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Instrumentation for Measuring Characteristics of Concrete

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Contents

A Standardizing Strain Gage for Measurements Requiring Long-Time Stability

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A new type of unbonded elastic wire strain gage is described. Strains are determined by measuring the changes in electrical resistance of the elastic wire with conventional strain bridges, but long-time stability is achieved in a novel manner by referring all strain measurements to a built-in Invar length standard. The performance of one standardizing strain gage was evaluated by comparison with a 10-in. Whittemore gage. The standardizing gage can be surface-mounted or embedded in concrete.

● DEVELOPMENT OF THE bonded wire strain gage shortly before 1940 increased the accuracy and convenience of many strain analyses. A large number and variety of mechanical and structural members have since been studied with the aid of this new tool. As is the case with most instruments, however, the bonded wire gage is better suited for some fields of study than others. The measurements of strains over periods longer than several days have not always been reliable.

During long periods of time there may be changes in the response of the gage which are not a direct result of changes in strain in the material being investigated. These long-time effects are commonly called "drift." The resistance of the wire in the bonded gage is measured at the start of a test, and subsequent changes in the gage resistance are interpreted as dimensional changes in the material. Should there be drift changes also, the separation of these drift changes from the real dimensional changes may be impossible, even though unstressed dummy gages are used to achieve a degree of compensation. Drift in bonded wire gages may be due to causes which cannot be accurately compensated by unstressed "dummies" including relaxation effects in the crystalline structure of the wire, dimensional changes in the bonding cement, changes in adhesion between the bonding cement and the surface under study, changes in electrical resistance between the gage wire and ground, changes in lead wires, or changes in the elements of the measuring circuits.

A well-known method of achieving long-time stability in length measurements is that of comparing the unknown with a standard. Such a method is commonly used with dial gages; the Whittemore strain gage is one example. The thought occurred to the author, when employed in the Denver Laboratories of the United States Bureau of Reclamation, that the incorporation of a length standard in an elastic wire strain gage would eliminate drift effects. The resultant gage should have long-time stability plus the accuracy and convenience associated with a resistance-type gage. The immediate problem was the measurement of creep in foundation rock, a property of considerable importance in the design of large concrete dams. The idea was developed to the point where one basic model was built and tested. The results indicated that a standardizing electrical resistance strain gage was feasible.

The project was renewed in the research laboratories of the Portland Cement Association with the objective of developing a gage suitable for measuring long-time dimensional changes which may occur in various concrete products and structures. The present report describes a standardizing strain gage which was designed for use either on the surface or embedded in concrete. Evaluation tests to which the gage was subjected are also discussed.

A patent application covering the standardizing strain gage has been filed with the U. S. Patent Office by the Solicitor of the Department of the Interior, and, in accordance with usual Federal procedure, all rights to any patent which may be issued thereon are assigned to the Federal Government.

OPERATION OF GAGE

The operation of the gage is best described by means of Figure 1, which shows the gage mounted on the surface of a solid. The essential parts of the gage are a tube, a piston fitted into one end of the tube, and a small-diameter elastic wire stretched inside the tube from the piston to the other end of the tube.

The wire is adjusted so that it is under slight tension when the piston is in the normal position (that is, when the piston shoulders are in contact with the end of the tube). A spring (not shown in Fig. 1) assures a positive contact between the piston shoulders and the end of the tube. The tube and piston assembly is attached to the solid by means of insert 1. Insert 2, located a distance L from insert 1, serves as a stop for the outward movement of the piston, which is accomplished by applying air pressure within the tube.

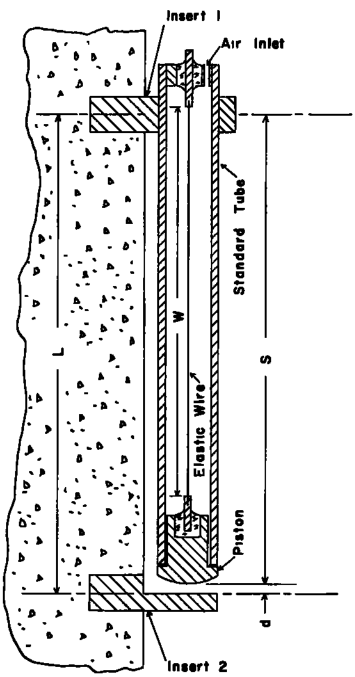

Figure 1. Standardizing strain gage.

The purpose of the gage is to measure changes in length L; that is, changes in the gage length. From Figure 1,

$$L = S + d \tag{1}$$

in which S is the length of the standard, which in the present gage was made of Invar. For small temperature changes length S will be essentially constant; for larger temperature changes a small correction may be applied. If S is assumed to be constant, changes in L may be measured by measuring the equal changes in d. The elastic wire is used as a convenient and accurate method of measuring d. The change in the electrical resistance of the wire as the piston is moved outward from the standardizing position until it contacts insert 2 provides the data necessary for determining d.

The change in resistance per unit resistance of small diameter Advance wire, which was used in the standardizing strain gage, has been found experimentally by many investigators to be proportional to the strain of the wire; that is,

$$\Delta R/R = K \; \Delta W/W = Kd/W \qquad (2)$$

in which ΔR is the change in resistance and ΔW (= d) is the change in length of a wire of initial resistance R and length W. K is a proportionality constant and is a property of the wire; it is logically called the strain coefficient of resistance. A similar proportionality constant between resistance change and strain in the material under study is called gage factor. Gage factor and strain coefficient are equal when W = L. If K and W are known, d may be determined from resistance measurements. At the beginning of a test d is measured by the change in resistance caused by moving the piston from the standardizing position to the gaging position. At any later time d is measured in the same manner by a resistance change from the standardizing to the gaging position. Thus a "zero" reading is taken for each measurement, and drift effects are thereby eliminated.

The strain in the material under test is equal to $\Delta d/L$, and may be read directly from bridges calibrated in strain units.

The maximum value which d may have is fixed by the elastic properties of the wire; the wire strain d/W must not exceed the elastic limit. For hard-tempered Advance wire, used in the present gage, this limit is about 0.005 in. per in. If W = L, the maximum strain which can be measured in the material under study is likewise 0.005 in. per in. millionths. However, W and L do not necessarily have to be equal, as the gage insert 1 (Fig. 1) may be fixed anywhere along the tube. For example, if W = 2L, strains up to 0.01 in. per in. may be measured.

The purpose of the present paper is primarily to explain the principle of the standardizing strain gage, rather than to discuss details of construction. Several additional gages are being built and modifications will certainly be made in some details. In fact, one gage has been built in which the piston is mechanically rather than pneumatically actuated. Anyone interested in fabrication details may correspond with the author.

EVALUATION TESTS

The length standard of the gage used in the tests to be described was made entirely of Invar. The gage was $\frac{1}{4}$ in. in diameter and the hard-tempered Advance wire was 0.001 in. in diameter and 4 in. long. The gage length was also 4 in. The gage was calibrated by applying known movements to the gage by means of a Gaertner micrometer slide and measuring gage response with a Baldwin type L strain indicator. Values obtained for the gage factor from calibrations made during the 15 weeks of tests were 2.17, 2.17, 2.16, and 2.17.

In all of the tests the response of the standardizing strain gage was compared to that of a 10-in. Whittemore gage. The Whittemore gage was chosen because it is also a standardizing gage and hence is inherently stable. An Invar bar was used as the standard for the Whittemore gage.

In the first comparison, strains along the same gage line on the surface of a 6- by 18-in. lightweight aggregate concrete cylinder were measured with the two different gages. Four inserts were cast in the cylinder. The standardizing gage was fastened to the two inner inserts, and adapters for the Whittemore gage were screwed into the two outer inserts. Figure 2 shows the Whittemore adapters and the standardizing strain gage in place on the cylinder. The lead wires from the standardizing gage were contained in the plastic tube fastened to one end of the gage. This tube served also

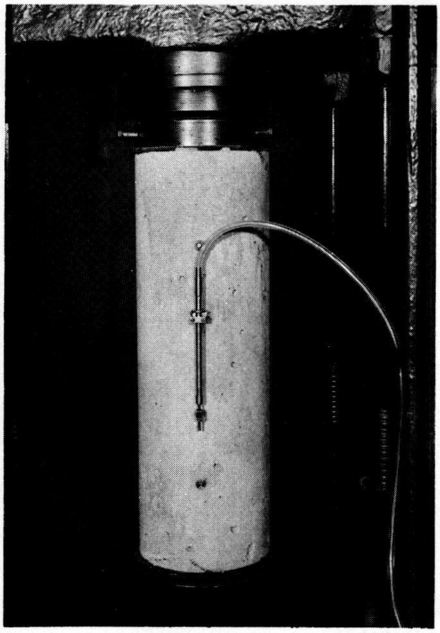

Figure 2. Gage attached to surface of 6- by 18-in. cylinder.

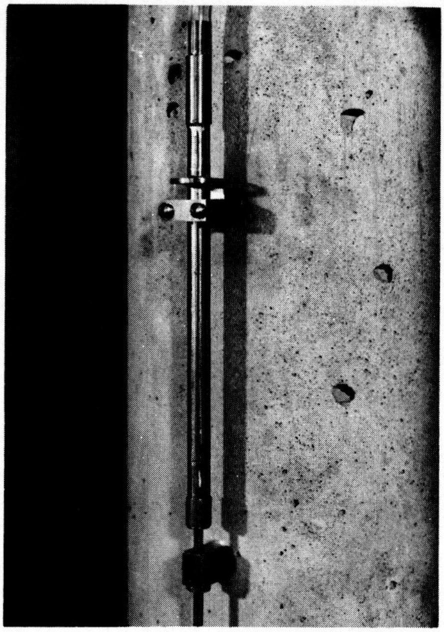

Figure 3. Details of surface mounting.

as the air line for operating the gage piston. A close-up of the standardizing gage is shown in Figure 3.

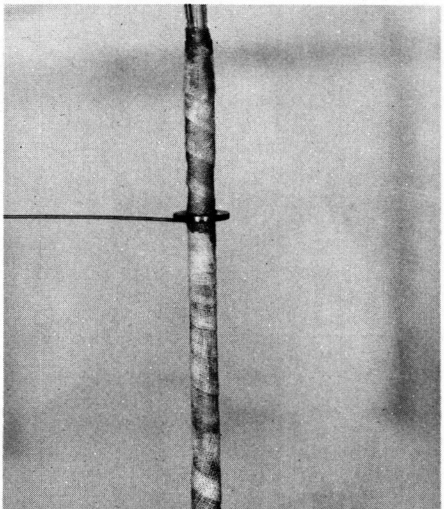

Figure 4. Gage with flanges for embedment.

In the second series of tests, the standardizing gage was embedded on the axis of a 6- by 18-in. lightweight aggregate concrete cylinder and was compared to Whittemore readings taken on two sets of gage points located 180 deg apart. For this test the standardizing gage was fitted with 5/8- by 1/16-in. flanges, as shown in Figure 4. One flange was fastened to the standard tube and the other served as the stop for the piston. The body of the gage was wrapped with gauze so that the only bond between gage and concrete would be at the flanges. The steel wires extending from the flanges were used to fix the gage in the mold while the concrete was being cast. The cylinder was cast on its side in a special mold to insure good contact between the flanges and concrete.

