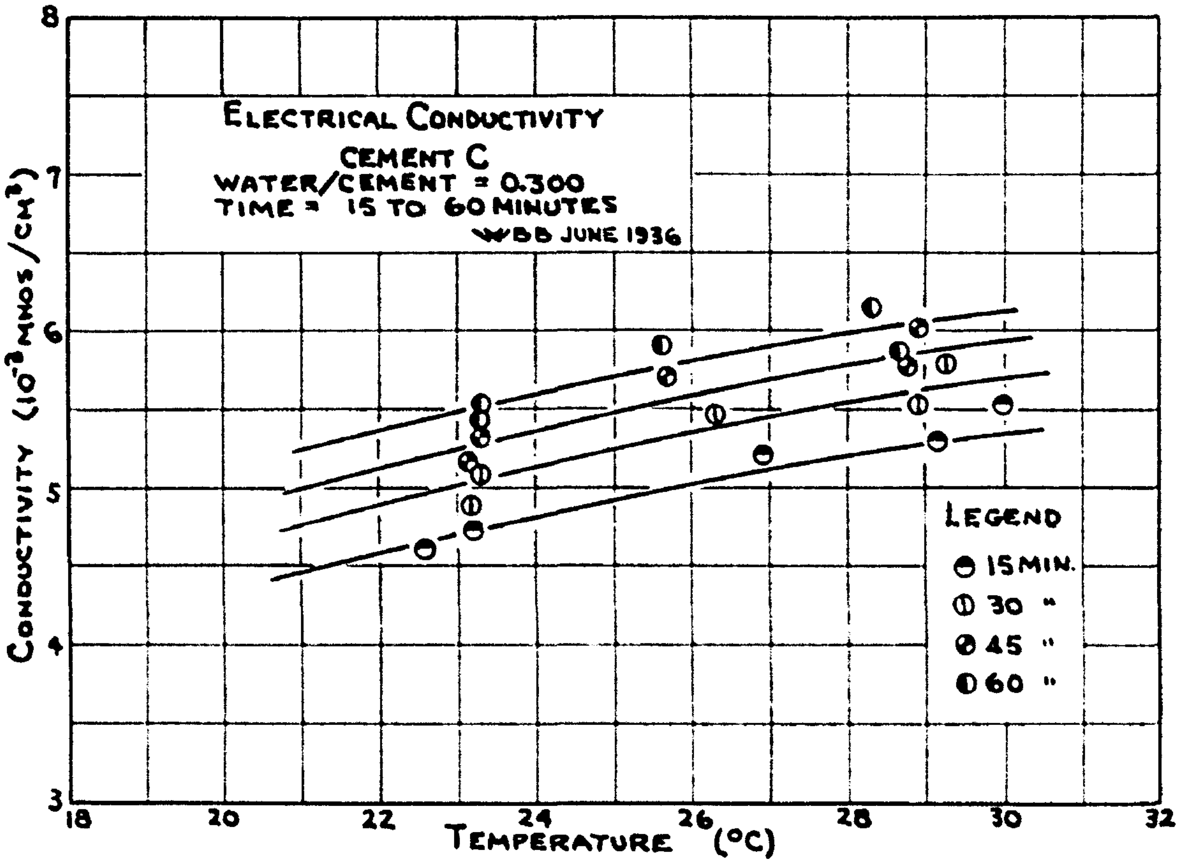


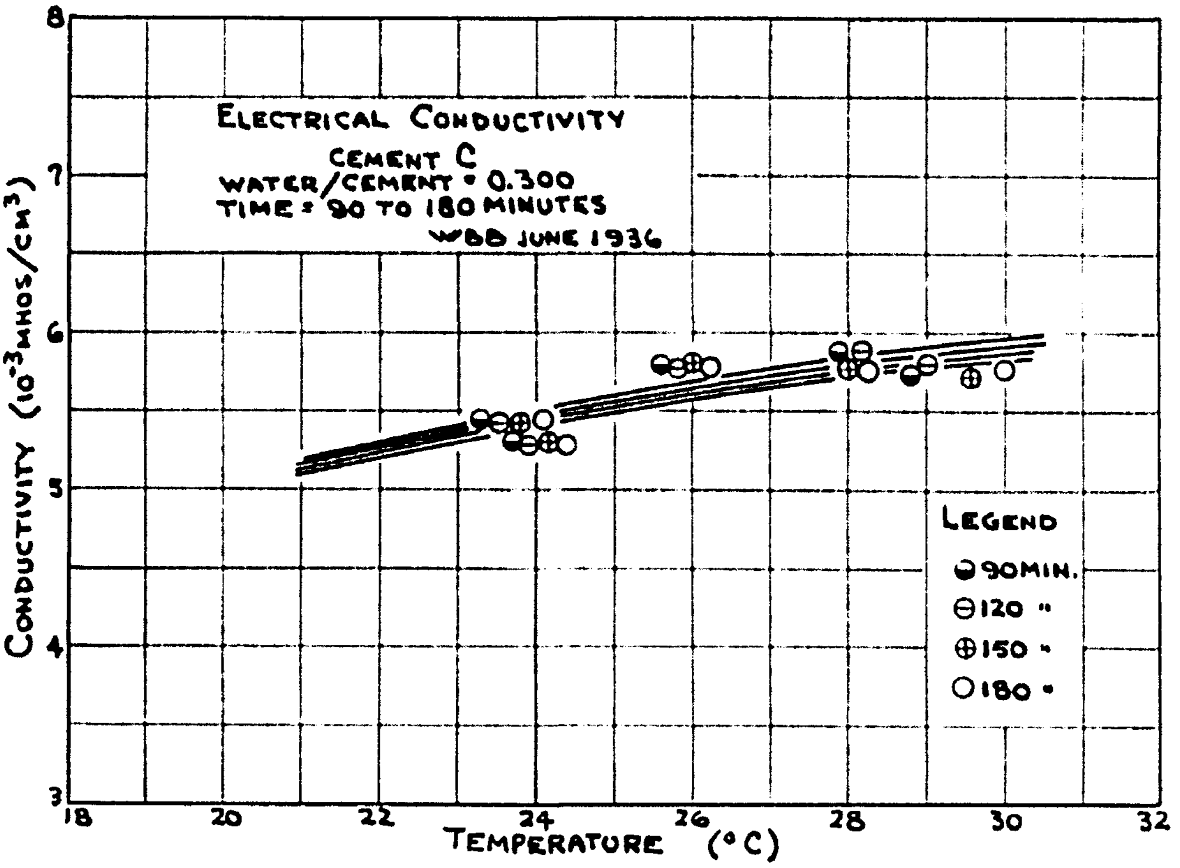


Figures 13 o & p

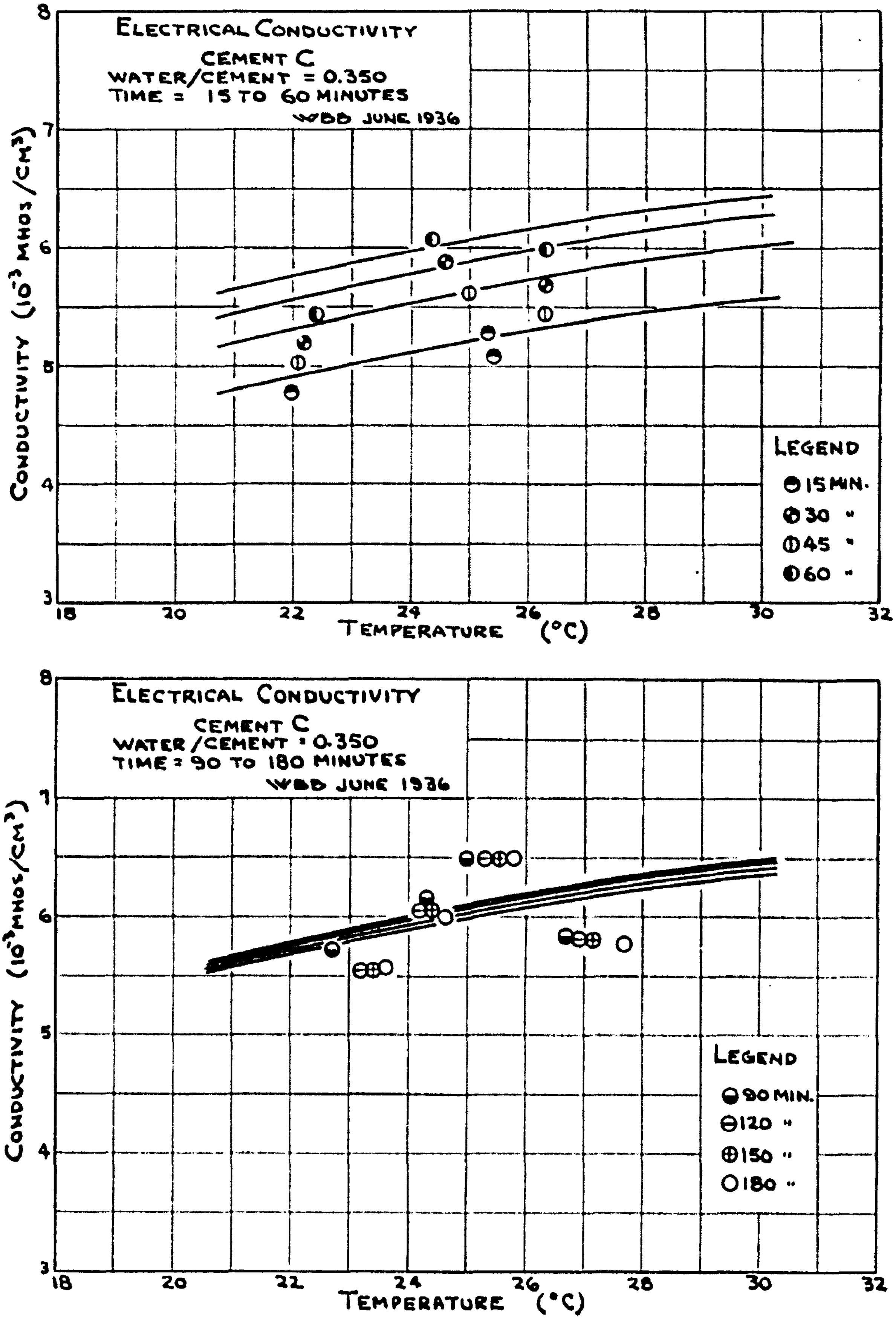


Figures 14 a & b

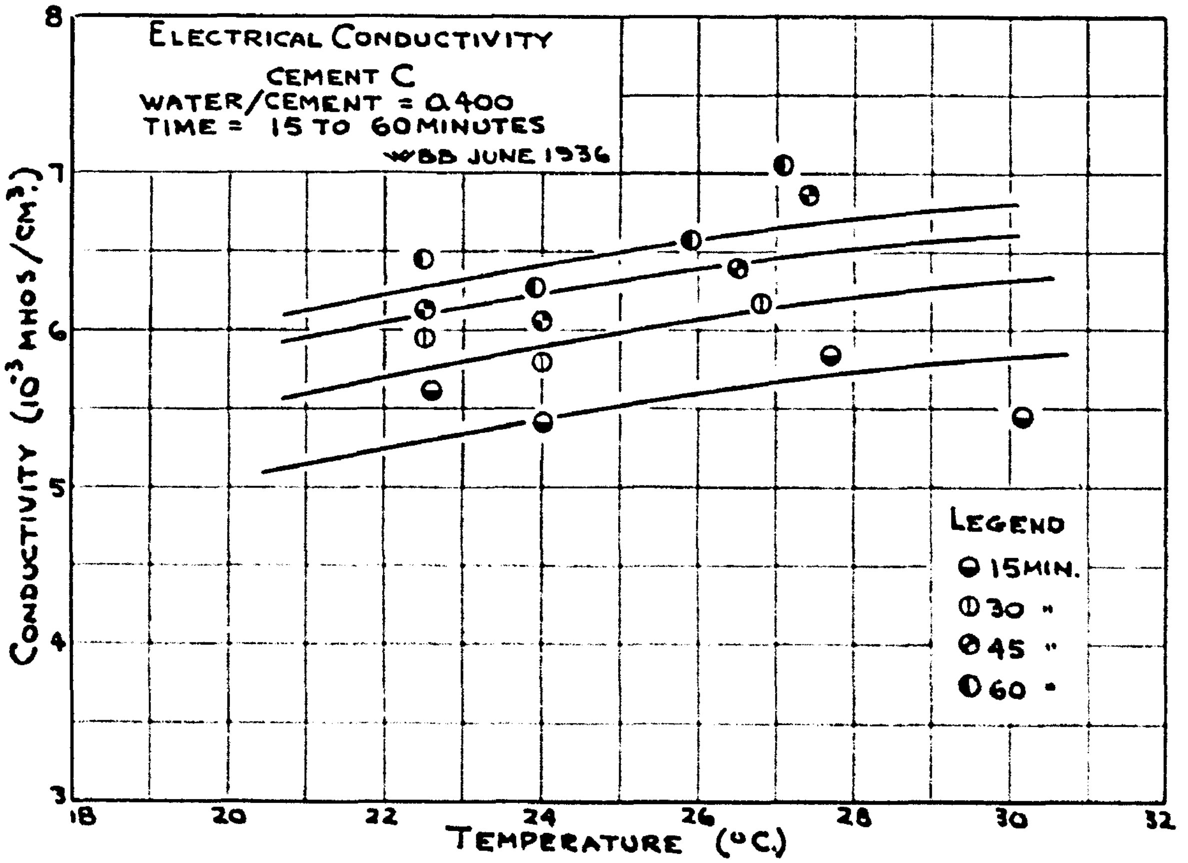


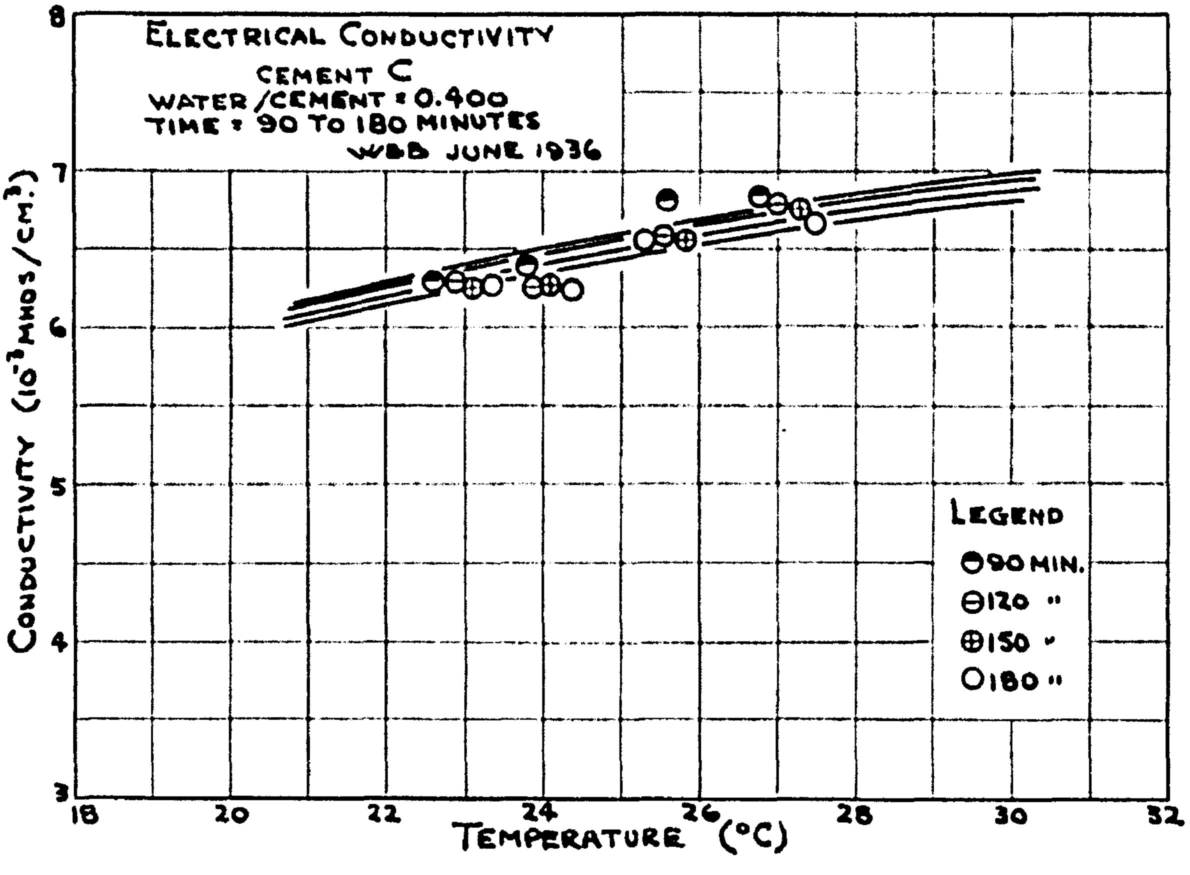


Figures 14 c & d

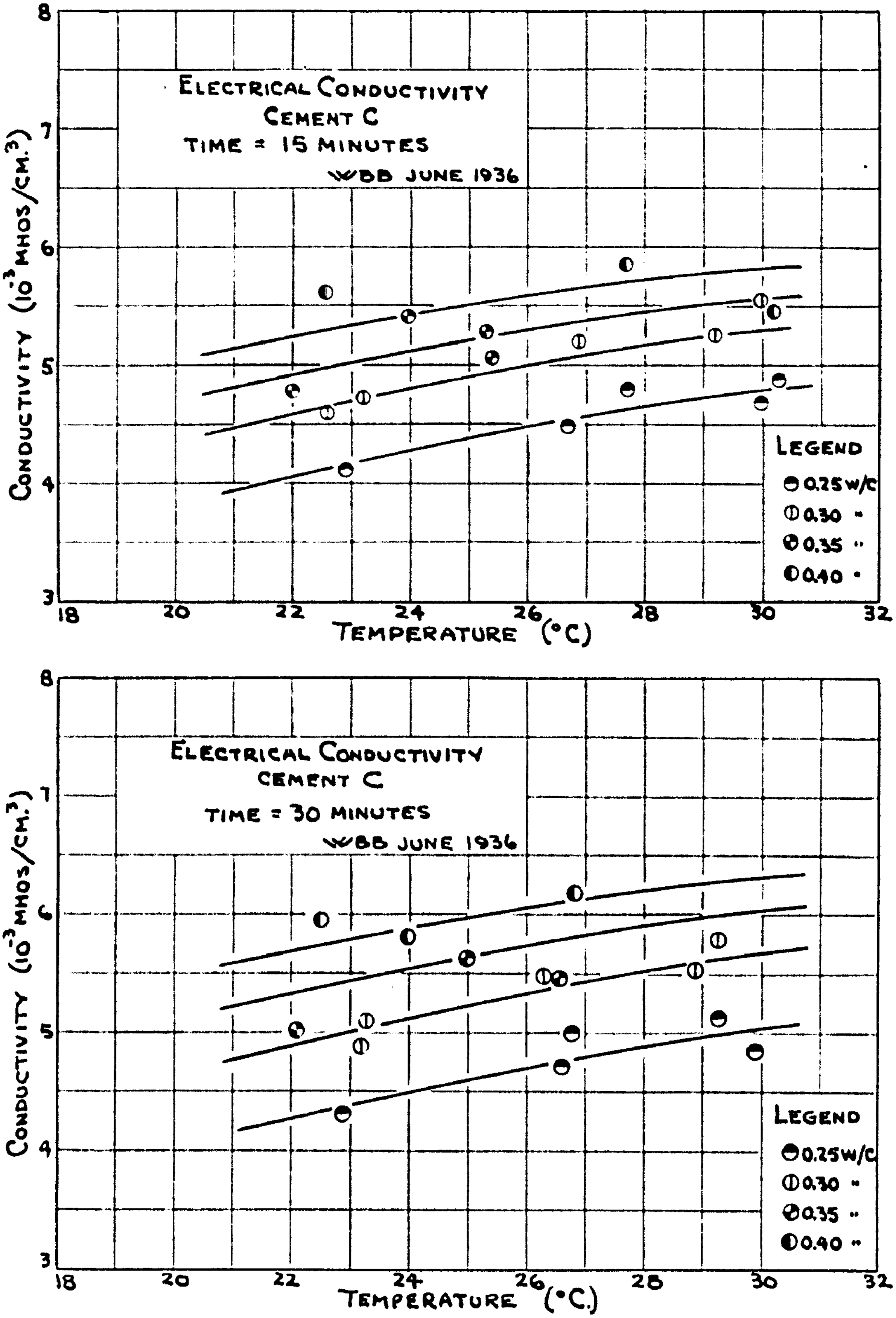


Figures 14 e & f

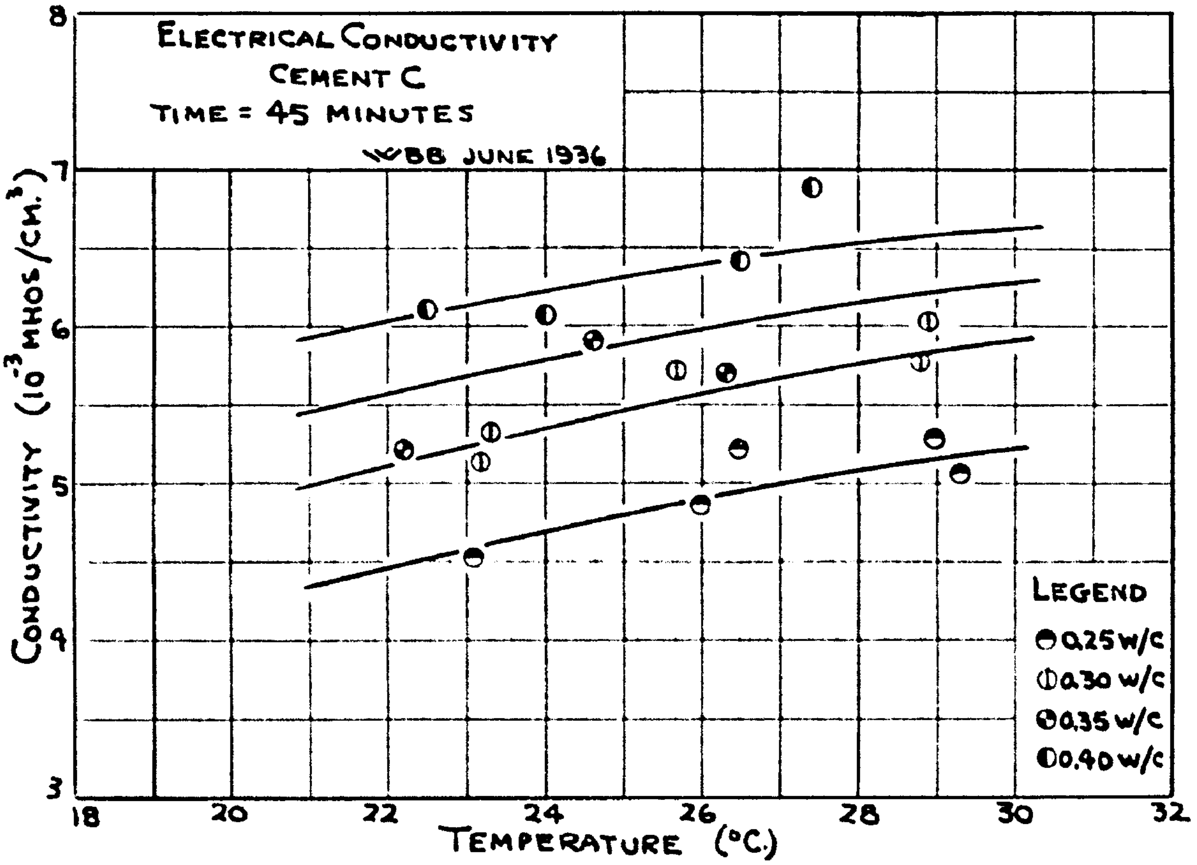


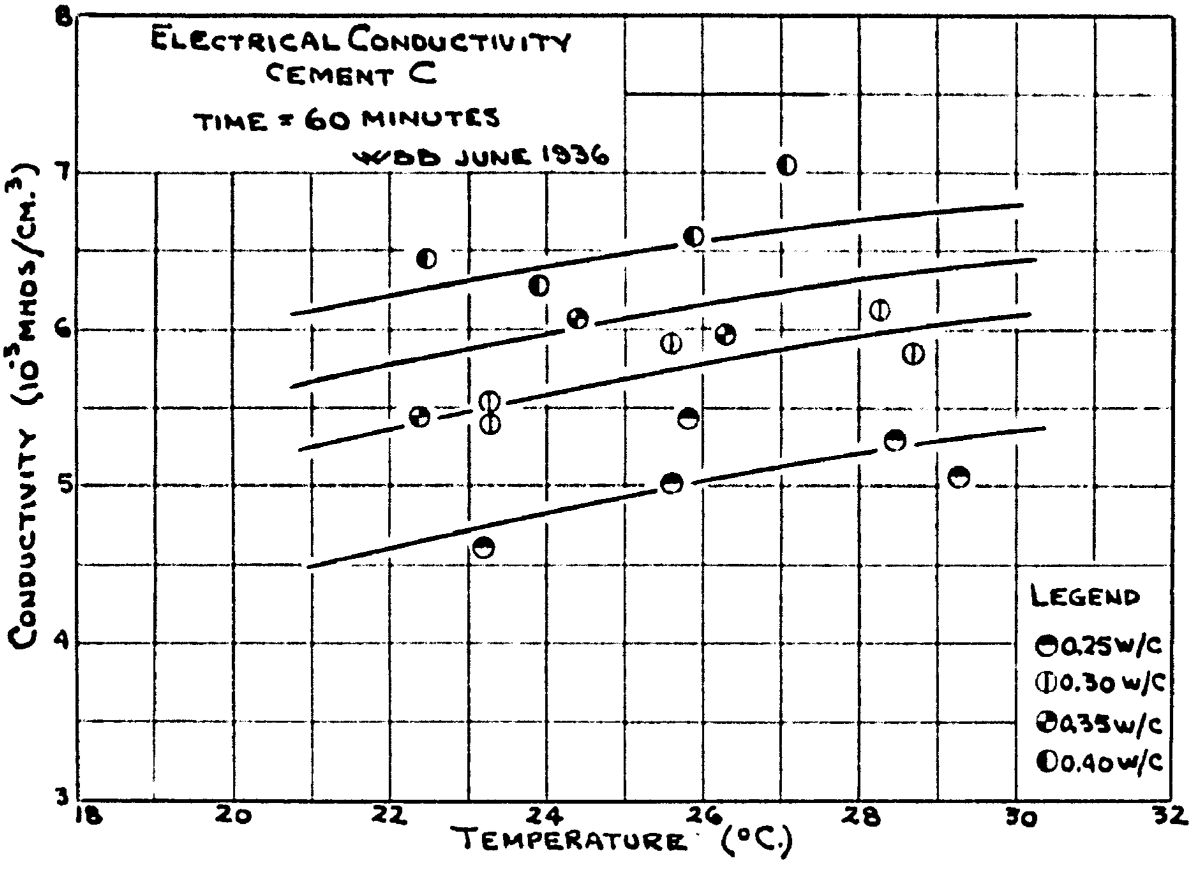


Figures 14 g & h

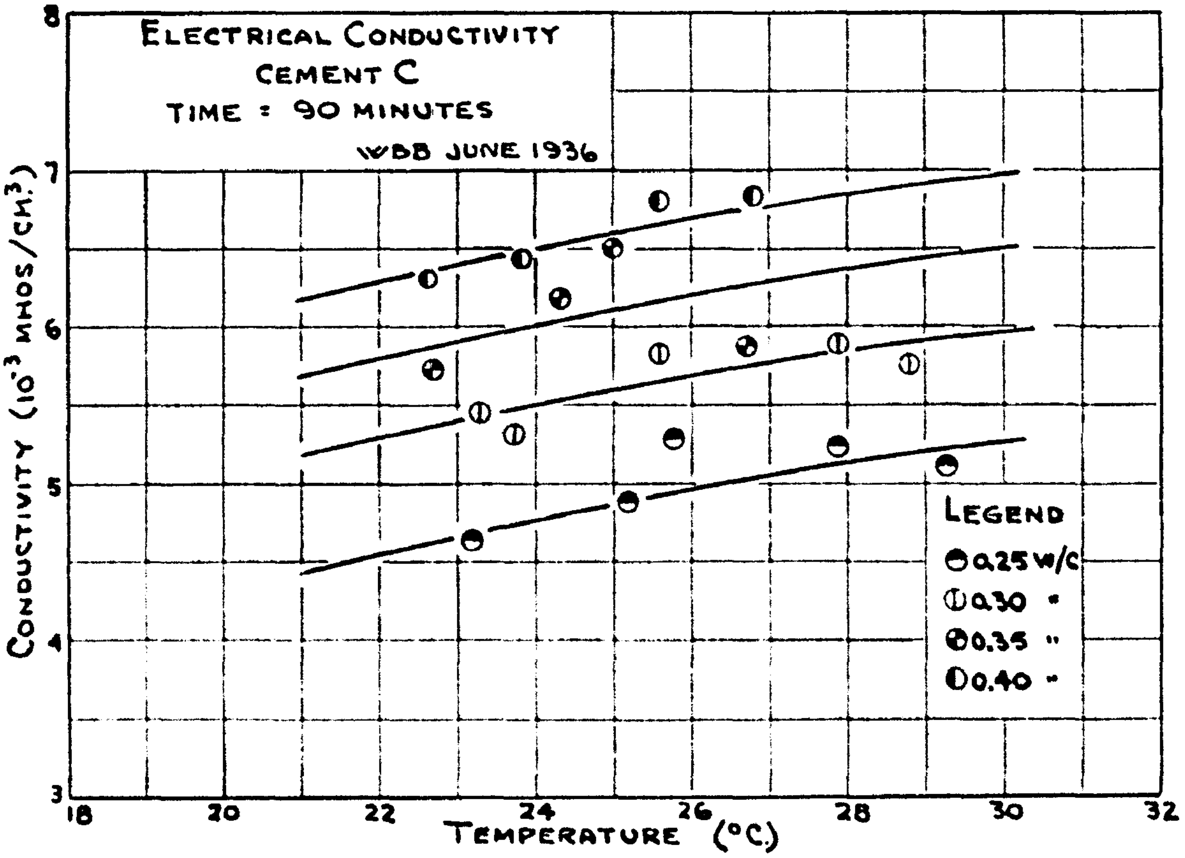


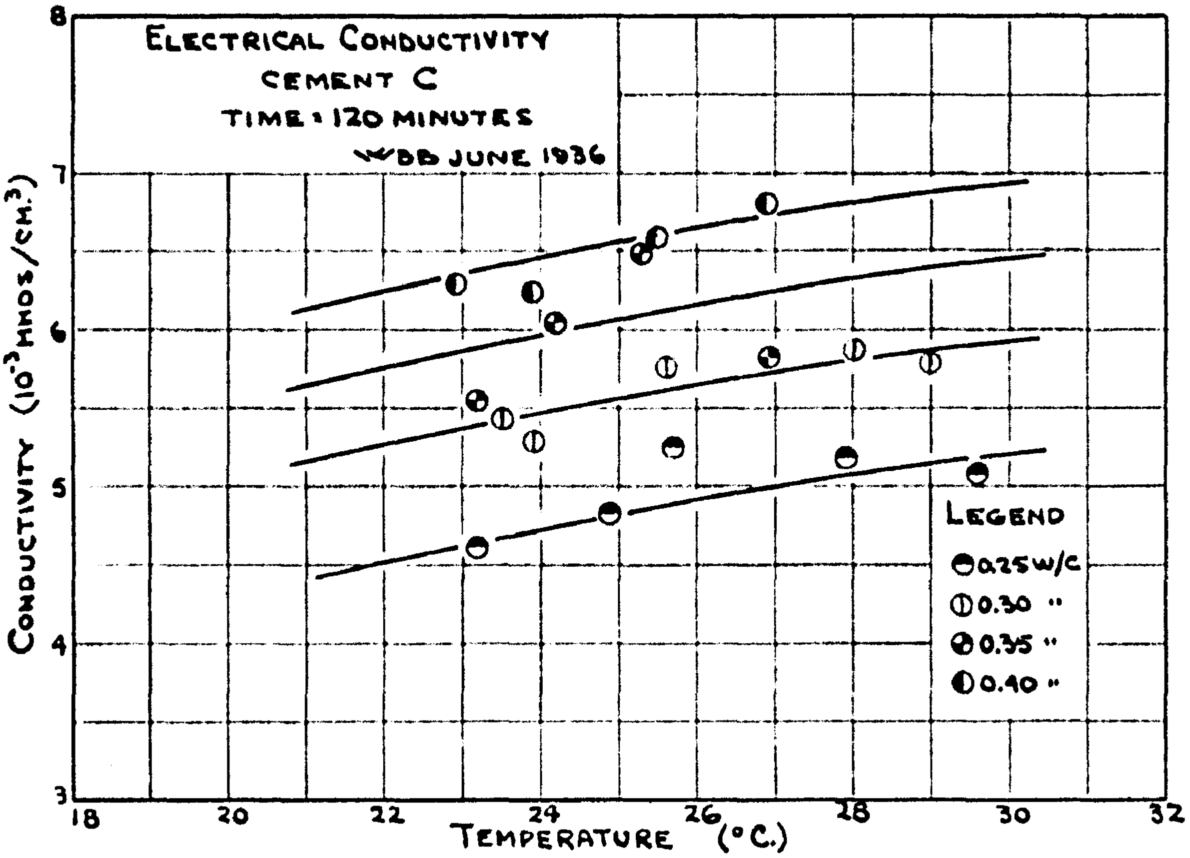
Figures 14 i & j



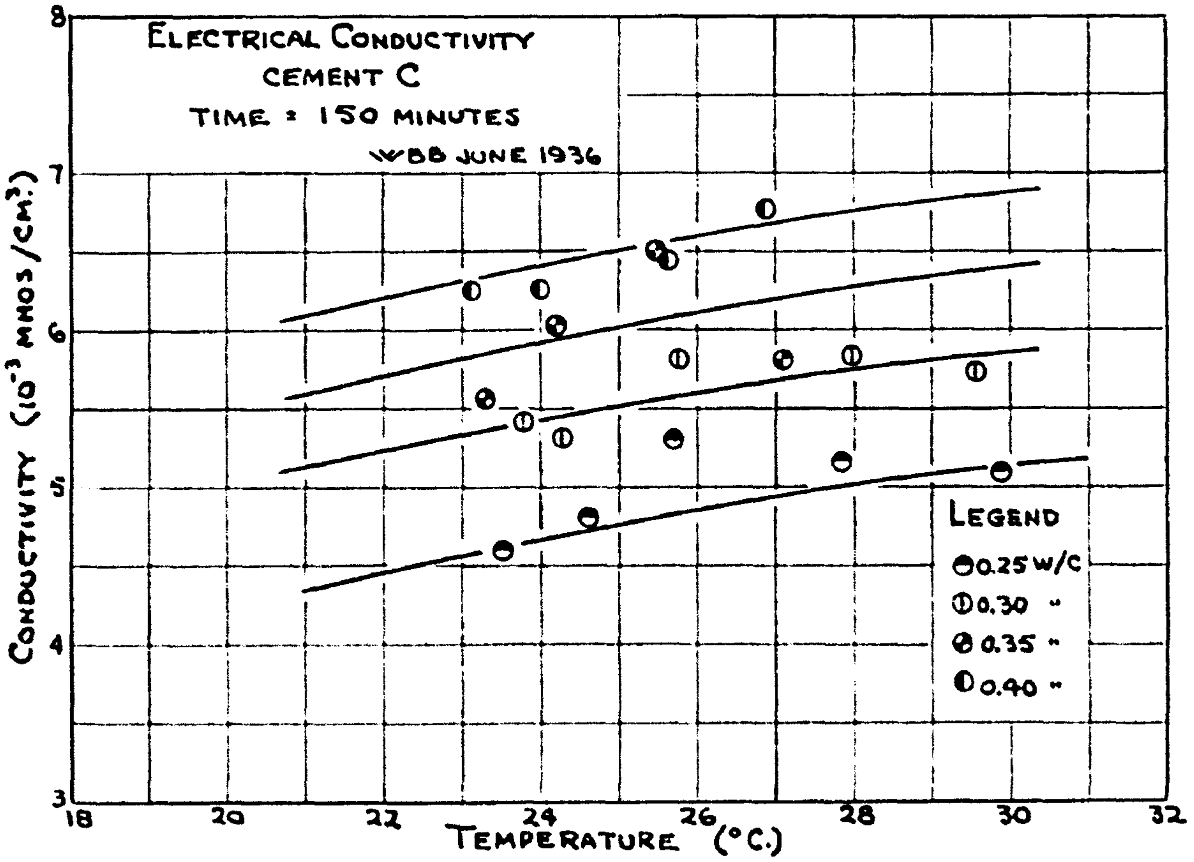


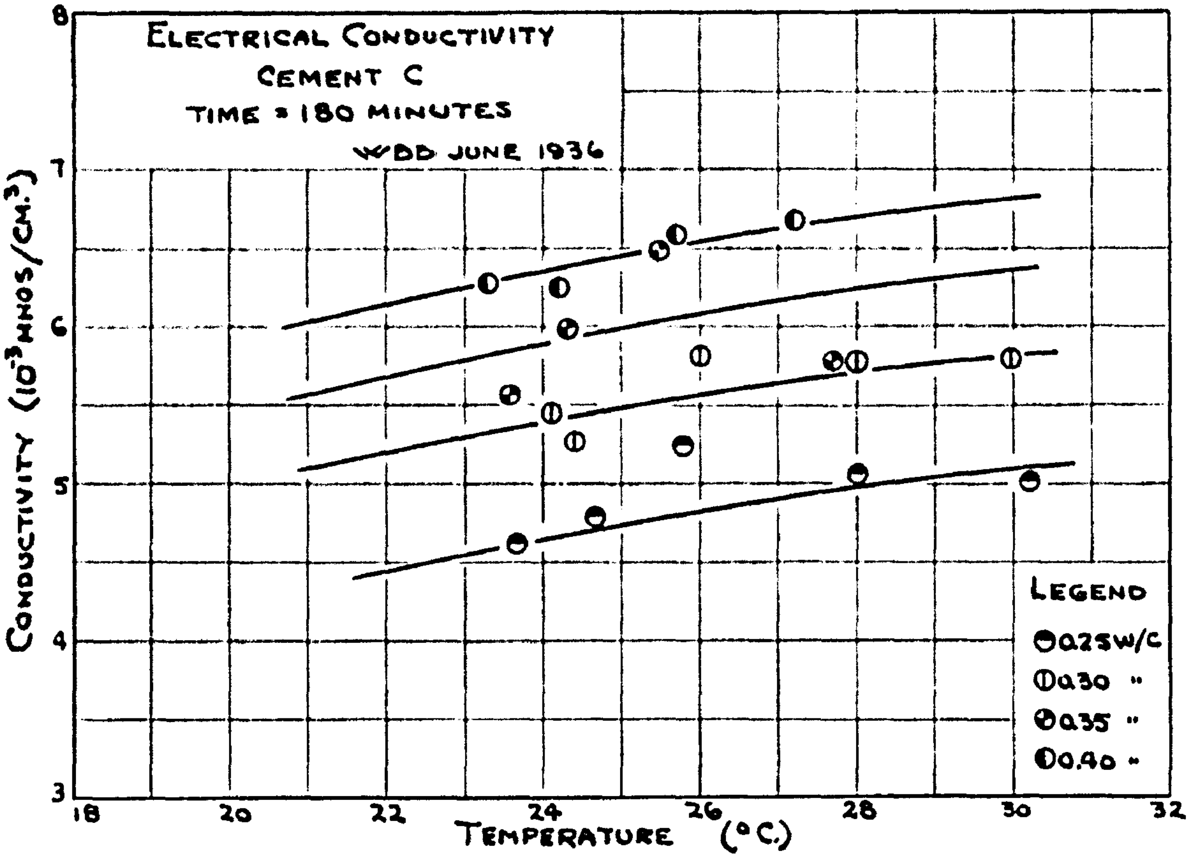
Figures 14 k & l





Figures 14 m & n





Figures 14 o & p

INSTRUCTIONS FOR USE OF FIGURES 15, 16, and 17:

Enter at the water-cement ratio scale; proceed vertically to the desired temperature, interpolating if necessary. Then with this level fixed, proceed to the left to the other desired quantity, the time. Below this intersection will be found the desired conductivity corresponding to the three quantities (water-cement ratio, temperature, and time). The procedure may be reversed, starting at conductivity and proceeding to the water-cement ratio.

