Title

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Publication Date

1963-06-01

REPORT NO.
63-3

STRUCTURES AND MATERIALS RESEARCH
DEPARTMENT OF CIVIL ENGINEERING

THERMAL PROPERTIES OF LEAN MASS CONCRETES FOR OROVILLE DAM

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UNDER CALIFORNIA STANDARD AGREEMENT NO. 350498
OROVILLE DAM MATERIAL STUDIES

JUNE 1963

STRUCTURAL ENGINEERING LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY CALIFORNIA

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Department of Civil Engineering

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Table of Contents

Figures (Appendix)

(Al) (B3)

Report
to

Department of Water Resources
State of California

on

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by

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INTRODUCTION

This report presents the results of tests of thermal properties of concretes proposed for use in the construction of Oroville Dam, a part of the California Water Plan.

The test program included adiabatic temperature-rise tests of concrete having 4 sacks of cementing materials per cubic yard, and of very lean mass concrete having 2 sacks of cementing materials per cubic yard. Thermal properties, including specific heat and thermal diffusivity, were determined for concretes having 2 sacks of cementing materials per cubic yard, and concretes having 3-1/2 sacks of cementing material per cubic yard. Thermal conductivities were calculated from the results of tests for specific heat and thermal diffusivity. The tests of thermal properties were made at various ages for concretes given simulated adiabatic curing.

Thermal properties also were determined for a structural concrete having 6-1/2 sacks cementing material per cubic yard. These data are required for design of concrete to be used in lining the diversion tunnels, which may carry high-flood flows, and in which it is desirable to have high-quality concrete. An estimated cooling curve was followed for the curing cycle for concretes designed for use in the diversion tunnels.

Adiabatic temperature-rise properties of the several concretes were determined in an improved automatically controlled adiabatic calorimeter developed at the University of California[1]. The calorimeter consists of an outer chamber maintained at a controlled temperature slightly below that of the inner chamber, in order that the inner chamber need never be cooled. A row of resistance thermometers is mounted across the section of the concrete specimen and its immediately surrounding insulation, and the temperature difference across the specimen is maintained essentially zero.

Tests of specific heat and thermal diffusivity of the several concretes were determined using a method also developed at the University of California in connection with research on concretes for Bonneville Dam. Rather than determining these thermal properties for concretes cured in fog at 70°F. to various ages, the tests were made at various ages for concretes contained and sealed in the forming containers, the specimens being cured along a predetermined adiabatic temperature-rise curve to the time of test at each curing age. Detailed procedures for adiabatic temperature-rise tests and for tests of thermal properties are presented in Appendices A and B.

MATERIALS FOR CONCRETES

Sources and Nature

Concrete materials were specified by and supplied by the Department of Water Resources, State of California. The materials used for all tests are shown in Table I. All portland cements were ASTM Type II.

Basalt pozzolan was employed in all concrete mixes. It consisted of a natural pozzolan, quarried and calcined in California and ground to a fineness of about 13,000 square centimeters per gram as measured by the Blaine air-permeability method. This pozzolan met all physical and chemical requirements specified in ASTM Designation C 402-58 T, Tentative Specifications for Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete. The compressive strength of 2-inch 1:2.75 mortar cubes at 28 days was 95 percent of compressive strength of control, the pozzolanic activity index at 7 days was 1230 psi, the water requirement was 106.5 percent of control, the autoclave expansion was 0.008 percent, and the reduction of mortar expansion at 14 days was 90.5 percent.

All coarse aggregate was obtained from Oroville dredger tailings. This aggregate is composed mainly of fine-grained metamorphic rocks and moderately recrystallized volcanic rocks. The dominant constituents are meta-andesites and metabasalts, fine-grained amphibole schists and epidote-amphibole schists, and fine-grained gneisses. Moderately weathered or fractured particles constitute 10 to 35 percent of the various size fractions. These particles are considered fair in physical quality. Highly porous and deeply weathered particles of poor physical quality constitute less than one percent of the gravel.

Sands were obtained from two sources--Oroville dredger tailings and, subsequently, from the Dry Creek deposit. The fine aggregate from the Oroville dredger tailings was similar to the gravel in lithologic composition except that particles of quartz and of quartzite constituted 18 percent of the sand. Particles of fair quality amounted to 25 percent and of poor quality to 8 percent of sand retained on the No. 100 sieve. This amounts to 6.6 percent by particle count (not weight) of the sand retained on the No. 100 sieve.

The sand from the Dry Creek deposit was composed almost entirely of quartz grains and particles of quartzite. Other rock types amounted to 12 percent of the sand retained on the No. 100 sieve. For sand retained on the No. 100 sieve, 1.7 percent of particles were of fair quality, and 2.6 percent of particles were of poor quality.

Gradation of Aggregates

The gradation of aggregates was varied somewhat for the several concretes of different richnesses of mix. For convenience in reporting, each different concrete mix is designated by a mix number. In Table 2, there are shown the gradations of aggregates both for concrete mixes used in adiabatic temperature-rise tests and for tests of thermal properties.