The stress-strain relations of the cylinders were determined first;

the cylinders were then subjected to constant stress for about three weeks; and finally the stress-strain relations were determined again. The results of the stress-strain tests served as a comparison of the calibrations of the standardizing and Whittemore gages. The results of the sustained load tests compared the stability of the standardizing gage to that of the Whittemore gage.

For the tests in which the standardizing gage was mounted on the surface of the cylinder on the same gage line as the Whittemore gage, Figure 5 shows that the calibrations of the two gages were nearly the same. For the cylinder with the embedded gage, however, the Whittemore readings taken on one gage line differed considerably from those taken on the other

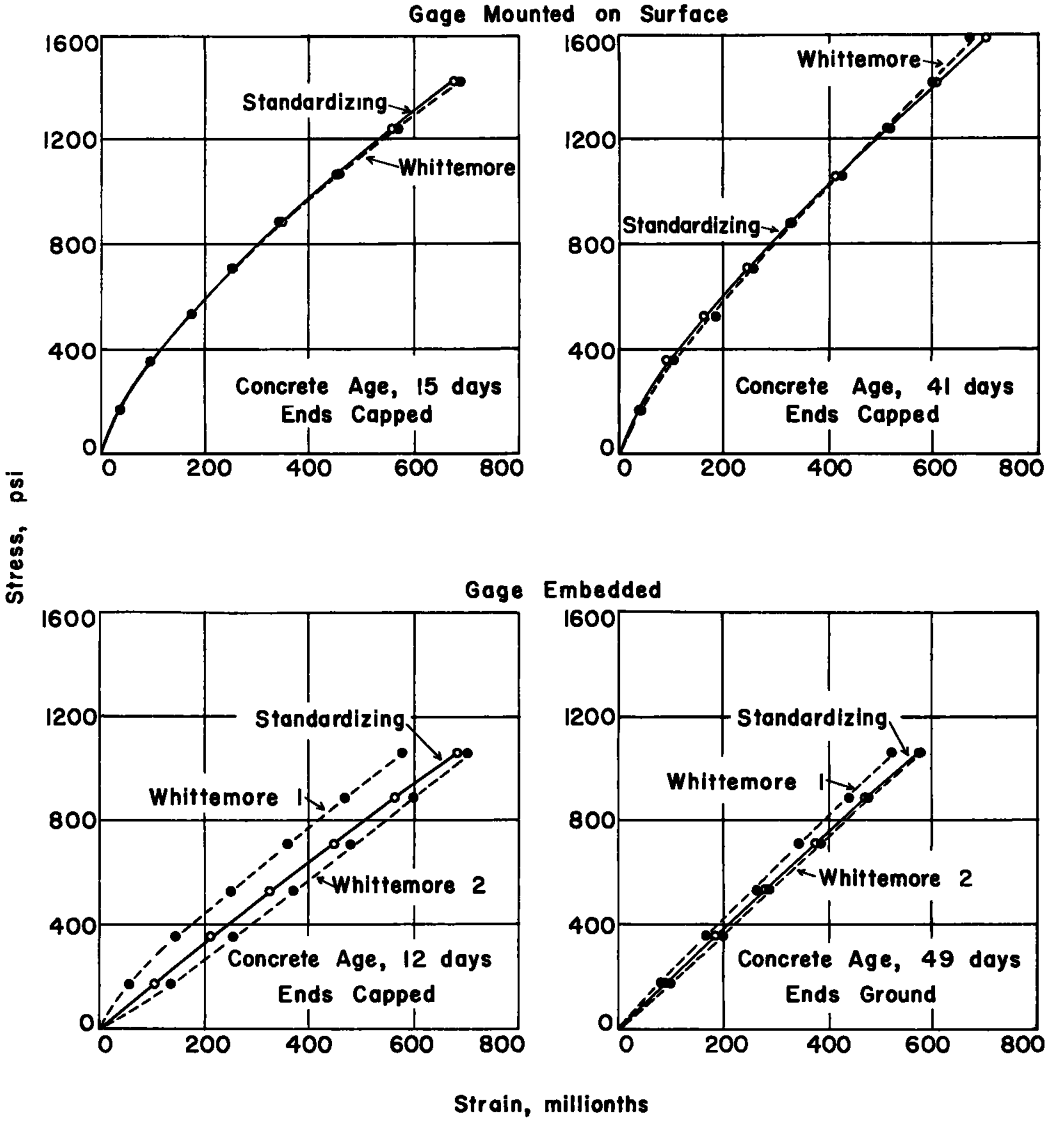

Figure 5. Stress-strain curves.

gage line. This difference may have been caused by non-uniform stress in the cylinder, somehow associated with end conditions. The cylinder ends were capped with sulfur and fire-clay when the first stress-strain tests were made. Before the second stress-strain test, which was made upon completion of the sustained loading, the caps were removed and the cylinder ends were ground flat. This second test (Fig. 5) showed a considerable improvement in the response of the Whittemore for the two gage lines.

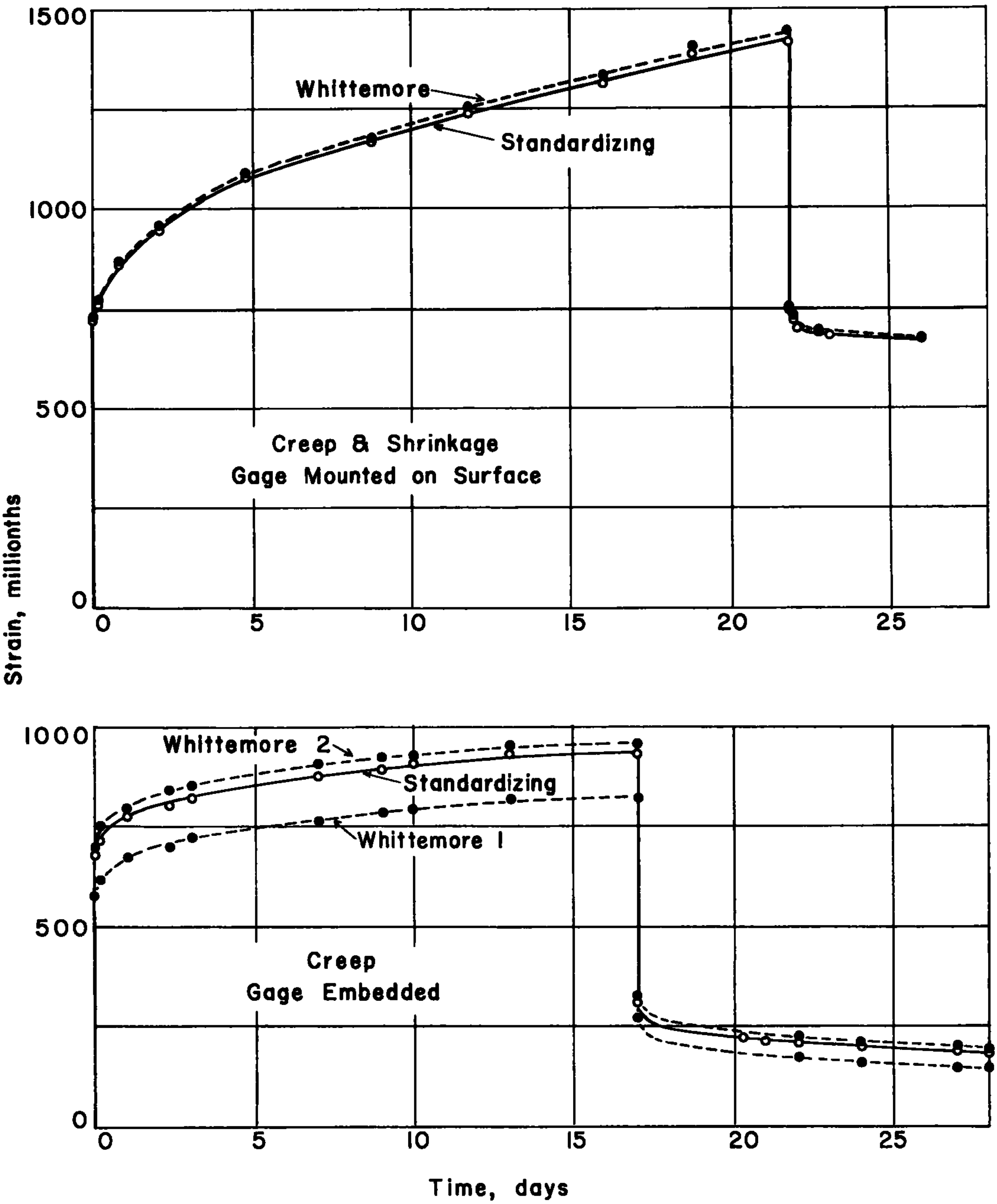

Figure 6. Strain-time curves.

These results indicated that the differences between readings for the Whittemore gage line 1, Whittemore gage line 2, and the standardizing gage were not caused by differences in calibration, but were due to nonuniform stresses in the cylinder.

The cylinder with the standardizing gage mounted on the surface was loaded in a mechanical testing machine when the concrete was 15 days old. The stress in the cylinder was maintained constant at 1,400 psi for 22 days. As the cylinder was not shielded in any way, there was drying shrinkage as well as creep. This was of no consequence, however, because both gages were mounted on the same gage line and the purpose was not to determine the properties of the concrete but to evaluate the performance of the standardizing gage. The strains in the cylinder as a function of time are shown graphically in Figure 6. The readings from the standardizing gage agreed well with the readings from the Whittemore gage.

The cylinder in which the standardizing gage was embedded was loaded in the mechanical testing machine when the concrete was 12 days old. A constant stress of 1,060 psi was maintained for 17 days (Fig. 6). The elastic strains obtained upon application of the load were different for the two Whittemore gage lines, as previously discussed. However, the increases in strains with time were nearly the same for Whittemore gage line 1, Whittemore gage line 2, and the standardizing gage. Shrinkage during drying of a concrete cylinder being greater on the surface than at the center, drying was prevented in this test by enclosing the cylinder in an aluminum sheath.

The standardizing strain gage is independent of changes which may occur in the bridge circuit. This was illustrated during the creep and shrinkage test by substituting another bridge for the one usually used. The strain reading by the usual bridge was 0.001392 and that by the substitute was 0.001388 in. per in.

The effect of temperature was determined by placing the cylinder containing the embedded gage successively in rooms controlled at 40, 70, and 100 F and measuring the resultant strains. The standard bar for the Whittemore gage was subjected to the same temperature, so that the Whittemore readings would be comparable to the standardizing gage readings. The strains per degree measured by the gages should be equal to the difference between the coefficient of expansion of the concrete and the coefficient of expansion of Invar. From the measured strains, and assuming the coefficient of expansion of Invar to be 0.000006 in. per in. per degree F, the values calculated for the coefficient of expansion of the concrete were as follows:

Temp. Range, F	Coefficient of Expansion, 0.000001 in./in./deg F		
	Standardizing Gage	Whittemore Gage Line 1	Whittemore Gage Line 2
40 to 70	3.4	3.1	2.9
70 to 100	4.4	4.4	4.3

At the conclusion of the tests on the second cylinder, two axial slots were sawed in the cylinder about 180 deg apart, the cylinder was split open, and the standardizing strain gage was recovered undamaged. The calibration of the recovered gage was the same as the calibration made at the beginning of the tests.