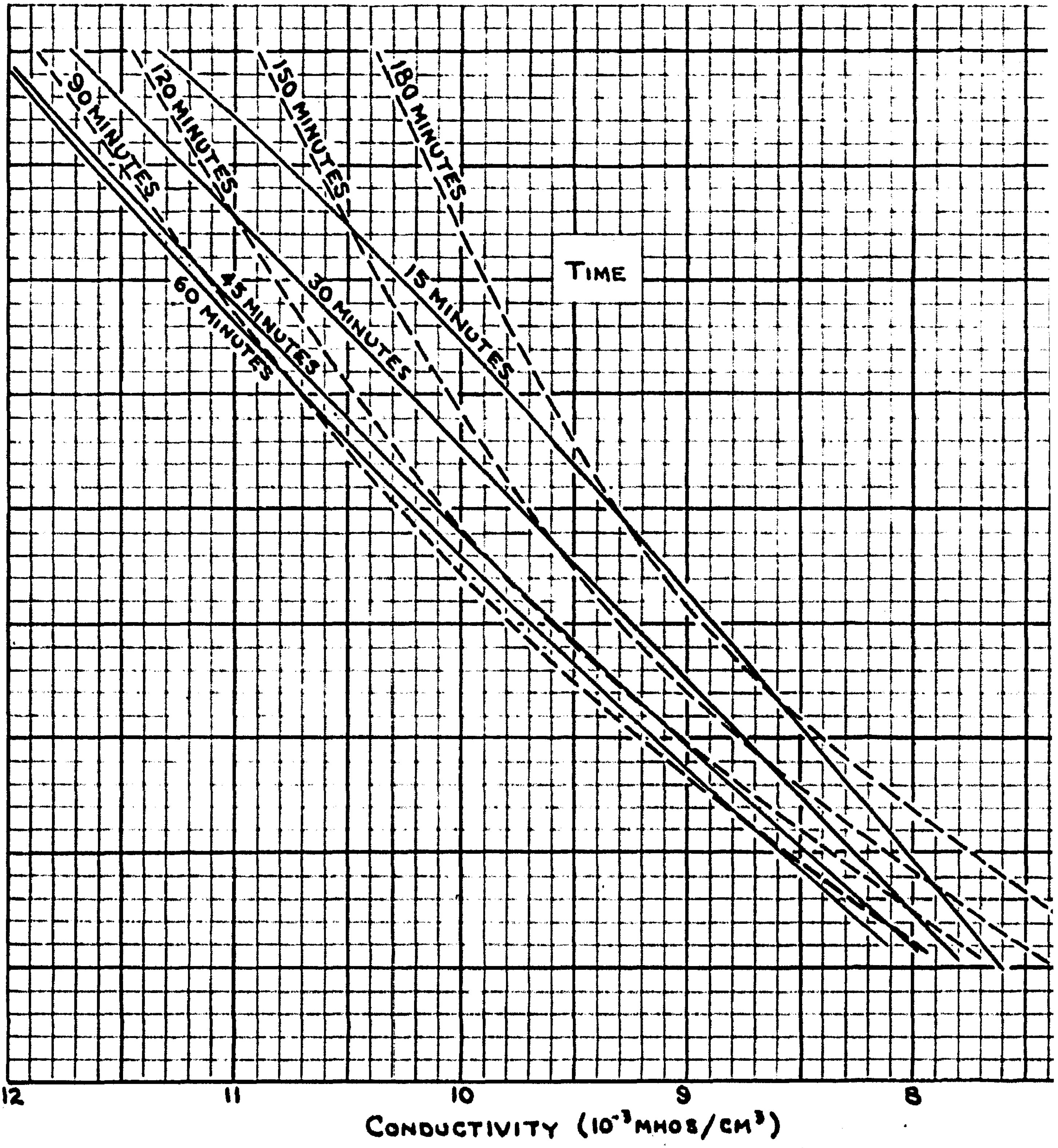
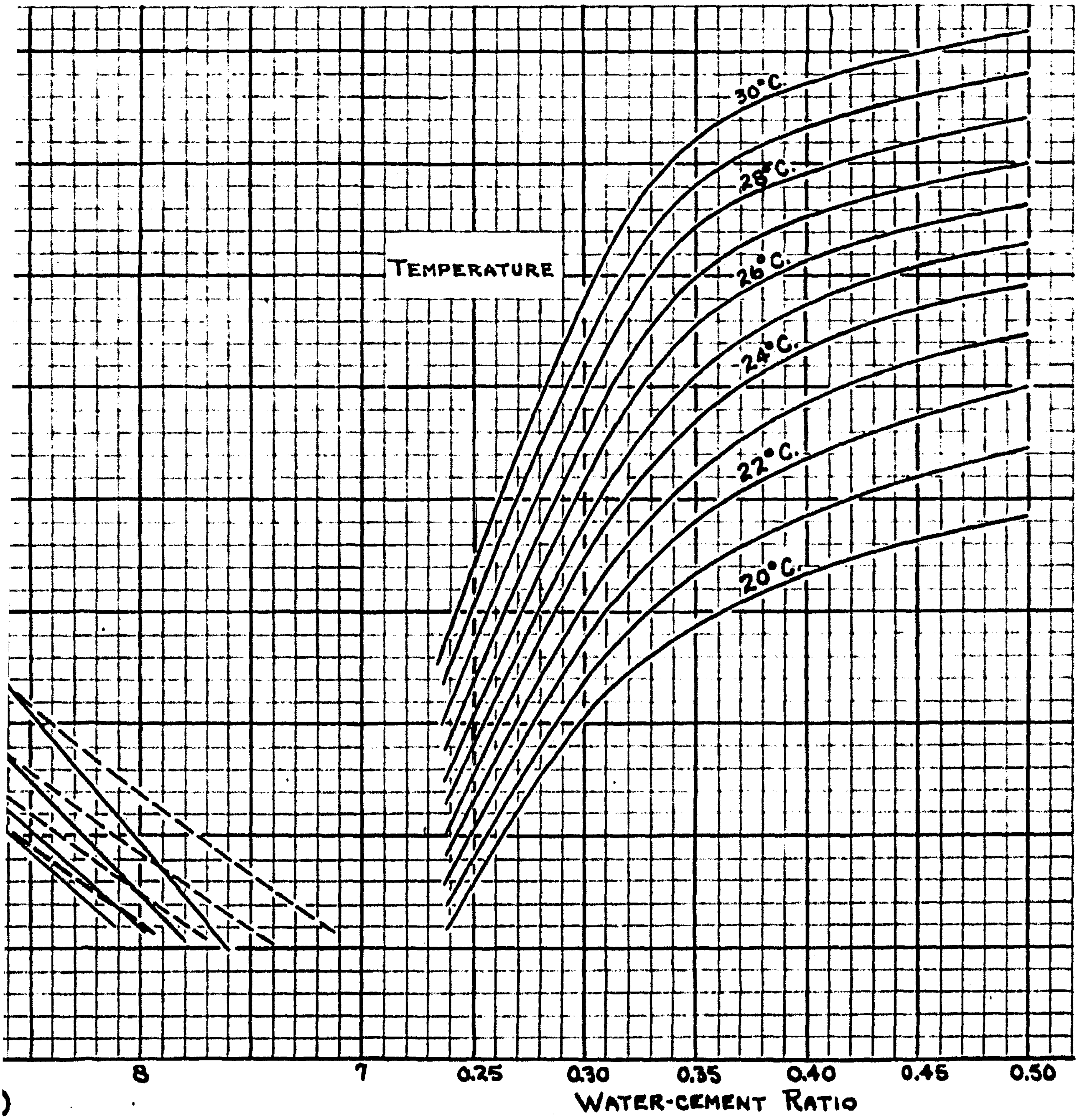


FIGURE 15. NETWORK CHART RELATING THE FOUR VARIABLES, W
ELECTRICAL CONDUCTIVITY FOR



E FOUR VARIABLES, WATER-CEMENT RATIO, TEMPERATURE, TIME, AND
CONDUCTIVITY FOR CEMENT A.

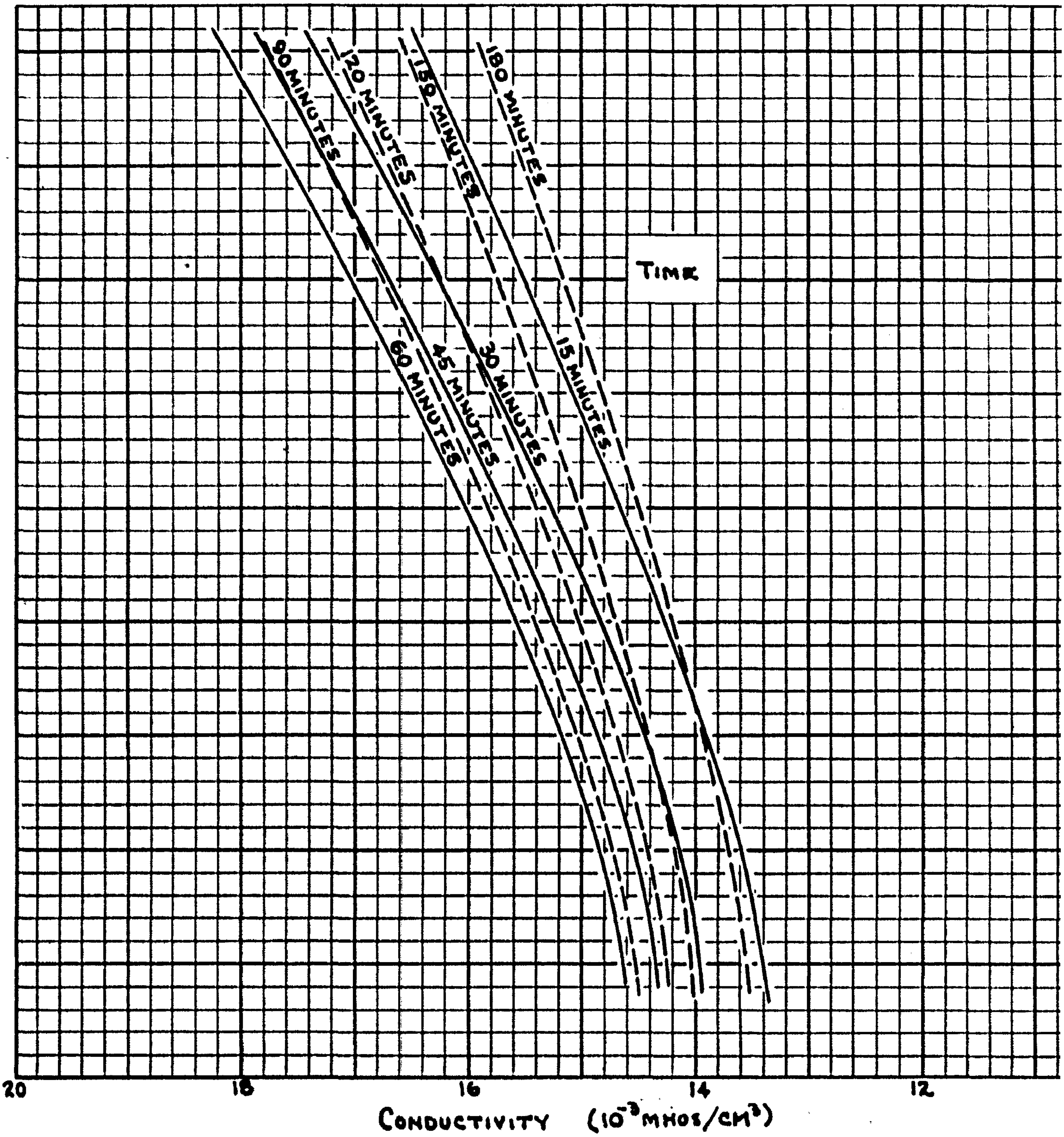
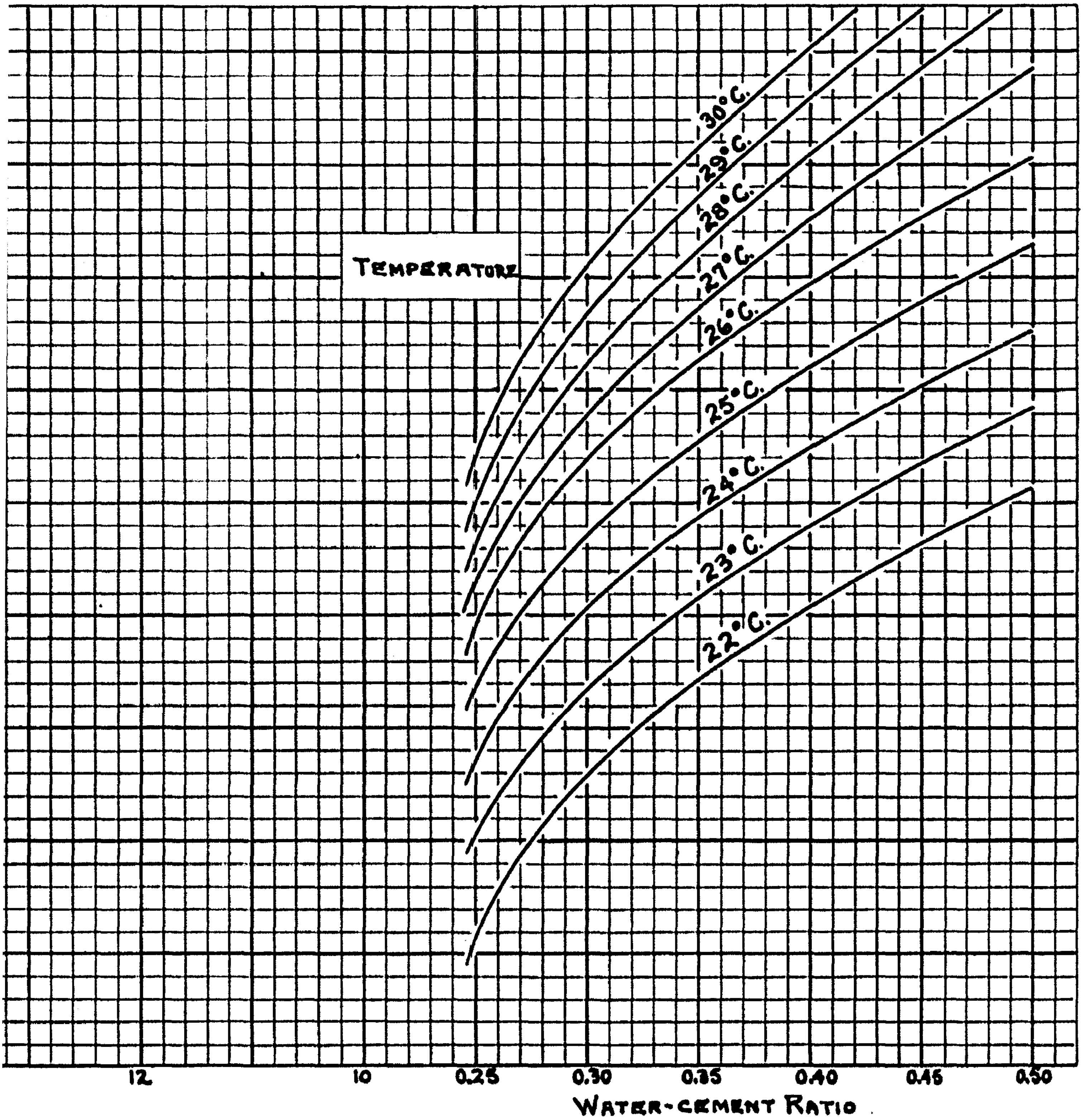


FIGURE 16. NETWORK CHART RELATING THE FOUR VARIABLES, W

ELECTRICAL CONDUCTIVITY FOR



: FOUR VARIABLES, WATER-CEMENT RATIO, TEMPERATURE, TIME, AND CONDUCTIVITY FOR CEMENT B.

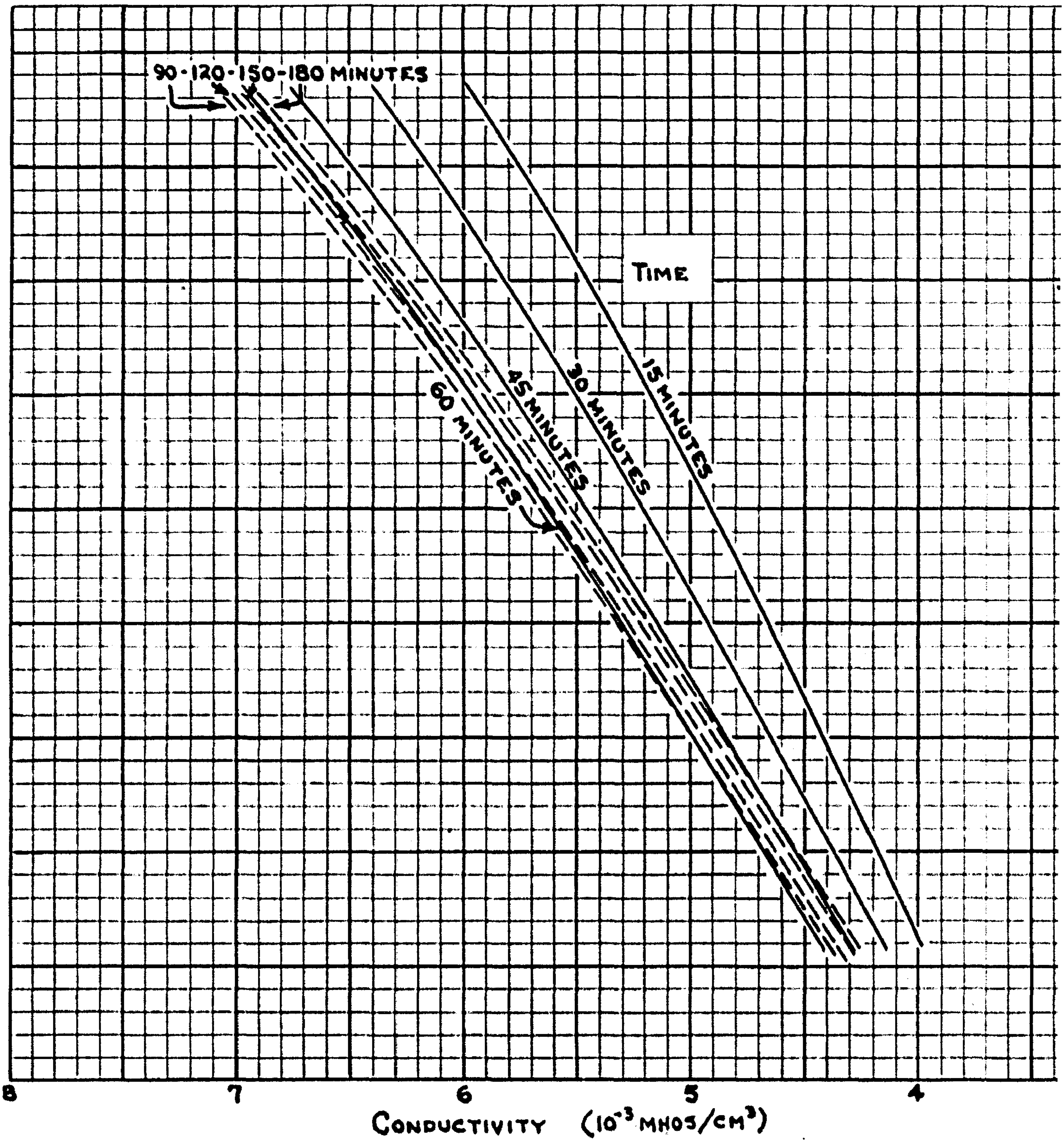
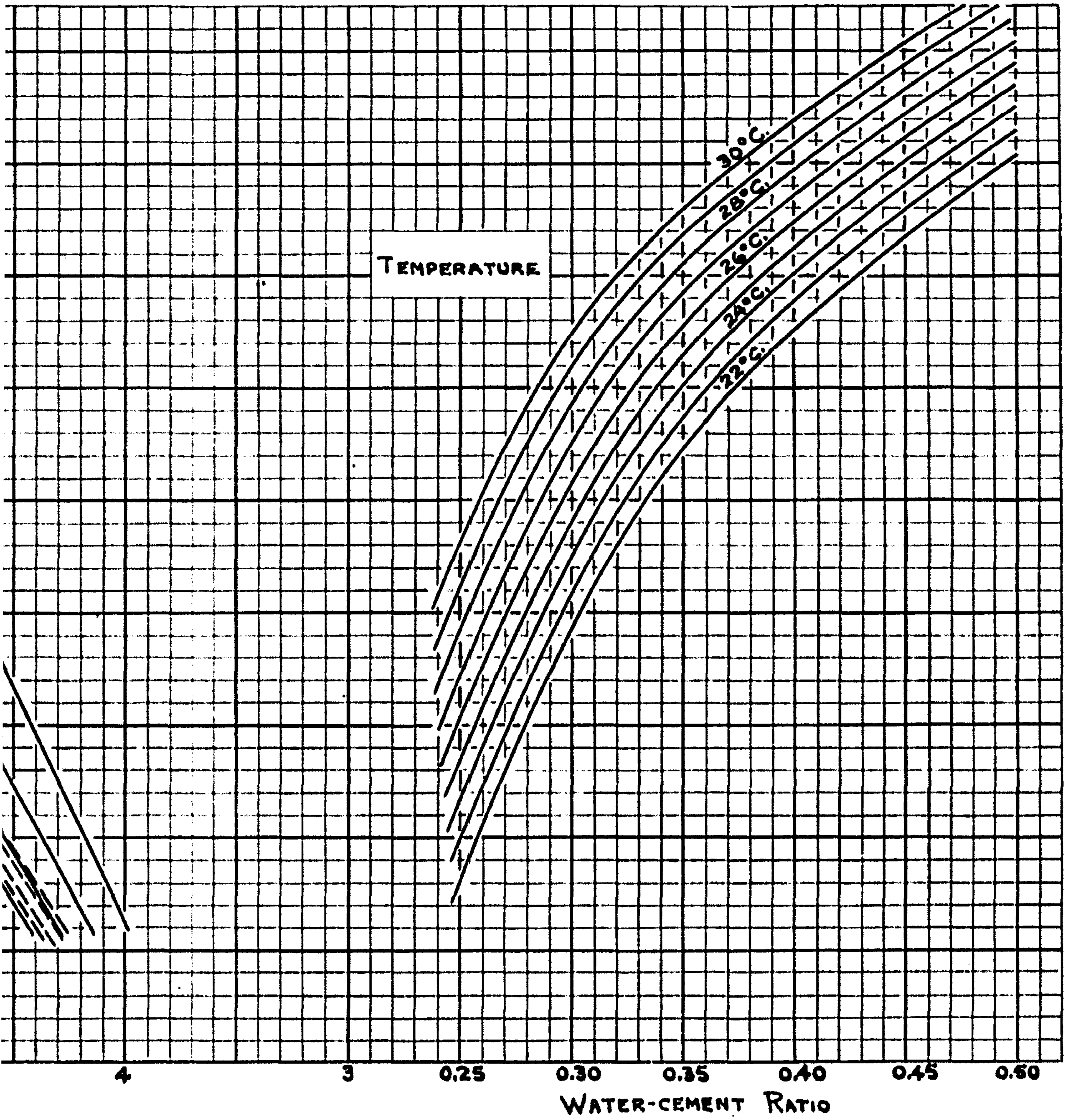


FIGURE 17. NETWORK CHART RELATING THE FOUR VARIABLES, W
ELECTRICAL CONDUCTIVITY FOR



FOUR VARIABLES, WATER-CEMENT RATIO, TEMPERATURE, TIME, AND
ONDUCTIVITY FOR CEMENT C.

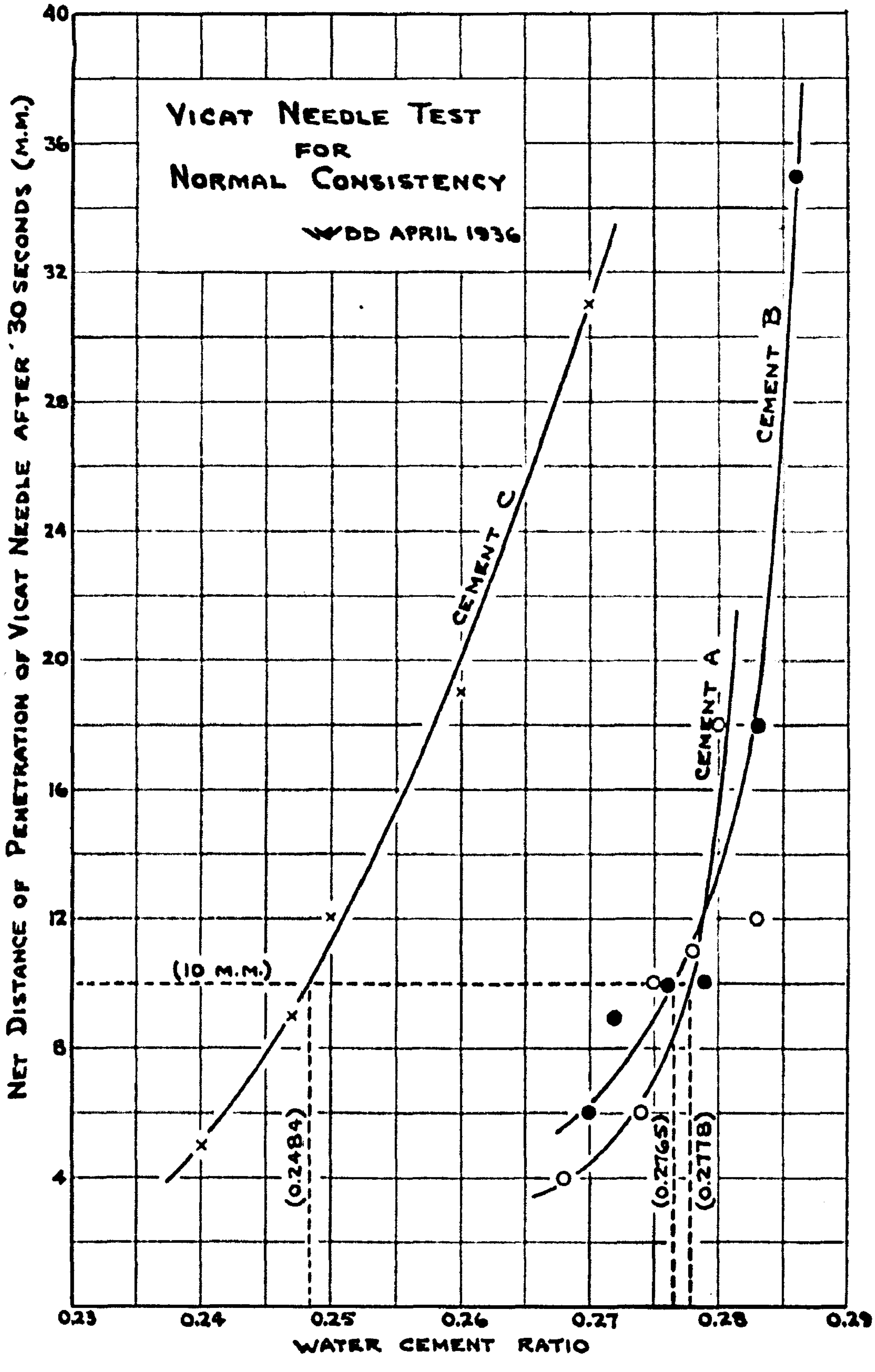
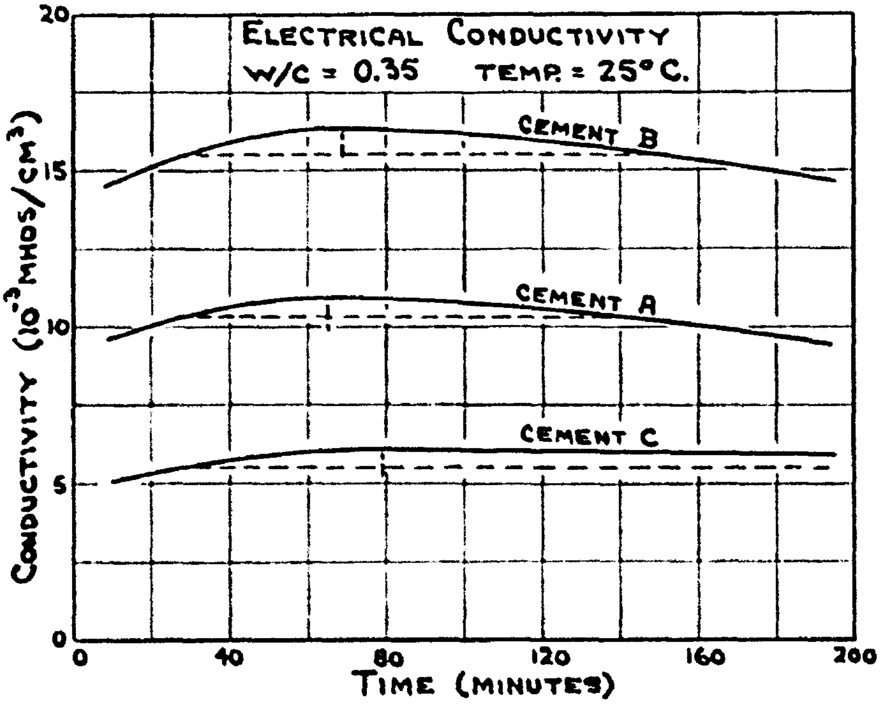
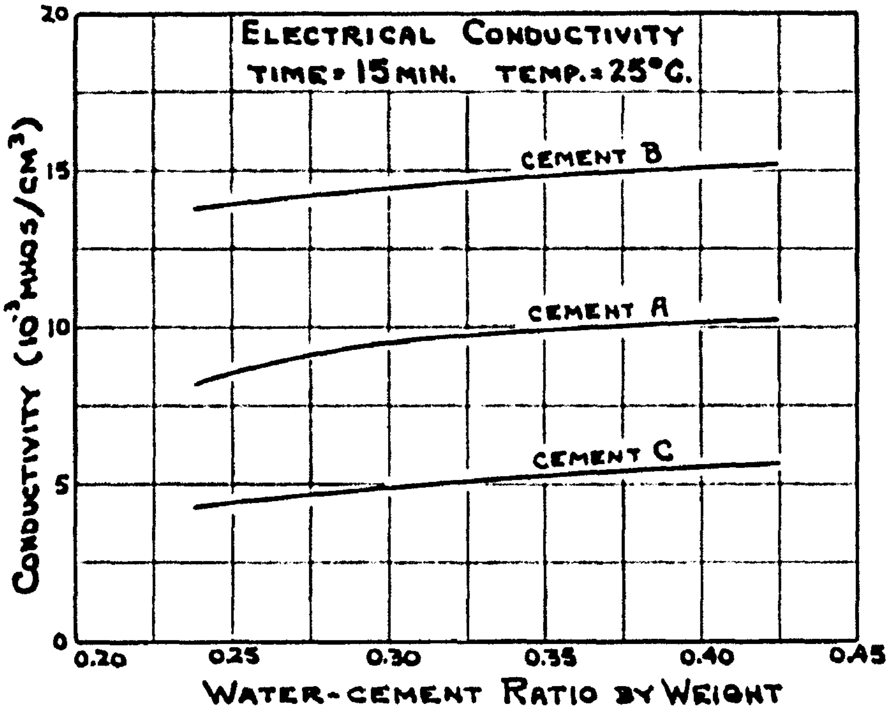

VICAT NEEDLE TEST
FOR
NORMAL CONSISTENCY
WDD APRIL 1936
NET DISTANCE OF PENETRATION OF VICAT NEEDLE AFTER 30 SECONDS (M.M.)
WATER CEMENT RATIO
40
36
32
28
24
20
16
12
8
4
0.23
0.24
0.25
0.26
0.27
0.28
0.29
CEMENT C
CEMENT B
CEMENT A
(10 M.M.)
(0.2484)
(0.2765)
(0.2778)

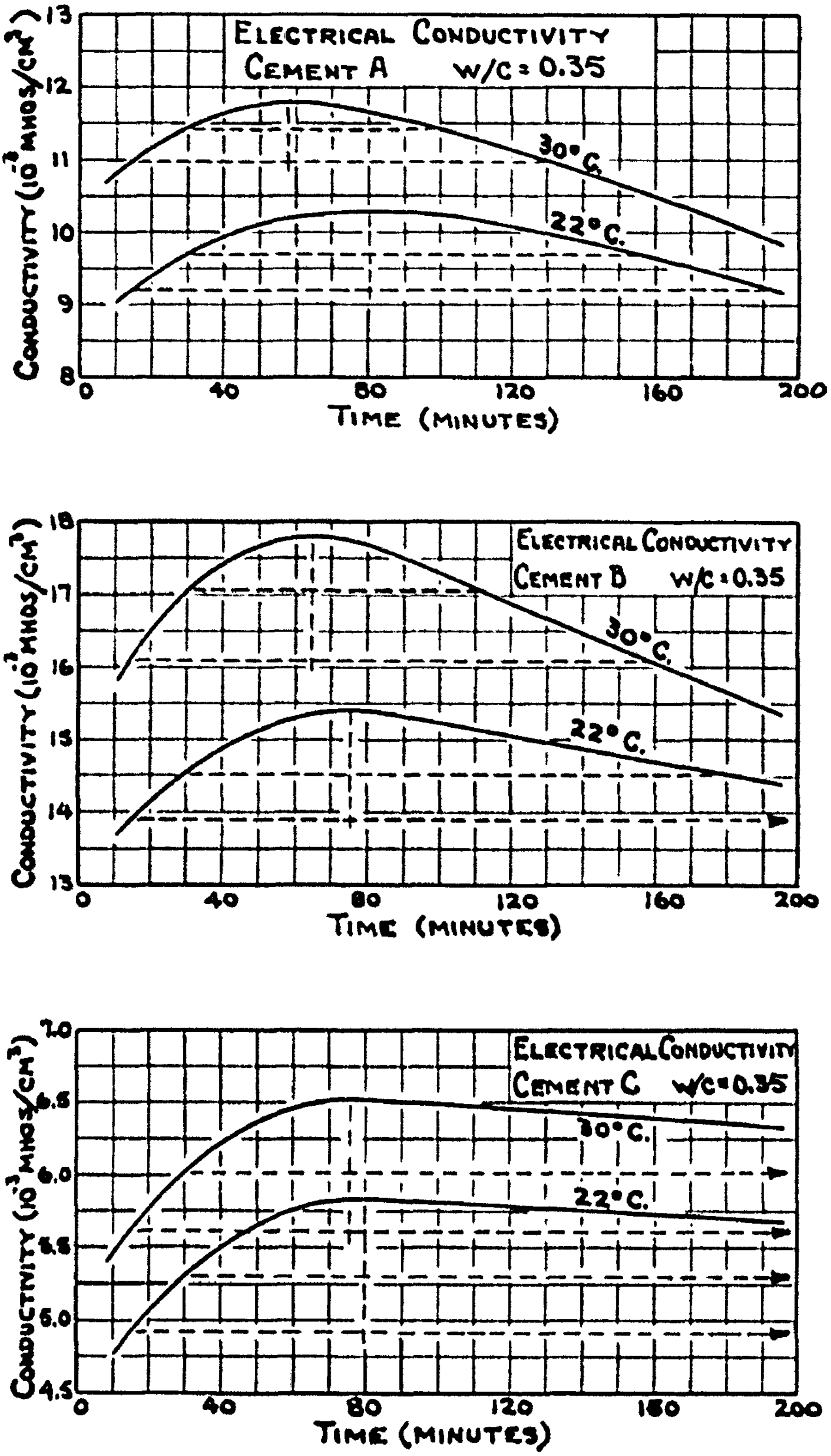
Figure 18





WDB

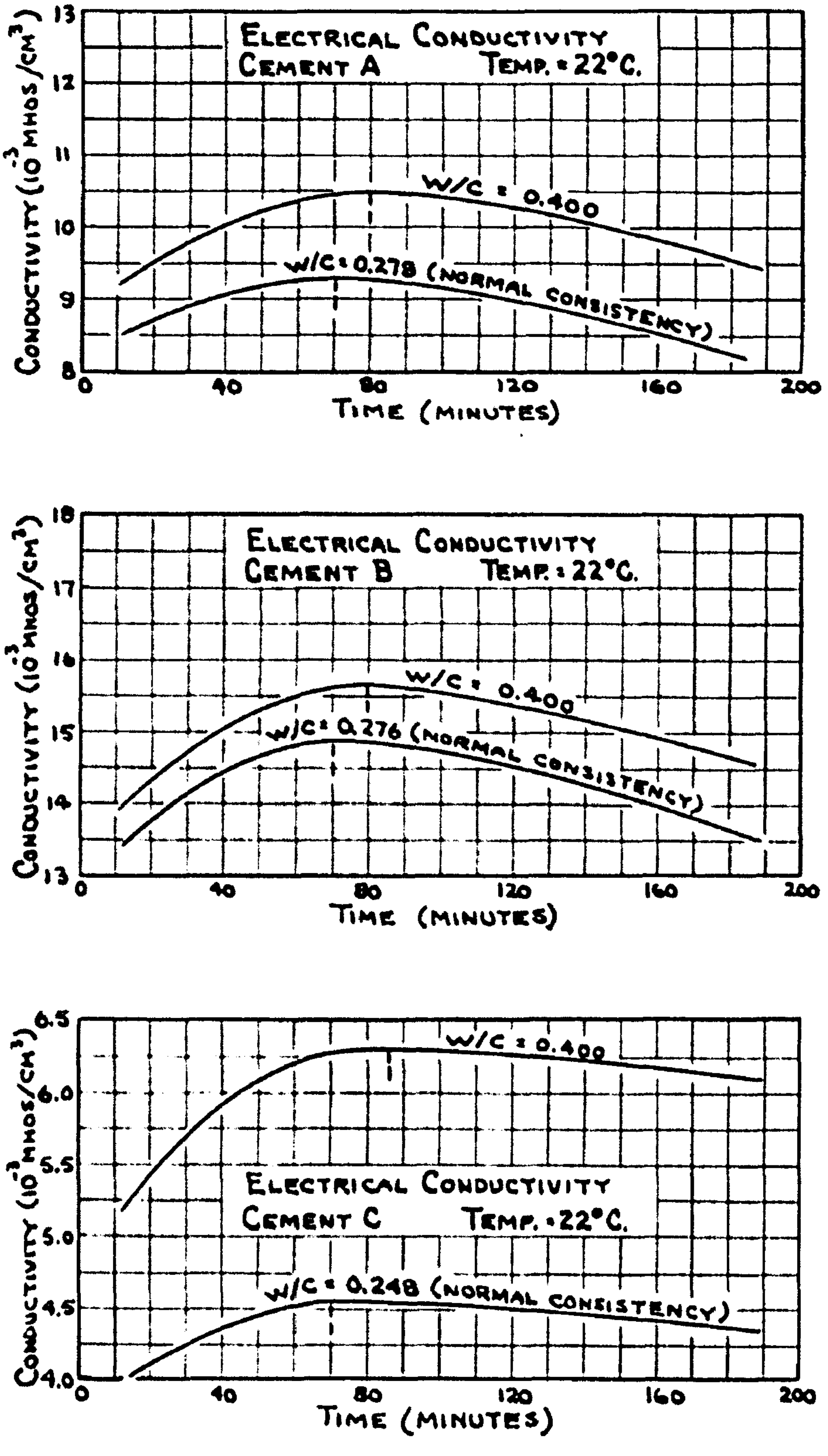
Figures 19 & 20



EFFECT OF TEMPERATURE UPON THE SETTING CHARACTERISTICS OF THE THREE CEMENTS

WBB

Figure 21



EFFECT OF WATER-CEMENT RATIO UPON THE SETTING CHARACTERISTICS OF THE THREE CEMENTS

WBB

Figure 22

3. Excess water tendency in sand-water mixtures.

The results of the calculations for the Weymouth grading of sand mixtures, as described on page 48, are presented in Table X, page 107.