Cements, Pozzolan, Air-Entraining Agents

The portland cements used in this investigation were of three different brands, and all of Type II composition. The three brands used were Permanente, Ideal, and Calaveras. In two concrete mixes, a blend of equal parts of each brand of portland cement was utilized, but in all other concrete mixes a single brand of portland cement was used, as indicated in Table 1. For all concrete mixes, the cementing material consisted of a blend of portland cement and Basalt pozzolan. Also used in all concrete mixes (see Table 1) was air-entraining agent in amounts sufficient to produce a nominal air content of 3 percent.

The oxide analyses of portland cements and pozzolan, together with calculated compound composition of portland cements are shown in Table 3. The average compound composition for a blend of equal parts of each of the three different brands is about 49 percent C3S, 29 percent C2S, 6 percent C3A and 10 percent C4AF. The average alkali content for the same blend, expressed as Na_20, is about 0.36 percent; hence the blend was equivalent to a Type II, low-alkali portland cement.

The physical properties of the three portland cements and of the Basalt pozzolan are listed in Table 4. The portland cements all meet the requirements for Type II portland cement as listed in ASTM Specification C 150, Specifications for Portland Cement, and the Basalt pozzolan meets the requirements of ASTM Specification for Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete (Tentative), C 402-58-T. Of specific interest in the properties of the portland cements is the relatively high fineness of the permanente Type II cement having an air permeability fineness of about 3600 square centimeters per gram as compared to finenesses of about 3000 to 3300 square centimeters per gram for the other Type II portland cements. Reference to Table 3 shows that the C3A content for Permanente cement at 3 percent could, at lower values of fineness, be too slow in setting. The higher fineness for the Permanente cement is reflected in the relatively high compressive strength of 2-in. mortar cubes at 3 days, being 2250 psi as compared to an average of about 1900 psi for the 3-day compressive strengths of the other portland cements.

Concrete Mixes

For tests to determine the adiabatic temperature rise of mass concrete, three mass-concrete mixes were employed. Mix 1-A contained two sacks of cementing material per cubic yard, and Mixes 3-A and 3-B each contained 4 sacks of cementing material per cubic yard. For these three concretes the maximum size of aggregates was 4-1/2 inches.

For tests to determine the specific heat and diffusivity of concretes there were employed three concretes. Mix 1-B, containing two sacks of cementing material per cubic yard, was similar to Mix 1-A except that the maximum size of aggregate was reduced to 2-1/2 in. in view of the relatively smaller sizes of specimens than used for adiabatic temperature-rise tests. Mix 2 contained 3-1/2 sacks of cementing material per cubic yard, with maximum size of aggregate 3 in. Mix 4 was designed for use as a structural concrete in the diversion tunnels and contained 6-1/2 sacks of cementing material per cubic yard, with maximum size of aggregate 2-1/2 in.

The cementing material for all concrete mixes consisted of a blend of portland cement and pozzolanic material. Dry Creek sand was used in Mixes 1-A and 1-B (2 scy) and Mix 4 (6-1/2 scy). Sand from Oroville dredger tailings was used in Mixes 2 (3-1/2 scy) and in 3-A and 3-B (4 scy). All concrete mixes were made with sufficient commercial air-entraining agent to provide a nominal air content of 3 percent. For the several concretes the mix proportions, by weight except where noted otherwise, are shown in Table 5.

ADIABATIC TEMPERATURE-RISE TESTS

The time-temperature rise characteristics of several mass concrete mixes were determined under conditions of adiabatic curing. The adiabatic curing was unique in that an improved automatically controlled adiabatic calorimeter, developed at the University of California specifically for the research on mass concretes for Oroville Dam, was used for the first time and provided very close control of the adiabatic curing. The complete details of calorimeter construction, and the procedure employed in adiabatic curing and control is presented in Appendix A of this report.

A total of six adiabatic temperature-rise tests, involved the use of three different mass-concrete mixes, using three different portland cements in equal parts by weight. Material used in the concretes for the adiabatic tests are given in Table 1 and the mix designs in Table 5. Hereafter there is given a summary of the various concrete mixes, portland cements, and test numbers for the six adiabatic temperature-rise tests.

The six temperature-rise tests were designed in such a manner as to:

1. Determine the time-temperature rise relationship for a mass concrete having a content of cementing material of 4 sacks per cubic yard, (Mix 3-A) employing a blend in equal parts by weight of three different brands of Type II portland cement, the temperature rise test having a starting temperature of approximately 50°F.
2. Determine the time-temperature rise relationships for three mass concretes, each having a content of cementing material of 4 sacks per cubic yard, and each containing one of the three Type II portland cements used in the test with the blend of portland cements (Mixes 3-B I, 3-B II, and 3-B III), each test having a starting temperature of approximately 50°F.
3. Determine the time-temperature rise relationships for two mass concretes of very lean mix, having a content of cementing material of 2 sacks per cubic yard (Mix 1-A), one test (No. 5) having a starting temperature of approximately 70°F, and the other test (No. 6) having a starting temperature of approximately 45°F.

For the first four tests, Nos. 1, 2, 3 and 4, all materials were stored for some time before manufacture of concretes at approximately 40°F in order to obtain the predetermined starting temperature of about 50°F.