APPLICATIONS

The standardizing strain gage was designed primarily for measurements which require remote readings and long-time stability. These measurements include various long-time dimensional changes, such as creep and shrinkage, which may occur in concrete. The gage is adapted to different measuring problems simply by changing the method of attaching it. For instance, in the first evaluation test the gage was attached to inserts at the surface of the concrete; in the second test flanges were fitted to the same gage so that strains could be measured at the interior of the concrete. Another type of clamp has been designed for attaching the gage to the steel wire used in prestressed concrete. Many other applications are possible by the use of suitable clamps.

In 1949 the author designed and built several small disc-shaped stress gages, which were later used successfully for measuring the stresses in the compression zone of a large reinforced concrete beam. These stress gages consisted essentially of two parts: the disc-shaped cases, which reacted elastically to the stress in the concrete, and electrical resistance strain gages for measuring the elastic deformations of the discs. Although the stress gages were satisfactory for short-time tests, they were not useful for long-time studies because of drift effects in the strain-measuring elements. The incorporation of the standardizing strain gage for measuring the elastic deformations of the disc should produce an instrument suitable for measuring stresses over long periods of time.

Calorimeter-Strain Apparatus for Study of Freezing and Thawing Concrete

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Information and techniques available in the past have not been sufficient for a complete evaluation of the role of the various factors influencing the resistance of concrete to freezing and thawing.

It has long been recognized that the destruction of concrete exposed to freezing and thawing is due principally to the freezing of water within the concrete; concrete in a dry state will not be damaged by freezing. Water-saturated non-air-entrained concrete of normal water-cement ratio cannot resist the disruptive forces generated by the freezing of the water. Air entrainment provides a practical and fundamental solution to this freezing problem. Frost resistance is controlled by the freezable water content, air void characteristics, paste permeability, aggregate characteristics, and other factors, none of which are readily evaluated experimentally.

This paper describes the development and operation of an apparatus for determining (a) the amount of water actually freezing within a concrete specimen as a function of temperature and time, and (b) the physical response of the specimen in terms of length change as this water is frozen. Examples of the type of information that can be obtained are presented and discussed.

● WHEN WATER is cooled, its heat content as a function of temperature is almost linear, indicating almost constant specific heat, until the freezing point is reached. When water freezes, a definite amount of heat, proportional to the amount of water frozen, is liberated (latent heat of fusion of water = 80 calories per gram at 32 F). The apparatus described here utilizes this latent heat of fusion as a means of measuring the amount of water freezing within a concrete specimen at various temperatures.

As water is frozen within the concrete specimen, the amount of dilation observed for the concrete is evidence of the magnitude of the internal pressure developed. This dilation, measured in terms of length change, is indicated by deviations from the normal thermal contraction line at temperatures below the freezing point. Generally, for frost-resistant concretes, such as air-entrained concretes, the specimen actually contracts more during freezing than would be anticipated from thermal contraction alone. These length changes are measured by means of an external indicating system utilizing SR-4 electrical strain gages.

The apparatus makes it possible to measure the amount of ice produced and the changes in length of a test specimen caused by cooling the specimen into the range of freezing temperatures. This enables the study of the influence of such variables as air void characteristics, water-cement ratio, curing, and aggregates, on these aspects of freezing and thawing of concrete.

DESCRIPTION OF APPARATUS

The apparatus was designed for specimens used in regular freezing and thawing tests in the Portland Cement Association laboratory; that is, concrete prisms measuring 3 by 3 by $11\frac{1}{4}$ in. This size specimen permits the use of concrete, rather than paste or mortar, hence various coarse aggregates can be studied. In addition, specimens can be tested periodically during their exposure to the laboratory freezing and thawing test.

Figure 1 shows a cross-section of essential features of the calorimeter-strain apparatus. The concrete prism is housed in a copper jacket open at the top (Fig. 2), with about 1/8-in. clearance between the sides of the concrete prism and the inside surfaces of the copper jacket. The bottom of the jacket is reinforced with additional thicknesses of copper plate. A washer, centered at the bottom's inside surface, provides the centering necessary for the stainless steel gage plug in the bottom of the concrete prism. The top of the jacket is closed off with a housing containing the SR-4 strain indicator (Fig. 3).

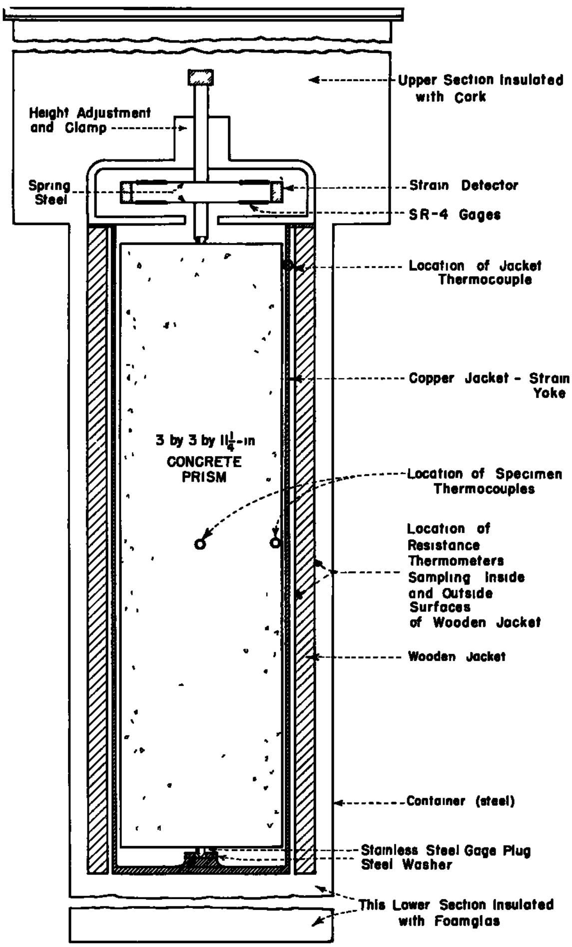

Figure 1. Cross-section of calorimeter-strain apparatus.

This jacket and housing provides the yoke within which length changes are measured. The stainless steel gage plug in the top of the specimen bears against the stem projecting through the base of the strain indicator housing. This stem is fastened to the center of one of two spring steel leaves, which are approximately $\frac{1}{4}$ in. apart and fastened rigidly together at the ends by means of separator blocks.

The stem fastened to the center of the upper spring steel leaf passes through a block at the top of the housing. This block is slotted and provides for vertical adjustment of the stem and spring leaf assembly. set screws enable rigid fastening of this upper stem in its final adjusted position. Affixed to the top and bottom of each spring leaf are SR-4 electrical strain gages comprising four arms of a Wheatstone bridge. As the specimen changes in length, the spring leaves flex. Changes in the electrical output of this gage circuit indicate the length change taking place.

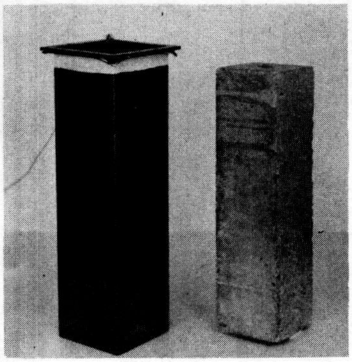

Figure 2. Copper jacket and concrete specimen.

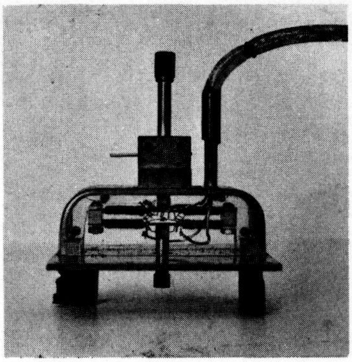

Figure 3. Strain indicator and housing.

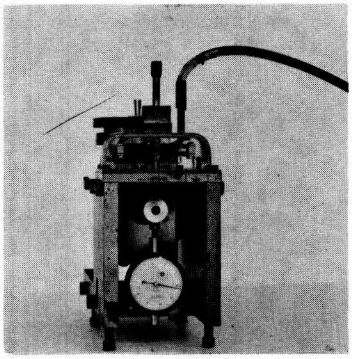

Figure 4. Calibration apparatus for strain indicator.

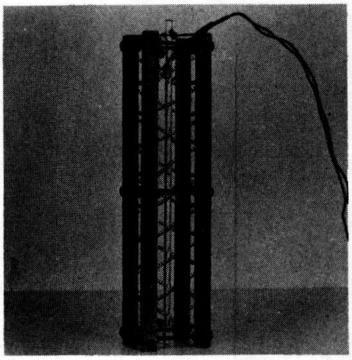

Figure 5. Resistance coil for heat heat calibration.

Figure 4 shows the device used for calibrating the electrical output of the gage circuit in terms of vertical length changes as measured by a dial indicator having readability of 0.0001 in. The output of the gage circuit is recorded on a 1-millivolt full-scale 12-point recorder. For this strain device, 1-mv output equals 0.0077-in. length change; 0.001 mv (smallest chart division 0.005 mv) represents slightly less than 0.0000008 in. per in. strain (10-in. gage length).

This measuring device was designed to be temperature compensating. The output of the gage vs the length change was demonstrated to be linear, as indicated by various check calibrations made at -20, 0, and 83 F. The slopes of these calibration lines were the same at these temperatures.

The output of the strain indicator depends on the resultant of two simultaneous length changes: (a) that of the yoke (copper jacket and strain indicator housing), and (b) that of the concrete specimen. Knowing the thermal coefficient of the yoke, the length change of the concrete specimen can be calculated. The thermal coefficient of the yoke is determined by using a rod of Pyrex glass of known thermal coefficient in place of a specimen. The Pyrex rod can be seen at the center of the heater shown in Figure 5.

Surrounding the four sides and covering the full length of the copper jacket is a 3/8-in. thick wooden jacket. This wooden jacket was dried and then sealed to prevent ingress of moisture. Zig-zag patterns of No. 40 copper wire fastened to the inside and outside surfaces, serve as resistance thermometers. As heat is withdrawn from a specimen through this wooden jacket, the difference in resistance between these two resistance thermometers changes. The amount of heat per unit time represented by a unit change in resistance is determined directly by placing an electrical resistance heater within the jacket and determining the resistance changes for known quantities of heat per unit time supplied by this heater. The heater used for this calibration is shown in Figure 5. By suitable bridge circuitry, these resistance changes are converted to potential changes (bridge unbalance). The millivolt recorder used for the strain indicator is used to record these potential changes as heat is withdrawn from the specimen in the copper jacket.

Figure 6 shows the strain indicator and the copper jacket containing a concrete prism assembled and ready for test. The thin wire to the left

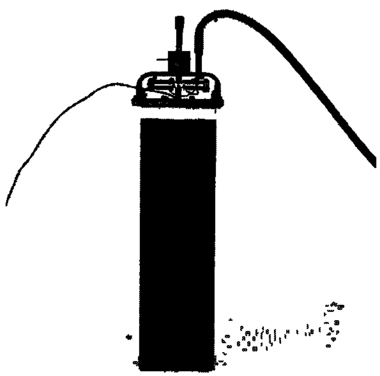

Figure 6. Copper jacket and strain indicator assembly.