The measurements and calculations for dry voids of the three sizes and two gradings of sand are tabulated in Table XI, page 108.

The results of the measurements of electrical resistance at various temperatures for the above sizes and gradings of sand are tabulated in Table XII, page 109, and plotted in Figure 23, page 111. The calculations of excess water tendency which is described on page 48 are presented in Table XIII, page 110, and the results are plotted in Figure 25, page 112.

TABLE X

DESIGN OF WEYMOUTH GRADING OF SAND MIXTURE

Size Groups (Tyler Sieves)	d_o	d_a $(0.296\ d_o)$	Space Available of Unit Volume	Absolute Volume	Weight (per cent)
#14-#28	0.637	0.188	1.000	0.188	41.50
#28-#48	0.611	0.181	0.812	0.147	32.45
#48-#100	0.598	0.177	0.665	0.118	26.05

TABLE XI

DRY VOID MEASUREMENTS

Sand or Grading	Sample Number	Water	Sand	Combined Sand and Water	Voids	Average Voids
		(c.c.)	(c.c.)	(c.c.)	(per cent)	(per cent)
A	271	130.0	46.5	159.5	36.6	36.3
	274	147.0	48.5	177.0	36.1	
B	272	158.0	48.5	187.5	39.2	38.9
	275	157.5	48.0	187.0	38.6	
C	273	152.0	45.5	178.5	41.8	40.2
	276	128.0	45.8	155.5	40.0	
	277	171.5	46.5	200.0	38.7	
Straight Line	278	139.5	49.5	172.0	34.3	35.1
	279	139.0	48.0	169.5	36.5	
	280	138.5	48.0	170.0	34.4	
Weymouth	291	117.8	49.3	160.0	34.7	33.4
	292	177.0	47.6	209.3	32.1	
	293	119.8	50.2	153.2	33.5	

TABLE XII

CONDUCTANCE MEASUREMENTS OF SAND-WATER MIXTURES

July, 1936

Water: Tap Water
Sand A: Pass #14 Sieve, Retained on #28
Sand B: Pass #28 Sieve, Retained on #48
Sand C: Pass #48 Sieve, Retained on #100

Group	Sample Number	Resistance (ohms)	Temperature (°C)
Water	254	1070	24.0
	255	1100	22.5
	256	1090	22.9
	257	1060	25.2
	258	1030	25.6
	260	1040	25.2
	262	1050	25.3
	264	1030	26.5
	266	1140	20.0
	268	1080	22.4
	296	1060	22.7
Sand A and Water	271	4620	19.9
	272	4480	22.0
	273	4460	22.9
	274	4580	19.3
	275	4220	25.4
	276	4190	25.0
	277	4090	27.0
Sand B and Water	259	4390	24.0
	261	4250	25.4
	263	4260	26.3
Sand C and Water	265	4100	26.7
	267	4140	27.1
	269	4280	24.8
	270	4510	21.6
Straight-Line Grading	282	4950	24.6
	283	5230	22.5
Weymouth Grading	294	5200	24.8
	295	5160	26.4

TABLE XIII

CONDUCTANCE CALCULATIONS OF SAND-WATER MIXTURES

Group	Resistance at 25°C. (ohms)	Conductance Ratio (ratio)	Dry Voids (ratio)	Excess Water Tendency (ratio)
Water	1050			
Sand A and Water	4235	0.248	0.363	0.683
Sand B and Water	4275	0.246	0.389	0.632
Sand C and Water	4275	0.246	0.402	0.612
Straight-Line Grading	4980	0.211	0.351	0.601
Weymouth Grading	5230	0.201	0.334	0.602

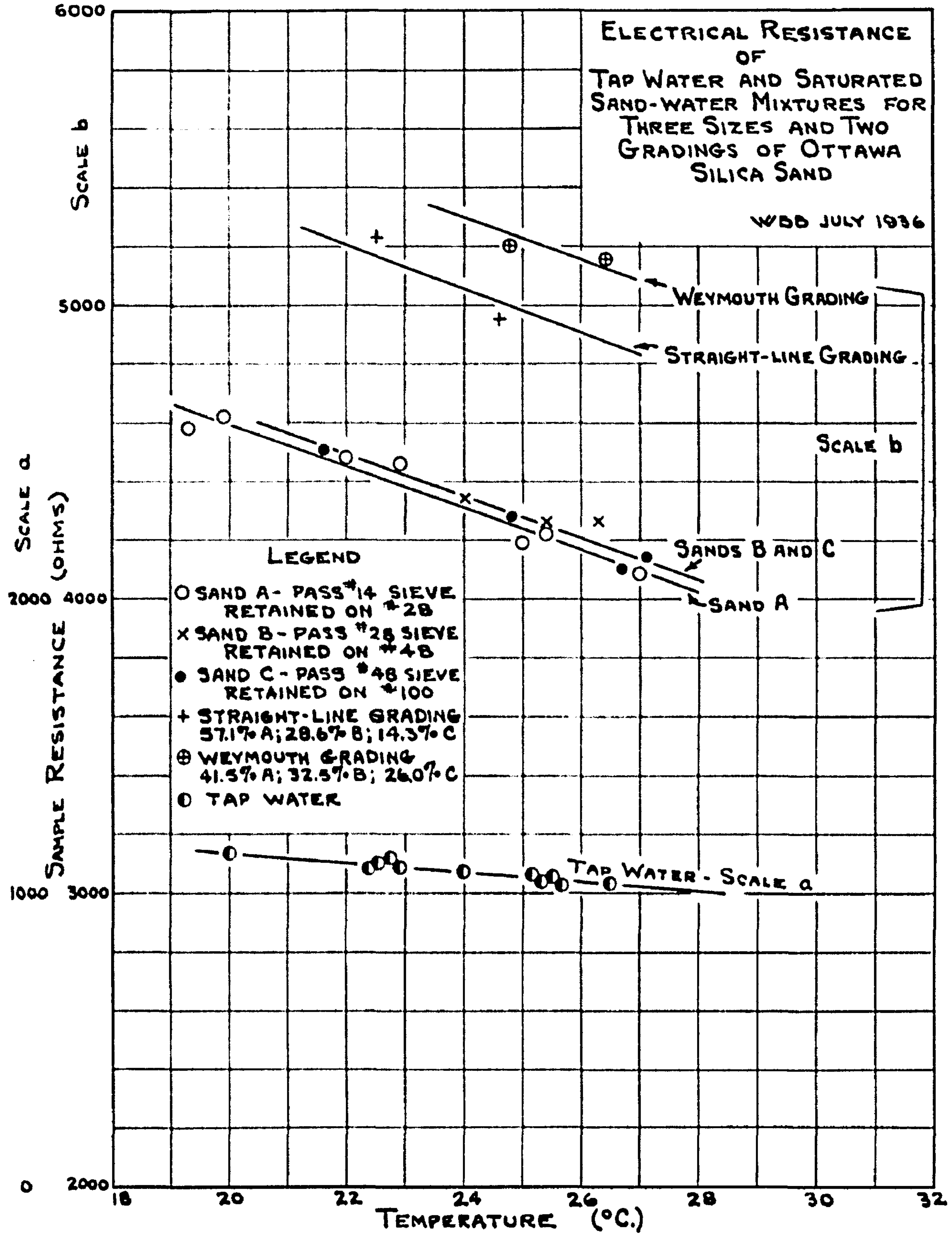
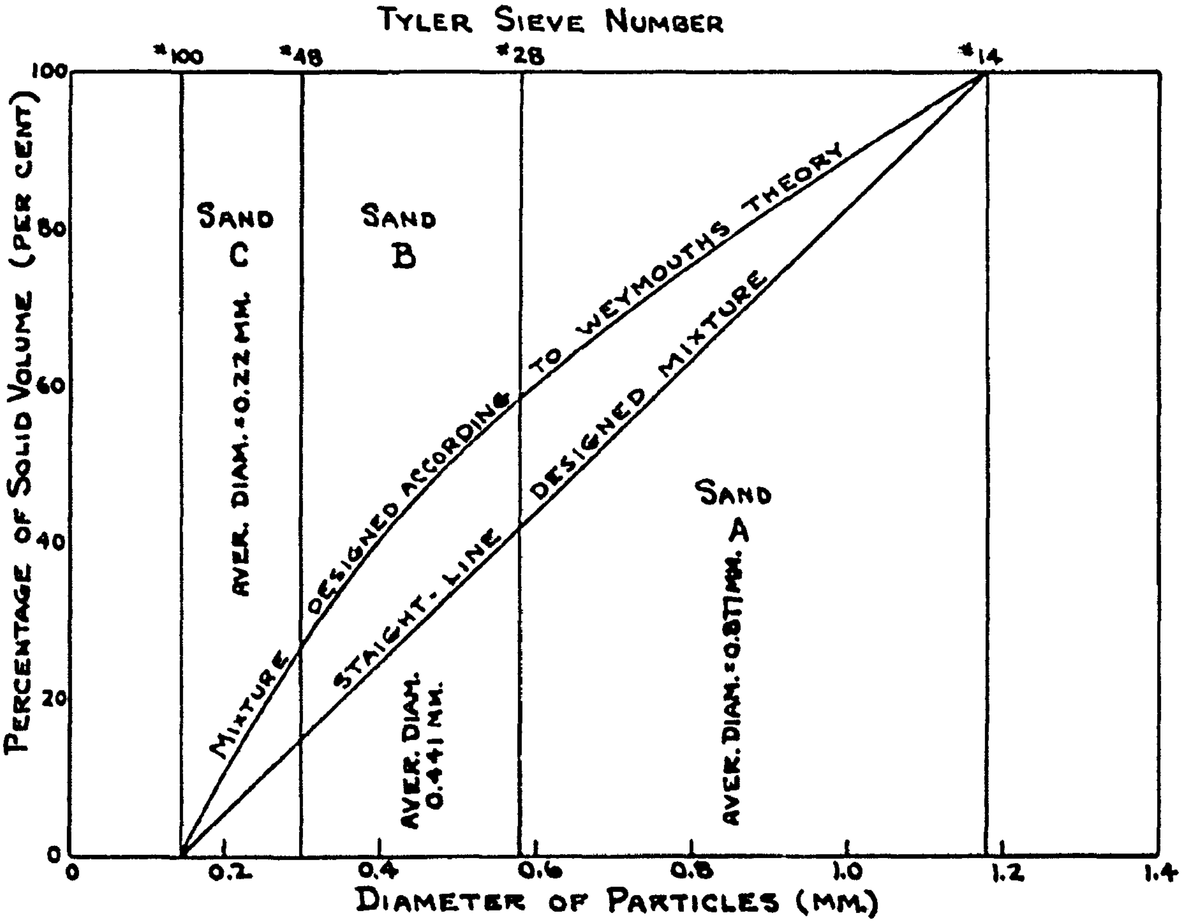
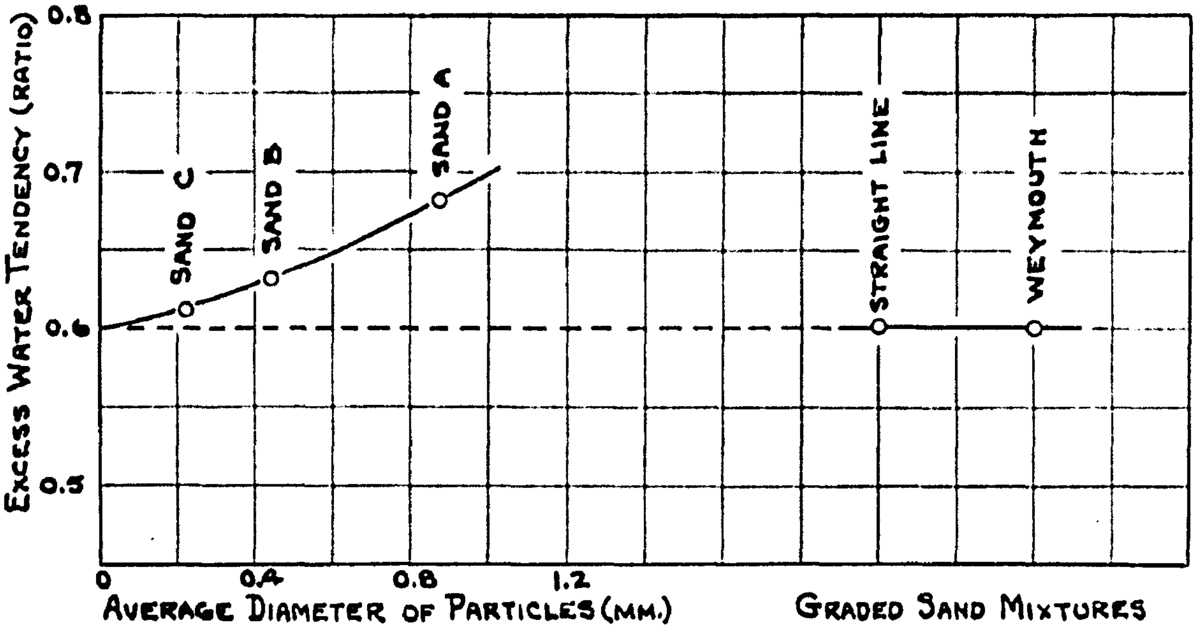

ELECTRICAL RESISTANCE OF TAP WATER AND SATURATED SAND-WATER MIXTURES FOR THREE SIZES AND TWO GRADINGS OF OTTAWA SILICA SAND
WBB JULY 1936
WEYMOUTH GRADING
STRAIGHT-LINE GRADING
SCALE b
SANDS B AND C
SAND A
TAP WATER - SCALE a
LEGEND
○ SAND A - PASS #14 SIEVE RETAINED ON #28
× SAND B - PASS #28 SIEVE RETAINED ON #48
● SAND C - PASS #48 SIEVE RETAINED ON #100
+ STRAIGHT-LINE GRADING 57.1% A; 28.6% B; 14.3% C
⊕ WEYMOUTH GRADING 41.5% A; 32.5% B; 26.0% C
◐ TAP WATER
SAMPLE RESISTANCE (OHMS)
SCALE a
SCALE b
6000
5000
2000 4000
1000 3000
0 2000
18
20
22
24
26
28
30
32
TEMPERATURE (°C.)

Figure 23





Figures 24 & 25

4. Internal stratification in cement pastes.

The measurements and calculations for the calibration of the vacuum-tube voltmeter are listed in Table XIV, page 114. Those for the calibration of the container and shunts are presented in Table XV, pages 115 and 116.

The data of the tests upon the three cements for internal stratification are tabulated in Tables XVI to XXVI, pages 117 to 127, inclusive, and plotted in Figures 26 to 36, pages 148 to 158, inclusive.

The results from those samples which were used in determining the conductance of the surface water are summarised in Table XXVII, page 128.

Calculations of the conductance of the six lateral sections of the sample and of the percentage conductance, as described on pages 49 to 52, are shown in Tables XXVIII to XXXVIII, pages 129 to 147, inclusive. The percentage conductance was plotted against electrode numbers at increments of time for the three cements at 0.350 water-cement ratio and for cement A at 0.400 water-cement ratio. These plots are shown in Figures 37 to 40, pages 159 to 162, inclusive. Finally, from the smooth curves thus obtained, percentage conductance for the six sections were plotted against time as is shown in Figures 41 to 44, pages 163 and 164.

TABLE XIV

CALIBRATIONS OF VOLTMETER FOR STRATIFICATION MEASUREMENTS

Sample Number	Resistance of Shunt	Current	Potentiometer Reading	Voltage Used in Test	Resistance
	(ohms)	(amperes)		(volts)	(ohms)
193	2.00	0.00495	1000	0.547	0.0552 P x F
194	5.00	0.00338	400	0.547	0.0809 P x F
195	5.00	0.00338	400	0.547	0.0809 P x F
197	20.00	0.00143	350	0.547	0.0546 P x F
198	20.00	0.00143	350	0.547	0.0546 P x F
200	5.00	0.00274	400	0.547	0.0998 P x F
201	10.00	0.00193	244	0.547	0.1161 P x F
202	10.00	0.00193	244	0.547	0.1161 P x F
207	10.00	0.00190	532	0.547	0.0541 P x F
210	10.00	0.00190	532	0.547	0.0541 P x F
211	10.00	0.00190	532	0.547	0.0541 P x F

TABLE XV

CALIBRATIONS OF CONTAINERS AND SHUNTS FOR STRATIFICATION MEASUREMENTS

Sample Number	Electrode Number	Average Potentiometer Reading	Factor	Resistance (ohms)
193	1	476.2	1.094	0.0605 P
	2	516.8	1.009	0.0557 P
	3	512.6	1.017	0.0561 P
	4	507.2	1.028	0.0567 P
	5	529.2	0.985	0.0544 P
	6	586.8	0.889	0.0491 P
194	1	257.0	1.068	0.0880 P
	2	277.5	1.006	0.0814 P
	3	278.0	1.006	0.0814 P
	4	272.2	1.027	0.0831 P
	5	286.3	0.977	0.0790 P
	6	306.3	0.913	0.0739 P
195	1	385.2	1.103	0.0892 P
	2	411.8	1.032	0.0834 P
	3	421.0	1.009	0.0816 P
	4	412.8	1.029	0.0832 P
	5	436.2	0.974	0.0788 P
	6	482.5	0.881	0.0713 P
197	1	442.4	1.087	0.0594 P
	2	471.8	1.019	0.0556 P
	3	473.8	1.015	0.0554 P
	4	469.6	1.024	0.0559 P
	5	499.0	0.963	0.0526 P
	6	527.8	0.911	0.0497 P
198	1	578.4	1.063	0.0580 P
	2	601.8	1.021	0.0557 P
	3	612.8	1.003	0.0548 P
	4	598.4	1.027	0.0561 P
	5	630.6	0.975	0.0532 P
	6	666.4	0.922	0.0503 P
200	1	403.2	1.117	0.1115 P
	2	455.0	0.990	0.0988 P
	3	452.2	0.996	0.0994 P
	4	437.8	1.029	0.1027 P
	5	455.6	0.989	0.0987 P
	6	498.4	0.904	0.0902 P

TABLE XV (continued)

Sample Number	Electrode Number	Average Potentiometer Reading	Factor	Resistance (ohms)
201	1	153.6	1.080	0.1254 P
	2	163.4	1.015	0.1178 P
	3	167.0	0.993	0.1153 P
	4	161.6	1.026	0.1191 P
	5	167.2	0.992	0.1152 P
	6	182.4	0.909	0.1055 P
202	1	166.0	1.107	0.1285 P
	2	178.6	1.029	0.1195 P
	3	178.6	1.029	0.1195 P
	4	180.4	1.019	0.1183 P
	5	189.8	0.969	0.1125 P
	6	209.6	0.877	0.1018 P
207	1	267.4	1.200	0.0649 P
	2	288.6	1.112	0.0606 P
	3	307.0	1.045	0.0565 P
	4	324.4	0.989	0.0535 P
	5	349.8	0.917	0.0496 P
	6	388.2	0.827	0.0447 P
210	1	307.3	1.075	0.0582 P
	2	325.7	1.015	0.0549 P
	3	331.7	0.996	0.0539 P
	4	323.3	1.022	0.0563 P
	5	337.0	0.981	0.0531 P
	6	358.0	0.923	0.0499 P
211	1	499.5	1.095	0.0592 P
	2	543.2	1.007	0.0545 P
	3	543.0	1.007	0.0545 P
	4	539.2	1.014	0.0549 P
	5	557.8	0.980	0.0530 P
	6	598.5	0.914	0.0494 P

TABLE XVI

STRATIFICATION MEASUREMENTS

Cement A
Sample Number 193
Water/cement 0.350

May 6, 1936

Time (min)	Potentiometer Readings for Electrodes Number						Temper-ature (°C)	Surface Levels	
	1	2	3	4	5	6		Water (in)	Cement (in)
11	365	387	394	388	408	456			
13	363	389	394	389	406	458			
17	347	373	377	372	393	447	30.4	0.035	0.059
19	344	373	377	372	395	449			
23	337	356	362	361	384	439			
26	337	357	361	358	384	438			
29	338	355	358	353	382	433	30.1	0.047	0.094
34	332	350	353	348	373	423			
38	327	347	348	346	368	416			
44	330	350	350	347	367	413			
50	332	355	353	352	377	424	29.6	0.070	0.129
57	334	349	350	347	369	426			
63	338	353	353	349	372	420			
68	346	359	356	350	371	416	29.3	0.070	0.129
74	345	352	359	360	381	425			
80	346	357	363	361	383	430			
86	355	363	361	365	380	426			
93	366	363	359	368	379	428			
98	373	367	367	373	384	427			
105	382	367	367	373	387	429			0.140
110	393	369	368	372	383	430			
121	396	376	374	380	390	431			
132	404	377	375	379	388	429	29.1		
148	403	375	374	377	386	426			
156	405	378	377	382	393	433			
165	405	376	380	384	393	436			
173	403	380	378	386	395	438			
179	407	386	379	388	397	442			

TABLE XVII

STRATIFICATION MEASUREMENTS

Cement A May 13, 1936
Sample Number 194
Water/cement 0.350

Time	Potentiometer Readings for Electrodes Number						Temperature	Surface Levels	
	1	2	3	4	5	6		Water	Cement
(min)							(°C)	(in)	(in)
12	223	246	248	244	256	280			
16	220	240	241	239	252	278	26.3		
20	220	242	243	238	252	279			
24	217	238	238	236	246	271			
28	214	234	234	228	243	268	26.0	0.059	0.082
32	217	239	239	237	250	274	25.8		
36	220	239	239	235	250	274	25.8	0.059	0.106
40	219	241	240	236	251	274			
44	214	233	235	232	247	271			
48	216	238	236	233	247	271	25.6	0.059	0.129
53	213	236	238	234	249	271			
58	211	233	231	230	246	266	25.3	0.070	0.141
63	212	233	235	233	246	266			
68	214	230	230	230	245	265	25.3	0.070	0.141
73	214	234	234	230	242	263			
78	215	236	237	231	249	269	25.2	0.077	0.152
86	215	235	234	231	247	265	25.0		
91	221	241	242	235	256	274			
96	224	246	245	239	259	278	25.0	0.094	0.152
101	227	245	243	237	256	275			
106	231	248	245	237	257	276	24.9	0.105	0.152
111	239	252	249	241	261	278			
121	244	254	250	242	262	280	24.8	0.140	0.152
131	247	253	250	242	260	280			
141	252	253	252	241	259	277	24.7		0.152
151	259	257	251	241	260	276	24.7		
161	262	261	253	245	265	283			
171	261	260	252	245	264	283			
181	264	263	259	252	271	288	24.9		

TABLE XVIII

STRATIFICATION MEASUREMENTS

Cement A
Sample Number 195
Water/cement 0.350

May 13, 1936

Time (min)	Potentiometer Readings for Electrodes Number 1	2	3	4	5	6	Temperature (°C)	Surface Levels Water (in)	Cement (in)
12	223	248	261	258	277	311			
16	222	249	261	257	277	311	26.8		
20	220	248	260	258	273	310			
24	219	246	258	255	274	308	26.8		0.023
28	216	242	253	250	271	309			
32	214	240	252	247	269	306	26.7		0.035
37	213	238	251	246	268	304			
42	210	237	250	245	268	303	26.4		0.058
47	210	239	251	246	268	302			
52	208	238	251	245	266	300	26.2	0.023	0.094
57	206	236	249	244	266	300			
62	206	237	249	244	264	297	26.0	0.023	0.105
68	204	237	249	244	264	297			
74	201	234	246	240	260	292	25.7	0.023	0.105
* 80	227	240	250	242	262	290		0.105	0.105
86	203	237	251	244	265	293	25.6	0.023	0.117
92	206	240	255	248	269	297			
98	208	246	258	251	272	200			

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* Water poured from top of cement for a determination of the conductance of the surface water. The disturbance thus produced rendered inaccurate further readings on this sample.

TABLE XIX

STRATIFICATION MEASUREMENTS

Cement B
Sample Number 197
Water/cement 0.350

May 30, 1936

Time	Potentiometer Readings for Electrodes Number						Temperature	Surface Levels	
	1	2	3	4	5	6		Water	Cement
(min)							(°C)	(in)	(in)
10	303	326	326	323	349	366	28.9		
15	298	322	321	317	343	361			
20	299	319	318	313	339	359	28.9		0.044
25	302	319	317	313	339	358			
30	301	319	316	312	338	357	28.8		0.055
35	301	318	314	311	337	355			
40	300	316	312	308	334	352	28.7		0.066
45	299	313	309	306	331	349			
50	299	312	308	303	328	346			
55	302	313	308	303	328	346	28.4		0.087
60	301	312	306	301	326	343			
65	301	312	307	302	327	344			
70	300	313	308	304	328	345	27.9		0.099
75	301	314	309	305	330	347			
80	308	323	318	312	336	355			
85	309	323	316	310	336	353	27.8		0.099
90	311	324	317	311	336	354			
95	311	324	317	311	336	354			
100	312	325	318	313	337	355			
110	313	326	319	314	337	355	27.8		0.110
120	313	326	320	314	338	356			
130	313	327	322	316	340	358			
140	314	328	322	318	343	361			
150	314	331	324	320	344	363			
160	316	332	326	323	347	367			
170	317	334	330	326	351	372			
180	318	336	331	328	353	373	30.1		0.110

TABLE XX

STRATIFICATION MEASUREMENTS

Cement B
Sample Number 198
Water/cement 0.350

May 31, 1936

Time	Potentiometer Readings for Electrodes Number						Temperature	Surface Levels	
	1	2	3	4	5	6		Water	Cement
(min)							(°C)	(in)	(in)
10	296	310	313	314	328	350	30.0		0.033
15	293	302	304	302	319	342	30.3		
20	293	299	302	300	316	340	30.4		
25	294	299	299	298	315	337	30.2		0.066
30	294	297	298	298	313	335			
35	294	296	294	294	310	331	30.0		0.077
40	296	295	294	292	308	329			
45	296	294	294	291	308	328	29.9		0.087
50	296	296	293	290	308	325			
55	294	301	291	293	302	324	29.6		0.098
60	294	302	292	294	301	324			
65	293	303	293	296	303	326			
70	294	304	296	298	306	327			
75	296	307	297	298	305	328			
80	299	308	297	299	306	328	29.1		0.109
85	299	308	296	299	304	327			
90	300	309	296	297	304	328			
95	300	309	297	298	304	327			
100	300	309	298	298	305	327			
110	304	315	303	304	310	332			
120	303	314	303	304	309	332	29.3		0.120
130	305	317	306	308	313	335			
140	308	317	307	309	314	337	30.0		0.120
150	309	317	309	308	313	337			
160	310	317	311	309	315	340	31.0		0.120
170	315	327	321	318	323	347			
180	325	341	331	330	334	360	31.9		0.120

TABLE XXI

STRATIFICATION MEASUREMENTS

Cement C June 5, 1936
Sample Number 200
Water/cement 0.350

Time	Potentiometer Readings for Electrodes Number						Temperature	Surface Levels	
	1	2	3	4	5	6		Water	Cement
(min)							(°C)	(in)	(in)
10	434	483	489	475	484	547	28.9		
15	418	469	470	461	472	536	28.8		
20	412	457	460	451	465	530			
25	408	456	456	447	459	526	28.7	0.022	0.055
30	404	452	450	444	460	522			
35	401	451	448	443	458	519	28.4	0.033	0.077
40	399	446	446	437	453	513			
50	387	432	431	424	438	495	28.2	0.033	0.098
60	380	423	423	415	428	485			
70	378	425	424	421	432	489	28.0	0.033	0.098
80	385	428	425	421	433	489			
90	400	440	435	430	444	502	28.0	0.066	0.109
100	404	439	435	430	442	501			
110	409	442	434	432	444	502	28.2	0.077	0.109
120	413	442	434	430	443	502			
130	420	443	432	430	442	500	28.4	0.098	0.120
140	428	447	436	435	443	503			
150	431	449	439	436	445	503	28.9		0.120
160	431	449	439	436	444	502			
170	431	450	440	436	447	506	29.1		0.120
180	431	450	441	436	446	505			

TABLE XXII

STRATIFICATION MEASUREMENTS

Cement C
Sample Number 201 — June 15, 1936
Water/cement 0.350

Time	Potentiometer Readings for Electrodes Number						Temper-ature	Surface Levels	
	1	2	3	4	5	6		water	cement
(min)							(°C)	(in)	(in)
10	357	409	419	406	413	455	29.3		
15	360	403	404	392	409	452			
20	352	389	394	383	401	442	29.4	0.055	0.088
25	352	386	391	379	397	437			
30	346	378	382	372	387	429	29.2		
35	345	378	379	371	387	427			
40	347	376	379	369	386	426	28.9	0.066	0.098
45	343	373	376	365	382	420			
50	340	367	369	359	375	411			
55	341	367	369	357	374	411			
60	341	365	368	358	373	410	28.4	0.088	0.111
70	343	371	374	363	380	418			
80	350	376	378	367	382	419			
90	357	377	375	364	379	416	27.9		0.111
100	360	378	375	364	380	418			
110	362	381	375	367	382	419			
120	366	388	378	370	385	422	27.7		0.120
130	367	390	378	370	386	422			
140	367	391	380	371	386	422			
150	369	395	387	375	388	426			
160	368	394	387	375	387	426	27.8		0.120
170	369	394	387	376	386	425			
180	370	394	388	381	388	426			

TABLE XXIII

STRATIFICATION MEASUREMENTS

Cement C June 16, 1936
Sample Number 202
Water/cement 0.350

Time	Potentiometer Readings for Electrodes Number						Temperature	Surface Levels Water	Surface Levels Cement
	1	2	3	4	5	6			
(min)							(°C)	(in)	(in)
10	352	403	403	389	414	467	29.3		
15	352	397	393	384	412	465			
20	352	394	392	382	410	464	29.3	0.044	0.066
25	353	388	385	379	404	456			
30	349	381	375	370	395	446			
35	351	379	375	368	394	446			
45	346	378	374	368	393	446		0.044	0.066
* 50	359	378	375	369	390	445		0.066	0.066

* Water poured from top of cement for a determination of the conductance of the surface water. The disturbance thus produced rendered inaccurate further readings on this sample.

TABLE XXIV

STRATIFICATION MEASUREMENTS

Cement A
Sample Number 207
Water/cement 0.400

June 24, 1936

Time	Potentiometer Readings for Electrodes Number						Temperature	Surface Levels	
	1	2	3	4	5	6		Water	Cement
(min)							(°C)	(in)	(in)
10	493	559	592	606	652	759	25.2		
15	490	549	582	600	651	759			
20	497	546	582	600	652	760	25.3	0.066	0.087
25	497	541	576	596	647	753			
30	498	539	572	593	644	748	25.2	0.066	0.098
35	498	536	569	587	636	739			
40	499	535	567	583	634	737	25.2	0.077	0.110
45	499	528	558	577	625	726			
50	500	528	557	576	625	726	25.1	0.110	0.110
55	502	526	555	573	621	724			
60	504	528	556	573	620	722	24.9		0.110
70	506	526	551	569	616	719			
80	503	521	547	565	610	713			
90	496	513	539	555	600	702	24.8		0.110
100	495	513	540	559	603	705			
110	495	516	541	560	605	705			
120	499	521	546	564	607	709	24.8		0.110
130	500	524	546	562	606	708			
140	499	525	544	560	605	707			
150	501	528	548	562	606	709	24.8		0.110
160	502	531	552	566	609	710			
170	503	536	556	570	611	713			
180	504	535	557	571	612	715			

TABLE XXV

STRATIFICATION MEASUREMENTS

Cement A
Sample Number 210
Water/cement 0.400

June 24, 1936

Time (min)	Potentiometer Readings for Electrodes Number 1	2	3	4	5	6	Temperature (°C)	Surface Levels Water (in)	Cement (in)
10	510	576	583	570	590	646	26.3		
15	499	560	574	561	584	642			
20	494	557	571	562	587	645	26.4	0.000	0.033
25	488	556	570	561	589	645			
30	487	554	569	561	589	645	26.4	0.000	0.055
* 35	516	556	567	559	588	643		0.056	0.055

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* Water poured from top of cement for a determination of the conductance of the surface water. The disturbance thus produced rendered further readings on this sample inaccurate.