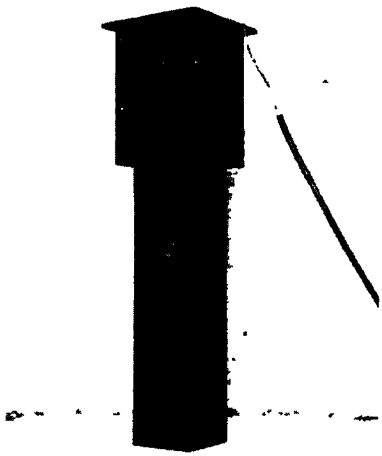

Figure 7. Container for copper jacket and strain indicator assembly.

is a thermocouple used to measure specimen temperature. The plastic tube at the right of the strain indicator housing contains the lead wires to the SR-4 electrical strain gages. This assembly is placed in the container shown in Figure 7, in which the wooden jacket outfitted with the resistance thermomemters is already in place. Figure 8 is a top view of the container, in which some of the inside surfaces of this wooden jacket can be seen. The lead wires extending up to the top of this container connect the two resistance thermometers to the recorder circuit. The copper jacket fits into this wooden jacket in the area of the container immediately below the widened top portion. The remainder or bottom of this narrow portion is filled with about 6 in. of foam glass. The section above the copper jacket, that surrounding the strain indicator housing, is insulated with cork blocks. The amount of insulation between the container and the outer surfaces of the wooden jacket regulates the rate of freezing. The thick insulation at the top and bottom insures that practically all the heat withdrawn from a specimen will pass through the wooden jacket containing the resistance thermometers.

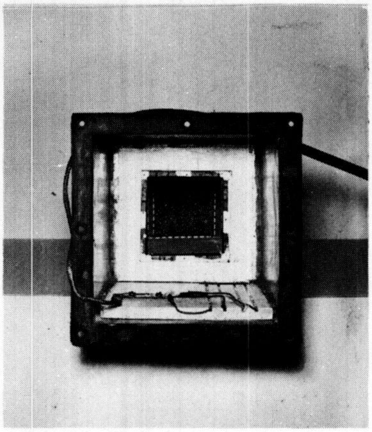

Figure 8. Top view of container, showing wooden jacket.

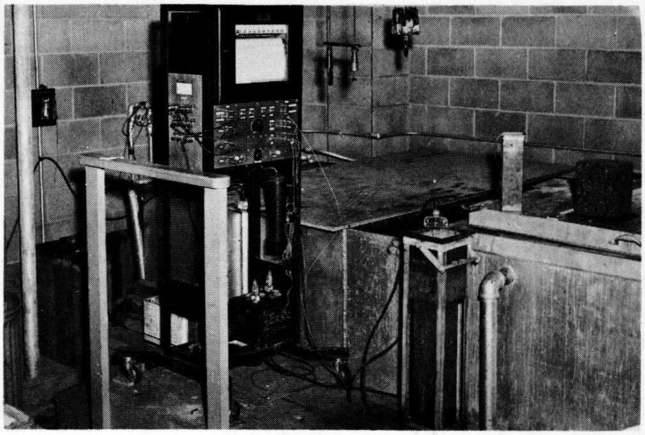

Figure 9. Assembly of calorimeter-strain apparatus. Freezing cabinet to right of container; thaw tank immediately behind container; recording equipment at left provides a continuous record of heat flow from specimen, length change, and temperature of specimen during test.

Figure 9 is an over-all view showing the assembled calorimeter-strain unit. To the left is the recorder which provides a continuous record of length change, heat flow, and temperature. The tank at the right contains -30 F brine. Freezing is accomplished by lowering the assembled container into the brine tank with the brine level approximately 2 in. above the top of the housing of the strain indicator (about halfway up the enlarged top portion of the container). Once the unit is assembled and lowered into the brine tank, no further manipulations other than minor recorder adjustments are required. The tank to the left contains water at room temperature for thawing after the freeze portion of the cycle.

EXPERIMENTAL RESULTS

Relative heat content and change in length of specimen as a function of temperature are readily calculated from heat calibration and length change calibration data. The deviations from the extrapolation of the normal thermal contraction line (length change as a function of temperature above the freezing point) below the freezing point represent the expansion or shrinkage of the concrete specimen due to freezing. The deviation from the extrapolation of the relative heat content line (relative heat content as a function of temperature above the freezing point) below the freezing point represents the cumulative heat given off by all of the water which has frozen down to that particular temperature.

Initially, two thermocouples were used to measure specimen temperature, one at the surface and one at the center of the specimen. It was observed that the difference in these two temperatures ranged from 1 to 2 F during the early stages of freezing; during the latter stages of freezing the two temperatures were nearly equal. Because the average concrete temperature would more nearly approach the surface temperature than the temperature at the center, and because the difference was relatively small, tests were generally conducted using only surface temperature measurements.

In these tests the cooling was relatively slow (approximately 20 F per hour, depending on the water content of the specimen).

Typical data are shown in Figure 10. The specimen was a non-air-entrained concrete prism cured continuously moist for eight days. The

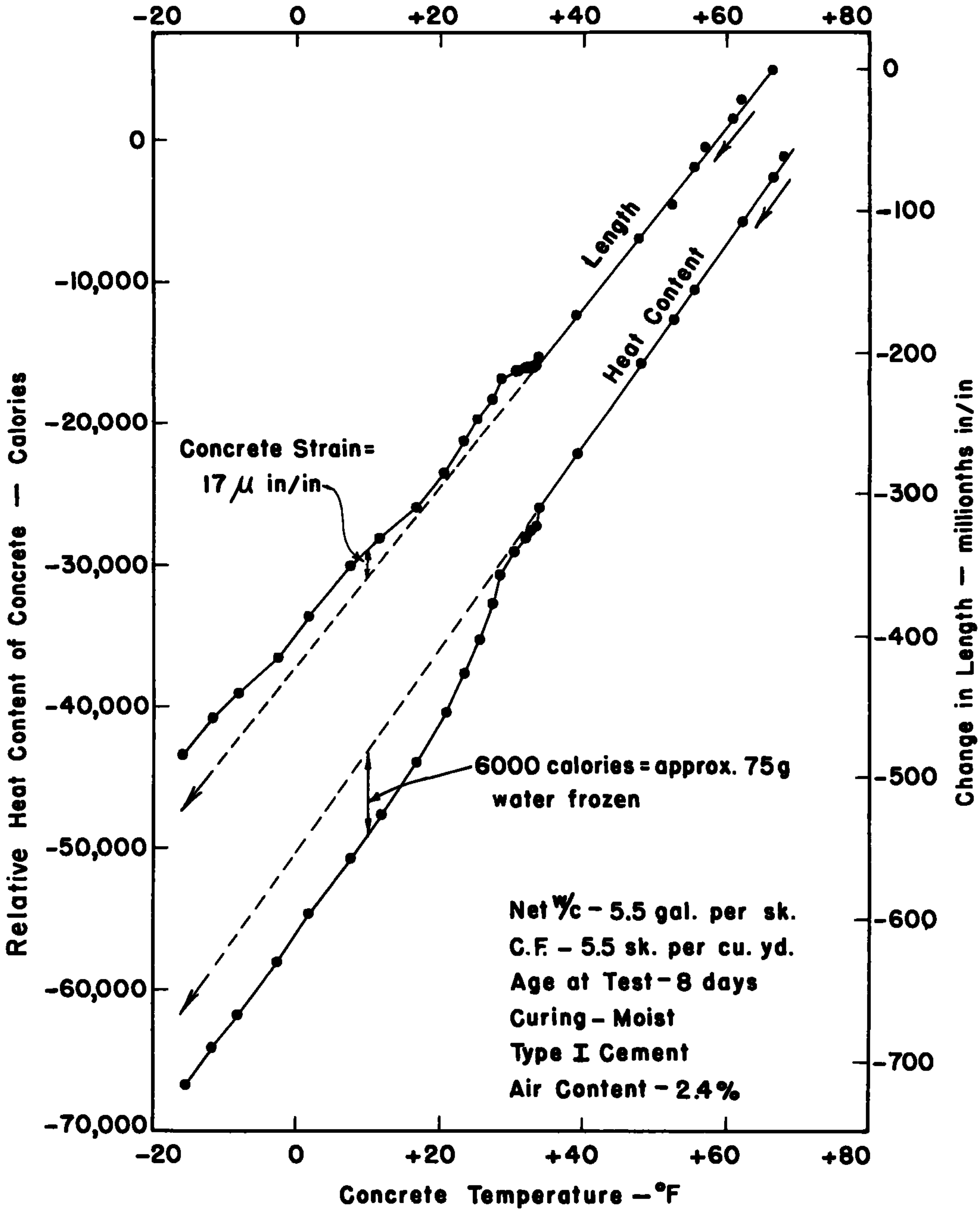

Figure 10. Typical heat content and length change data obtained by means of calorimeter-strain apparatus during freezing of concrete specimen.

specimen temperature at the start of this test was 68 F. The bottom line shows the relative heat content (relative to the heat content at 68 F) in calories as a function of temperature. As the specimen cooled, the relative heat content-temperature line remained linear until freezing began. Below this point, greater increments of heat were extracted as the temperature continued to decrease, indicating that water was freezing within the specimen. Freezing was progressive as the temperature dropped below 32 F and reached a maximum at about +10 F. At this point, 6,000 calories had been withdrawn in addition to the amount necessary to bring the temperature of the specimen to this level in the absence of freezing. For a latent heat of fusion of 80 cal. per gram of ice formed, this represents approximately 75 grams of ice. Actually, in calculating the amount of ice formed, corrections are made for the change in latent heat of fusion with temperature (decrease with decrease in temperature) and the change in the slope of the extrapolated relative heat content line, because the ice already formed affects the heat capacity of the concrete.

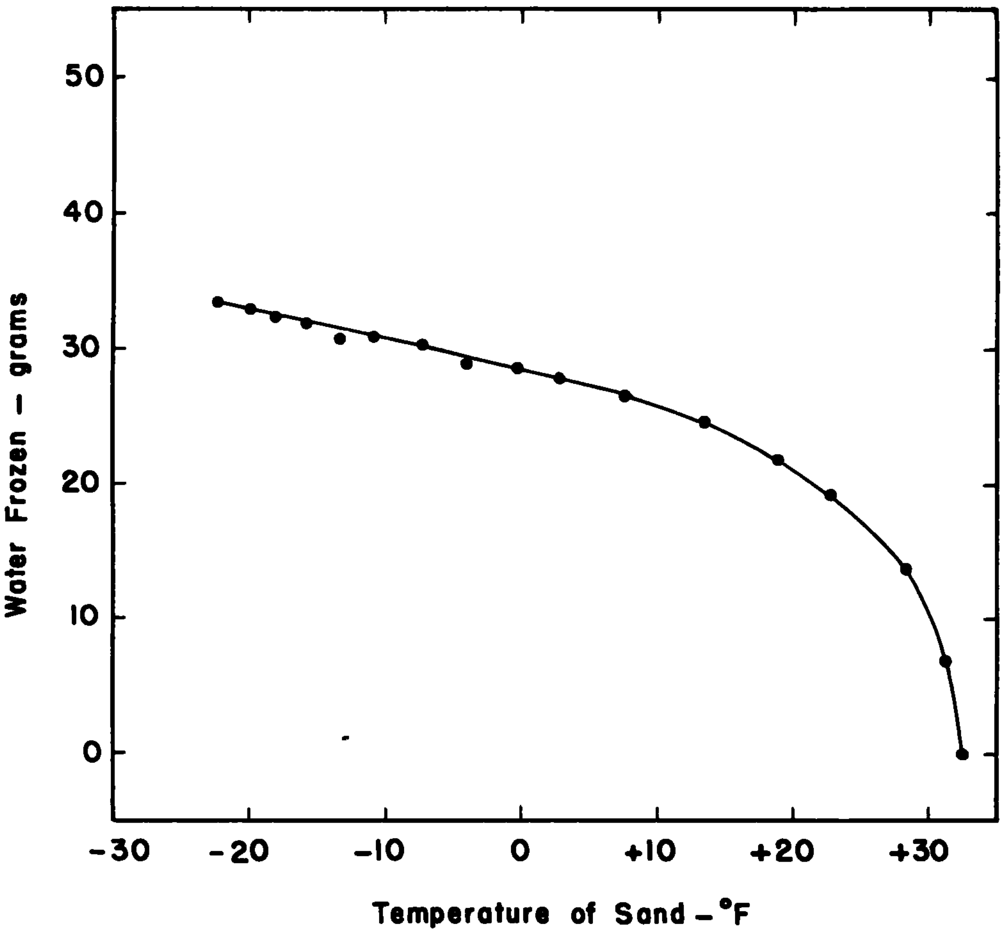

Figure 11. Freezable water in fine aggregate as a function of temperature; Elgin, Ill., sand; saturated surface-dry sample containing 34 grams of absorbed water.

The top line shows the length as a function of specimen temperature. Above the freezing point the line is linear, the slope representing the thermal coefficient of the concrete. Below the freezing point the deviations from this line represent the length changes due to the freezing of water within the specimen. At +10 F, the point at which the maximum amount of ice was formed, the specimen strain was about 0.000017 in. per in. An average internal hydraulic pressure of about 200 psi would produce a strain of this magnitude.

Freezing of Known Amount of Water

To demonstrate the accuracy of the calorimeter-strain apparatus in determining the amount of freezable water, a sample of saturated surface-dry sand was used in place of the test specimen. This sand sample contained 34 grams of absorbed water. Figure 11 shows the plot of the amount of water frozen as a function of temperature. Freezing was progressive, and at the final temperature the amount of water frozen was indicated to be slightly over 34 grams. The observed depression may be due to materials dissolved by the water in the aggregate, or due to the water being contained in pores of various sizes within the aggregate, or both.

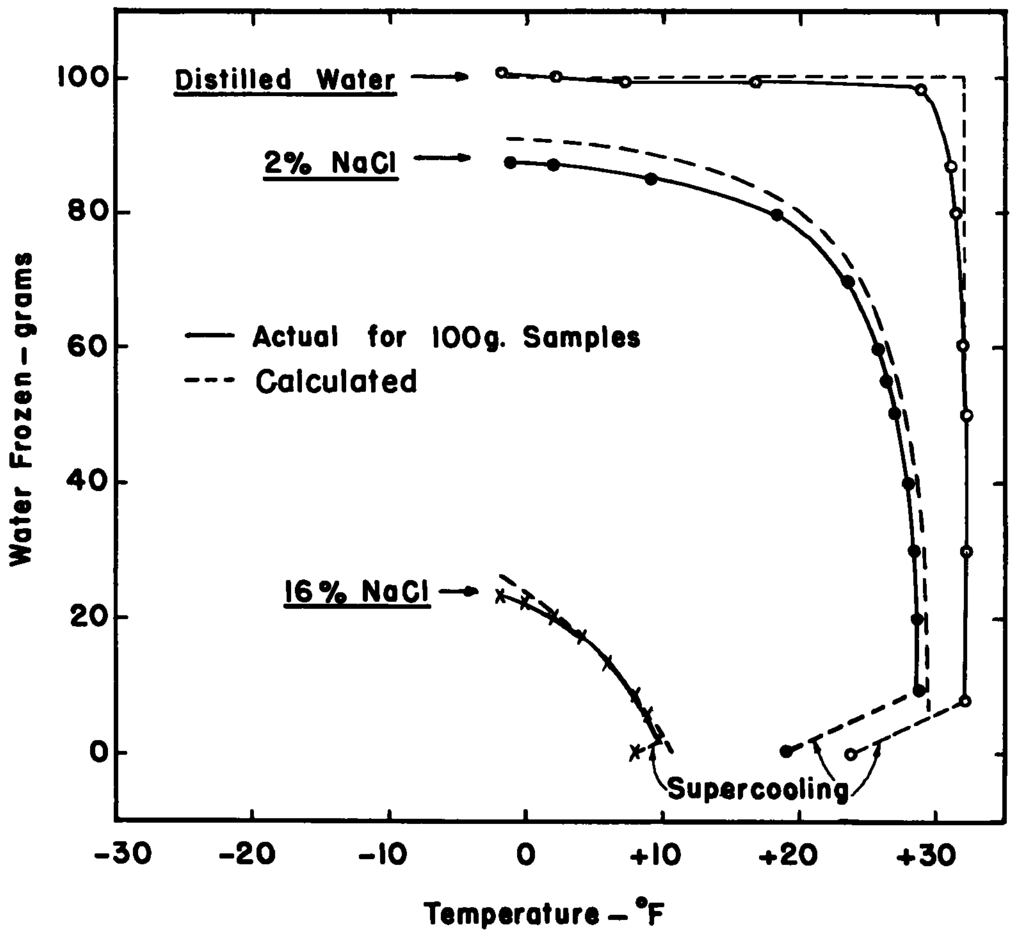

Figure 12. Amount of water frozen, as a function of temperature.

More positive checks were afforded by the freezing of 100 grams of distilled water, a 20 percent NaCl solution, and a 16 percent NaCl solution. The results of these determinations, together with the amounts which should have frozen as a function of temperature, are shown in Figure 12. The actual determinations and the calculated amounts were nearly the same at the various temperatures.

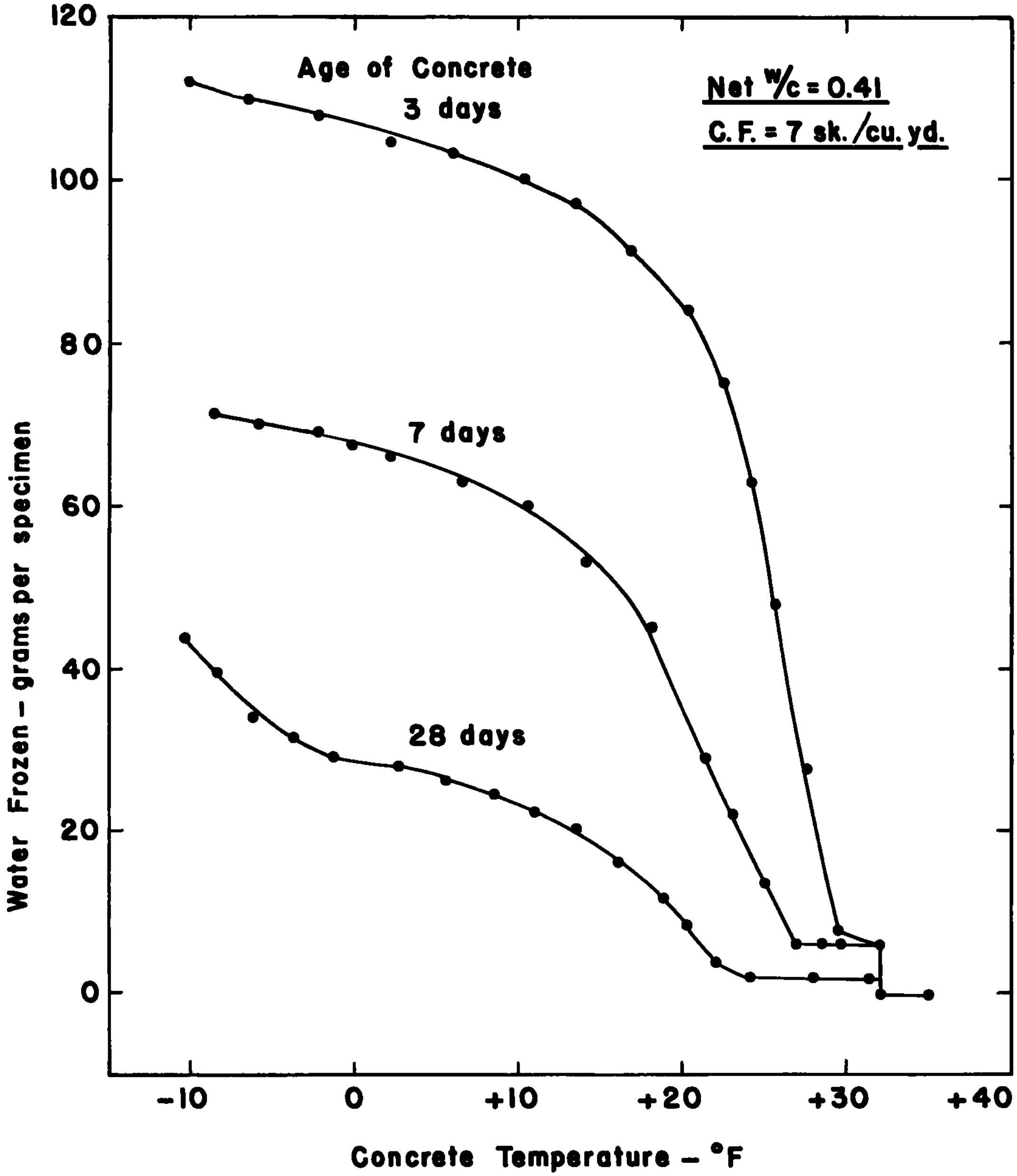

Figure 13. Effect of age of concrete on amount of water freezing as a function of temperature; concretes cured continuously moist at 73 F, Type I cement, no entrained air, Elgin, Ill., sand and Eau Claire, Wis., gravel.

Effect of Concrete Age on Amount of Freezable Water

Figure 13 shows freezable water data obtained for a 7-sack per cu yd non-air-entrained concrete for three different periods of continuous moist curing. Continued hydration reduces the amount of water that will freeze at any particular temperature. At 3 days the amount of water frozen at -10 F was 112 grams, at 7 days 71 grams, and at 28 days 44 grams. In addition, as hydration proceeds the alkalies in solution in the remaining paste water become more concentrated and result in a further depression of the freezing point. The few grams of water that froze at 32 F for each of the concretes shown in Figure 13 possibly represent free surface water on the specimen. The actual freezing point of the water within the concrete is believed to be indicated if this small amount of water initially freezing is disregarded. On this basis, the actual freezing points of the water within the concrete decreased with continued curing, being 30 F at 3 days, 27 F at 7 days, and about 23 F at 28 days.