TABLE XXVI

STRATIFICATION MEASUREMENTS

Cement A
Sample Number 211
Water/cement 0.400

June 24, 1936

Time	Potentiometer Readings for Electrodes Number						Temper- ature	Surface Levels	
	1	2	3	4	5	6		Water	Cement
(min)							(°C)	(in)	(in)
10	507	565	567	563	581	637	26.9		
15	492	544	552	550	568	628			
20	486	541	551	551	570	629	26.9	0.022	0.066
25	481	540	551	552	573	629			
30	474	533	545	547	567	622	26.7	0.044	0.088
35	465	525	538	540	560	614			
40	458	518	532	551	551	604	26.7	0.044	0.100
45	454	513	528	530	547	598			
50	454	514	528	531	547	599	26.7	0.055	0.110
55	456	515	529	530	547	599			
60	457	515	527	528	546	598	26.6	0.055	0.110
70	451	506	517	516	534	585			
80	449	501	513	510	527	577			
90	446	495	504	503	520	569	26.3	0.066	0.110
100	445	492	504	504	519	569			
110	447	495	507	508	522	574			
120	452	503	513	511	528	579	26.2	0.077	0.110
130	465	512	522	518	537	587			
140	467	513	521	518	536	586			
150	472	515	524	520	537	588	26.2	0.100	0.110
160	478	518	525	521	538	589			
170	489	520	523	537	588	588			
180	494	520	523	521	535	588	26.1		0.110

TABLE XXVII

CONDUCTANCES OF SURFACE WATER

Cement	Sample Number	$\frac{\text{Water}}{\text{cement}}$	(G_w) Conductance with water (10^{-2} mhos)	(G_g) Conductance without water (10^{-2} mhos)	(d_w) Depth of water (in)	$\frac{G_w - G_g}{d_w}$ (10^{-2} mhos/in)
A	195	0.350	5.88	6.21	0.083	8.10
B		0.350	(no water on top of sample)			
C	202	0.350	2.30	2.22	0.022	3.63
A	210	0.400	3.69	3.46	0.060	3.83

TABLE XXVIII

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement A
Sample Number 193
Water/cement 0.350

Time	Electrode Number	Potentiometer Reading	Sample Resistance	(G_s) Sample Conductance	Water Depth	(G_s') Conductance	Cement Level	(G_s'') Conductance	Percentage Conductance
(min)			(ohms)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(per cent)
15	1	345	19.8	5.06	0.017	4.91	0.035	5.08	105.0
	2	378	20.1	4.98					103.0
	3	386	20.7	4.83					100.0
	4	381	20.7	4.85					100.4
	5	400	20.8	4.81					99.5
	6	453	21.2	4.72					97.6
30	1	333	19.0	5.26	0.050	4.86	0.098	5.40	103.9
	2	352	18.6	5.38					103.5
	3	355	18.9	5.29					101.8
	4	362	19.0	5.26					101.2
	5	378	19.6	5.10					98.2
	6	432	20.2	4.95					95.3
45	1	330	18.9	5.29	0.063	4.78	0.122	5.45	103.0
	2	348	18.4	5.43					102.6
	3	350	18.7	5.35					101.1
	4	347	18.7	5.35					101.1
	5	369	19.1	5.24					99.1
	6	419	19.6	5.10					96.4
60	1	336	19.2	5.21	0.068	4.66	0.130	5.36	101.9
	2	352	18.6	5.38					102.3
	3	353	18.8	5.32					101.1
	4	350	18.8	5.32					101.1
	5	371	19.2	5.21					99.0
	6	420	19.6	5.10					97.0
90	1	362	20.8	4.81	0.040	4.49	0.140	5.23	102.3
	2	362	19.2	5.21					102.2
	3	364	19.4	5.15					101.0
	4	365	19.7	5.08					99.4
	5	381	19.7	5.08					99.4
	6	427	20.0	5.00					97. 8

TABLE XXVIII (continued)

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
120	1	397	22.9	4.37	0.000	4.37	0.140	5.08	101.9
	2	372	19.7	5.08					101.9
	3	374	20.0	5.00					100.3
	4	377	20.4	4.90					98.3
	5	387	20.1	4.97					99.7
	6	431	20.2	4.95					99.3
150	1	410	23.7	4.22	0.000	4.22	0.140	4.92	100.0
	2	377	20.0	5.00					101.6
	3	378	20.2	4.95					100.7
	4	384	20.8	4.81					97.8
	5	392	20.3	4.93					100.2
	6	435	20.4	4.90					99.6
180	1	411	23.8	4.20	0.000	4.20	0.140	4.89	100.2
	2	379	20.1	4.96					101.6
	3	381	20.4	4.90					100.4
	4	387	20.9	4.78					98.0
	5	396	20.6	4.88					100.0
	6	438	20.5	4.88					100.0

TABLE XXIX

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement A
Sample Number 194
Water/cement 0.350

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
15	1	222	18.4	5.43	0.000	5.43	0.000	5.43	103.7
	2	245	18.9	5.29					101.0
	3	246	19.0	5.26					100.5
	4	241	19.0	5.26					100.5
	5	254	19.1	5.24					100.1
	6	278	19.5	5.13					98.0
30	1	216	17.9	5.59	0.030	5.35	0.080	5.82	108.4
	2	237	18.3	5.46					101.7
	3	239	18.5	5.41					100.8
	4	235	18.5	5.41					100.8
	5	250	18.7	5.35					99.7
	6	274	19.2	5.21					97.1
45	1	213	17.6	5.68	0.060	5.19	0.120	5.90	108.2
	2	233	18.0	5.56					102.0
	3	236	18.2	5.50					100.9
	4	231	18.2	5.50					100.9
	5	247	18.5	5.41					99.2
	6	270	18.9	5.29					97.0
60	1	212	17.6	5.68	0.075	5.07	0.140	5.92	107.8
	2	232	18.0	5.59					102.1
	3	235	18.1	5.52					100.9
	4	231	18.2	5.49					100.3
	5	247	18.5	5.41					98.9
	6	267	18.7	5.35					97.8
90	1	220	18.3	5.46	0.065	4.93	0.150	5.86	109.8
	2	241	18.6	5.38					100.8
	3	240	18.5	5.41					101.9
	4	235	18.6	5.38					100.8
	5	253	19.0	5.26					98.5
	6	271	19.0	5.26					98.5

TABLE XXIX (continued)

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
120	1	242	20.2	4.95	0.000	4.95	0.150	5.80	112.4
	2	252	19.5	5.13					99.4
	3	249	19.3	5.18					100.4
	4	241	19.0	5.26					101.9
	5	260	19.5	5.13					99.4
	6	278	19.6	5.10					98.8
150	1	258	21.6	4.63	0.000	4.63	0.150	5.45	107.5
	2	258	20.0	5.00					98.6
	3	254	19.7	5.08					100.2
	4	244	19.3	5.18					102.1
	5	263	19.8	5.05					99.6
	6	282	19.8	5.05					99.6
180	1	264	22.1	4.52	0.000	4.52	0.150	5.32	105.8
	2	261	20.2	4.95					98.4
	3	256	19.8	5.05					100.4
	4	247	19.5	5.13					102.0
	5	265	19.9	5.03					100.0
	6	285	20.1	4.98					99.0

TABLE XXX

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement A
Sample Number 195
Water/cement 0.350

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
15	1	222	18.7	5.35	0.005	5.31	0.011	5.37	109.5
	2	248	19.7	5.08					103.6
	3	261	20.3	4.93					100.6
	4	256	20.3	4.93					100.6
	5	275	20.7	4.83					98.5
	6	311	21.1	4.74					96.7
30	1	216	18.2	5.49	0.028	5.26	0.029	5.42	107.9
	2	241	19.1	5.24					104.4
	3	254	19.7	5.08					101.2
	4	249	19.7	5.08					101.2
	5	271	20.3	4.93					98.2
	6	307	20.9	4.78					95.2
45	1	210	17.6	5.68	0.065	5.15	0.076	5.57	109.1
	2	236	18.7	5.35					104.8
	3	250	19.4	5.15					100.9
	4	245	19.4	5.15					100.9
	5	267	20.0	5.00					97.9
	6	302	20.5	4.88					95.6
60	1	205	17.2	5.81	0.083	5.14	0.104	5.67	109.7
	2	234	18.4	5.43					105.0
	3	248	19.2	5.21					100.8
	4	243	19.2	5.21					100.8
	5	264	19.8	5.05					97.7
	6	297	20.2	4.95					95.7

TABLE XXXI

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement B
Sample Number 197
Water/cement 0.350

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
15	1	301	16.8	5.95	0.000	5.95	0.025	6.10	103.6
	2	323	17.0	5.88					99.8
	3	323	16.9	5.92					100.5
	4	318	16.8	5.95					101.0
	5	344	17.1	5.85					99.3
	6	362	17.1	5.85					99.3
30	1	300	16.7	5.99	0.000	5.99	0.060	6.37	105.5
	2	318	16.7	5.99					99.2
	3	314	16.4	6.10					101.0
	4	311	16.4	6.10					101.0
	5	337	16.7	5.99					99.2
	6	355	16.6	6.02					99.7
45	1	300	16.7	5.99	0.000	5.99	0.079	6.50	106.1
	2	314	16.5	6.06					98.9
	3	309	16.1	6.21					101.4
	4	306	16.3	6.13					100.3
	5	331	16.4	6.10					99.6
	6	349	16.3	6.13					100.1
60	1	301	16.8	5.95	0.000	5.95	0.090	6.54	105.3
	2	312	16.3	6.13					98.7
	3	307	16.0	6.25					100.6
	4	302	15.9	6.29					101.3
	5	327	16.2	6.17					99.4
	6	344	16.1	6.21					100.0
90	1	311	17.4	5.75	0.000	5.75	0.102	6.40	106.6
	2	324	17.0	5.88					98.0
	3	317	16.6	6.02					100.3
	4	312	16.4	6.10					101.6
	5	336	16.7	5.99					99.8
	6	354	16.6	6.02					100.3

TABLE XXXI (continued)

Time	Electrode Number	Potentiometer Reading	Sample Resistance	(G_s) Sample Conductance	Water Depth	(G_s') Conductance	Cement Level	(G_s'') Conductance	Percentage Conductance
(min)			(ohms)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(per cent)
120	1	314	17.6	5.68	0.000	5.68	0.110	6.38	107.3
	2	328	17.2	5.81					97.7
	3	321	16.8	5.95					100.1
	4	315	16.6	6.02					101.3
	5	339	16.8	5.95					100.1
	6	357	16.7	5.99					100.8
150	1	315	17.6	5.68	0.000	5.68	0.110	6.38	108.8
	2	331	17.4	5.75					98.1
	3	324	16.9	5.92					101.0
	4	319	16.8	5.95					101.5
	5	344	17.1	5.85					99.8
	6	364	17.1	5.85					99.8
180	1	318	17.8	5.62	0.000	5.62	0.110	6.31	110.7
	2	336	17.7	5.65					99.1
	3	331	17.3	5.78					101.4
	4	328	17.5	5.71					100.2
	5	353	17.6	5.68					99.6
	6	374	17.6	5.68					99.6

TABLE XXXII

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement B
Sample Number 198
Water/cement 0.350

Time	Electrode Number	Potentiometer Reading	Sample Resistance	(G_s) Sample Conductance	Water Depth	(G'_s) Conductance	Cement Level	(G''_s) Conductance	Percentage Conductance
(min)			(ohms)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(per cent)
15	1	294	16.0	6.25	0.000	6.25	0.030	6.44	102.9
	2	302	15.8	6.33					101.2
	3	305	15.7	6.37					101.8
	4	304	16.1	6.21					99.2
	5	320	16.0	6.25					99.9
	6	343	16.3	6.13					98.0
30	1	294	16.0	6.25	0.000	6.25	0.071	6.73	104.6
	2	297	15.5	6.45					100.2
	3	298	15.3	6.54					101.6
	4	295	15.5	6.45					100.2
	5	312	15.6	6.41					99.6
	6	334	15.8	6.33					98.4
45	1	294	16.0	6.25	0.000	6.25	0.090	6.87	105.1
	2	294	15.4	6.49					99.3
	3	293	15.1	6.62					101.3
	4	291	15.3	6.54					100.1
	5	306	15.3	6.54					100.1
	6	327	15.4	6.49					99.3
60	1	294	16.0	6.25	0.000	6.25	0.100	6.89	106.5
	2	302	15.8	6.33					97.2
	3	292	15.0	6.67					102.4
	4	294	15.5	6.45					99.0
	5	303	15.2	6.58					101.0
	6	324	15.3	6.54					100.4
90	1	300	16.3	6.13	0.000	6.13	0.110	6.89	107.7
	2	310	16.3	6.13					95.8
	3	297	15.3	6.54					102.2
	4	299	15.8	6.33					98.9
	5	306	15.3	6.54					102.2
	6	328	15.5	6.45					100.8

TABLE XXXII (continued)

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
120	1	304	16.5	6.06	0.000	6.06	0.120	6.89	109.2
	2	314	16.5	6.06					96.1
	3	303	15.6	6.41					101.6
	4	303	16.0	6.25					99.1
	5	310	15.5	6.45					102.3
	6	332	15.7	6.37					101.0
150	1	309	16.8	5.95	0.000	5.95	0.120	6.76	108.9
	2	318	16.7	5.99					96.5
	3	309	15.9	6.29					101.4
	4	309	16.3	6.13					98.8
	5	314	15.7	6.37					102.6
	6	338	16.0	6.25					100.7
180	1	325	17.8	5.62	0.000	5.62	0.120	6.39	110.4
	2	340	17.9	5.59					96.6
	3	331	17.1	5.85					101.0
	4	329	17.5	5.71					98.6
	5	335	16.8	5.95					102.8
	6	360	17.1	5.85					101.0

TABLE XXXIII

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement C
Sample Number 200
Water/cement 0.350

Time	Electrode Number	Potentiometer Reading	Sample Resistance	(G_s) Sample Conductance	Water Depth	(G_s') Conductance	Cement Level	(G_s'') Conductance	Percentage Conductance
(min)			(ohms)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(per cent)
15	1	410	45.6	2.19	0.010	2.15	0.020	2.19	101.6
	2	471	45.5	2.20					102.0
	3	476	46.3	2.16					100.2
	4	484	46.6	2.15					99.7
	5	478	46.2	2.16					100.2
	6	537	47.4	2.11					97.9
30	1	403	43.8	2.28	0.042	2.13	0.068	2.29	101.5
	2	451	43.6	2.29					101.5
	3	461	43.8	2.28					101.1
	4	442	44.1	2.25					99.7
	5	457	44.1	2.27					100.6
	6	517	45.6	2.19					97.1
45	1	391	42.5	2.35	0.055	2.15	0.092	2.34	100.2
	2	436	42.1	2.38					101.9
	3	436	42.3	2.36					101.0
	4	428	43.0	2.33					99.7
	5	443	42.7	2.34					100.2
	6	500	44.1	2.27					97.2
60	1	381	41.4	2.42	0.061	2.20	0.100	2.44	101.7
	2	424	40.9	2.44					101.7
	3	424	41.1	2.43					101.2
	4	418	41.9	2.39					99.6
	5	431	41.5	2.41					100.4
	6	487	42.9	2.33					97.1
90	1	396	43.1	2.32	0.038	2.18	0.104	2.43	103.4
	2	434	41.9	2.39					101.7
	3	430	41.7	2.40					102.1
	4	427	42.9	2.33					99.1
	5	441	42.5	2.35					100.0
	6	498	43.9	2.28					97.0

TABLE XXXIII (continued)

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
120	1	417	45.4	2.20	0.026	2.11	0.111	2.37	102.4
	2	444	42.9	2.33					100.7
	3	436	42.3	2.36					102.0
	4	433	43.5	2.30					99.4
	5	445	42.9	2.33					100.7
	6	504	44.5	2.25					97.2
150	1	429	46.7	2.14	0.000	2.14	0.120	2.43	105.8
	2	448	43.3	2.31					100.3
	3	439	42.6	2.35					102.1
	4	435	43.7	2.29					99.5
	5	447	43.1	2.32					100.8
	6	505	44.6	2.24					97.3
180	1	433	47.2	2.12	0.000	2.12	0.120	2.41	105.0
	2	450	43.5	2.30					100.2
	3	440	42.7	2.34					101.9
	4	436	43.8	2.28					99.3
	5	447	43.1	2.32					101.0
	6	506	44.6	2.24					97.6

TABLE XXXIV

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement C
Sample Number 201
Water/cement 0.350

Time	Electrode Number	Potentiometer Reading	Sample Resistance	(G_s) Sample Conductance	Water Depth	(G_s') Conductance	Cement Level	(G_s'') Conductance	Percentage Conductance
(min)			(ohms)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(per cent)
15	1	355	43.4	2.30	0.022	2.22	0.060	2.36	108.5
	2	400	46.1	2.17					99.7
	3	407	45.9	2.16					100.2
	4	392	45.7	2.19					100.6
	5	407	45.9	2.18					100.2
	6	449	46.4	2.16					99.7
30	1	348	42.5	2.35	0.025	2.26	0.092	2.49	109.2
	2	379	43.6	2.29					100.4
	3	383	43.2	2.32					101.8
	4	374	43.6	2.29					100.4
	5	391	44.0	2.27					99.6
	6	433	44.7	2.24					98.2
45	1	342	41.8	2.39	0.030	2.28	0.105	2.55	107.0
	2	369	42.5	2.35					100.0
	3	373	42.0	2.38					101.3
	4	363	42.2	2.37					100.9
	5	380	42.8	2.34					99.6
	6	419	43.2	2.31					98.3
60	1	341	41.7	2.40	0.024	2.31	0.110	2.60	109.6
	2	366	42.1	2.38					100.3
	3	369	41.6	2.40					101.1
	4	360	41.9	2.39					100.7
	5	374	42.1	2.38					100.3
	6	412	42.5	2.35					99.0
90	1	356	43.5	2.30	0.009	2.27	0.115	2.56	109.5
	2	376	43.3	2.31					98.8
	3	375	42.2	2.37					101.4
	4	367	42.7	2.34					100.1
	5	379	42.7	2.34					100.1
	6	417	43.0	2.33					99.7

TABLE XXXIV (continued)

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G'_s) Conductance (10^{-2} mhos)	Cement Level (in)	(G''_s) Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
120	1	366	44.8	2.23	0.000	2.23	0.120	2.53	109.7
	2	386	44.5	2.25					97.6
	3	381	42.9	2.33					101.0
	4	372	42.7	2.34					101.5
	5	384	43.2	2.31					100.2
	6	421	43.4	2.30					99.7
150	1	369	45.2	2.21	0.000	2.21	0.120	2.51	110.3
	2	393	45.3	2.21					97.1
	3	385	43.4	2.30					101.1
	4	375	43.7	2.29					100.6
	5	387	43.6	2.29					100.6
	6	424	43.7	2.29					100.6
180	1	370	45.3	2.21	0.000	2.21	0.120	2.51	110.8
	2	395	45.6	2.19					96.7
	3	387	43.6	2.29					101.1
	4	378	44.0	2.27					100.3
	5	388	43.7	2.29					101.1
	6	426	43.9	2.28					100.7

TABLE XXXV

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement C
Sample Number 202
Water/cement 0.350

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
15	1	352	44.1	2.27	0.010	2.23	0.018	2.28	104.1
	2	397	46.4	2.16					98.6
	3	397	46.4	2.16					98.6
	4	384	44.3	2.26					103.2
	5	412	45.2	2.21					100.9
	6	465	46.3	2.16					98.6
30	1	351	44.0	2.27	0.020	2.20	0.066	2.36	104.1
	2	384	44.9	2.23					98.4
	3	381	44.5	2.25					99.3
	4	372	43.0	2.33					102.8
	5	397	43.7	2.29					101.1
	6	450	44.8	2.23					98.4
45	1	347	43.5	2.30	0.022	2.22	0.066	2.38	103.7
	2	378	44.2	2.26					98.4
	3	374	43.7	2.29					99.7
	4	368	42.5	2.35					102.4
	5	392	43.1	2.32					101.0
	6	445	44.3	2.26					98.4

TABLE XXXVI

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement A
Sample Number 207
Water/cement 0.400

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
15	1	495	31.0	3.23	0.020	3.16	0.045	3.31	106.0
	2	552	32.5	3.08					98.6
	3	585	32.1	3.12					99.9
	4	603	31.3	3.19					102.1
	5	652	31.3	3.19					102.1
	6	759	32.9	3.04					97.3
30	1	498	31.2	3.21	0.040	3.06	0.100	3.40	106.8
	2	539	31.7	3.15					98.9
	3	572	31.3	3.19					100.2
	4	592	30.7	3.26					102.4
	5	643	30.9	3.24					101.8
	6	749	32.5	3.08					96.7
45	1	501	31.4	3.18	0.030	3.07	0.105	3.43	105.4
	2	530	31.1	3.22					99.0
	3	561	30.7	3.26					100.2
	4	580	30.0	3.33					102.3
	5	620	30.2	3.31					101.7
	6	732	31.7	3.15					96.8
60	1	504	31.6	3.16	0.010	3.12	0.105	3.49	105.7
	2	525	30.8	3.25					98.4
	3	554	30.3	3.30					99.9
	4	572	29.6	3.38					102.4
	5	619	29.7	3.37					101.8
	6	720	31.2	3.21					97.2
90	1	499	31.3	3.19	0.000	3.19	0.110	3.58	106.5
	2	516	30.3	3.30					98.2
	3	543	29.7	3.37					100.2
	4	563	29.1	3.44					102.3
	5	607	29.1	3.44					102.3
	6	709	30.7	3.26					97.0

TABLE XXXVI (continued)

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
120	1	496	31.1	3.22	0.000	3.22	0.110	3.62	107.6
	2	520	30.5	3.28					97.5
	3	541	29.6	3.38					100.5
	4	562	29.1	3.44					102.3
	5	605	29.0	3.45					102.6
	6	707	30.6	3.27					97.2
150	1	501	31.4	3.18	0.000	3.18	0.110	3.57	107.1
	2	528	31.0	3.23					96.9
	3	548	30.0	3.33					99.9
	4	565	29.2	3.42					102.6
	5	608	29.2	3.42					102.6
	6	710	30.7	3.26					97.8
180	1	506	31.7	3.15	0.000	3.15	0.110	3.54	107.5
	2	537	31.5	3.17					96.2
	3	558	30.5	3.28					99.6
	4	570	29.5	3.39					102.9
	5	612	29.4	3.40					103.2
	6	715	31.0	3.23					98.1

TABLE XXXVII

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement A
Sample Number 210
Water/cement 0.400

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
15	1	502	28.1	3.56	0.020	3.48	0.020	3.55	107.4
	2	562	29.9	3.34					101.1
	3	575	30.0	3.33					100.8
	4	564	30.2	3.31					100.2
	5	584	30.0	3.33					100.8
	6	645	31.2	3.21					97.2
30	1	486	27.2	3.68	0.055	3.47	0.055	3.67	110.3
	2	554	29.4	3.40					102.2
	3	568	29.6	3.38					101.6
	4	560	30.0	3.33					100.1
	5	588	30.2	3.31					99.5
	6	644	31.1	3.22					96.8

TABLE XXXVIII

CALCULATIONS OF PERCENTAGE CONDUCTANCE BASED UPON THE AVERAGE CONDUCTANCE OF SAMPLE BETWEEN ELECTRODES 2 TO 6

Cement A
Sample Number 211
Water/cement 0.400

Time	Electrode Number	Potentiometer Reading	Sample Resistance	(G_s) Sample Conductance	Water Depth	(G_s') Conductance	Cement Level	(G_s'') Conductance	Percentage Conductance
(min)			(ohms)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(in)	(10^{-2} mhos)	(per cent)
15	1	495	28.2	3.55	0.020	3.47	0.040	3.61	106.5
	2	546	28.8	3.47					102.4
	3	554	29.2	3.42					100.9
	4	559	29.7	3.37					99.4
	5	577	29.6	3.38					99.7
	6	631	30.2	3.31					97.6
30	1	473	26.9	3.72	0.050	3.53	0.080	3.84	110.6
	2	531	27.9	3.58					103.1
	3	543	28.6	3.50					100.8
	4	547	29.0	3.45					99.4
	5	566	29.0	3.45					99.4
	6	620	29.6	3.38					97.4
45	1	456	25.9	3.86	0.055	3.65	0.105	4.08	114.2
	2	514	27.0	3.70					103.5
	3	530	27.9	3.58					100.2
	4	533	28.3	3.53					98.8
	5	549	28.1	3.56					99.6
	6	599	28.6	3.50					97.9
60	1	456	25.9	3.86	0.050	3.67	0.110	4.12	114.5
	2	514	27.0	3.70					102.8
	3	526	27.7	3.61					100.3
	4	528	28.0	3.57					99.2
	5	545	27.9	3.58					99.5
	6	594	28.3	3.53					98.1
90	1	447	25.4	3.94	0.040	3.79	0.110	4.26	113.2
	2	496	26.0	3.85					102.3
	3	504	26.5	3.77					100.2
	4	505	26.7	3.75					99.7
	5	521	26.6	3.76					99.9
	6	570	27.2	3.68					97.8

TABLE XXXVIII (continued)

Time (min)	Electrode Number	Potentiometer Reading	Sample Resistance (ohms)	(G_s) Sample Conductance (10^{-2} mhos)	Water Depth (in)	(G_s') Conductance (10^{-2} mhos)	Cement Level (in)	(G_s'') Conductance (10^{-2} mhos)	Percentage Conductance (per cent)
120	1	452	25.7	3.89	0.030	3.78	0.110	4.25	114.9
	2	502	26.4	3.74					102.4
	3	513	27.0	3.70					100.0
	4	512	27.1	3.69					99.7
	5	528	27.0	3.70					100.0
	6	579	27.6	3.62					97.8
150	1	473	26.9	3.72	0.010	3.68	0.110	4.13	113.6
	2	515	27.1	3.69					101.5
	3	523	27.5	3.64					100.1
	4	520	27.5	3.64					100.1
	5	537	27.5	3.64					100.1
	6	588	28.0	3.57					98.2
180	1	493	28.1	3.56	0.000	3.56	0.110	4.00	110.6
	2	520	27.3	3.66					101.2
	3	525	27.6	3.62					100.1
	4	522	27.7	3.61					99.8
	5	538	27.5	3.64					100.6
	6	589	28.1	3.56					98.4

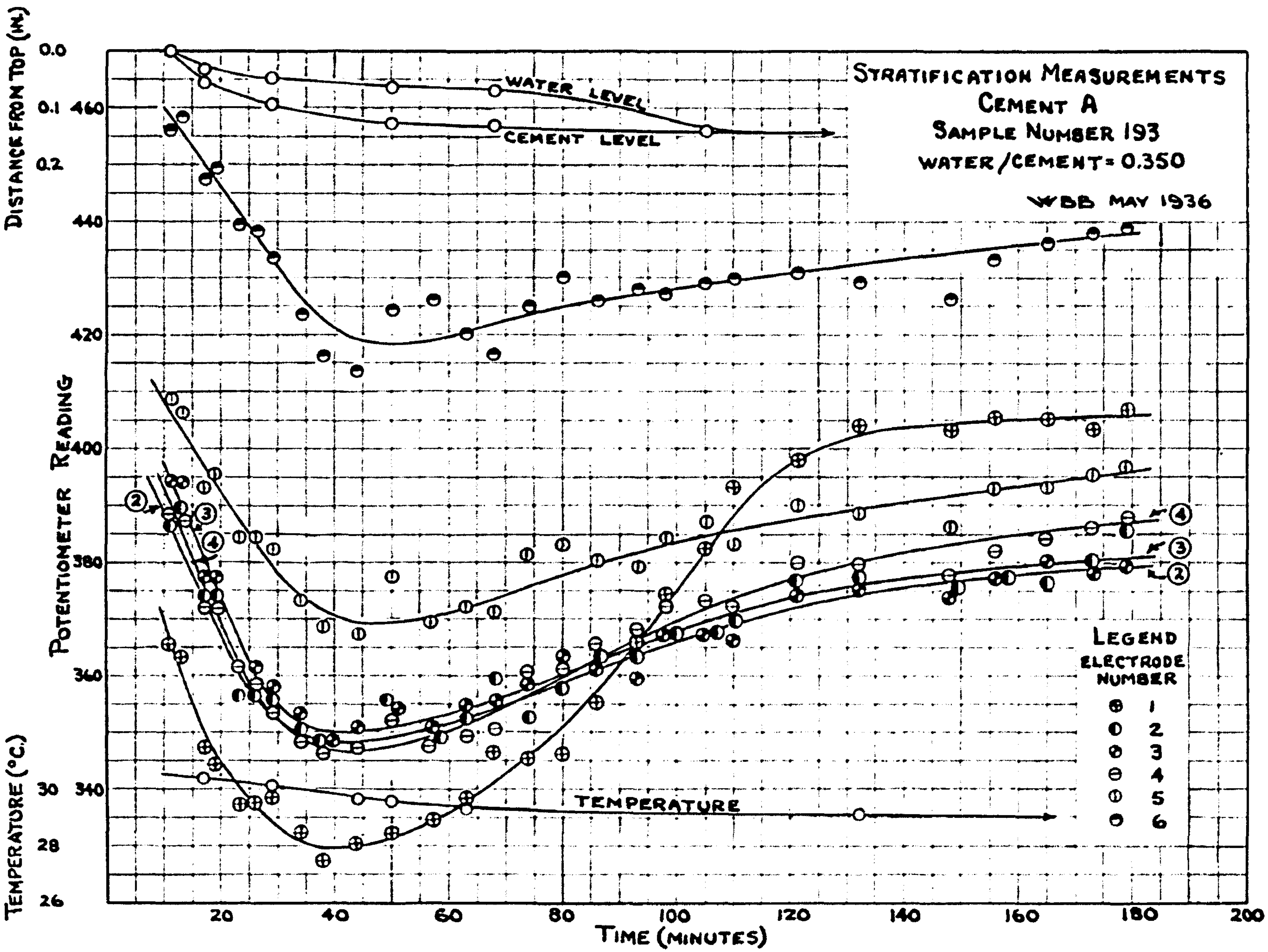

STRATIFICATION MEASUREMENTS
CEMENT A
SAMPLE NUMBER 193
WATER/CEMENT = 0.350
WBB MAY 1936
WATER LEVEL
CEMENT LEVEL
TEMPERATURE
DISTANCE FROM TOP (IN.)
0.0
0.1
0.2
POTENTIOMETER READING
460
440
420
400
380
360
340
TEMPERATURE (°C.)
30
28
26
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200
②
③
④
LEGEND
ELECTRODE NUMBER
⊕ 1
◐ 2
◒ 3
⊖ 4
⦶ 5
◓ 6

Figure 26

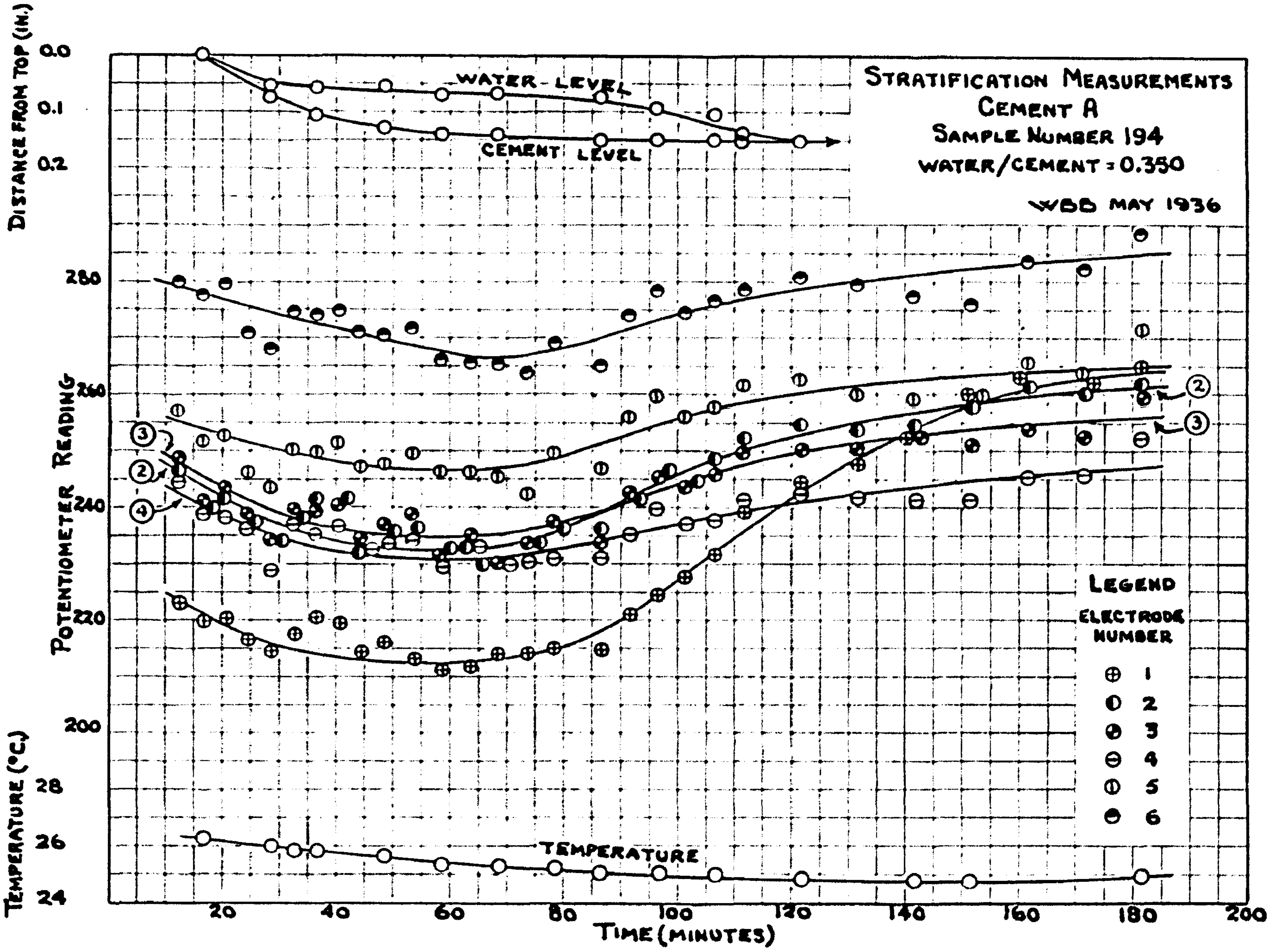
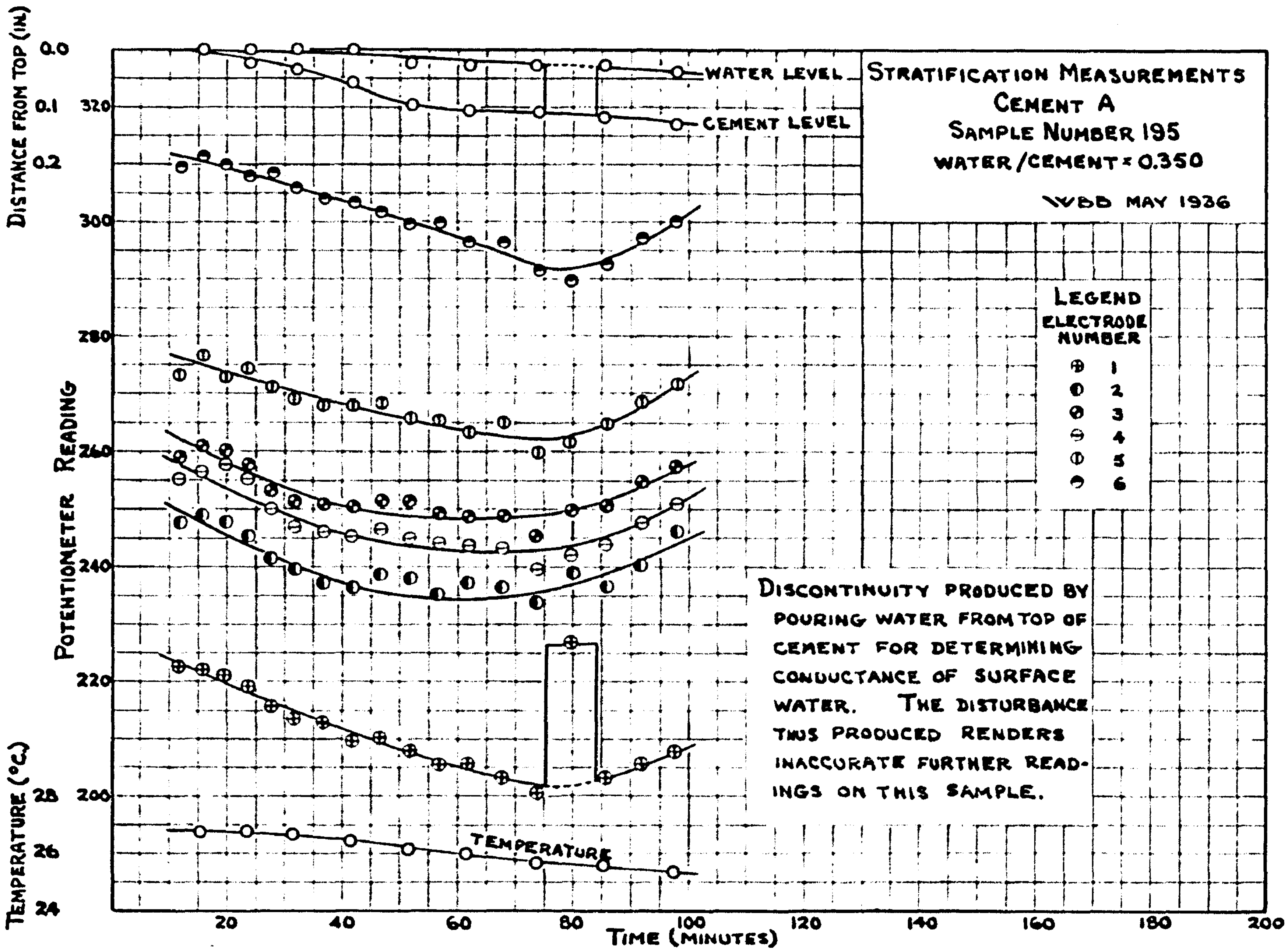

STRATIFICATION MEASUREMENTS
CEMENT A
SAMPLE NUMBER 194
WATER/CEMENT = 0.350
WBB MAY 1936
WATER-LEVEL
CEMENT LEVEL
DISTANCE FROM TOP (IN.)
0.0
0.1
0.2
POTENTIOMETER READING
280
260
240
220
200
TEMPERATURE (°C.)
28
26
24
TEMPERATURE
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200
LEGEND
ELECTRODE NUMBER
⊕ 1
2
3
⊖ 4
5
6
①
②
③
④

Figure 27


STRATIFICATION MEASUREMENTS
CEMENT A
SAMPLE NUMBER 195
WATER/CEMENT = 0.350

WBD MAY 1936

DISCONTINUITY PRODUCED BY POURING WATER FROM TOP OF CEMENT FOR DETERMINING CONDUCTANCE OF SURFACE WATER. THE DISTURBANCE THUS PRODUCED RENDERS INACCURATE FURTHER READINGS ON THIS SAMPLE.