Effect of Water-Cement Ratio on Freezable Water

The effect of water-cement ratio on the amount of water freezing as a function of temperature is shown in Figure 14. Non-air-entrained concrete specimens were prepared at water-cement ratios of 0.41, 0.49, and

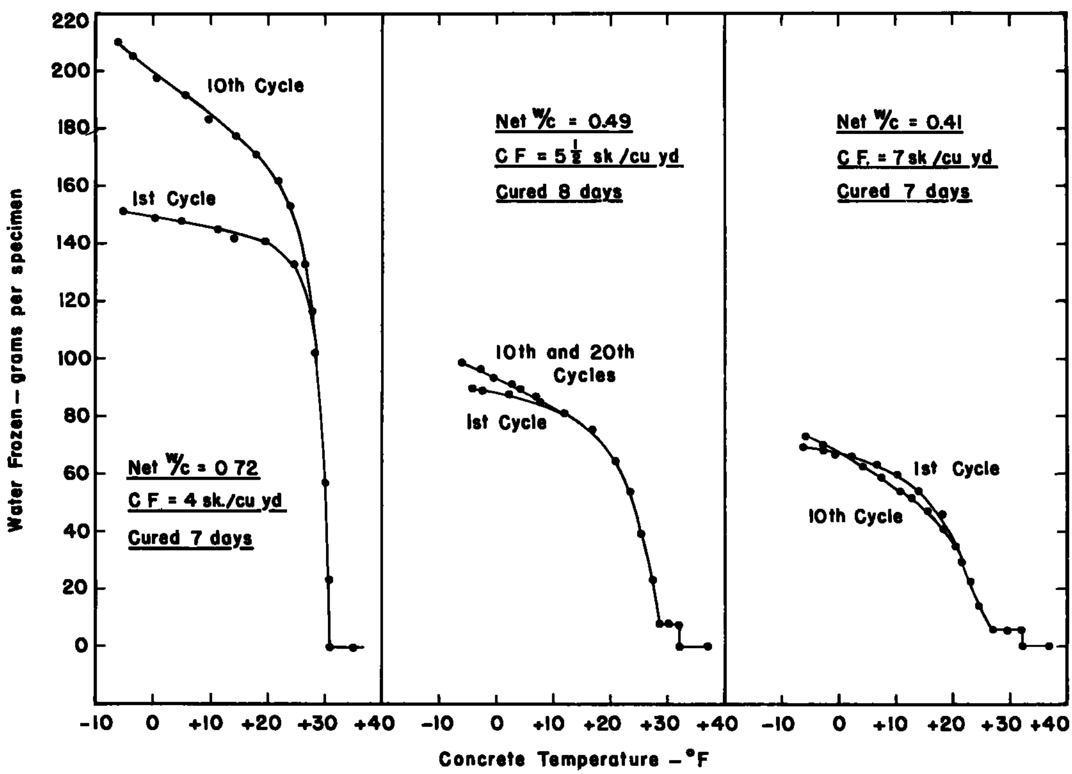

Figure 14. Effect of water-cement ratio and cycles of freezing and thawing on amount of water freezing as a function of temperature; concretes cured continuously moist at 73 F prior to test.

0.72 by weight. Concretes were cured moist for 7 days (8 days for the 0.49 water-cement ratio). For each concrete the first and tenth cycles of freezing were performed in the calorimeter-strain apparatus, and in one case the 20th cycle. The intervening cycles were performed in the laboratory freezing and thawing apparatus.

For the first cycle, the amount of water frozen at -5 F was 69 grams for 0.41 water-cement ratio, 90 grams for 0.49 water-cement ratio, and 151 grams for 0.72 water-cement ratio. For 0.41 water-cement ratio, the 10th cycle produced about the same freezing curve as the first; for 0.49 water-cement ratio the 10th and 20th cycles showed slightly more freezable water than the first; whereas for 0.72 water-cement ratio the 10th cycle showed a considerable increase in the freezable water.

This increase in freezable water for 0.72 water-cement ratio concrete after 10 cycles may be attributed to the early disintegration of this non-air-entrained concrete of relatively high water-cement ratio. The expansions and gains in weight per specimen during the cycles of freezing and thawing were as follows:

Net W/C	Expansion, %		Weight Gain, g		Water Frozen*, g	
(by wt)	10 cycles	20 cycles	10 cycles	20 cycles	10 cycles	20 cycles
0.41	0.009	—	7	—	72	—
0.49	0.014	0.050	7	5	98	98
0.72	0.273	—	26	—	208	—

*See Figure 14.

These data indicate that concretes remaining relatively undamaged by the freezing and thawing exposure exhibit little differences when retested for freezable water. When expansion is excessive, water enters the concrete during the period of thawing in water, as indicated by the 26-g weight gain for the 0.72 water-cement ratio concrete. The measured increase in freezable water was actually about 60 g. The weight gain observed does not reflect the total gain in water of the specimen, because this deterioration simultaneously caused the loss of solid material.

Effect of Brine Solution Storage on Freezable Water

In current studies of "salt" scaling, it was of interest to determine the influence of different concentrations of de-icer solution on the amount of freezable water. Companion concrete specimens were cured continuously moist for 28 days and then stored for 7 days in a calcium chloride solution of either 4, 8, or 16 percent concentration by weight. Figure 15 shows the influence of these storage conditions on the amount of water frozen as a function of temperature. The top line indicates the data from the 28-day continuously moist-cured specimens. A test of a companion specimen cured 90 days moist indicates that an additional 7 days after 28-day curing would only have reduced the freezable water at -10 F about 3 to 4 g below that shown for the 28-day specimen.

The reduction in freezable water with increased de-icer concentration is attributable to two factors: (a) water moves from the concrete specimen into the relatively more concentrated surrounding solution by osmosis, and (b) diffusion of the de-icer into the water within the concrete raises the concentration of electrolyte and depresses the freezing point and amount of freezable water. This depression of the freezing point can be seen in

Figure 15. The weight changes of the specimens during the 7-day storage in the de-icer solutions were as follows:

Solution Conc., % (by wt)	Change in Specimen Weight, g
4	-2
8	-6
16	-14

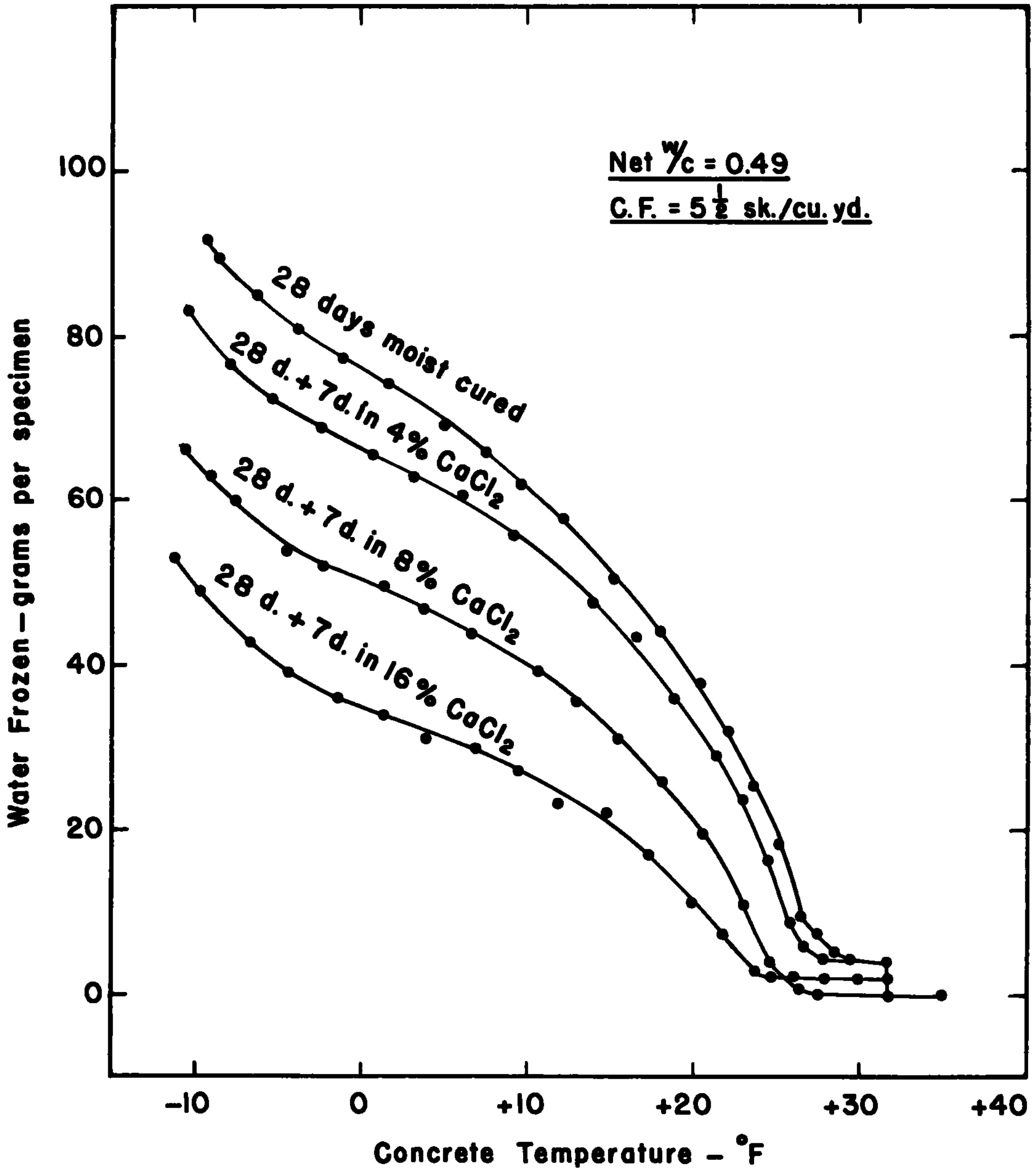

Figure 15. Effect of storage in $CaCl_2$ solutions on amount of water freezing as a function of temperature; concretes cured continuously moist for first 28 days, Type I cement, no entrained air, Elgin, Ill., sand and Eau Claire, Wis., gravel.

Influence of Air Content on Length Change During Freezing

To illustrate the influence of entrained air on the length change during freezing, concrete specimens were prepared using 3/4-in. maximum size aggregate and having air contents ranging from 3 percent (non-air-entraining cement) to 9.1 percent (air-entraining cement plus additional air-entraining agent). After moist curing for 28 days, followed by 3 days in water, the concretes were tested in the calorimeter-strain apparatus.

Figure 16 shows the concrete strain as a function of the amount of water frozen within the various specimens. Somewhat similar relationships are obtained if these strains are plotted against concrete temperature. All of the concretes showed an initial dilation, presumably due to the generation of hydraulic pressures (the forced movement of water during freezing), this being followed by a relief of this pressure. As freezing progresses the non-air-entrained concrete shows further expansion with increase in the amount of water frozen. The air-entrained concretes show