Figure 28

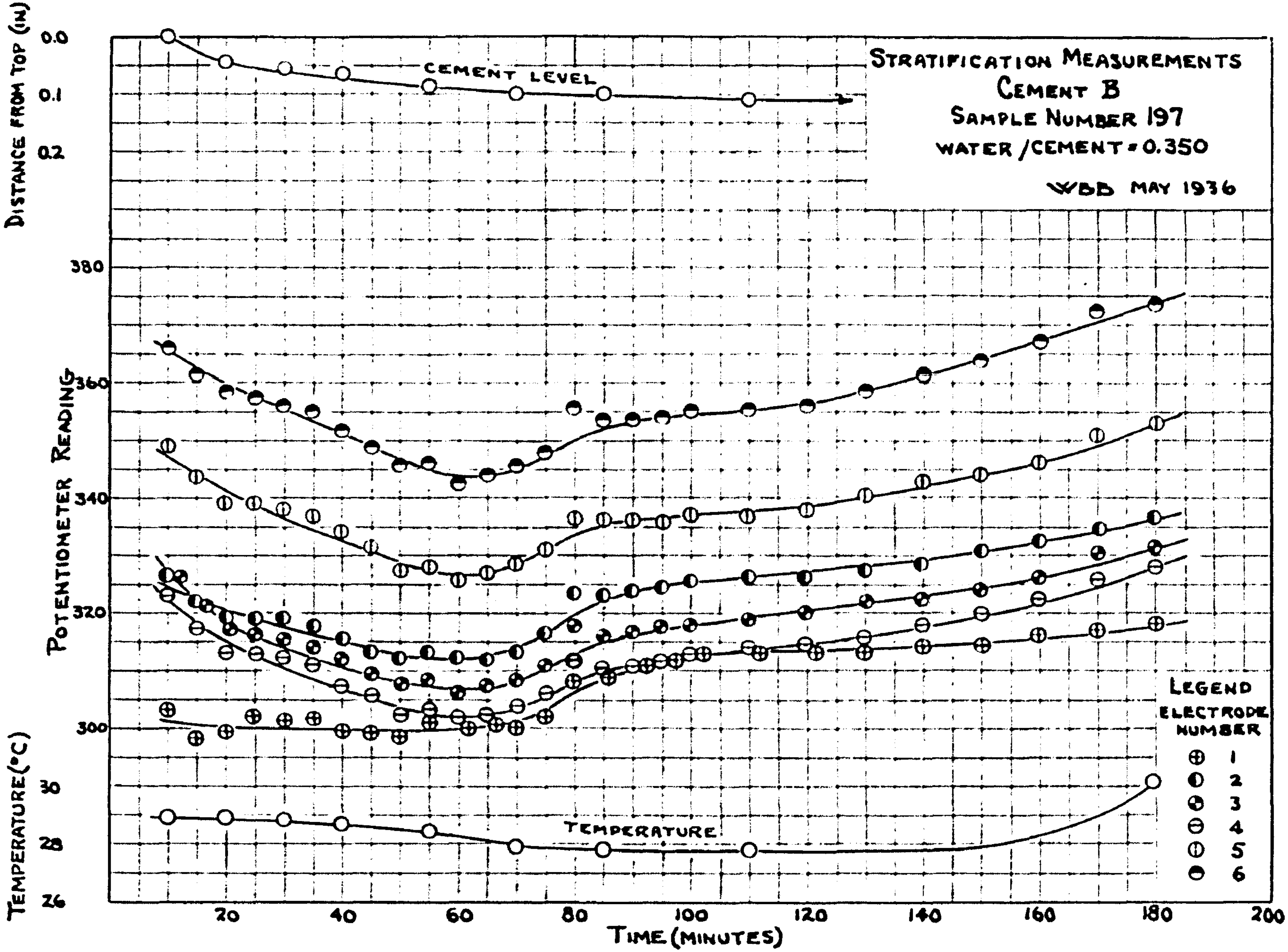

STRATIFICATION MEASUREMENTS
CEMENT B
SAMPLE NUMBER 197
WATER/CEMENT = 0.350
WBD MAY 1936
DISTANCE FROM TOP (IN)
0.0
0.1
0.2
CEMENT LEVEL
POTENTIOMETER READING
380
360
340
320
300
TEMPERATURE (°C)
30
28
26
TEMPERATURE
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200
LEGEND
ELECTRODE NUMBER
⊕ 1
◐ 2
3
⊖ 4
⦶ 5
◒ 6

Figure 29

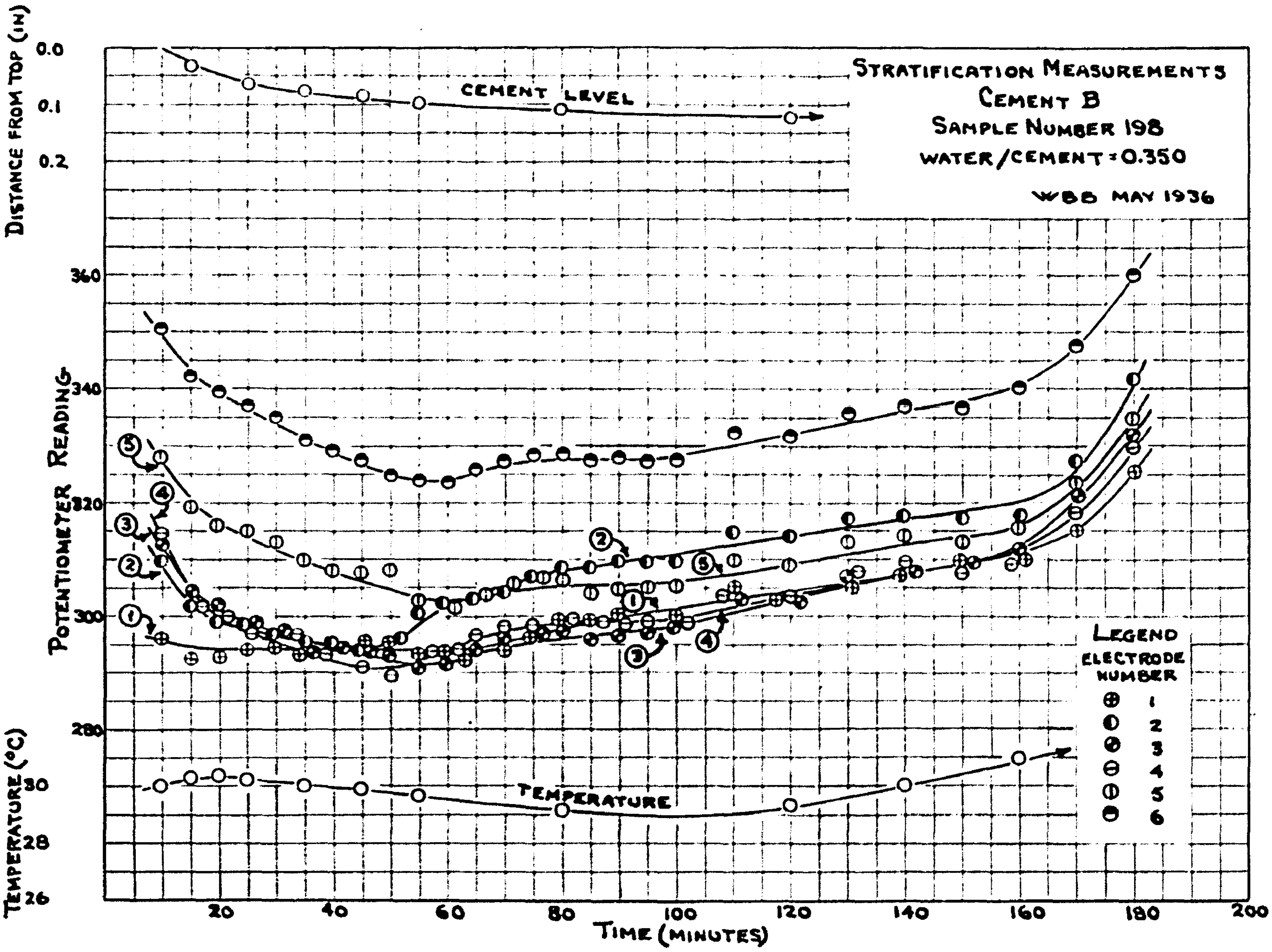

STRATIFICATION MEASUREMENTS
CEMENT B
SAMPLE NUMBER 198
WATER/CEMENT = 0.350
WBB MAY 1936
DISTANCE FROM TOP (IN)
0.0
0.1
0.2
CEMENT LEVEL
POTENTIOMETER READING
360
340
320
300
280
TEMPERATURE (°C)
30
28
26
TEMPERATURE
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200
①
②
③
④
⑤
LEGEND
ELECTRODE NUMBER
⊕ 1
◐ 2
⊘ 3
⊖ 4
⦶ 5
◒ 6

Figure 30

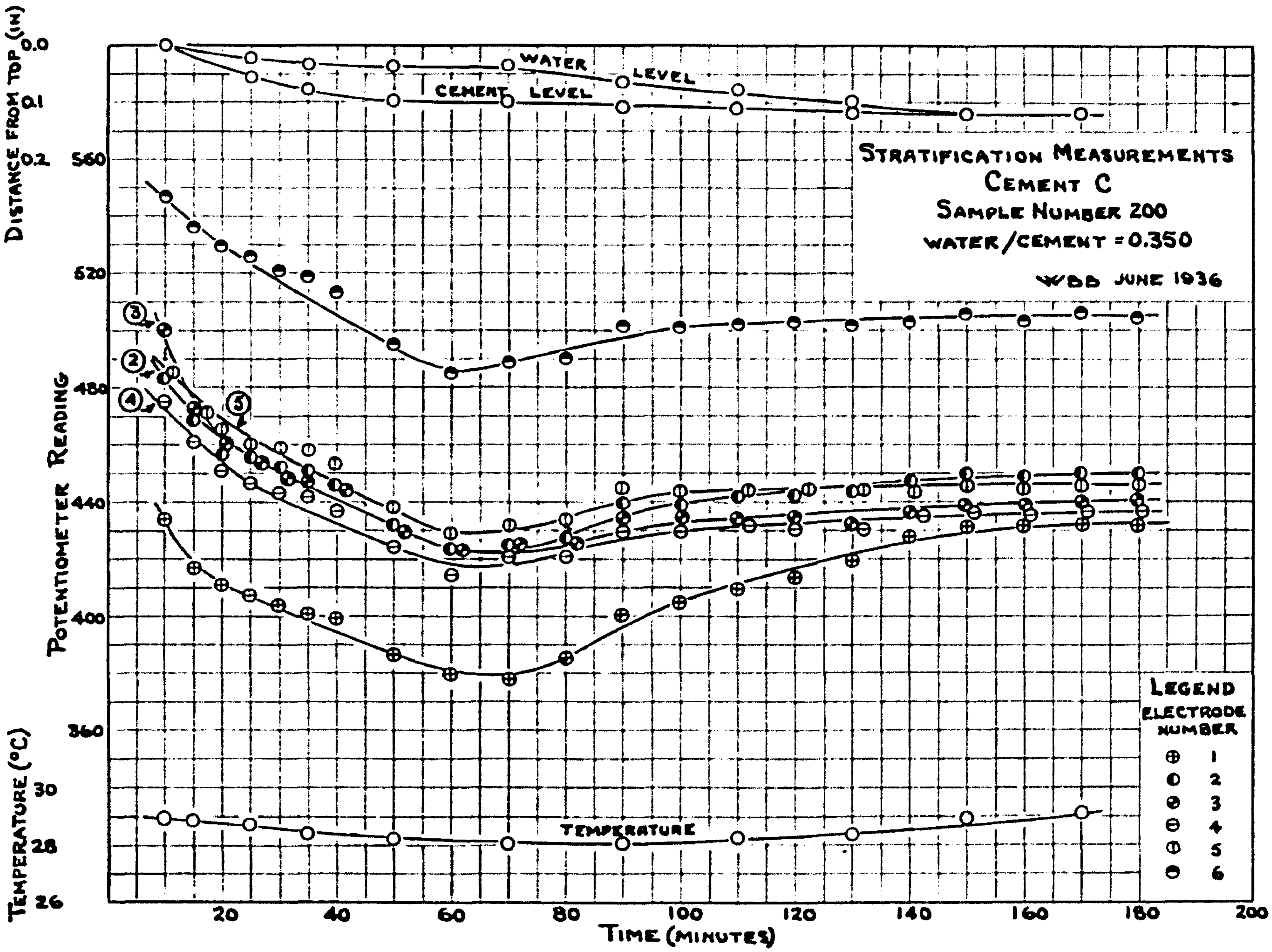
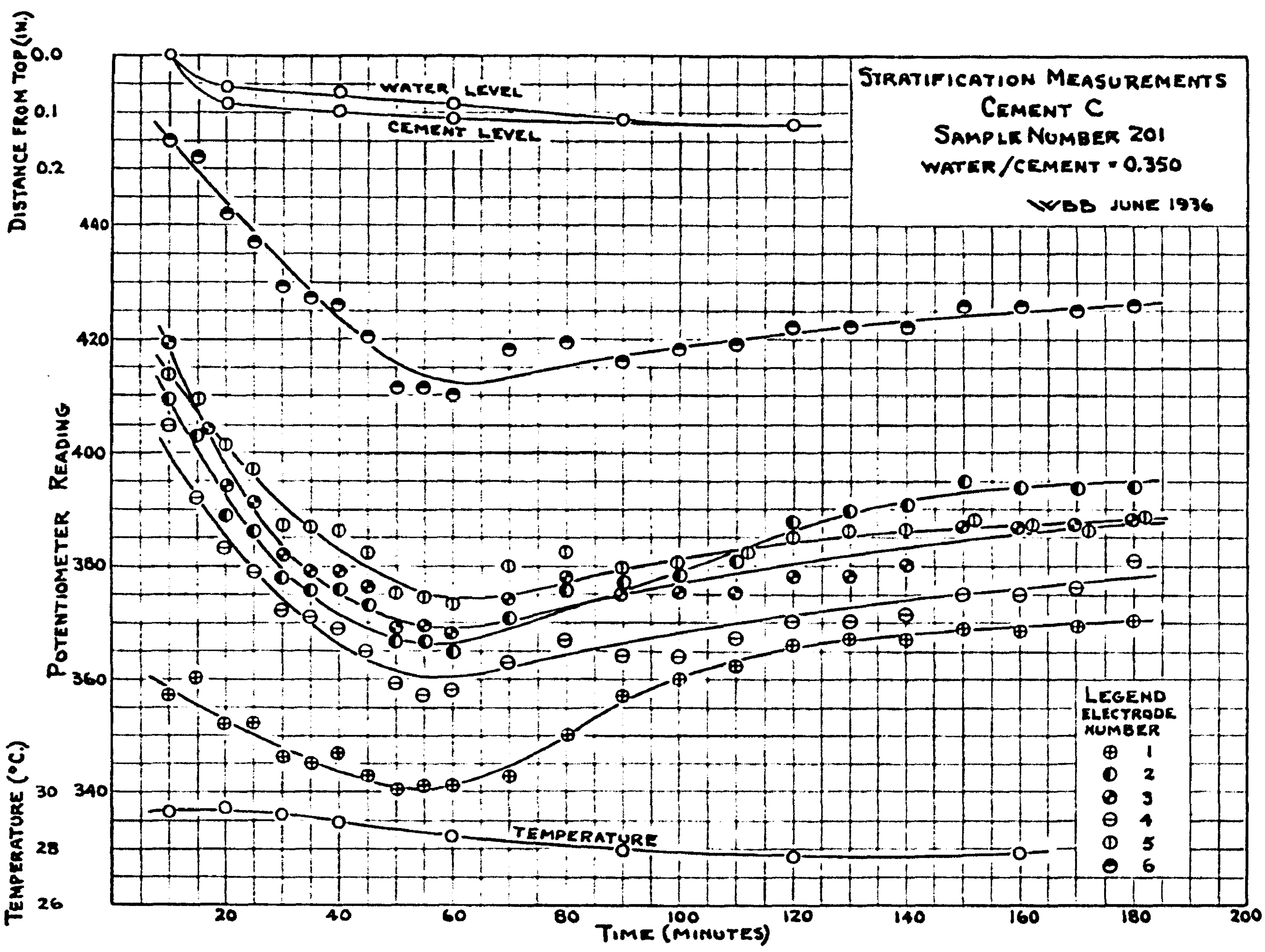

STRATIFICATION MEASUREMENTS
CEMENT C
SAMPLE NUMBER 200
WATER/CEMENT = 0.350
WBB JUNE 1936
DISTANCE FROM TOP (IN)
0.0
0.1
0.2
WATER LEVEL
CEMENT LEVEL
POTENTIOMETER READING
560
520
480
440
400
360
③
②
④
⑤
TEMPERATURE (°C)
30
28
26
TEMPERATURE
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200
LEGEND
ELECTRODE NUMBER
⊕ 1
◐ 2
⊖ 3
⊖ 4
⦶ 5
⊖ 6

Figure 31

Figure 32



STRATIFICATION MEASUREMENTS
CEMENT C
SAMPLE NUMBER 201
WATER/CEMENT = 0.350
WBB JUNE 1936

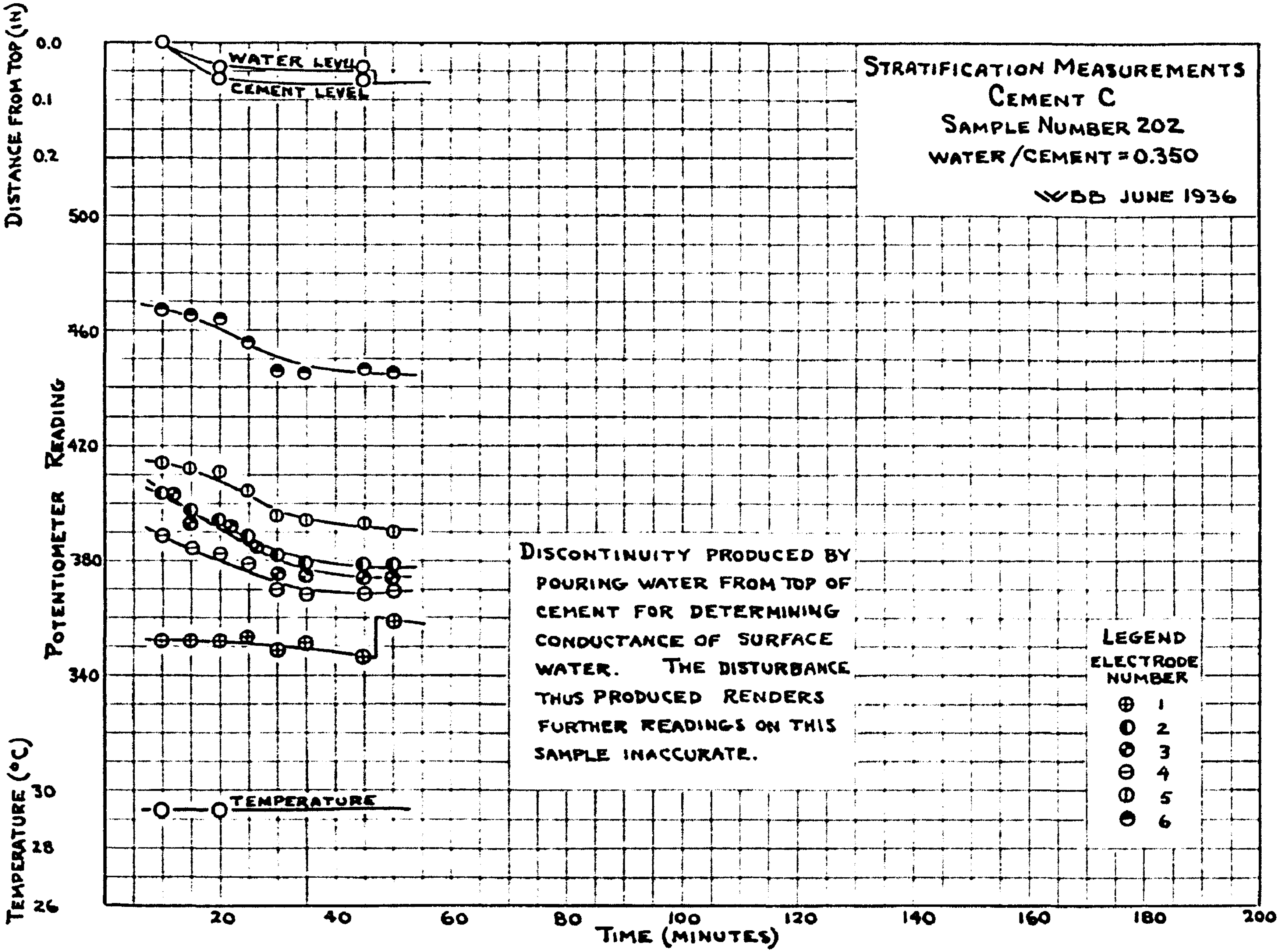

STRATIFICATION MEASUREMENTS
CEMENT C
SAMPLE NUMBER 202
WATER/CEMENT = 0.350
WBB JUNE 1936
DISTANCE FROM TOP (IN)
0.0
0.1
0.2
WATER LEVEL
CEMENT LEVEL
POTENTIOMETER READING
500
460
420
380
340
TEMPERATURE (°C)
30
28
26
TEMPERATURE
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200
DISCONTINUITY PRODUCED BY POURING WATER FROM TOP OF CEMENT FOR DETERMINING CONDUCTANCE OF SURFACE WATER. THE DISTURBANCE THUS PRODUCED RENDERS FURTHER READINGS ON THIS SAMPLE INACCURATE.
LEGEND
ELECTRODE NUMBER
⊕ 1
◐ 2
⊗ 3
⊖ 4
⦶ 5
◓ 6

Figure 33

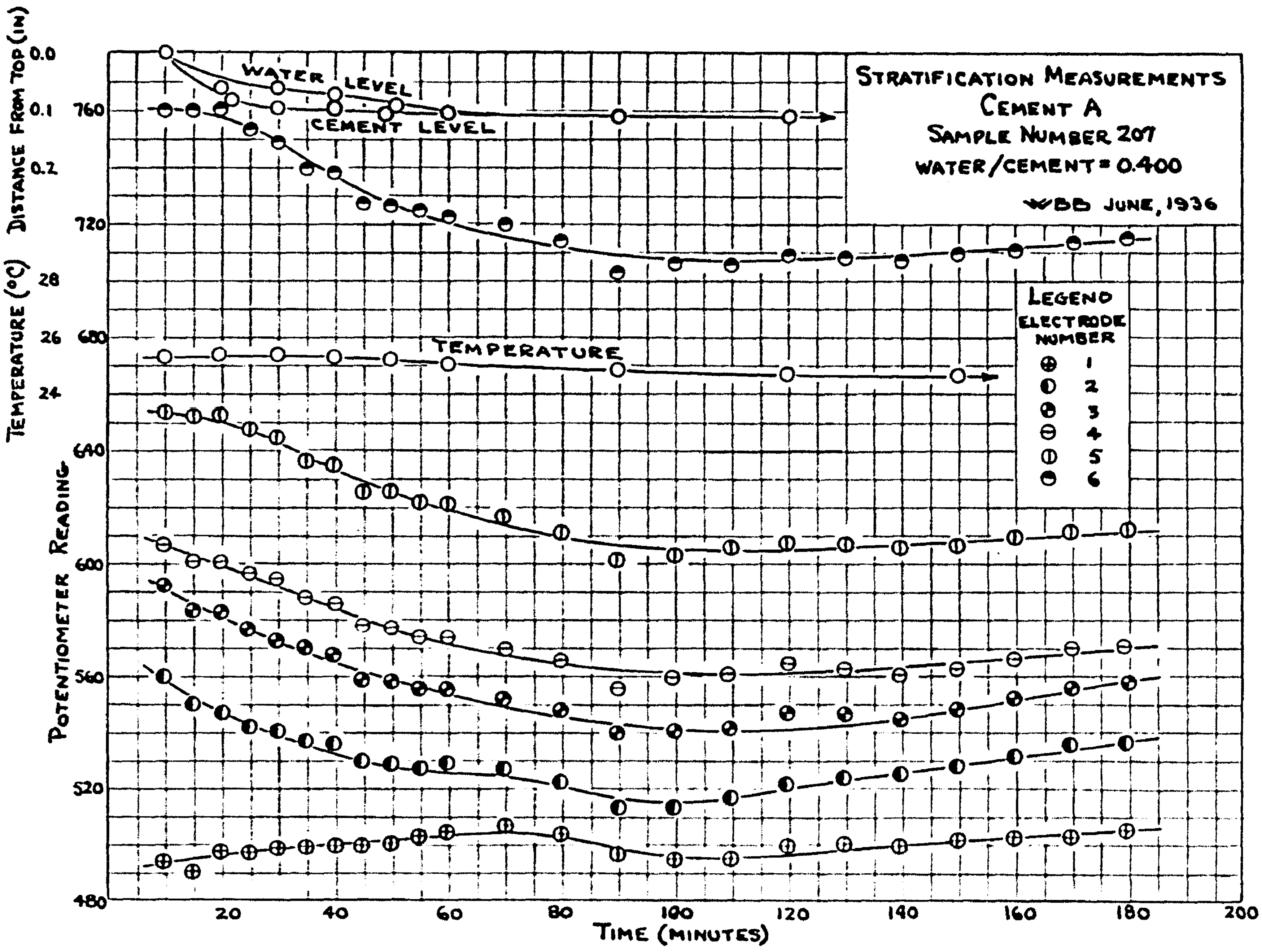

STRATIFICATION MEASUREMENTS
CEMENT A
SAMPLE NUMBER 207
WATER/CEMENT = 0.400
WBB JUNE, 1936
WATER LEVEL
CEMENT LEVEL
TEMPERATURE
LEGEND
ELECTRODE NUMBER
1
2
3
4
5
6
DISTANCE FROM TOP (IN)
0.0
0.1
0.2
TEMPERATURE (°C)
28
26
24
POTENTIOMETER READING
760
720
680
640
600
560
520
480
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200

Figure 34

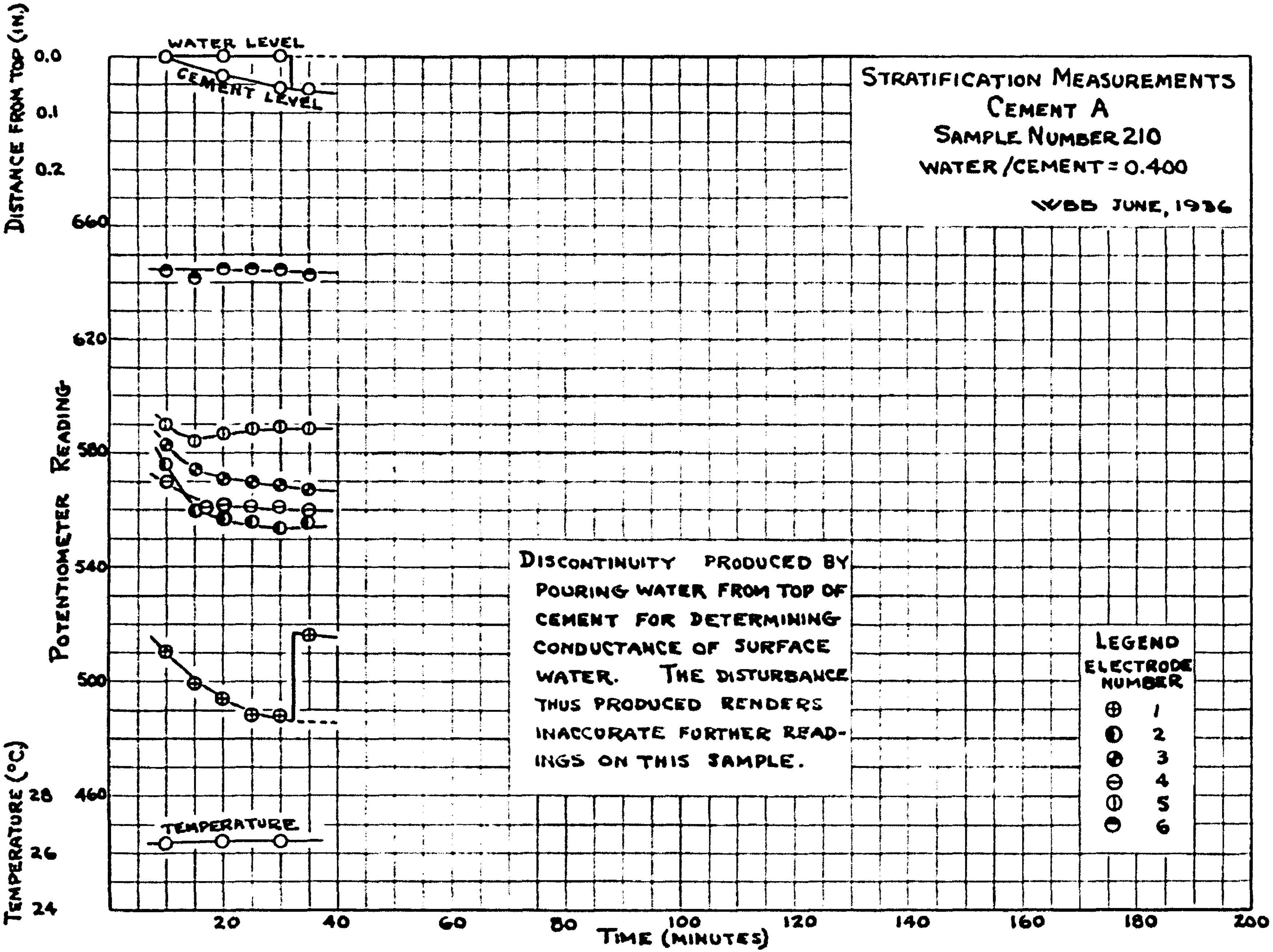

STRATIFICATION MEASUREMENTS
CEMENT A
SAMPLE NUMBER 210
WATER/CEMENT = 0.400
WBB JUNE, 1936
WATER LEVEL
CEMENT LEVEL
TEMPERATURE
DISCONTINUITY PRODUCED BY POURING WATER FROM TOP OF CEMENT FOR DETERMINING CONDUCTANCE OF SURFACE WATER. THE DISTURBANCE THUS PRODUCED RENDERS INACCURATE FURTHER READINGS ON THIS SAMPLE.
LEGEND
ELECTRODE NUMBER
⊕ 1
◐ 2
⊘ 3
⊖ 4
⦶ 5
● 6
DISTANCE FROM TOP (IN.)
0.0
0.1
0.2
POTENTIOMETER READING
660
620
580
540
500
460
TEMPERATURE (°C)
28
26
24
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200

Figure 35

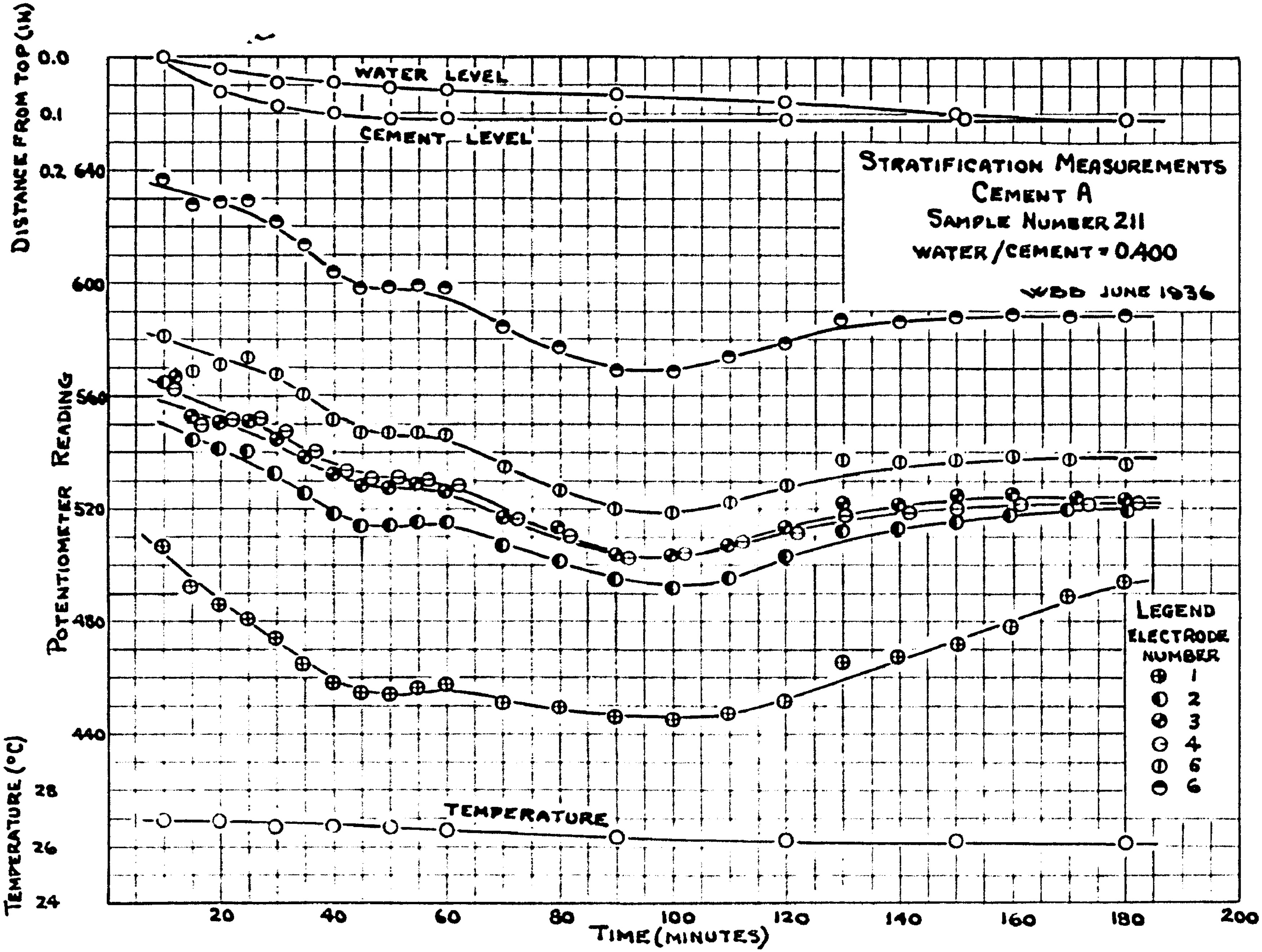
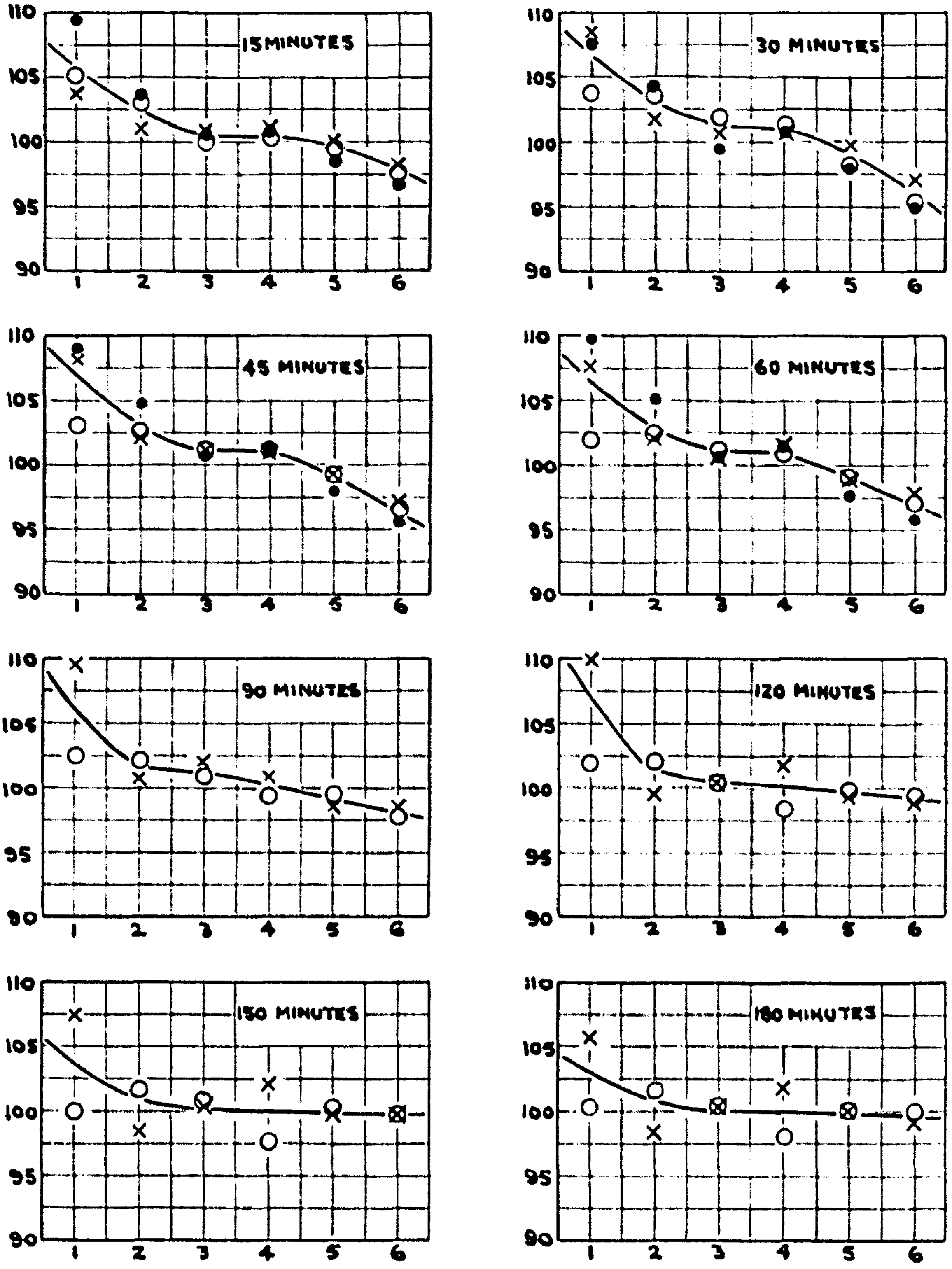

STRATIFICATION MEASUREMENTS
CEMENT A
SAMPLE NUMBER 211
WATER/CEMENT = 0.400
WBD JUNE 1936
WATER LEVEL
CEMENT LEVEL
TEMPERATURE
DISTANCE FROM TOP (IN)
0.0
0.1
0.2
POTENTIOMETER READING
640
600
560
520
480
440
TEMPERATURE (°C)
28
26
24
TIME (MINUTES)
20
40
60
80
100
120
140
160
180
200
LEGEND
ELECTRODE NUMBER
⊕ 1
◐ 2
⊗ 3
⊖ 4
⦶ 6
⊖ 6

Figure 36

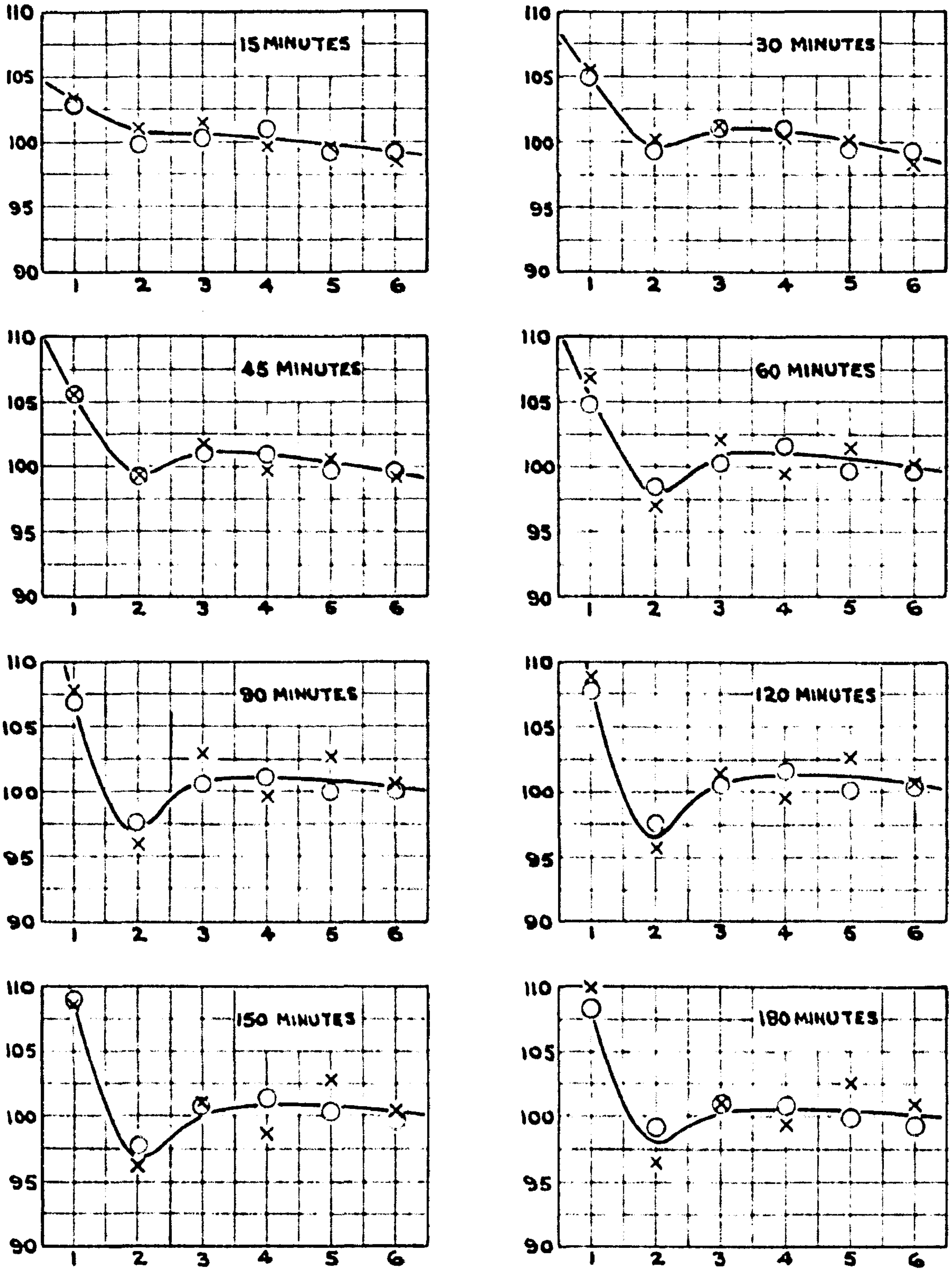


ORDINATES: PERCENTAGE CONDUCTANCE BASED UPON ELECTRODES 2 TO 6 (AVERAGED)
ABSCISSAE: ELECTRODE NUMBER (NO. 1, TOP; NO. 6, BOTTOM)

CEMENT A	SAMPLE NUMBER 193:	○
0.35 W/C	" " 194:	×
	" " 195:	●

WDB

Figure 37

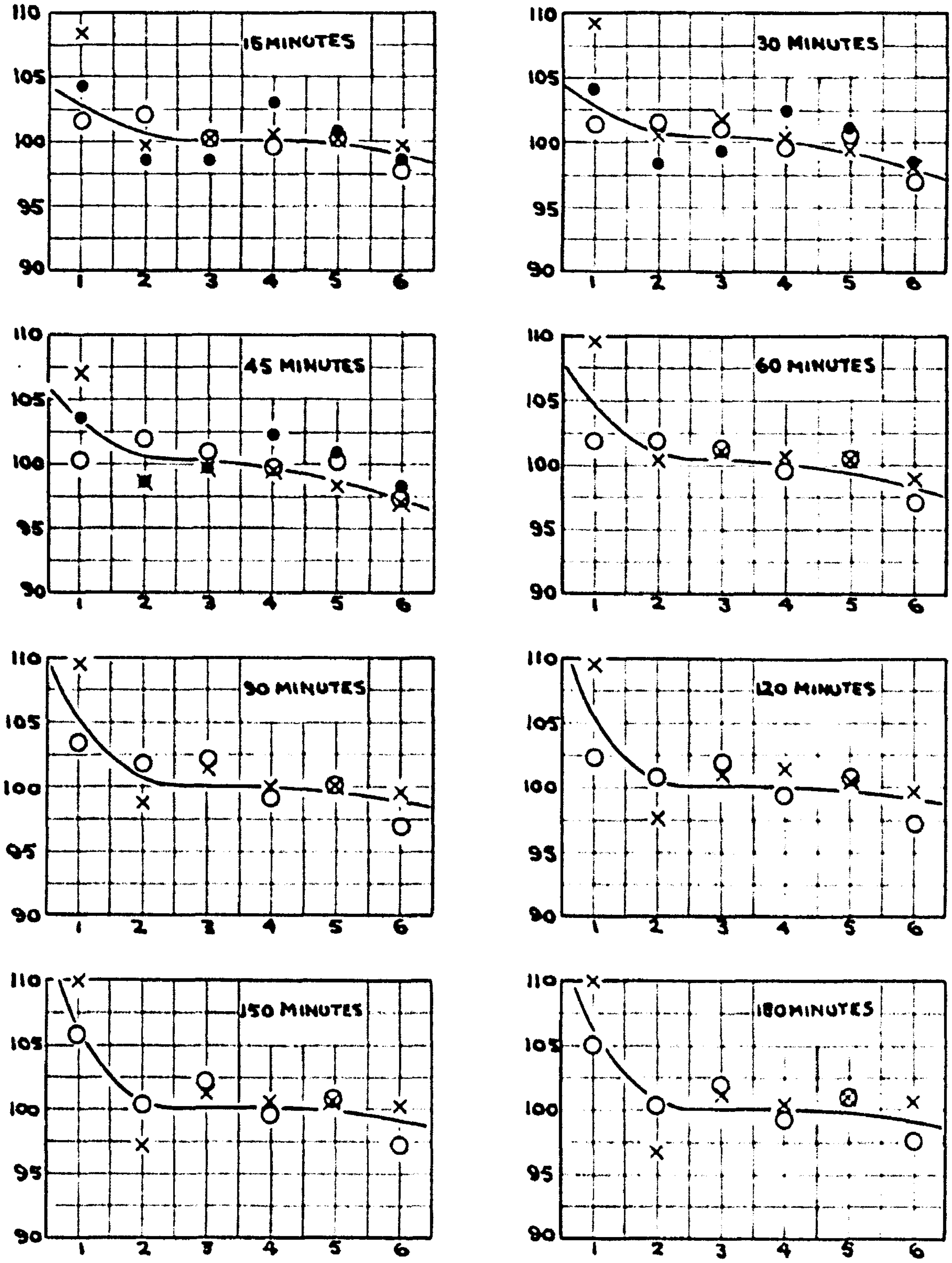


ORDINATES: PERCENTAGE CONDUCTANCE BASED UPON ELECTRODES 2 TO 6 (AVERAGED)
ABSCISSAE: ELECTRODE NUMBER (NO. 1, TOP; NO. 6, BOTTOM)

CEMENT B   SAMPLE NUMBER 197: ○
0.35 W/C   "   "   198: ×

WDD

Figure 38



Ordinates: Percentage Conductance Based upon Electrodes 2 to 6 (Averaged)

Abscissae: Electrode Number (No. 1, Top; No. 6, Bottom)

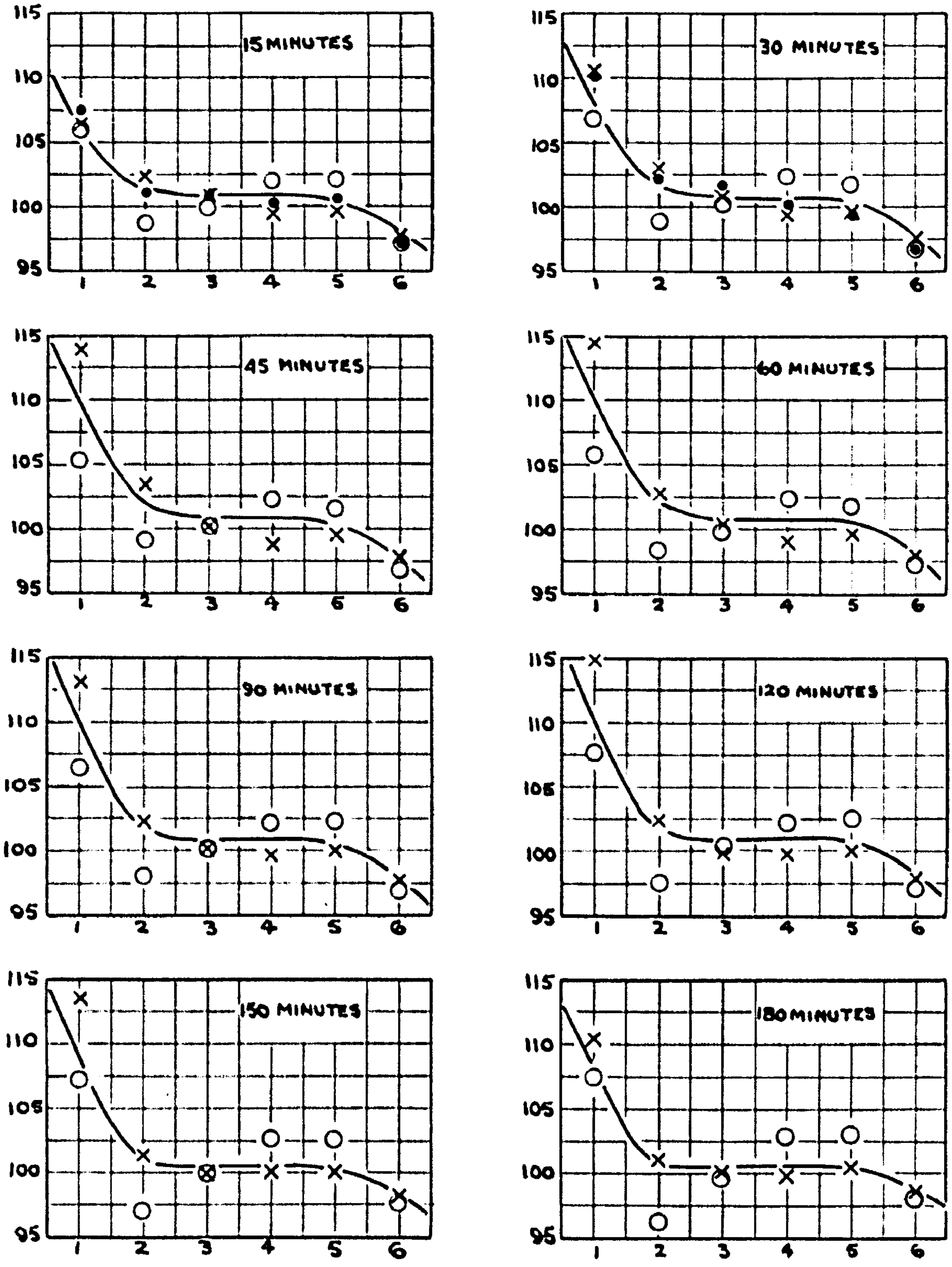
Cement C Sample Number 200: ○

0.35 W/C " " 201: ×

" " 202: ●

WBB

Figure 39

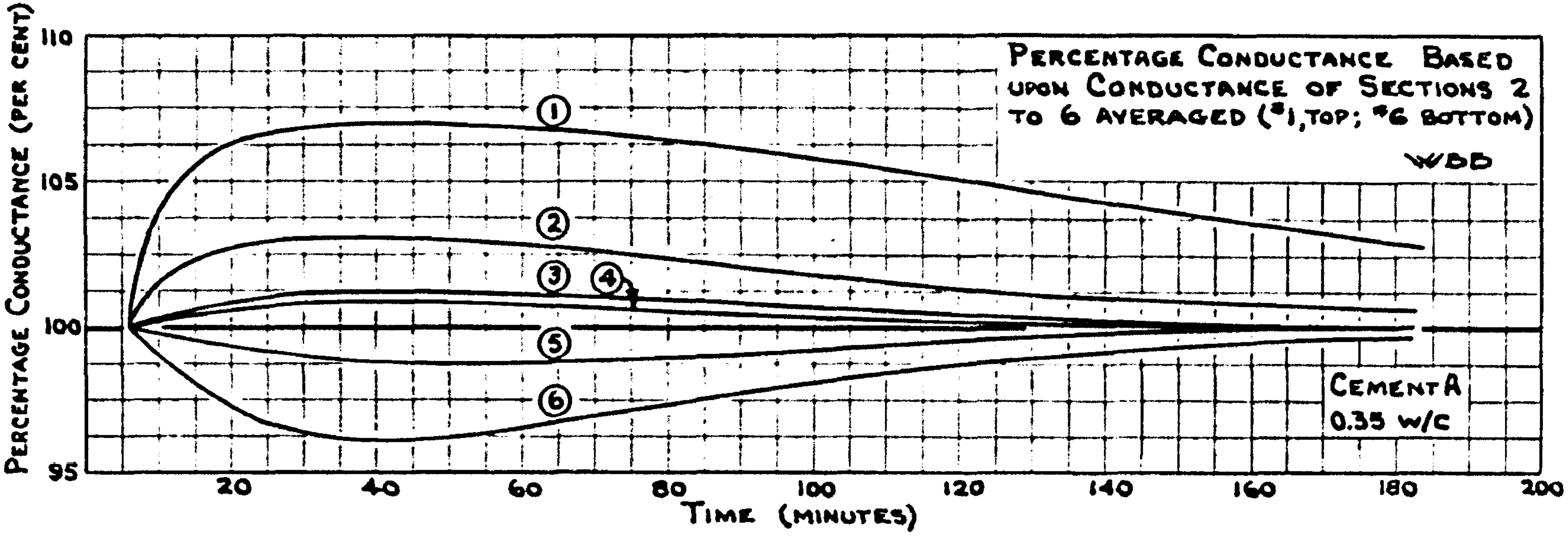


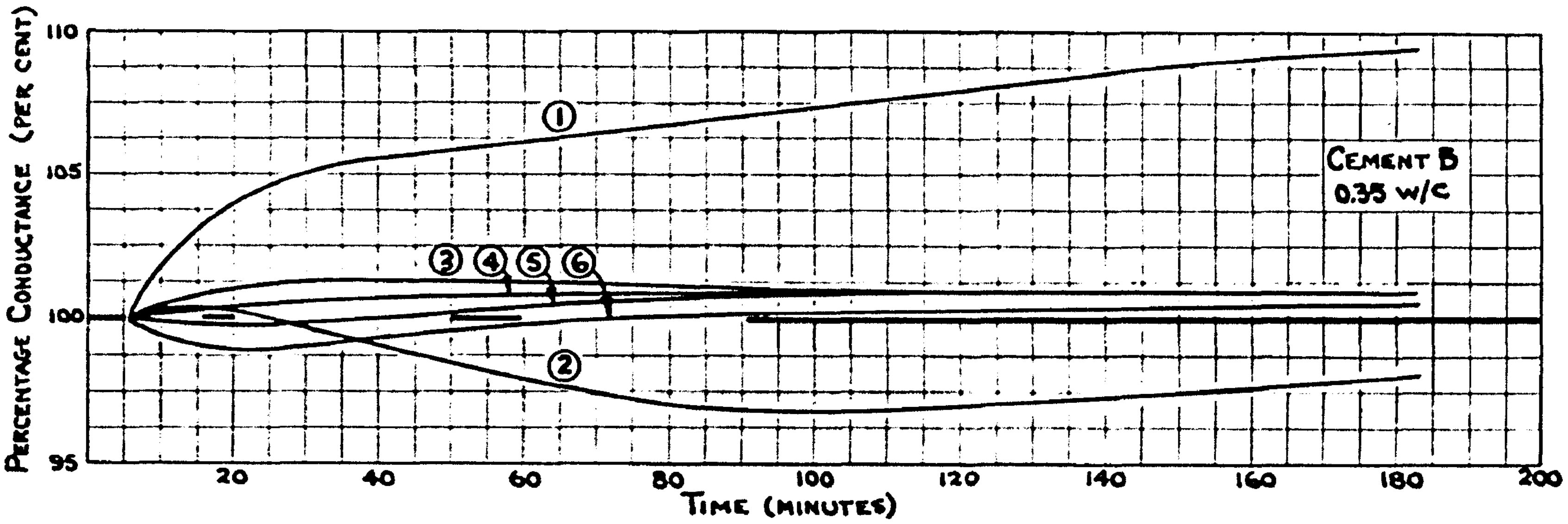
ORDINATES: PERCENTAGE CONDUCTANCE BASED UPON ELECTRODES 2 TO 6 (AVERAGED)
ABSCISSAE: ELECTRODE NUMBER (NO. 1, TOP; NO. 6, BOTTOM)

CEMENT A SAMPLE NUMBER 207: ○
0.40 w/c " " 210: ●
" " 211: ×

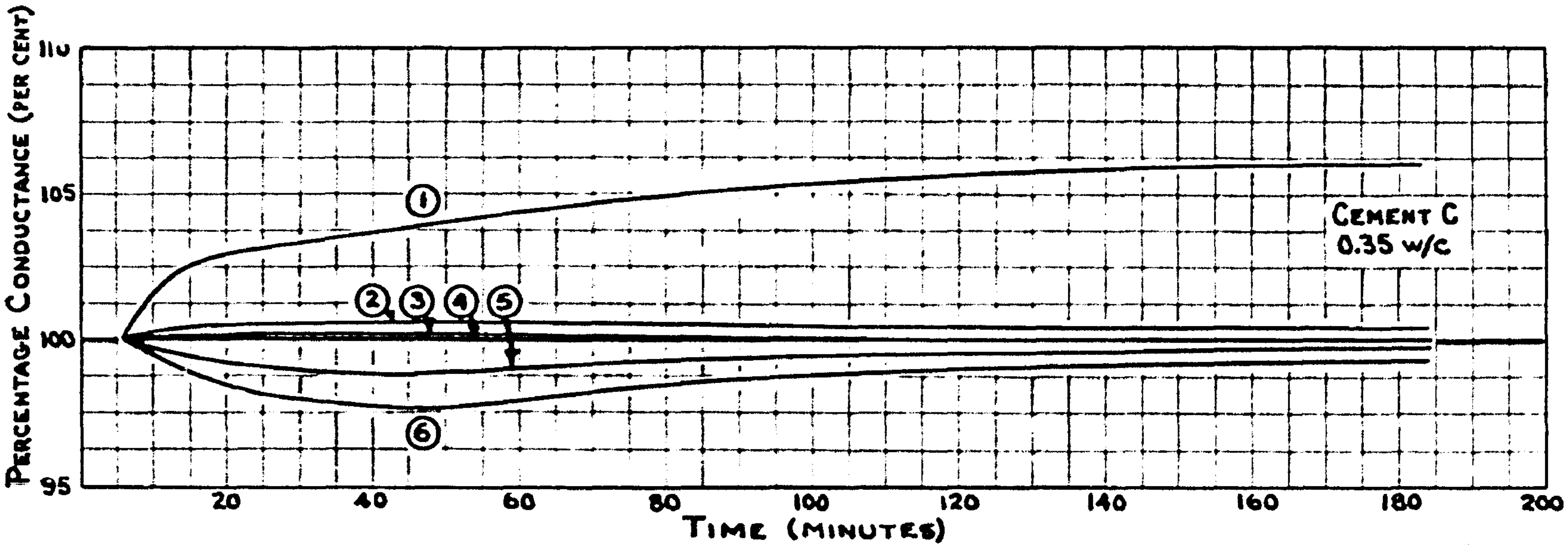
WDB

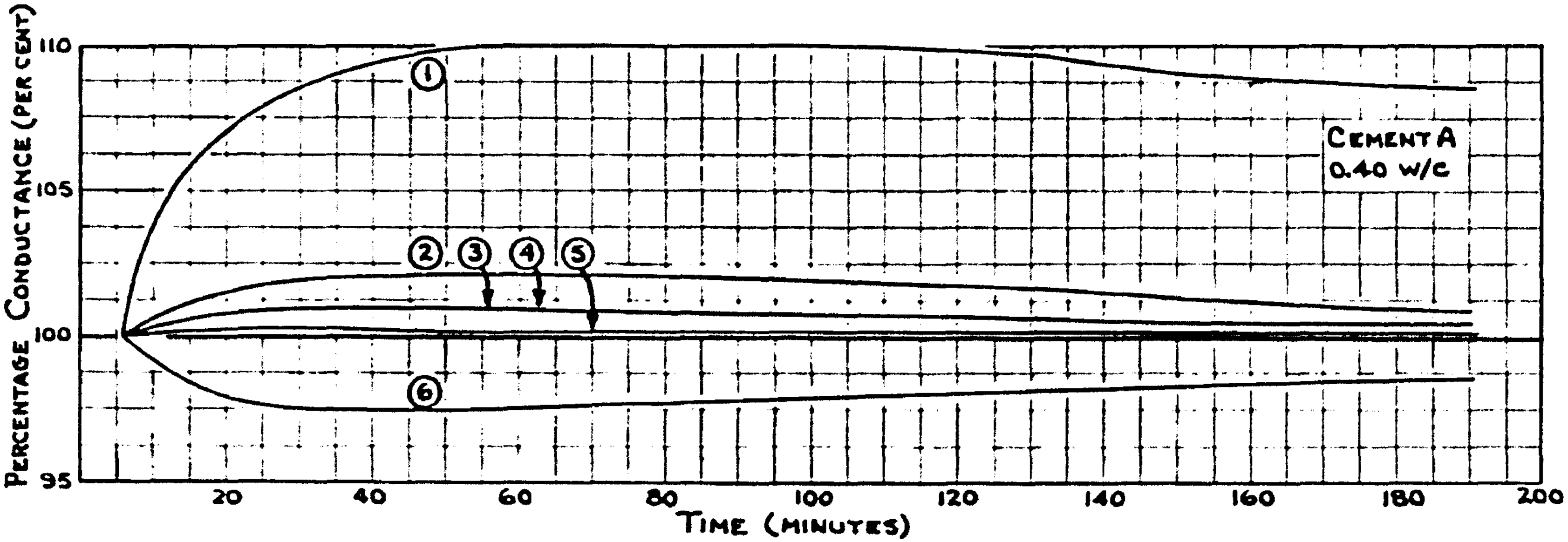
Figure 40





Figures 41 & 42





Figures 43 & 44

5. Correlation of electrical conductivity and compressive strength of cement mortars.

A large group of samples of cement mortar were tested to determine the variation of conductivity with temperature. The data for this test are presented in Table XXXIX, pages 166 and 167, and plotted in Figure 45, page 172. From the smooth curves thus obtained conductivities at 20°, 22°, 24°, 25°, 26°, and 28° C. were chosen and correction factors based upon the 25° C. value were obtained. These calculations and factors are listed in Table XL, page 168, and the average values of the factors are plotted in Figure 46, page 172.

The results of tests for electrical conductivity at 25° C. and 15 minutes after gauging, and compressive strength at 28 days are tabulated in Tables XLI and XLII, pages 169 to 171, inclusive. The results as functions of water-cement ratio and of sand-cement ratio are shown in Figures 47 to 50, pages 173 and 174. The direct relationships between conductivity and strength are shown in Figures 51 and 52, page 175.

TABLE XXXIX

CONDUCTIVITY OF CEMENT A MORTAR

Sand/cement 2.50
Time 15 minutes

April, 1936

Water/cement	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)	Water/cement	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
0.250	100a	24.0	1.12	0.275	101a	23.9	1.40
	100b	23.8	1.01		101b	23.9	1.50
	146a	21.7	0.96		147a	20.8	1.22
	146b	21.3	1.01		147b	20.8	1.39
	155a	26.6	1.03		156a	24.4	1.24
	155b	24.8	0.80 *		156b	24.4	1.15 *
	157a	27.6	1.04		158a	25.6	1.17 *
	157b	26.7	0.94		158b	25.7	1.22
	159a	27.9	1.10		160a	27.8	1.36
	159b	27.8	0.99		160b	27.0	1.19 *
	172	26.0	1.15		167	24.4	1.32
					173	25.6	1.22
0.300	119a	22.8	2.08 *	0.325	120a	24.0	2.43
	119b	22.7	2.01		120b	23.4	2.39
	148a	23.3	1.75		149a	21.1	1.72 *
	148b	22.2	1.67		149b	20.1	1.99
	154a	19.1	1.69		162a	26.7	2.07
	154b	19.1	1.64		162b	26.2	1.78 *
	161a	26.4	1.81		168	25.1	1.89 *
	161b	25.0	1.55 *		175	25.6	2.13
	171	25.9	1.84		182	24.0	2.12
	174	23.8	1.72				
	183	24.1	1.71				
0.350	121a	23.9	2.59	0.375	122a	24.6	2.87
	121b	23.6	2.49		122b	24.4	2.82
	150a	21.1	2.32		151a	21.3	2.40
	150b	20.9	2.09		151b	21.0	2.52
	163a	27.0	2.39		164a	27.6	2.62
	163b	25.8	2.06 *		164b	26.4	2.33
	169	24.3	2.41		170a	24.2	2.51
	176	24.6	2.58		170b	24.0	2.58
	181	27.4	2.43		177	25.8	2.77
					180	28.0	2.78

* indicates an error of more than 14.38 per cent. See Appendix B.

TABLE XXXIX (continued)

Water/cement	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)	Water/cement	Sample Number	Temperature (°C)	Conductivity (10^{-3} mhos/cm^3)
0.400	144a	25.3	2.89	0.450	145a	25.2	2.92
	144b	24.3	2.78		145b	24.9	2.90
	152a	21.0	2.45		153a	21.2	2.70
	152b	20.6	2.49		153b	20.9	2.63
	165a	26.7	2.84		166a	26.2	2.96
	165b	25.7	2.67		166b	27.1	3.02
	179	23.3	2.68		178	22.6	2.78

TABLE XL

CALCULATIONS OF CONDUCTIVITY CORRECTION FACTORS FOR CEMENT MORTAR

Cement A
Sand/cement 2.50
Time 15 minutes

Conductivity (10^{-3} mhos/cm^3) at

Water / cement	20°C.	22°C.	24°C.	25°C.	26°C.	28°C.
0.250	0.92	0.99	1.05	1.06	1.08	1.10
0.275	1.25	1.33	1.39	1.40	1.42	1.47
0.300	1.65	1.76	1.83	1.86	1.90	1.93
0.325	1.97	2.10	2.20	2.23	2.26	2.29
0.350	2.21	2.33	2.43	2.48	2.50	2.52
0.375	2.40	2.52	2.61	2.66	2.69	2.72
0.400	2.51	2.64	2.74	2.79	2.82	2.86
0.450	2.63	2.79	2.89	2.93	2.99	3.03

Correction Factor for Conductivity (per cent)

0.250	115.2	107.0	101.0	100	98.2	96.4
0.275	112.0	105.3	100.8	100	98.6	95.3
0.300	112.7	105.6	101.6	100	97.8	96.4
0.325	113.2	106.1	101.2	100	98.7	97.3
0.350	112.2	106.3	102.0	100	99.2	98.3
0.375	110.9	106.5	101.9	100	98.8	97.7
0.400	111.0	105.8	101.9	100	98.8	96.7
0.450	111.1	105.0	101.2	100	97.9	96.7
Average:	112.3	106.0	101.4	100	98.5	96.9

TABLE XLI

ELECTRICAL CONDUCTIVITY——COMPRESSIVE STRENGTH DATA

Cement A
Sand/cement 2.50
Time (conductivity measurements) 15 minutes
Time (strength measurements) 28 days

Water/cement	Sample Number	Compressive Force (lbs)	Compressive Strength (lbs/in^2)	Conductivity (10^{-3} mhos/cm^3)	Temperature (°C)	Conductivity Corrected to 25°C. (10^{-3} mhos/cm^3)
0.250	100a	7,200	1,800	1.01	24.0	1.03
	100b	8,560	2,140	1.12	23.8	1.14
	100c	6,480	1,620	1.06	23.9	1.08
	172	10,420	2,605	1.15	26.0	1.14
0.275	101a	9,050	2,263	1.39	23.9	1.41
	101b	9,230	2,308	1.44	23.9	1.46
	101c	9,400	2,350	1.50	23.9	1.53
	173	11,000	2,750	1.22	25.6	1.21
0.300	119a	21,750	5,438	2.06	22.7	2.14
	119b	16,500	4,125	2.01	22.8	2.09
	119c	22,020	5,505	2.08	22.7	2.17
	174	15,830	3,958	1.72	23.8	1.75
	183	16,200	4,050	1.71	24.1	1.74
0.325	120a	22,160	5,540	2.39	23.9	2.43
	120b	22,670	5,668	2.43	24.0	2.47
	120c	23,200	5,800	2.41	23.9	2.45
	175	24,750	6,188	2.13	25.6	2.11
	182	33,300	8,325	2.12	24.0	2.15
0.350	121a	25,000	6,250	2.54	23.7	2.59
	121b	21,950	5,488	2.49	23.6	2.55
	121c	23,700	5,925	2.59	23.9	2.63
	176	24,320	6,080	2.58	24.6	2.60
	181	26,860	6,715	2.43	27.4	2.38
0.375	122a	27,600	6,900	2.82	24.4	2.84
	122b	28,700	7,175	2.87	24.6	2.89
	122c	27,800	6,950	2.84	24.5	2.86
	177	26,300	6,575	2.77	25.8	2.74
	180	30,720	7,680	2.78	28.0	2.70

TABLE XLI (continued)

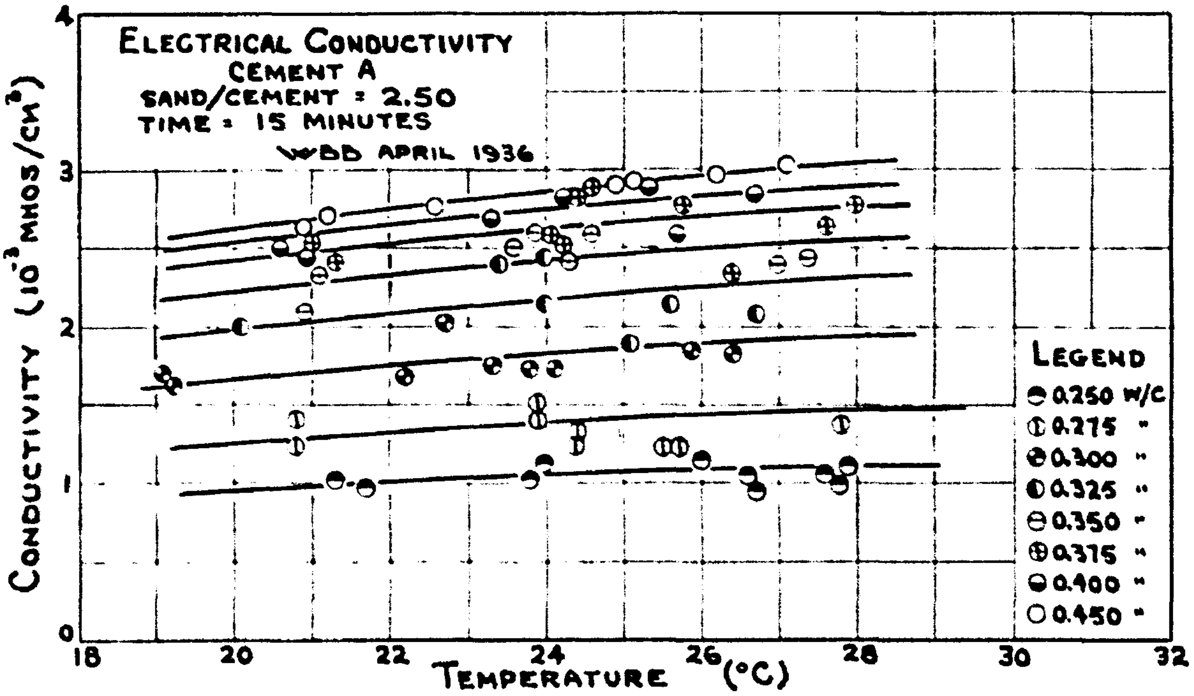
$\frac{\text{Water}}{\text{cement}}$	Sample Number	Compressive Force (lbs)	Compressive Strength (lbs/in^2)	Conductivity (10^{-3} mhos/cm^3)	Temperature (°C)	Conductivity Corrected to 25°C. (10^{-3} mhos/cm^3)
0.400	144a	25,750	6,438	2.78	24.3	2.81
	144b	26,850	6,713	2.89	25.3	2.89
	144c	27,120	6,780	2.82	24.8	2.83
	179	30,980	7,745	2.68	23.3	2.77
0.450	145a	22,690	5,673	2.90	24.9	2.90
	145b	23,680	5,920	2.92	25.2	2.91
	145c	22,460	5,615	2.91	25.0	2.91
	178	24,400	6,100	2.76	22.5	2.89
0.500	203a	16,900	4,225	3.06	25.4	3.03
	203b	19,900	4,975	3.04	24.6	3.07
	203c	21,000	5,250	3.05	25.0	3.05
0.550	204a	18,200	4,550	3.28	26.0	3.24
	204b	19,900	4,975	3.29	26.2	3.24
	204c	18,600	4,650	3.26	25.9	3.22
0.600	205a	14,100	3,525	3.36	24.3	3.39
	205b	13,400	3,250	3.38	24.3	3.41
	205c	14,000	3,500	3.40	24.3	3.43
0.650	206a	11,200	2,800	3.40	25.0	3.40
	206b	11,400	2,850	3.76	25.2	3.74
	206c	11,500	2,875	3.58	25.1	3.57