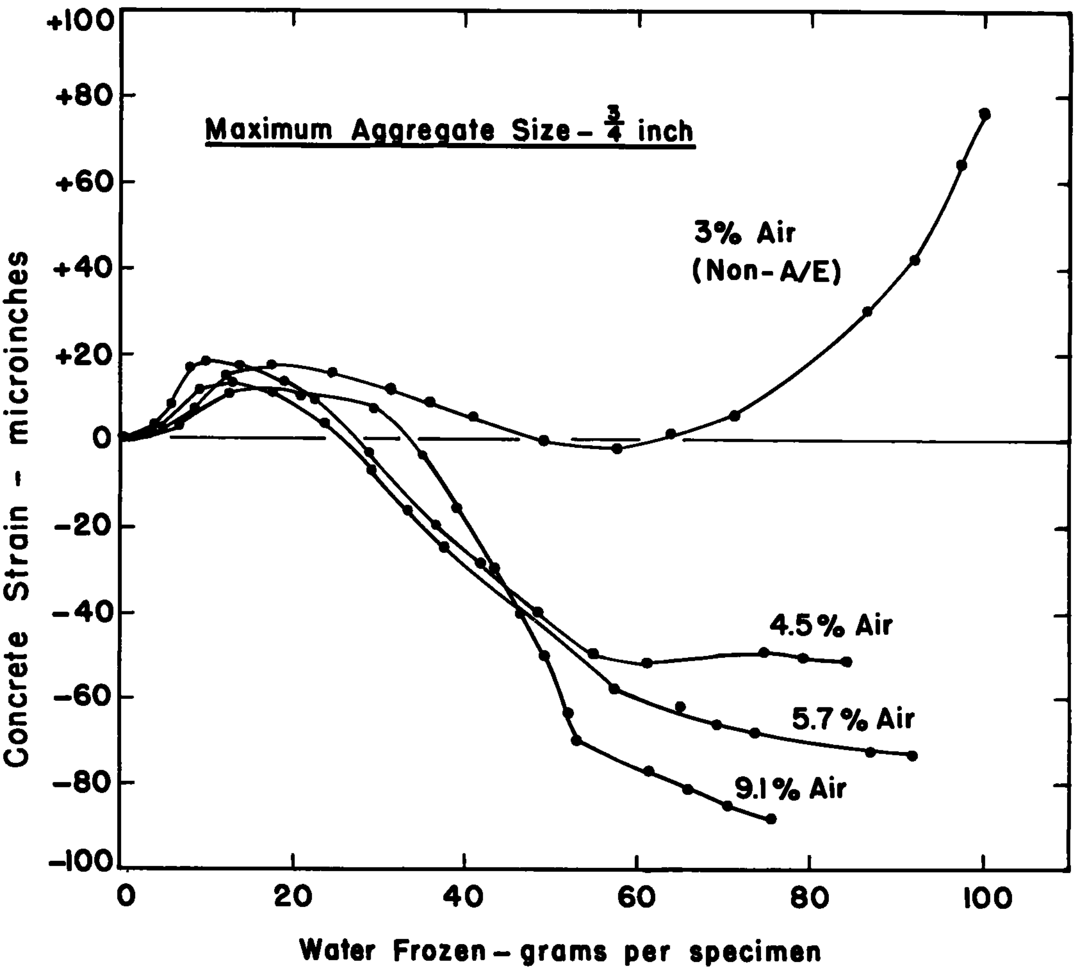

Figure 16. Effect of amount of water frozen on concrete strain for concretes of different air contents; cement content - $5\frac{1}{2}$ sacks per cu yd, slump - 2 to 3 in., curing - 28 days moist followed by 3 days in water, Elgin, Ill., sand and Eau Claire, Wis. gravel.

instead a net shrinkage as freezing continues, the magnitude of this shrinkage increasing with increase in air content. A detailed explanation of phenomena of this type is available in the studies of freezing of pastes conducted by Powers and Helmuth (1). These concretes containing intentionally entrained air showed excellent resistance in the laboratory freezing and thawing test, as shown in the following:

Air Content, %	No. of Cycles for 0.10% Expansion
3.0	92
4.5	850
5.7	1,150
9.1	1,150+*

*Discontinued at 1,150 cycles due to lack of freezer space.

SUMMARY

The calorimeter-strain apparatus described in this report appears to be an excellent means for studying the mechanism of frost action and the influence of various factors on the frost resistance of the concrete. The apparatus enables simultaneous determination of the amount of water actually freezing in concrete and the length changes resulting from this freezing. All measurements are automatically recorded.

The apparatus can be constructed to accommodate any standard laboratory concrete freezing and thawing specimen, thus enabling correlation with actual freezing and thawing tests and "spot" testing of concrete specimens at any time during the standard laboratory freezing and thawing test or after different periods of water saturation.

REFERENCES

1. Powers, T. C., and Helmuth, R. A., "Theory in Volume Change in Hardened Portland Cement Paste During Freezing." HRB Proc., 32:285 (1953).

The AE-55 Indicator for Air in Concrete

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Physical Research Branch, Bureau of Public Roads

● THE AE-55 AIR INDICATOR, or Chace air meter, is a pocket-sized device intended for use in the field to estimate the air content of plastic concrete. This apparatus, developed by L. M. Chace, a consulting engineer of North Bridgton, Me., has been purchased by a number of state highway departments and other organizations for experimental use. The interest stems from its low cost, rapidity of operation, and convenience to the engineer in the field.

Tests were made in the Bureau of Public Roads laboratory to obtain information on the accuracy and dependability of the apparatus. The air content of a large number of concrete mixes prepared in the laboratory was determined using this indicator, the results being compared with those obtained by the gravimetric and the pressure methods (AASHO T 121 and T 152, respectively).

The AE-55 air indicator (Fig. 1) consists of two parts. One part is a small cylinder of Pyrex glass about 1 in. in diameter and 3 in. long, which tapers at one end to a stem or tube about $\frac{1}{4}$ in. in diameter and 3 in. in length. This is similar to the filtration crucible holders shown in catalogs of laboratory apparatus. The other part is a rubber stopper with a brass cup mounted on the smaller end. The stopper fits the larger end of the glass cylinder. The brass cup is 3/4 in. in diameter and $\frac{1}{2}$ in. in depth, and has a volume of approximately 3.7 ml. When the stopper and cup are inserted into the cylinder, the volume of the latter is about 27 ml. Eleven equally-spaced graduations are etched on the stem of the cylinder, each pair indicating a volume of about 0.08 ml.

When the concrete tested contains 15 cu ft of mortar per cu yd, each graduation on the stem of the indicator represents 1 percent of air in the concrete. If the concrete contains a different amount of mortar, the correction factors given in Table 1 are applied.

In determining the air content of concrete with the indicator, the following procedure was used: The brass cup was filled with mortar from the concrete, excluding particles of sand larger than about 0.1 in. The mortar was compacted by rodding with a thin, stiff wire (the wire in a No. 1 Gem paper clip is suitable) and then struck off flush with the top of the cup. The sides of the cup and stopper were cleaned of mortar. The stem end of the cylinder was closed by holding the thumb over the end, and the cylinder was filled with denatured alcohol (used instead of water to prevent foaming of the liquid when mortar was added) to the mark on the cylinder.

The stopper and cup were then inserted into the cylinder. The indicator was inverted, the thumb removed, and the stopper pressed firmly into the cylinder. The level of the alcohol was brought to the upper graduation on the stem of the cylinder by addition of alcohol or by slight movement of the stopper. When alcohol was added, a small syringe or dropper was used. Care was taken to remove all air bubbles from the cylinder and to keep the stopper seated firmly enough to prevent leaking of the alcohol.

Figure 1. The AE-55 air indicator.

The thumb was replaced over the open end of the stem and the indicator turned gently from a vertical to a horizontal position while the body of the cylinder was tapped with the palm of the hand. Care was taken not to disturb the setting of the stopper. This procedure was continued until all of the mortar had been dispersed into the alcohol and no more air bubbles appeared. The indicator was then held in a vertical position and the new level of the alcohol read to the nearest half gradation on the graduated stem. The stopper was then removed and the indicator washed clean with water. Less than 3 min was required to make the test.

This method of determining the air is a volumetric method and is similar in principle to that described in ASTM Method C 173, "Air Content of Freshly Mixed Concrete by the Volumetric Method." In the ASTM method the air in the fresh concrete is measured by displacing it with a liquid and then determining the volume of liquid used. This method is not in common use except where the concrete contains slag or other porous aggregates.

TABLE 1

CONVERSION FACTORS FOR AE-55 AIR INDICATOR USED TO CORRECT INDICATED AIR CONTENT WHEN THE CONCRETE CONTAINS OTHER THAN 15 CUBIC FEET OF MORTAR1/

Mortar per Cu Yd of Concrete, Cu Ft	Conversion Factor2/	Mortar per Cu Yd of Concrete, Cu Ft	Conversion Factor2/
10.1	0.67	15.5	1.04
10.5	0.70	16.0	1.07
11.0	0.73	16.5	1.10
11.5	0.76	17.0	1.13
12.0	0.80	17.5	1.16
12.5	0.83	18.0	1.20
13.0	0.86	18.5	1.23
13.5	0.90	19.0	1.26
14.0	0.93	19.5	1.30
14.5	0.96	20.0	1.33
15.0	1.00		

1/Factors furnished by manufacturer of apparatus.
2/Multiply reading on stem of indicator by conversion factor to obtain correct air content.

Two other methods for the determination of air in plastic concrete are in general use. In ASTM Method C 231 (AASHO Method T 152), the air is determined by measuring the reduction in volume of the concrete when held in a closed container and subjected to a definite pressure. This method is used extensively and is considered the most reliable. In ASTM Method C 138 (AASHO Method T 121), the air is determined by calculation from the unit weight of the concrete and the batch weights and specific gravities of the materials used. This method is used where a pressure air meter is not available. Where specific gravities and weights are correct and a representative sample is obtained, this method should give an accurate measure of the air content.

To determine the suitability of the AE-55 indicator, tests of 84 different concrete mixes were made using this indicator and the pressure and gravimetric methods. The concrete mixes were prepared using different cements and aggregates, and different amounts of air-entraining admixtures to give air contents varying from 1 to 9 percent as determined by the pressure method. Each value reported for the AE-55 indicator is an average of two tests, usually made by two operators who generally found results agreeing within $\frac{1}{2}$ percent of air. Each value determined by the pressure or gravimetric methods is for a single test. A comparison between the results obtained for each mix by the pressure method and the AE-55 indicator is shown in Figure 2. A similar comparison between the results obtained by the AE-55 indicator and the gravimetric method is shown in Figure 3.

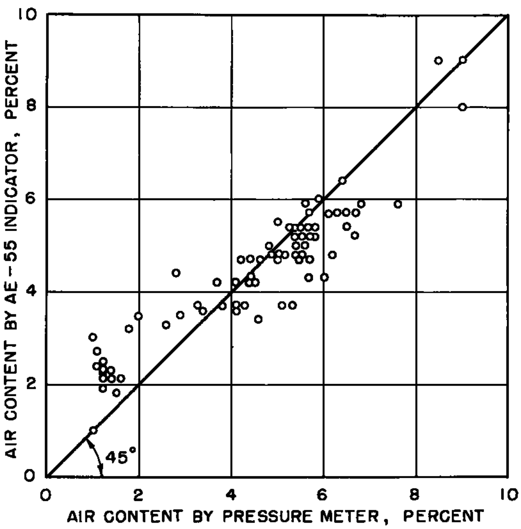

Figure 2. Air content of concrete as determined by AE-55 indicator and standard pressure meter.

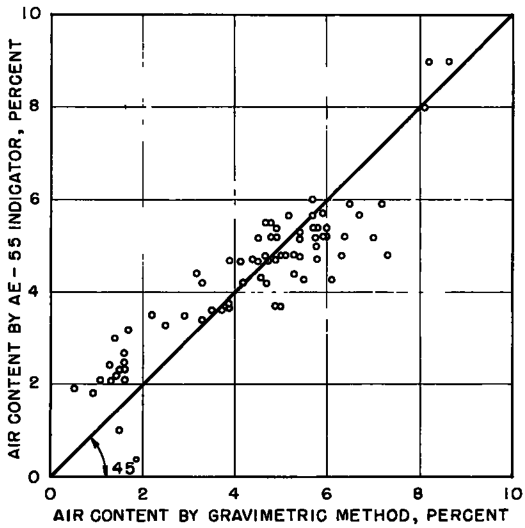

Figure 3. Air content of concrete as determined by AE-55 indicator and gravimetric method.