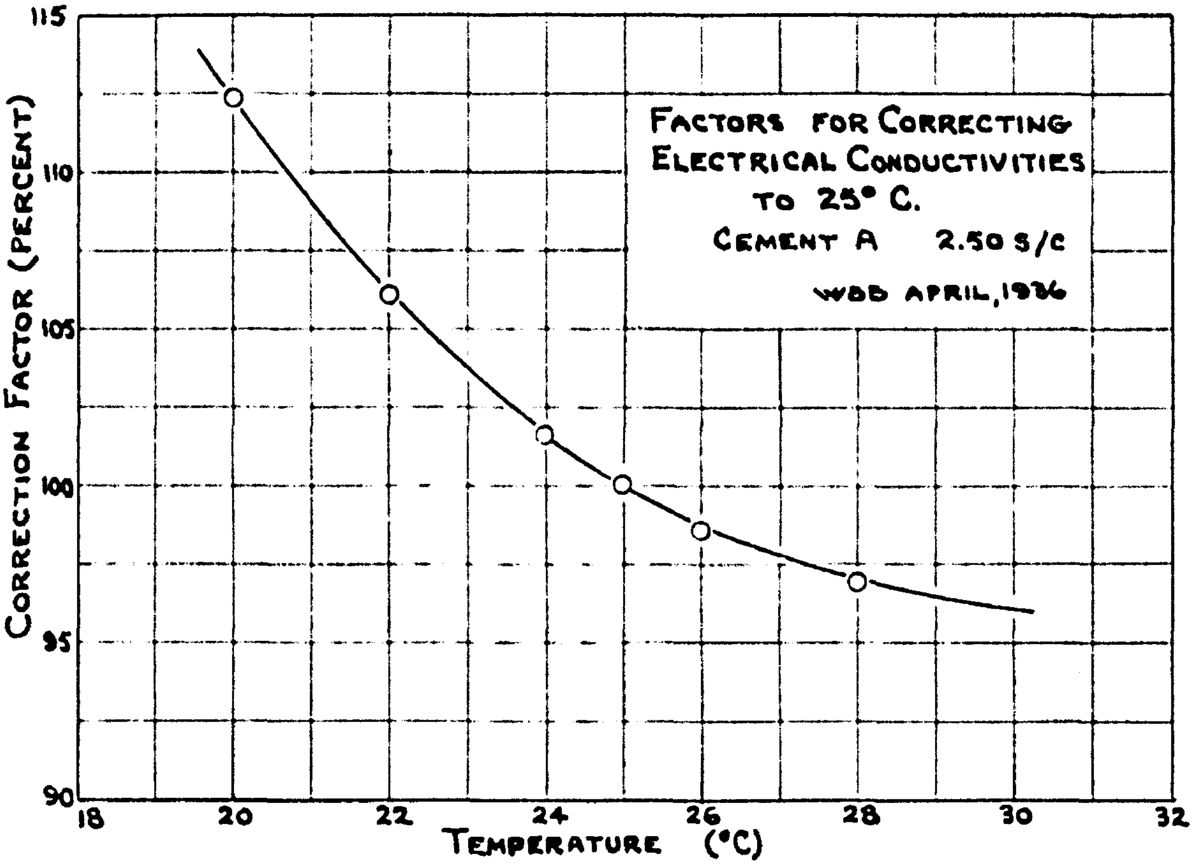
TABLE XLII

ELECTRICAL CONDUCTIVITY——COMPRESSIVE STRENGTH DATA

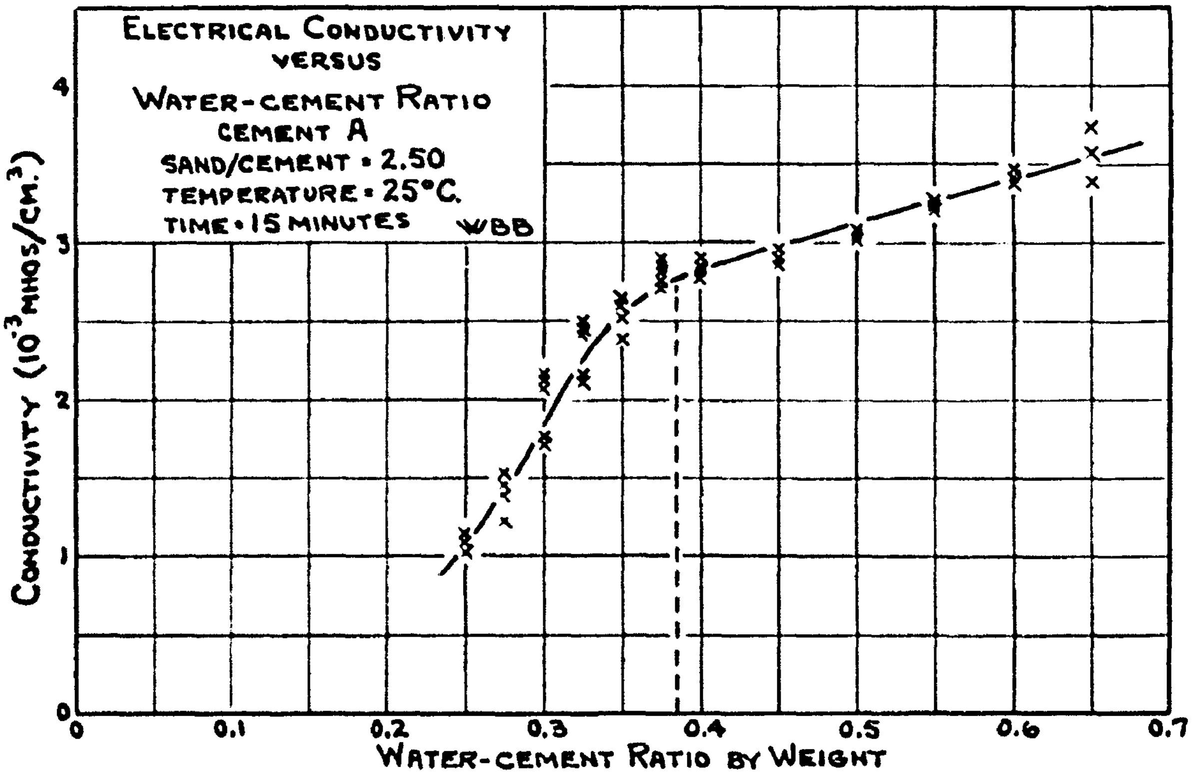
Cement A
Water/cement 0.350
Time (conductivity measurements) 15 minutes
Time (strength measurements) 28 days

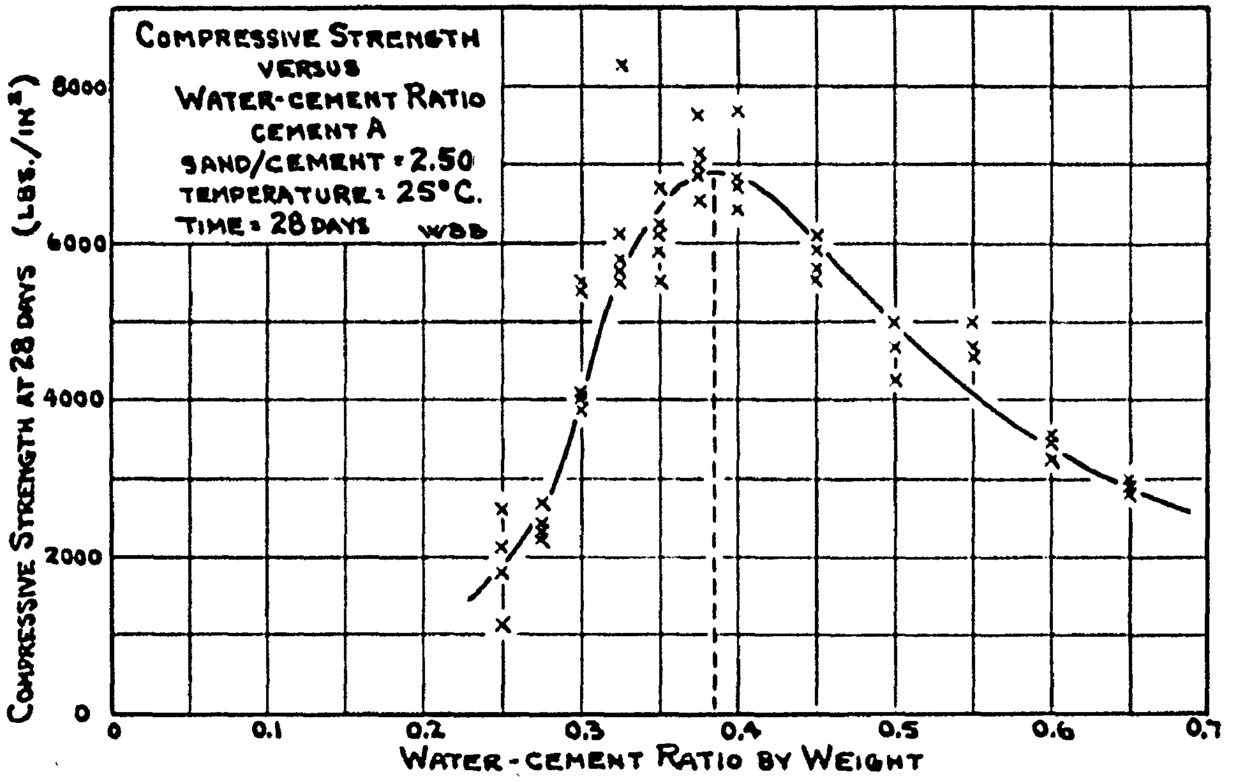
Sand / cement	Sample Number	Compressive Force (lbs)	Compressive Strength (lbs/in^2)	Conductivity (10^{-3} mhos/cm^3)	Temperature (°C)	Conductivity Corrected to 25°C. (10^{-3} mhos/cm^3)
0.50	208a	45,200	11,300	6.40	26.3	6.28
	208b	37,900	9,475	6.14	26.1	6.05
	208c	45,900	11,475	6.27	26.2	6.18
1.50	209a	35,400	8,850	3.63	26.6	3.56
	209b	37,700	9,425	3.67	26.1	3.63
	209c	35,400	8,850	3.63	26.3	3.60
2.50	120a	25,000	6,250	2.54	23.7	2.59
	121b	21,950	5,488	2.49	23.6	2.55
	121c	23,700	5,925	2.59	23.9	2.63
	176	24,320	6,080	2.58	24.6	2.60
	181	26,860	6,715	2.43	27.4	2.38
3.50	212a	9,400	2,350	1.45	24.9	1.45
	212b	9,700	2,425	1.40	24.3	1.42
	212c	11,100	2,775	1.42	24.6	1.43
4.50	213a	4,300	1,075	0.82	25.6	0.81
	213b	4,300	1,075	0.82	25.6	0.81
	213c	4, 200	1,050	0.80	25.6	0.79



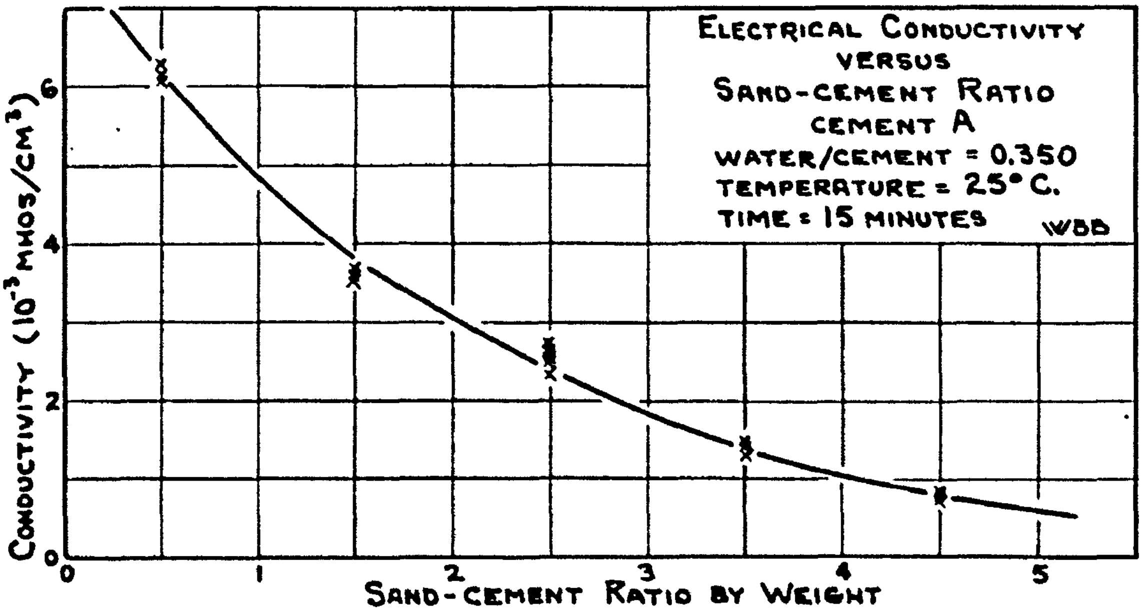


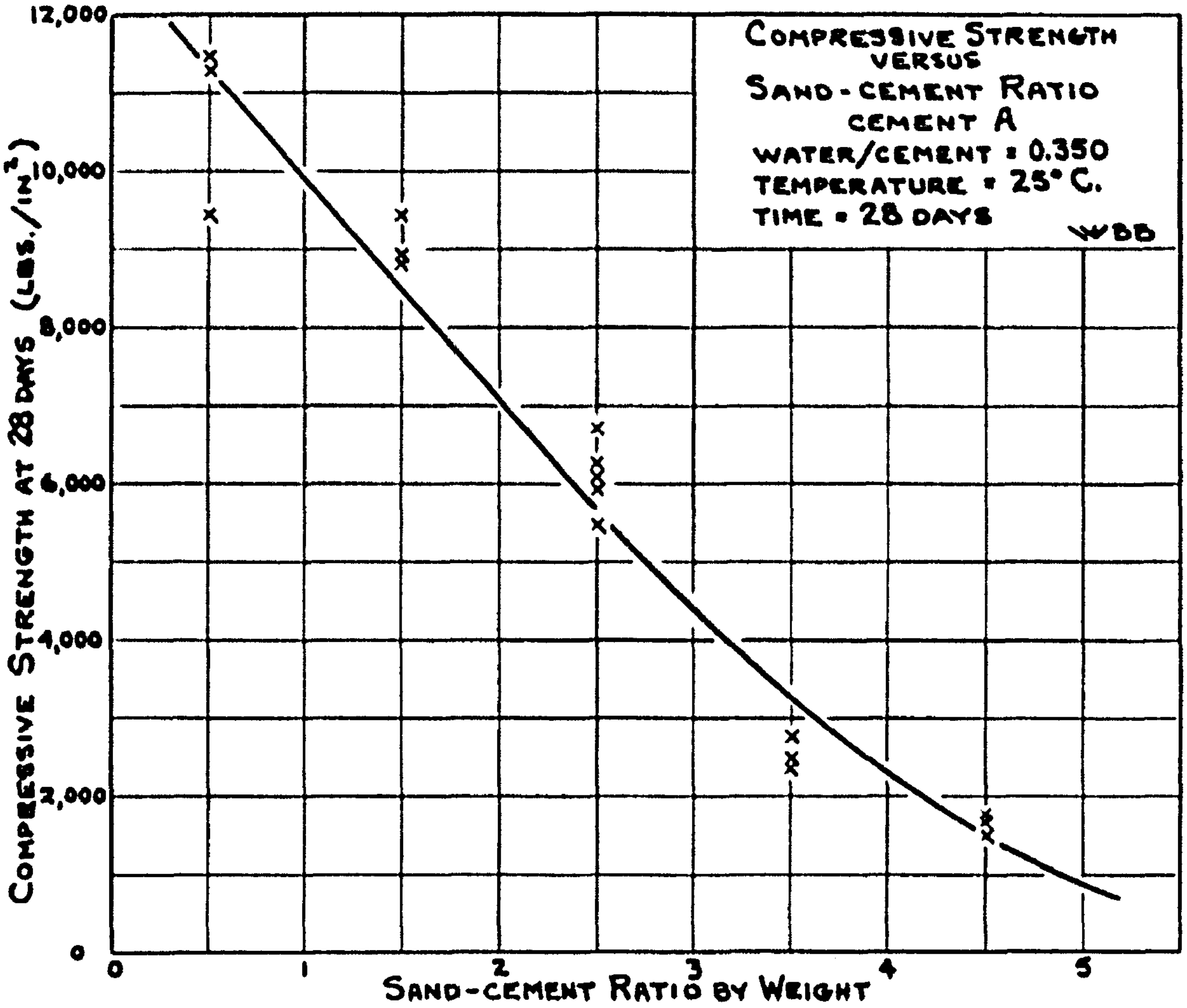
Figures 45 & 46



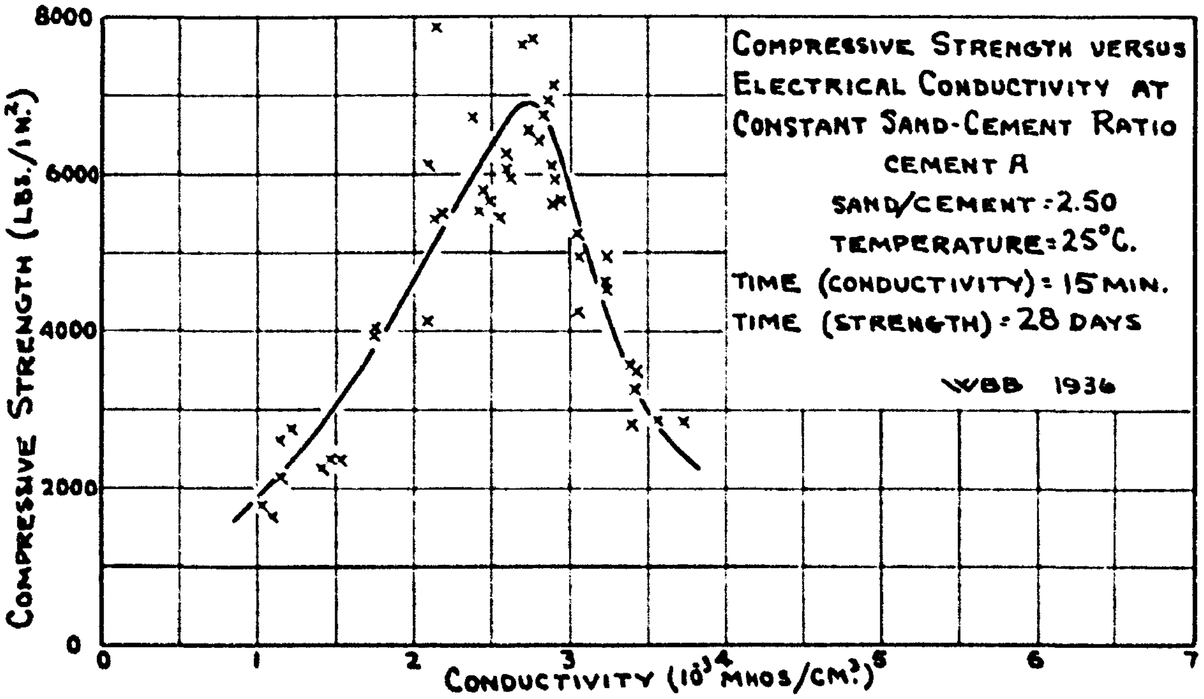


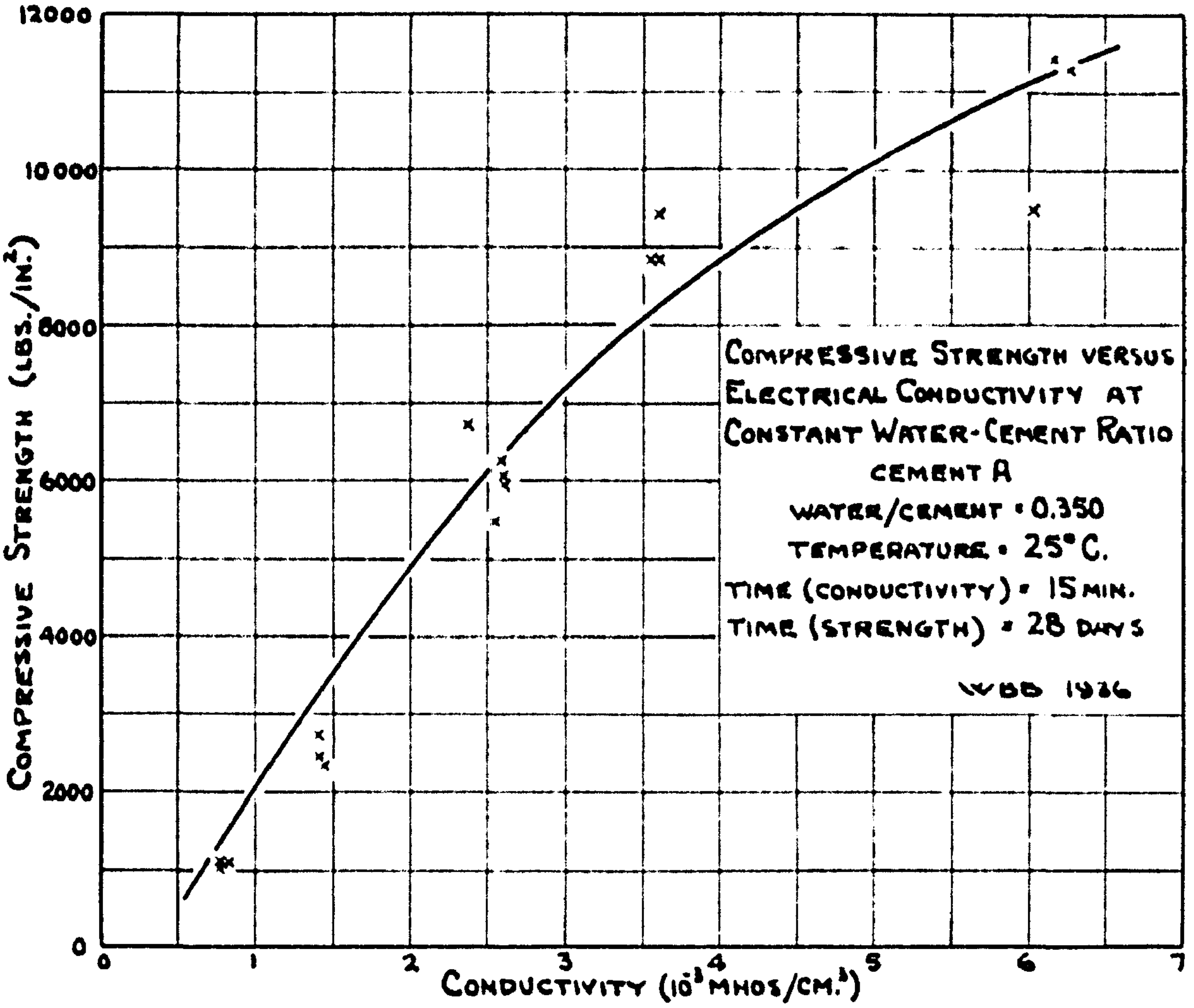
Figures 47 & 48





Figures 49 & 50





Figures 51 & 52

IV. DISCUSSION OF RESULTS

A. Preliminary Results

The results of the preliminary investigations involving field strength (applied voltage) and frequency verified the theory of electrolytes, that, at low field strengths and frequencies, the conductivity of an electrolyte is independent of these items.

Thus, Figure 10, page 56, being a straight line passing through the origin, indicates a constant conductivity over the range of voltages from 0 to 1 volt. All measurements of conductivity were made within this range.

Figure 11, page 56, plotted as resistance versus frequency, being a horizontal line, indicates a constant conductivity over the range, 200 to 1800 cycles per second. All measurements were made at 1000 cycles, inasmuch as this frequency is recognized as the standard frequency for conductivity measurements of electrolytes. The response of phones to this frequency is of course quite good.

B. Setting Phenomena of Cement Pastes

In this discussion of the results of the setting process in cement pastes as analyzed conductometrically, the author will first set forth the process as it appears to him as the result of the study, and then review the results of this portion of the investigation from the viewpoint thus presented.

First, let us visualize the particles of dry cement as finely ground cement clinker, not perfectly spherical in shape, but enough so that there is a considerable percentage of voids in the dry condition. Now, as water is added and the two constituents mixed together, the voids become filled with the fluid if sufficient water is added. At the same time the water begins to act upon the surfaces of these small particles of cement. The surfaces of the particles thus begin to dissolve, or become saturated with the water, and, as they do so, the water becomes more and more ionized. That is, it takes on the decided properties of an electrolyte. As the surface continues to dissolve, slowly to be sure, since at a single mixing only a portion of the cement particle ever becomes hydrated (Review of Literature, page 21), the hydrated silicates and aluminates perhaps produce the "gel" which Bates and Klein (4) have investigated. Whether this "solution" is a colloidal gel or merely a saturated or even supersaturated solution, the effect from an electrical viewpoint is an increased viscosity to the flow of ions moving in the electric field (page 14).

Hence we have two effects upon the electrical conductivity, first, the increasing ionisation of the water, and second, its increasing viscosity. These two processes overlap, perhaps to a considerable extent. However, we would expect the first process, that of increasing ionisation, to predominate in the early period following mixing, whereas the second process would predominate at a later time. Thus there would be a maximum point in the conductivity-time curve. That such a maximum occurs is evident from Figures 21 and 22, pages 104 and 105, as well as from Shimizu's work, Figure 1, page 11.

Now, let us investigate the effects of variation in water content (water-cement ratio) upon the electrical conductivity of the paste. As in increased amount of water is added, the average distance between particles must become larger, providing the minimum water content was sufficient to fill the voids. No doubt a swelling of the gel occurs in pastes so that this minumum water content is not of primary importance for the usual water-cement ratios. At least in the range of water-cement ratios investigated (0.250 to 0.400), no break or decided knee in the curve was discovered. An increase in the average distance between particles then indicates a larger effective cross sectional area available to the lines of current flow, and hence an increase in electrical conductivity.

As an experimental proof that an increase in water-cement ratio results in an increase in conductivity, reference is made to Figure 20, page 103, where the conductivity at 15 minutes as a function of water-cement ratio is given for the three cements analyzed.

The increase in conductivity with temperature (page 15), at least for the early periods of the setting process, is evident in Figure 21, page 104. More important, however, than the absolute magnitude of the conductivity as influenced by temperature, is the relative shapes of the conductivity curves as affected by this item; that is, the effect of temperature upon the setting characteristic of the cements.

It is a recognized fact (Review of Literature, page 20) that increased temperature results in faster setting of most cement pastes. The reason for this occurance is no doubt an increased rate of dissolving the surface of the cement particle with increased temperature, and then a resulting increase in the rate of chemical change (crystallization or formation of the colloidal gel). Thus, it would be expected that the maximum point in the conductivity-time curve would be reached in a shorter interval of time at the higher temperature. Also, the decrease in conductivity after the maximum was reached should be at a faster rate for the higher temperature.

Both of these effects are very pronounced for cement B, a high early strength cement. For cement A, a normal hardening cement, the maximum points occur at quite different times for the two temperatures investigated, but the negative slopes of the two curves are only slightly different. This indicates only slight influence of temperature upon the crystallization or colloidal formation, but a decided influence upon the hydration period. Cement C, another normal hardening cement, showed no appreciable difference in either negative slope or maximum point at the two temperatures (22° C. and 30° C.).

Instead of noting the time of maximum conductivity and the negative slope of the curve thereafter as measures of the hydration period and the rate of hardening it is possible to include both of these items in one measure. If the time required for the conductivity to return to the same value as it had at some earlier time (15 minutes perhaps) is determined for a cement, then both of these items are included. For some cements, however, this would require a test longer than three hours and as a result would not be as desirable. This is evidently the case for cement C, as is evident in Figures 19 and 21, pages 103 and 104.

It is also recognized (page 20) that the water content has an effect upon the setting process, an increase in water content decreasing the speed of the reactions. Vicat needle tests for normal consistency were made on the three cements so that the maximum electrical conductivities could be compared under the same conditions of plasticity. It was found that the maximum points of the three curves for normal consistency occurred at approximately the same value of time at a temperature of 22° C. (Figure 22, page 105). The time required for this maximum to be reached was 70 minutes. At a water-cement ratio of 0.400 the time required to reach a maximum was 10 to 15 minutes longer. This variation in time was more pronounced at lower temperatures. At higher temperatures the speed of the reactions were faster, thus masking to a large extent the effects of variations of water content.

Jesser (15) found that the galvanic action of cement mortars increased for a period of time and then decreased, thus producing the same shape of curve as does the conductivity. However, the maximum voltage obtained from Portland cement "cells" of 0.27 water-cement ratio occurred at approximately 10 hours after gauging, whereas the maximum conductivity occurs usually at about one hour. The present author can not reason why this maximum galvanic action should occur at such a later period of time than does the maximum conductivity.

C. Excess Water Tendency in Sand-Water Mixtures

The effects of particle size upon compactness of the solid particles under wet conditions are two fold. First, there exists a water film around each particle which tends to separate the particles. If this film were of constant thickness for all sizes of particles the effect upon the smaller size particles would be greater, producing the larger percentage of wet voids for the smaller size. The other effect of particle size is the effect of adhesion as discussed on page 22. Even if this force were not dependent upon particle size the compactness for the smaller particles would tend to be greater, that is, a smaller percentage of wet voids. The mass of the smaller particle is less and hence even a constant force acting upon a smaller mass would tend to produce more dense packing. The increase of the force of adhesion with decreased curvature of the film exaggerates this tendency.

Thus, there are two actions occurring simultaneously: the water film tending to hold the particles apart and the forces of adhesion, acting where the films of two particles join, tending to pull them together, thus squeezing the water film at their closest point.

It would be expected that the exaggerated action of the adhesion forces would overcome the tendency of the water films. However, a means of measuring these wet voids in comparison to the dry voids is very impractical by physical (mechanical) measurements, whereas the method as discussed on pages 26 and 28 is quite simple.

The results of these measurements as shown in Figure 25, page 112, indicate clearly that the excess water tendency (i. e., the excess of water above that necessary to fill the dry voids) decreases with a decrease in the average diameter of the particles. A minimum tendency ratio of approximately 0.6 at particles of very small diameters may be found from extrapolation.

When tests were made upon the graded sand mixtures, designed according to the two gradings as shown graphically in Figure 24, page 112, the results indicated in both cases an excess water tendency ratio of only 0.6, that is, the minimum excess water possible when using sands of only very small diameters. Thus, a graded mixture, even though graded perhaps only roughly, would be expected to produce a rather compact wet mass, the same results as could be obtained by using very small particles.

Sand-water mixtures were used, rather than cement mortars or pastes, because the sand particles were inert electrically, whereas very decided reactions occur with cement particles as has been discussed in the previous section.

The conclusions and their application to internal stratification, which can be obtained from this study, will be made later (page 191).

D. Internal Stratification in Cement Pastes

That water moves upward through a cement paste under certain conditions has been known for a great many years. Only recently, however, has any attempt been made to determine the causes for this rise and how it may be prevented. The experimental investigators have attacked the problem from an exterior viewpoint. That is, they have made observations upon the surface conditions only. Now it is also a well known fact that this water, for reasonable water-cement ratios, is absorbed back into the cement paste after a period of time. This is the point then at which other investigations have failed; that is, there was no means of determining the redistribution of water in the paste. And from an ultimate viewpoint this is the important item. There is no reason to believe that this redistribution of water should be uniform or that it should be the same for all cements.

Before proceeding further, reference should be made to the relationships between water-cement ratio and conductivity for the three cements as shown in Figure 20, page 103. A very nearly straight-line relationship may be observed between these two quantities for cements B and C and for cement A above 0.300 water-cement ratio. As a result percentage conductance is very nearly synonymous with percentage water content. The conversion would be quite possible if the conductivity versus water-cement ratio curves, as obtained from the analysis, were drawn for each point of time and temperature observed. However, since the relationships are so nearly linear, the expenditure is not deemed practical, since so very little additional accuracy is to be gained. Consequently, the term percentage water content, or simply water content, will be used in the subsequent discussion where the numerical results are in reality percentage conductance.

Figure 41, page 163, shows the change in water content of the six lateral layers of a sample of cement A as a function of time. It will be observed that the change in water content was quite rapid in the period 6 minutes to 10 minutes, especially for section one, the top section. This was the period in which the paste was placed in the container. The point at 6 minutes was, of course, an assumed point since the earliest readings were possible only 9 or 10 minutes after gauging. The 6-minute value therefore represented a homogeneous distribution of water throughout the sample; that is, 100 per cent conductance for each section.

The spread in water content reached a maximum for this cement at approximately 45 minutes. Furthermore the water content increased continuously from the lowest level to the top. At the end of three hours the water had redistributed itself so that the variation in the lower 5 inches of the sample was approximately 1 per cent. However, the top 1-inch section showed an excess of approximately 3 per cent. This was a rather small excess when compared to the other cements tested.

The variations of water content in the lateral layers for cement B, a high early strength cement, are shown in Figure 42, page 163. For this cement no appreciable water appeared on the surface, and yet the electrical measurements indicated a very poor distribution.

It should be remembered that all that is necessary to prevent water reaching the surface is to retard its progress so that the cement sets before the water reaches the top. From an external view cement B appeared to have no bleeding, and yet the final distribution of water was the poorest for the three cements tested.

The water content of section 2, that just below the top, first increased slightly and then began to decrease until at 100 minutes it had reached a percentage of approximately 97 per cent. From then until 180 minutes the water content increased slightly. The reason for this seeming discrepancy may perhaps be explained as follows:

The capillary and gravitational forces in this cement, as in others, tended to force the water up through the water passages of the sample. It may be that in this cement the effect of pressure, which of course would be greatest in the lower sections of the sample, compacted the paste to such a degree that the water was not free to move upward. The hydration period also may have been accelerated by this process. Hence the only action which could take place was in the top sections, resulting in the water being drawn from section 2 into section 1 and thus accounting for the decrease in water content of section 2.

The excess water in the top section (10 per cent at 180 minutes) was held there by the early hardening process which occurred in this type of cement. As a result no decrease in the water content of section 1 was observed.

The variations in water content for cement C, a very finely ground normal hardening cement, were very small except in the top section where the excess reached approximately 6 per cent at 180 minutes (Figure 43, page 164).

All of these above measurements were made at an initial water-cement ratio of 0.350. The author regrets that some account of the water required to produce normal consistency was not taken in these tests. A much better procedure would have been to take 150 per cent of the water required for normal consistency as the water content at which the cements were compared. Normal consistency would have produced a mix of such a plasticity that proper packing of the sample in the container would have been extremely difficult if not impossible.

To show that the initial water-cement ratio does influence the magnitude but perhaps not the general form of the curves, a group of tests were made at a water-cement ratio of 0.400 for cement A (Figure 44, page 164). The general tendencies were the same as those for a water-cement ratio of 0.350. The maximum excess in water content in the top section of the sample reached 10 per cent as compared to approximately 7 per cent at 0.350 water-cement ratio. At the end of 3 hours the water content of this section had decreased to only 8.5 per cent as against 3 per cent for the 0.350 water-cement ratio.

E. Correlation of Electrical Conductivity and Compressive Strength of Cement Mortars

When stating the electrical conductivity for an electrolyte a statement of the temperature at which the measurements was made is very important. For this reason temperature corrections enter in most of these applications of conductometric analysis.

The correction factors shown in Figure 48, page 172, indicate that the conductivity of the cement mortar was reaching a maximum very rapidly with regard to increased temperature. The reason for this maximum occurring at a temperature perhaps even below 40° C. was no doubt due to the extreme viscosity effects in the electrolyte in the case of mortars. This would be in agreement with Falkenhagen's expression of the tendency as discussed on page 15. The rough agreement of all these factors for the range of water-cement ratios investigated would also be an argument in favor of the independence of water-cement ratio upon the concentration at a fixed time after gauging (page 16).

Conductivity and compressive strength of cement mortars can best be compared by means of intermediary factors, either the water-cement ratio or the sand-cement ratio.

First, let us consider them as functions of the water-cement ratio, holding the sand-cement ratio constant.

Provided all the voids were filled for the water-cement ratios investigated, we should obtain a curve of conductivity versus water-cement ratio of the same form as was found for cement pastes; that is, nearly a straight-line relationship. However, there are now inert particles of sand in the mixture each of which is covered with a thin film of water, and this water does not react to produce swelling of the sand as it does the cement particles. Hence we would expect that more water would be required to produce the same plasticity. If less water than that required just to fill the voids completely existed, the mass would become loose, and as a result the conductivity would decrease faster than the straight-line relationship. That this is exactly what occurred is evident in Figure 47, page 173.

This effect of "unworkability" was recognized by Abrams (1) when he expressed his law regarding strength and water content (page 22). That is, at very low water contents the strength curve decreases with decreasing water-cement ratio. Using portions of the same sample for both conductivity and strength tests, it was found that the maximum strength occurred at precisely the same water-cement ratio as did the break in the conductivity curve. That is, the maximum strength occurred where the water content was just sufficient to fill the voids. Either an increase in amount of water, producing spreading of the cement and sand particles, or a decrease in water, leaving voids even in the wet condition, produced the same result, namely, loss of strength. The curve illustrating this fact, Figure 48, page 173, is plotted just below the conductivity curve so that comparison of water-cement ratios can be made.

Because the mortar must be plastic enough to be placed in forms, it is customary to work slightly above the most desired water-cement ratio. For this reason the portion of the curve to the right of the maximum will later be spoken of as the working range of this curve.

Now let us consider these two items as functions of sand-cement ratio, holding the water-cement ratio constant.

Since the sand grains are inert particles which reduce the effective cross sectional area of the sample from an electrical viewpoint, a decrease in conductivity with an increased sand-cement ratio would be expected. This curve is plotted in Figure 49, page 174.

Also an increase in the proportion of sand was found to produce a decrease in the compressive strength of the samples. This is a well recognized fact, the reason for making tests for this curve being merely to have data on conductivity and strength from the same samples.

The curve is shown in Figure 50, page 174.

The original hope of this portion of the investigation was to devise a means whereby the compressive strength of a mortar mix could be predicted from the conductivity measurements. That this was delusive reasoning will now be demonstrated.

First, let us note that for constant sand-cement ratio an increase in conductivity indicates a decrease in compressive strength in the working range. Whereas, for constant water-cement ratio an increase in conductivity indicates an increase in compressive strength. Thus from a proper choice of mixes the same conductivity could correspond within limits to any compressive strength. The above statements can be checked against the curves to which reference has already been made, but perhaps more easily from Figures 51 and 52, page 175, where the two quantities, compressive strength and conductivity, are plotted against each other.