Average values for several different ranges in air content are given in Table 2, together with the difference between the average values for the pressure meter and that for the AE-55 indicator. These show good concordance of the average air contents determined by the pressure and gravimetric methods for all values except those above 7 percent. However, the pressure air meter read only to 8 percent, and higher values shown for this meter were estimated. This shows that either method may be used, with general assurance that the values obtained accurately indicate the amount of air in the concrete.

The results obtained with the AE-55 indicator did not show as good concordance with those obtained by the pressure meter. For values of air less than 3.0 percent as determined by the pressure meter, the AE-55 indicator gave results averaging about 1.0 percentage point too high. For air

TABLE 2

AVERAGE VALUES FOR DIFFERENT RANGES IN AIR CONTENT OF CONCRETE

Air Content by Pressure Meter, %	No. Samples Tested	Average Air Content, %			
		Pressure Meter	Gravimetric Method	AE-55 Indicator	Difference Col. 3 minus Col. 5
1.0 - 1.9	14	1.28	1.36	2.26	-0.98
2.0 - 2.9	4	2.58	2.70	3.68	-1.10
3.0 - 3.9	4	3.55	3.65	3.80	-0.25
4.0 - 4.9	14	4.41	4.55	4.24	0.17
5.0 - 5.9	33	5.45	5.36	5.12	0.33
6.0 - 6.9	10	6.42	6.24	5.38	1.04
7.0 - 7.9	1	7.6	6.5	5.9	1.7
8.0 - 8.9 1/	4	8.75 1/	8.28 1/	8.75 1/	0.0

1/Estimated air only, meter can only be read to 8.0 percent.

contents of more than 6.0 percent the AE-55 indicator gave values averaging more than 1.0 percentage point too low. These values indicate that it might be feasible to prepare a correction curve (Fig. 4) for the AE-55 indicator readings, indicating the amount by which the reading for the AE-55 indicator should be corrected to bring the value to agree with that for the pressure meter. In Figure 4 the circles indicate the results for each mix, whereas the crosses are the average values given in Table 2.

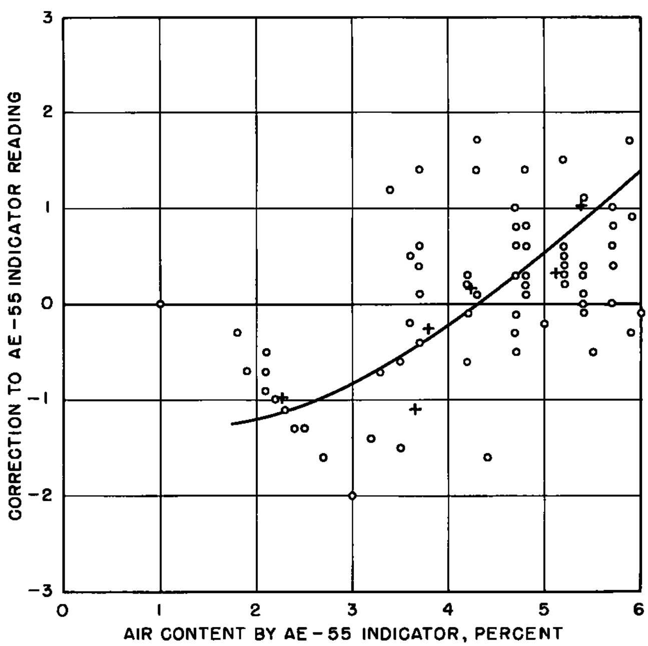

Figure 4. Correction for AE-55 indicator reading to agree with air content by pressure meter.

A limited number of tests were made in the field to determine the accuracy and usability of this apparatus on a paving job. Tests were made on concrete containing 4 percent air as determined by a pressure air meter. The values obtained with the AE-55 indicator were between 3.5 and 4.5 percent, with no correction for the mortar content. The corrected values would be from 3.2 to 4.1 percent. If these values were further corrected by use of Figure 4, the values obtained would be 3.9 to 4.3 percent, agreeing closely with the pressure air meter determination. The determinations were made by four different engineers, three of whom had not seen the apparatus before. The device was very favorably received because of its size and the rapidity with which the test could be made in the field.

SUMMARY

The AE-55 indicator is found to be an apparatus of considerable merit for use in the determination of the approximate air content of concrete in the field, providing the amount of mortar in the concrete is known. The test can be completed in less than 3 min and the apparatus can be carried in a pocket. Attention is called, however, to the small amount of mortar used in a test. To insure the most reliable result, at least three tests should be made for each determination of air content.

The AE-55 indicator method is considered not suitable as a replacement of the pressure or gravimetric methods for the air content of concrete, but is useful as a supplementary test. It appears to be of most value for use in determining the uniformity of the air content from batch to batch of concrete when no change in the materials or proportions occurs. It also may be used as a rapid check to determine whether the air content is probably within the specification limits. In no case, however, should the AE-55 indicator method be considered suitable for replacing any of the standard methods previously mentioned.

Discussion

BRYANT MATHER, Waterways Experiment Station, Corps of Engineers, Jackson, Miss.—This report shows remarkable similarity to the findings at the Waterways Experiment Station laboratory from a somewhat similar study. In this case an AE-55 indicator was used to test 158 mortar samples from 107 batches of 3/4-in. aggregate concrete, from which samples were also tested for air content by the pressure method. From 104 batches only one mortar sample was tested; from 4, a series of from 11 to 15 mortar samples were tested. The results are summarized in Figure 5.

The difference in indicated air content by the two methods is summarized in the following:

Air Content by Pressure Method, %	No. of Mortar Samples Tested	Deviation of Air Content Indicated for Mortar from that Indicated for Concrete	
		Average	Range
1.8 - 3.0	16	+1.4	+0.7 to +2.1
3.1 - 4.0	26	+0.8	-0.1 to +1.4
4.1 - 5.0	33	+0.4	-1.6 to +1.4
5.1 - 6.0	57	+0.3	-0.5 to +1.4
6.1 - 7.0	11	+0.2	-0.7 to +1.0
7.1 - 8.0	-	-	- -
8.1 - 9.0	15	+0.3	-0.2 to +1.3

The repeated mortar tests on the four batches gave the results tabulated on the following page.

Statistical analyses indicated that results obtained with the AE-55 meter would agree with those obtained by the pressure method within ±0.6 percent air two-thirds of the time for concrete with 3 percent or less of air and within ±0.5 percent air for concrete with 5 percent air or more,

Batch	Air Content by Pressure Method, %	No. of Mortar Samples Tested	Average Air Content by Mortar Test, %	Average Deviation of Air Content for Mortar Test from Pressure Test, %
1	3.1	11	3.7	+0.6
2	3.6	15	4.4	+0.8
3	4.1	14	5.1	+1.0
4	8.2	15	8.5	+0.4

provided correction factors such as shown in Figure 4 were established for the meter being used.

The results of these tests are given more fully in Waterways Experiment Station Miscellaneous Paper No. 6-189 (Nov. 1956), "A Limited Investigation of the Chace Air Meter," by C. H. Willetts and T. B. Kennedy. The tests were made under the direct supervision of W. O. Tynes and R. A. Bendinelli.

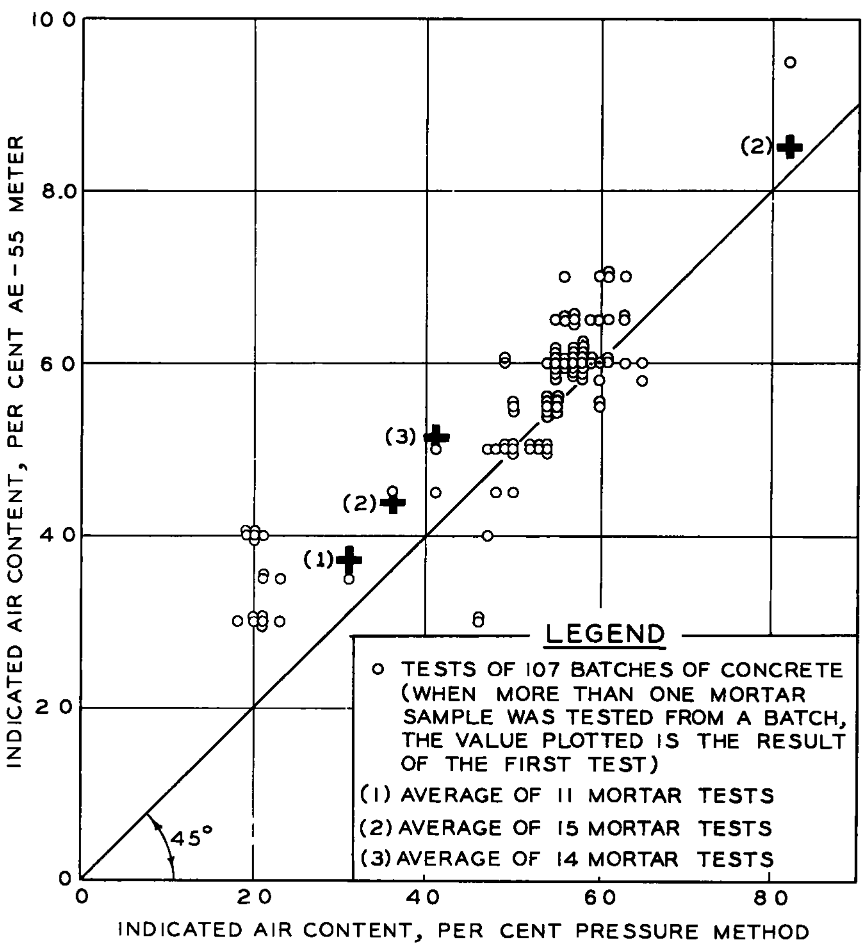

Figure 5. Air content of concrete as indicated by AE-55 meter and pressure method.

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THE NATIONAL ACADEMY OF SCIENCES—NATIONAL RESEARCH COUNCIL is a private, nonprofit organization of scientists, dedicated to the furtherance of science and to its use for the general welfare. The ACADEMY itself was established in 1863 under a congressional charter signed by President Lincoln. Empowered to provide for all activities appropriate to academies of science, it was also required by its charter to act as an adviser to the federal government in scientific matters. This provision accounts for the close ties that have always existed between the ACADEMY and the government, although the ACADEMY is not a governmental agency.

The NATIONAL RESEARCH COUNCIL was established by the ACADEMY in 1916, at the request of President Wilson, to enable scientists generally to associate their efforts with those of the limited membership of the ACADEMY in service to the nation, to society, and to science at home and abroad. Members of the NATIONAL RESEARCH COUNCIL receive their appointments from the president of the ACADEMY. They include representatives nominated by the major scientific and technical societies, representatives of the federal government, and a number of members at large. In addition, several thousand scientists and engineers take part in the activities of the research council through membership on its various boards and committees.

Receiving funds from both public and private sources, by contribution, grant, or contract, the ACADEMY and its RESEARCH COUNCIL thus work to stimulate research and its applications, to survey the broad possibilities of science, to promote effective utilization of the scientific and technical resources of the country, to serve the government, and to further the general interests of science.

The HIGHWAY RESEARCH BOARD was organized November 11, 1920, as an agency of the Division of Engineering and Industrial Research, one of the eight functional divisions of the NATIONAL RESEARCH COUNCIL. The BOARD is a cooperative organization of the highway technologists of America operating under the auspices of the ACADEMY–COUNCIL and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of highway transportation. The purposes of the BOARD are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.