V. CONCLUSIONS

A. Setting Phenomena of Cement Pastes

1. Two processes occur in the setting of cement pastes (the period 0 to 3 hours after gauging). These processes are evident from changes in the electrical conductivity.

2. The first process produces an increase in the electrical conductivity with increased values of time. It is a hydration process, causing increased ionization of the liquid portion of the paste.

3. The second process causes a decrease in electrical conductivity with increased values of time. It is either a crystallization or a colloidal-formation process, causing increased viscosity effects in the electrically conducting media.

4. The two processes no doubt overlap. In any case, they cause a maximum point in the conductivity curve. The time at which this maximum occurs gives a measure of the hydration period. This measurement has more meaning, and may be obtained much more accurately than a physical measurement of initial setting conditions.

5. The negative slope of the conductivity-time curve gives a measure of the rate of hardening. Thus, with respect to Shimizu's work (Figure 1, page 11) the sudden decrease in conductivity which he obtained at larger values of time (causing a large negative slope) was

indicative of the hardening (crystallization?) occurring at a faster rate.

6. An increase in the temperature produces a shorter hydration period (initial setting period) for most cements.

7. An increase in the water-cement ratio produces a longer hydration period (initial setting period) for most cements, especially at lower temperatures.

B. Excess Water Tendency in Sand-Water Mixtures

1. The excess water tendency (i. e., the excess water above that required to fill the dry voids of a granular material) decreases with decreased diameter of the particles.

2. Properly graded material has an excess water tendency of approximately the same amount as material which is all of very small diameter.

3. Internal stratification can be eliminated to a large extent by removing one of its principal causes——excess water tendency. Either properly graded materials or very fine grinding of the cement clinker are effective means of accomplishing the same effect.

C. Internal Stratification in Cement Pastes

The conclusions for this section will be presented in the form of a proposed method of test for internal stratification. This method of test was submitted to several cement research laboratories and members of the American Society for Testing Materials in June, 1936. The method of test follows:

TENTATIVE METHOD OF TEST
FOR
INTERNAL STRATIFICATION (BLEEDING) OF PORTLAND CEMENT PASTES

Scope

1. This test provides a quantitative measure of the "bleeding" property of Portland cement pastes from ratios of electrical conductance. This is accomplished by sectionalizing the sample electrically by a set of six pairs of fixed potential electrodes, each pair being placed in the center of a one-inch horizontal section of the sample.

APPARATUS

General

2. The electrical circuit shall consist of a constant voltage, 1000-cycle, vacuum-tube oscillator supply of five-tenths (0.5) volt, connected to the six pairs of electrodes in parallel in the sample container. In each electrode circuit shall be inserted a one (1.0) ohm non-inductively wound shunt. The voltage drop across each shunt shall be measured with a vacuum-tube voltmeter. A diagram of the circuit is shown in Figure A (Figure 3 of thesis, page 193). Each voltage-drop reading gives a measure of the electrical conductance of the corresponding one-inch section of the sample. General considerations indicate a direct (although not necessarily linear) relationship between electri-

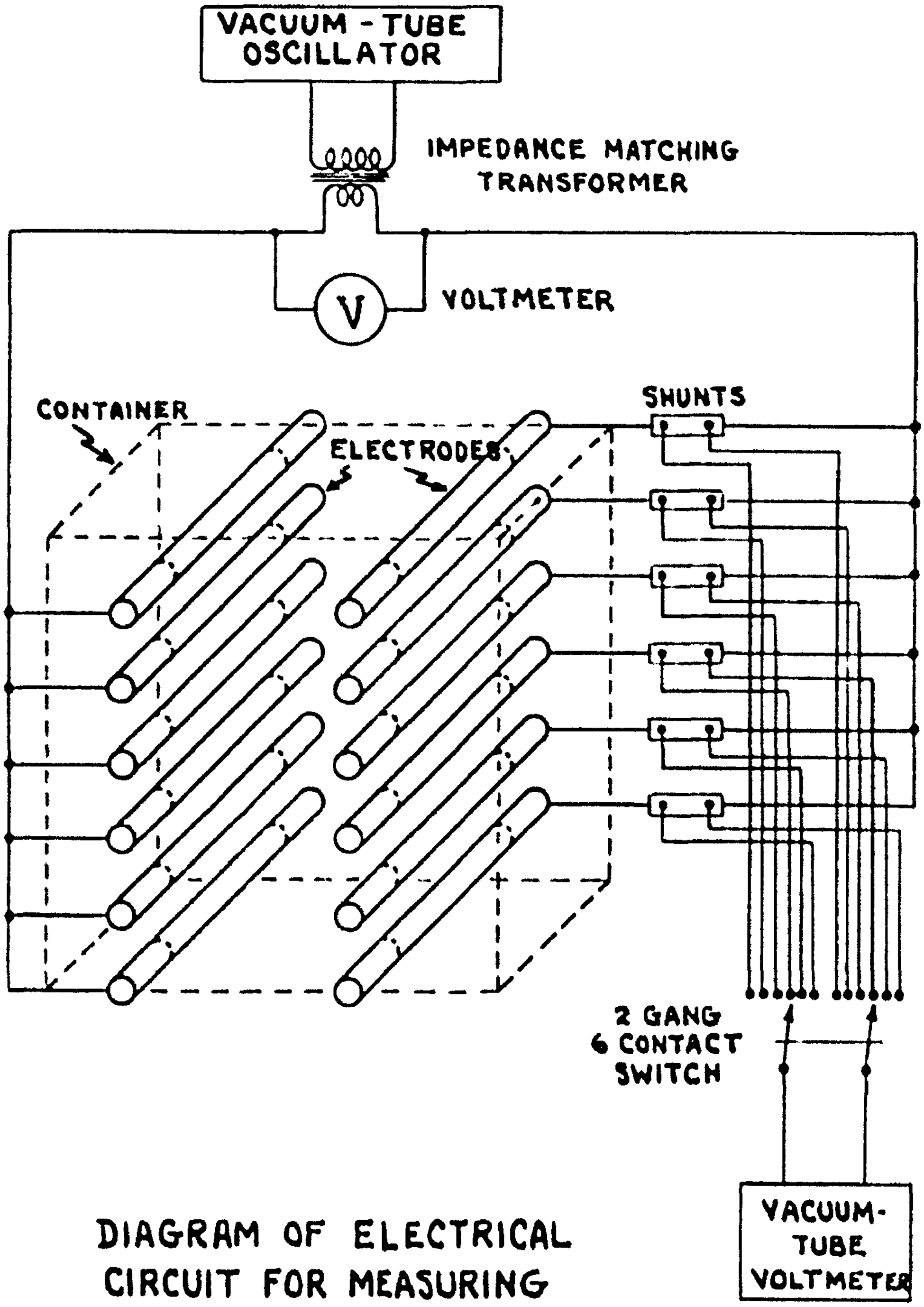


DIAGRAM OF ELECTRICAL CIRCUIT FOR MEASURING THE INTERNAL STRATIFICATION (BLEEDING) OF PORTLAND CEMENT PASTES

WDB

Figure A
(Figure 3 of
Thesis Repeated)

cal conductance and water content (or water-cement ratio) of the sample.

Oscillator

3. The source of voltage supply shall consist of a vacuum-tube oscillator and an impedance matching transformer such that a voltage of five-tenths (0.5) volt may be maintained under a load current of one hundred (100) milliamperes.

Voltmeter

4. The voltmeter for indicating the constancy of the voltage supply shall have a range of zero to one (0 - 1) volt.

Sample Container

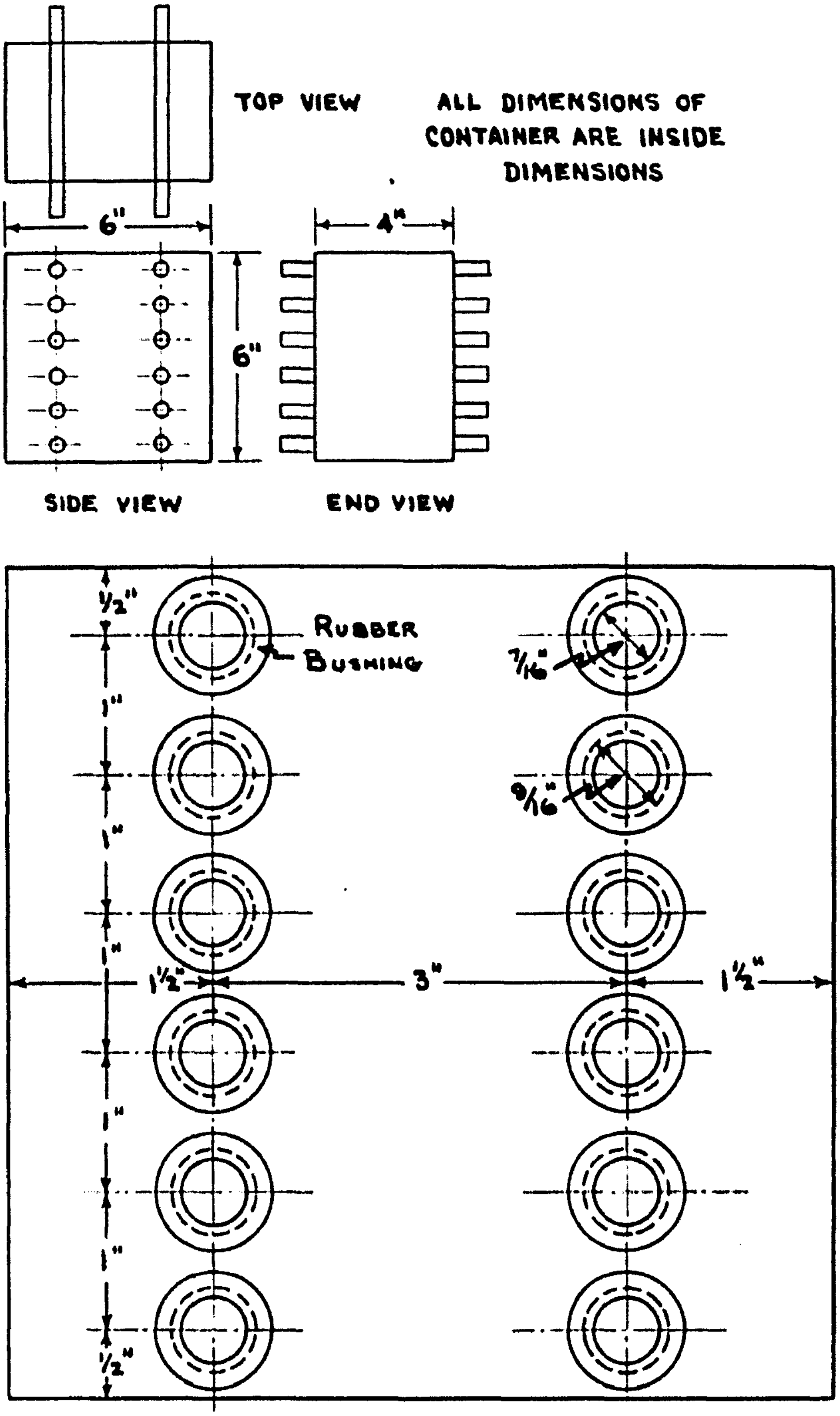
5. The sample container shall consist of the container proper and the electrodes, and shall include the following features:

(a) Container Proper----The container proper shall consist of a water-tight, non-conducting box preferably of molded hard rubber or bakelite of the following dimensions:

Height	6 inches ± 0.05 inches
Width	4 inches ± 0.2 inches
Length	6 inches ± 0.2 inches

The two sides of the container (6 by 6 inch dimensions) shall be drilled according to the diagram shown in Figure B (Figure 53 of thesis, page 195). The 9/16-inch diameter holes shall be fitted with water-tight, soft rubber bushings of 7/16-inch inside diameter.

(b) Electrodes----The electrodes shall consist of twelve (12) graphite carbons of 7/16-inch diameter, seven (7) inches or more in



ALL DIMENSIONS OF CONTAINER ARE INSIDE DIMENSIONS

SAMPLE CONTAINER FOR STRATIFICATION MEASUREMENTS

Figure B
(Figure 53 of
Thesis)

length.

(c) Connections---Connections to the electrodes shall be provided by Number 27 Universal test clips.

Metering Devise

6. The metering devise shall consist of six (6) shunts, one being inserted in each of the six (6) electrode circuits, and a vacuum-tube voltmeter for measuring the voltage drop across each shunt.

(a) Shunts---Each shunt shall be non-inductively wound and have a resistance of one (1.0) ohm ± 0.05 ohm.

(b) Vacuum-tube Voltmeter---The vacuum-tube voltmeter shall be capable of measuring voltages in the range of ten (10) to one hundred (100) millivolts with a sensitivity of one-tenth (0.1) millivolt (0.1 per cent at the upper limit).

CALIBRATION OF APPARATUS

Calibration of Vacuum-tube Voltmeter

7. The vacuum-tube voltmeter shall be calibrated by measuring a known voltage drop calculated from a measured current flow through a standard non-inductively wound resistance of known resistance.

Calibration of Container and Meter Shunts

8. The container and shunts shall be calibrated for variations with the container filled with a 0.3 normal solution of sodium chloride. The calibration shall consist of three or more (preferably five) sets of readings with the assigned voltage of 0.5 volt applied to the

combination. The electrodes shall be sand papered clean of encrusted cement before each calibration and test.

TEST SAMPLE

Size of Test Sample

9. The sample shall consist of 5000 grams of the cement to be tested and 150 per cent of the water required to produce normal consistency as determined by the Vicat needle test (A. S. T. M. Standards: C 77 - 30). Distilled water of conductivity less than 10^{-4} mhos/cm^3 shall be used for gauging.

Number of Test Samples

10. Not less than two (preferably three) complete samples shall be made before the final curves for a given cement are drawn.

Preparation of the Sample

11. The container, cement, and water shall be brought to a room temperature of 25° C. (78° F.) before the test is made. The cement shall then be placed upon a non-absorbent flat surface and cratered. At this point the cement should cover an area of approximately two (2) square feet. The water shall then be poured into the crater and a timing device (a stop watch for example) shall be set at zero and started. One (1) minute shall be allowed for turning the cement into the water with a trowel, care being taken that no liquid overflows the rim of the crater. The sample shall then be mixed thoroughly for five (5) minutes. At a total elapsed time of six (6) minutes the sample shall be placed in the

container, care being taken not to damage the electrodes. With the container filled as much as possible the sample shall be rodded ten (10) times in the region between the electrodes and five (5) times in each region behind the electrodes. (See note). The rod shall consist of a one half inch solid metal rod twelve (12) inches in length. The surface of the sample shall then be smoothed with as little agitation as possible, and the leads shall be made to the ends of the electrodes extending outside the box.

NOTE.——It is very important that this procedure be carefully followed. Any wide deviations as regard temperature, time, or conditions of rodding may give incomparable results.

TEST PROCEDURE

Readings

12. Two (2) sets of readings for the six electrode circuits shall be made each five (5) minutes beginning at ten (10) minutes total elapsed time, for the first sixty (60) minutes. For the remainder of the one hundred eighty (180) minutes of the test, two (2) sets of readings shall be made each ten (10) minutes. The two sets of readings shall be taken in succession and recorded as the readings at the average time of the readings. The external temperature of the container shall be maintained at 25° C. (78° F.) during the test. The temperature of the sample shall be measured by a thermometer placed just behind the common circuit electrodes in the cement paste. When testing high early strength cements this thermometer should be turned frequently to prevent it becoming sealed in the cement. Readings of the level of the water and

the cement at the center of the top surface of the sample shall be made each ten (10) minutes starting at twenty (20) minutes total elapsed time.

CALCULATIONS

Calculations of Results

13. Calculations of the electrical conductances shall be made according to the following procedure:

(a) Calibration of Equipment—(The following procedure applies specifically to the type of vacuum-tube voltmeter used by the author, and consequently that part pertaining to the voltmeter may require revision according to the equipment used.) Let

I_o = current through the shunt during calibration of voltmeter

R_o = resistance of the shunt for voltmeter calibration

P_o = potentiometer setting of vacuum-tube voltmeter during calibration of voltmeter

P_i $(i = 1, 2, \ldots 6)$ = average readings for the six electrodes circuits during the calibration with the NaCl solution

$P_a = 1/6 \sum_{i=1}^{6} P_i$ = grand average of NaCl calibration readings

$F_i = P_a/P_i$ = factor by which readings of potentiometer, when the voltmeter is connected across shunt i, must be multiplied to refer all readings to the same level of measurement

E = voltage applied to the sample during all the readings

R_{si} = resistance of shunt in circuit i;

then the sample resistance of section i, R_i, for any reading of the potentiometer, P, is

$$R_i = \frac{E \times F_i}{I_o \times P_o \times R_o} P - R_{si} \qquad \text{(Eq. 13)}$$

Converting to conductance,

$$G_i = 1/R_i \qquad \text{(Eq. 14)}$$

(b) Corrections for Surface Conditions—Inasmuch as water will collect on the top of the sample for some cements during a portion of the test, and as the cement paste also undergoes a shrinkage as it sets, it is necessary to make corrections to the conductance measurements of section one (top section) for these two items. One sample of each cement for which water collects on the surface shall be used in determining the conductance of the surface water. At a time when the amount of water on top is a maximum (See note) this water shall be poured or absorbed from the surface and the readings continued. If

G_w = conductance of the top section with the water
G_g = conductance of the top section without the water
d_w = depth of water during reading of G_w
d = depth of water during any reading for which the conductance is G_s,

then the corrected value of G'_s is

$$G'_s = G_s \left[1 - d/d_w \, (G_w - G_g)\right] \qquad \text{(Eq. 15)}$$

assuming that the water has the same conductivity during both readings. The correction for shrinkage of the cement paste shall be made on a volumetric basis. If d_c is the distance from the top level of the container to the cement level, measured in inches, then the completely corrected value of G_s'' is

$$G_s'' = G_s' / (1 - d_c) \qquad \text{(Eq. 16)}$$

The one (1) enters because the normal depth of the section is one (1) inch.

NOTE.----One sample should be run through the complete 180-minute period of test and from the data thus obtained the time at which the amount of water on top is a maximum may be determined.

(c) <u>Calculation of Percentage Conductance</u>----The percentage conductance shall be based upon the average conductance of sections two (2) to six (6), exclusing the top section (section one). If

$$G_i = \text{conductance of section } i \ (i = 1, 2, \ldots 6)$$

$$G_a = 1/5 \sum_{i=1}^{5} G_i = \text{average basic conductance,}$$

then the percentage conductance, M_i, of any section i, is

$$M_i = G_i/G_a \times 100 \text{ per cent}$$

RESULTS

Curves

14. When two (or three) complete samples have been tested, the data (potentiometer readings) obtained from the individual runs shall be plotted versus time and smooth curves drawn. From these curves readings at 15, 30, 45, 60, 90, 120, 150, and 180 minutes shall be picked and used in the calculations. Finally the average curves of percentage conductance versus time for each of the six sections of the sample shall be drawn.

(End of Tentative Method of Test for Internal Stratification)

D. Correlation of Electrical Conductivity and Compressive Strength of Cement Mortars

1. A break in the conductivity versus water-cement ratio curve, at constant sand-cement ratio, occurs where the water content is just sufficient to fill the voids of the sample. Above this point the conductivity increases slowly with increased water-cement ratio. Below the point the conductivity decreases rapidly with decreased water-cement ratio.

2. The compressive strength, at constant sand-cement ratio, is affected by the same requirement of sufficient water content as is the conductivity relationship. The optimum in compressive strength can be obtained when the water is just sufficient to fill the voids, but not in excess to produce excessive spacing of the mortar particles.

3. At constant sand-cement ratio an increase in electrical conductivity corresponds to a decrease in compressive strength in the working range.

4. At constant water-cement ratio an increase in electrical conductivity corresponds to an increase in compressive strength.

5. A correlation between electrical conductivity and compressive strength for mortar mixes in general is impossible.

VI. SUMMARY

This investigation deals with the application of conductometric analysis to several phenomena of Portland cement pastes and mortars. Much work involving conductometric analysis has been undertaken in allied fields, but only a very limited amount has dealt directly with Portland cement pastes or mortars.

A cement paste or mortar from an electrical viewpoint consists of a more or less granular substance saturated with an electrolytic solution. Variations in the ratio of electrolyte to the granular substance, and in the concentration and viscosity of the electrolyte produce variations in the conductance from which deductions may be drawn as to the physical processes which occur.

A. Setting Phenomena of Cement Pastes

The setting phenomena for three Portland cement pastes were followed conductometrically for three hours. The results of these analyses indicated that there are two definite periods in the setting process.

The first, which is predominately a hydration period, produced an increase in conductivity as time increased. The second, which is predominately a period of crystallization or colloidal formation, caused a decrease in the conductivity with increase in time.

These two influences resulted in a maximum conductivity being reached at 45 to 80 minutes following gauging, the exact time depending upon the cement, water content, and the temperature. At standardized temperature (25° C.) and water content (normal consistency) a very definite measure of the hydration period can be made by rather simple electrical measurements.

Likewise the rate of hardening, desiccation, or perhaps both, can be measured relatively by the negative slope of the conductivity curve after the maximum is reached.

B. Excess Water Tendency in Sand-Water Mixtures

Believing that stratification, or "bleeding", in cement pastes or mortars can be eliminated to a large extent by employing mixtures which have little or no tendency for requiring excess water, the author devised a means of measuring this excess water tendency for electrically inert particles. It is believed that the conclusions, namely, that either fine particles or properly graded mixes require a minimum of this excess water, can be applied to cement mortars and pastes as well as to sand-water mixtures. Thus, a very finely ground cement or a well graded sand-cement mixture will help reduce one of the primary causes of internal stratification.

C. Internal Stratification in Cement Pastes

An analysis of the problem of stratification, or "bleeding", in cement pastes or mortars indicates that such phenomena occur if there is an excess of water, and if capillary and gravitational forces can overcome its resistance to flow. A method of measuring the relative water content in lateral sections of the sample has been developed by the author and is presented in the conclusions as a proposed method of test.

Tests made upon the three cements, indicated that although the water did not rise above the surface for the high early strength cement samples, the final distribution of water in these samples was the poorest of all the cements tested.

A rather coarsely ground, normal hardening cement may under reasonable conditions of water content produce a good final distribution of water, since the combination of granular material and slow hardening allows the water to be absorbed rather uniformly back into the sample.

D. Correlation of Electrical Conductivity and Compressive Strength of Cement Mortars

Although a complete correlation between conductivity and strength was found impossible for cement mortars in general, a very interesting relationship was observed when the sand-cement ratio was held constant.

The maximum compressive strength was found to occur at the same water-cement ratio as did a decided break or knee in the electrical conductivity curve. This seems to indicate that the most desirable water content in a cement mortar is that content which will allow the particles of mortar to be as close together as possible and yet completely saturate the voids of the mixture.

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IX. VITA

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X. APPENDICES

Appendix A — Symbols

A	Area
C	Capacitance
d	Depth of water
d_a	Relative density, or concentration
d_o	Dry bulk density (percentage of solids)
d_w	Depth of water during conductance determination
E	Potential, potential difference, or applied voltage
f	Frequency
F	Charge on a univalent ion
F_i	P_a/P_i
G_a	Average basic conductance
G_g	Conductance without surface water
G_i	Conductance of section i
G_s	Sample conductance
G'_s	Sample conductance corrected for water conductance
G''_s	Sample conductance corrected for water conductance and for shrinkage of cement paste
G_w	Conductance with surface water
H	Force
i	An index number (1,2,...etc.)
I	Current
I_o	Current through standard resistor
k_d	Percentage of dry voids
k_w	Relative measure of wet voids
l	Length
M_i	Percentage conductance of section i of sample
n	Viscosity
N	Number of molecules per unit volume
P	Potentiometer reading
P_a	Grand average of calibration readings
P_i	Potentiometer readings for calibration of container and shunts
P_o	Potentiometer reading for calibration of voltmeter
Q	Polarization

r	Radius
R	Resistance
R_o	Resistance of standard resistor
R_s	Sample resistance
R_{si}	Resistance of shunt in circuit i
R_{sw}	Resistance of sand-water mixture
R_w	Resistance of water
s_c	Compressive strength
t	Time
u_a	Steady-state velocity of anion under unit potential gradient
u_c	Steady-state velocity of cation under unit potential gradient
V	Volume
V_o	Volume of water and sand
V_s	Volume of sand
V_w	Volume of water
W	Total load (force)
x	Distance ordinate
Z	Impedance
α	Fraction of molecules ionized
λ	Excess water tendency
μ	Temperature correction factor
ν	Valency of an ion
σ	Conductivity
ω	2π times frequency

Appendix B — Errors

The term <u>error</u> in this discussion is strictly technical and is not intended to include mistakes.

The designation of signs to errors is made according to the accepted sense (10), namely—an error is that quantity which must be added algebraically to the true (or smooth curve) value to give the observed value.

Errors which may occur in making samples of cement paste or mortar include:

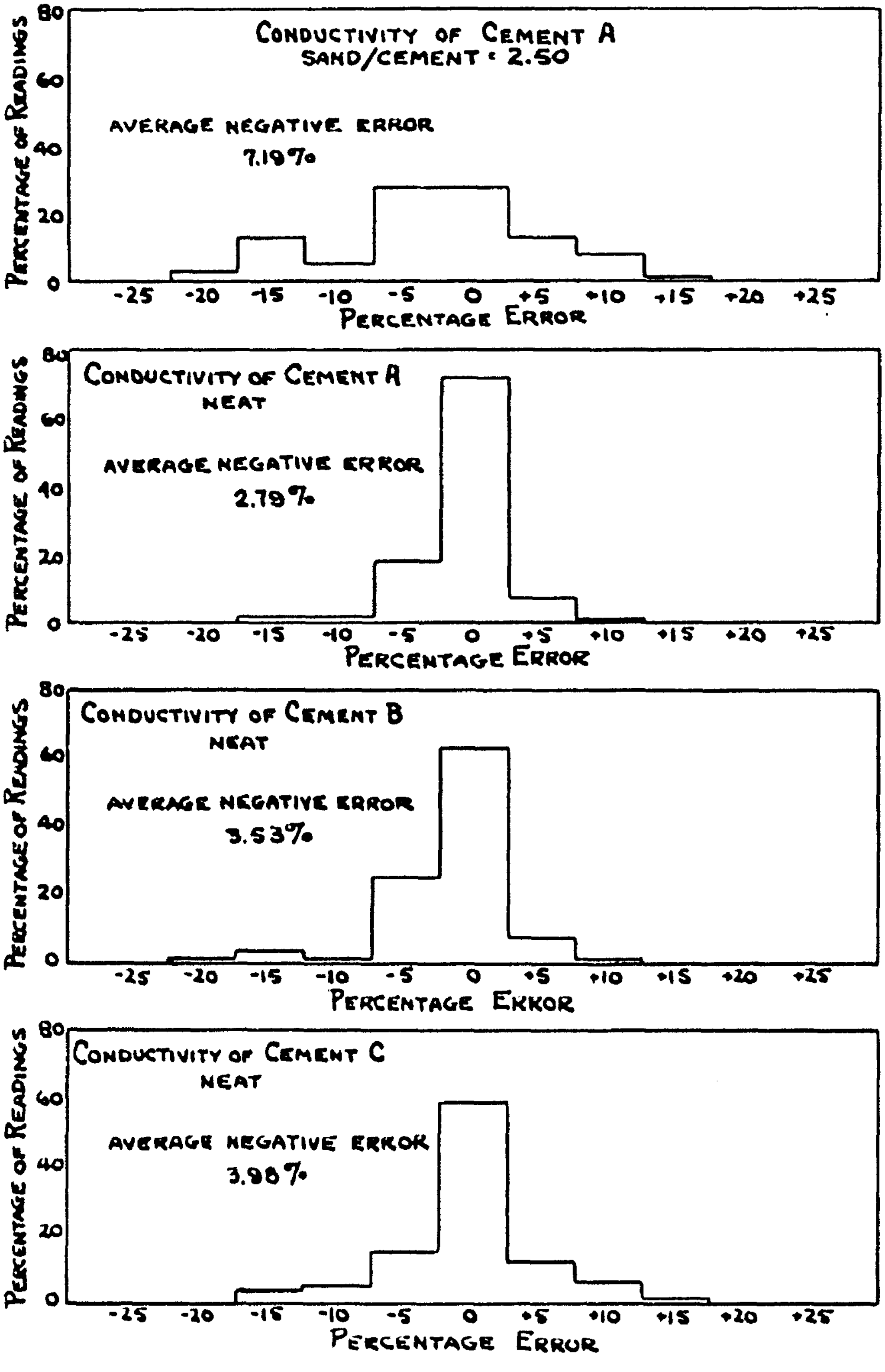
1. Errors in measuring the constituents
2. Errors in the degree or thoroughness of mixing
3. Errors in filling the sample containers or molds to the same level
4. Errors in the degree of packing the samples
5. Errors in holding setting or curing conditions at the same level
6. Errors in making readings upon the samples
7. Errors caused by conductance of the sample container
8. Errors caused by shrinkage of the sample

From the viewpoint of electrical conductivity measurements, errors 2, 4, and 8 tend to produce negative errors, whereas error 7 produces a positive error. These errors may therefore be termed systematic errors, with a predominance of causes for negative errors.

As a result, when drawing the smooth curves of conductivity an allowance was made for this possibility. Usually a definite indication of larger negative errors appeared as may be noticed in the error distribution curves dealing with the electrical measurements.

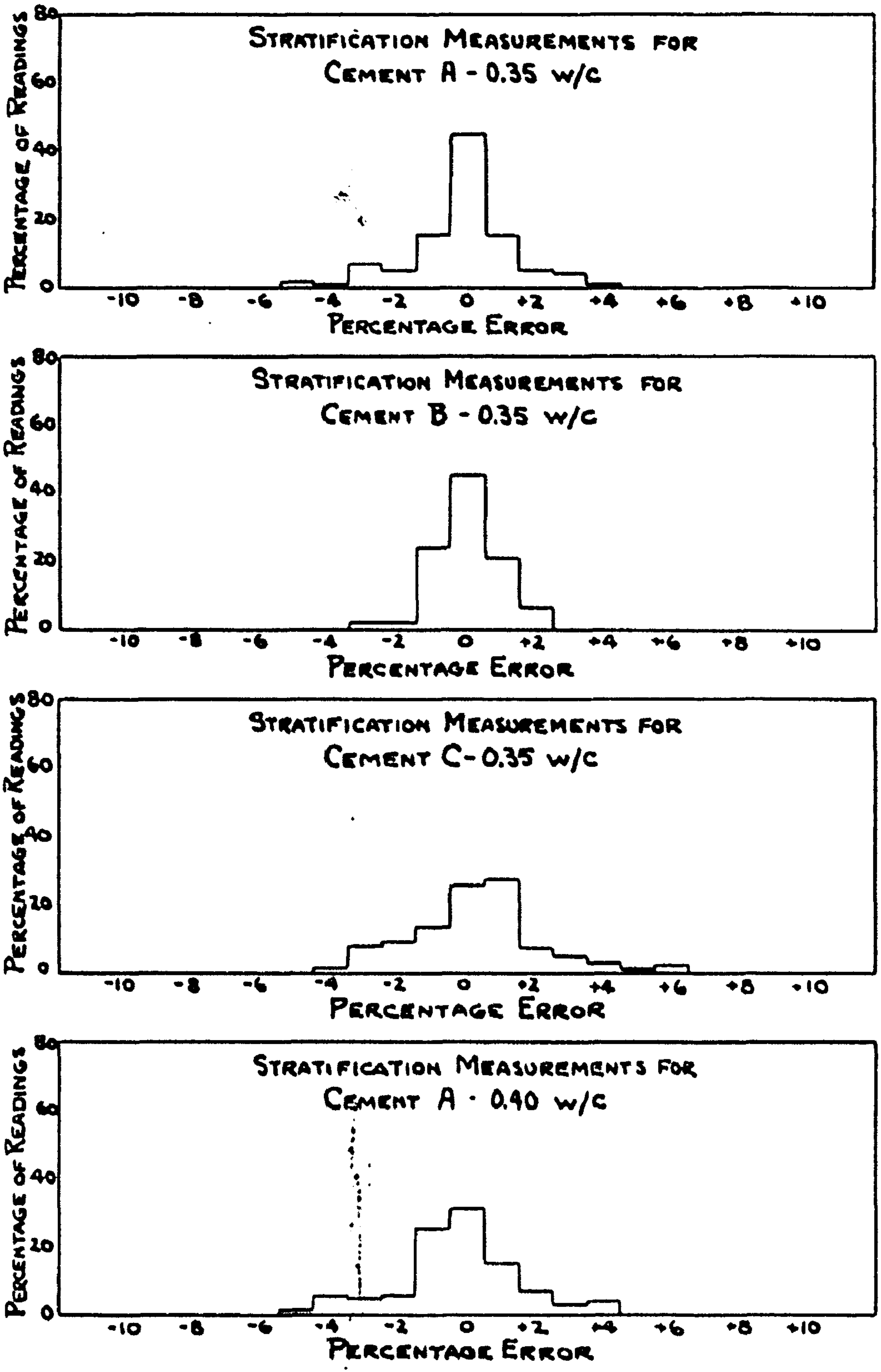
Error distribution curves for twelve sets of the most important determinations are given in Figures 54, 55, and 56, pages 217, 218, and 219.

An upper limit on the magnitude of error to be plotted in the measurements of conductivity of the neat samples of cements A, B, and C was arbitrarily set at twice the average negative error. This procedure eliminated those data which were most obviously in error due to any of the above mentioned causes. The average negative errors are indicated on these distribution curves.



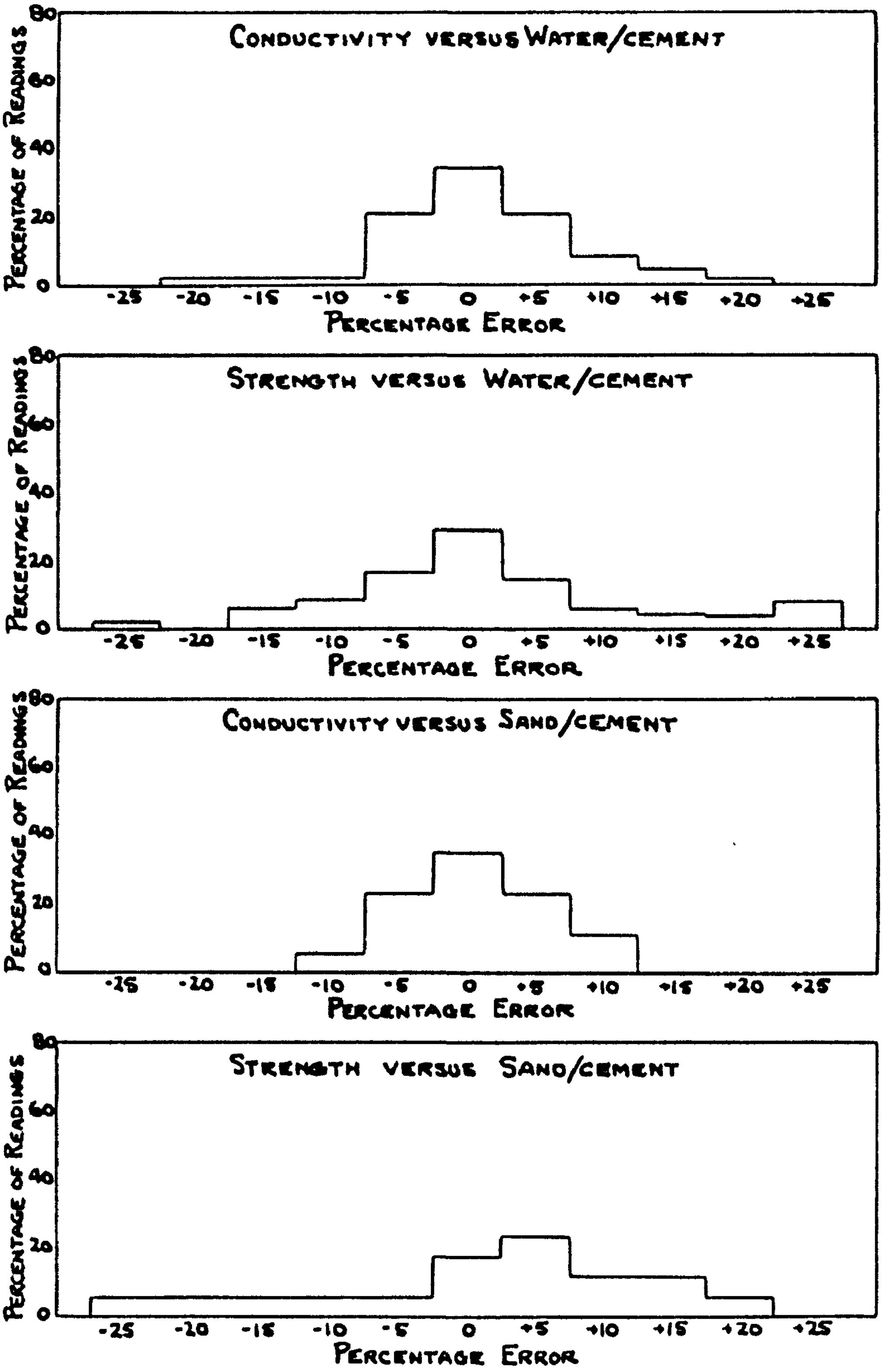
ERRORS FROM FIGURES 45, 12, 13, AND 14 RESPECTIVELY

Figure 54



Errors from Figures 37, 38, 39, and 40 respectively

Figure 55



ERRORS FROM FIGURES 47, 48, 49, AND 50 RESPECTIVELY

Figure 56