For the last two tests, No. 5 and 6, the mass concrete being of very lean mix (only 2 sacks cementing material per cubic yard), less temperature difference was required between the storage temperature of materials and the predetermined starting temperature of test. Hence for Test 5, for a starting temperature of about 70°F, materials were stored at 70°F and the temperature of starting adjusted through the use of cool water, and for Test 6, for a starting temperature of about 45°F, all materials were pre-stored at 40°F.

Results of Adiabatic Temperature-Rise Tests

In Table 6 there are shown for Tests 1, 2, 3 and 4 (all mass-concretes containing 4 sacks cementing material per cubic yard) time-temperature-rise data and time-temperature data up to age 28 days of adiabatic curing. The data of Table 6 are plotted in Fig. 1. The temperature rises at age 28 days for nominal starting temperatures of about 50°F. were determined to be:

Test 1	Blend of three portland cements	50.7°F.
Test 2	Permanente Type II portland cement	47.8°F.
Test 3	Calaveras Type II portland cement	55.5°F.
Test 4	Ideal Type II portland cement	55.8°F.

The average temperature rise at age 28 days, with respect to the initial temperature of materials before mixing, was 62°F. The average temperature rise at time of casting, with respect to the initial temperature of materials, was 10°F. Thus, on the average 16 percent of the total temperature rise to age 28 days had taken place by the time the concrete was cast in place. The ambient temperature near the mixer at the time of casting was between 63° and 65°F.

The average temperature rise for concretes containing the individual brands of portland cement was 53.0°F., whereas the temperature rise concrete containing a blend of equal parts by weight of the three brands of portland cement was 50.7°F. or about 5 percent less. It is noted also that there is reasonable correlation between the temperature rise of the concrete and the tricalcium aluminate content of the portland cements.

Also of interest, and presently unexplained, is the relatively slow rate of heat generation for the concrete containing the blend of the three portland cements up to age about 4 days.

In Table 7 there are shown for Tests 5 and 6 (mass concretes containing 2 sacks cementing material per cubic yard) time-temperature-rise data and time-temperature data up to age 28 days of adiabatic curing. The data of Table 7 are plotted in Fig. 2. As noted before, the difference between tests 5 and 6 is only in the starting temperatures for adiabatic curing.

Effect of Starting Temperature on Adiabatic Temperature and Adiabatic Temperature Rise of Concrete

The differences between Tests 5 and 6 were (1) the starting temperatures of the concrete mix and (2) the storage temperature of the cement, pozzolan, sand, gravel and mixing water. The starting temperature of the concrete mix in Test 5 was 69.6°F. and for that of Test 6 was 46.2°F. In Test 5 the cement, pozzolan, sand and gravel were **stored** at 70°F. and the mixing water was added at a lower temperature to produce a concrete having a temperature at time of placement of 69.6°F. In Test 6 all the materials including the mixing water were stored at 40°F. which produced a concrete having a temperature at time of placement of 46.2°F.

The temperature rise for the concrete of Test 5, with a starting temperature of 69.6°F., was 25.6°F. to age 28 days. The temperature rise for the concrete of Test 6, with a lower starting temperature at 46.2°F., was 19.8°F. to age 28 days. In other tests reporting on the effect of initial temperature on the temperature rise of concrete it was indicated that the lower the starting temperature the greater the temperature rise at 28 days.[1] These tests[3] indicate for a 2 sack mix that the temperature rise to 28 days for a concrete with a starting temperature of 44°F. might have a temperature rise of approximately 1/2°F. higher than that for a concrete having a starting temperature of 65°F.

It can be shown, using the transient temperature distribution in a 3-inch diameter solid sphere, that within 5 minutes after application of a step - function thermal input, 55% of the volume will have come to the input temperature. Using this approach in viewing the data from Test 6 the aggregate (being 6.2°F. colder at zero time than the paste temperature 5 minutes after gauging with water and mixing) had contributed to lowering the temperature of the concrete by approximately 2°F.

At 28 days the difference in temperature rise between Tests 5 and 6 amounted to 5.8°F., with Test 6 lagging. If one considers the reduction in temperature rise contributed by the colder aggregate in Test 6, the difference between the temperature rise of Test 5 and 6 is reduced to 3.8°F.

Since Tests 5 and 6 were such lean mixes (2 scy), the total heat of hydration was relatively low. It was so low, in fact, that increments of heat rise were close to the limits of control and measurement.

Unfortunately no data are available which would allow one to determine the reproducibility of the adiabatic temperature rise tests. It appears that control of the adiabatic curing is of a far higher order of precision than is possible in reproducing a given concrete mix.

SUMMARY OF ADIABATIC TEMPERATURE-RISE TESTS

Test No.	Cement (Type II)	Mix No.
1	Equal Parts by Weight Permanente (58 C 109) Ideal (59 C 36) Calaveras (59 C 93)	3-A
2	Permanente (58 C 109)	3-B (I)
3	Calaveras (59 C 93)	3-B (II)
4	Ideal (59 C 36)	3-B (III)
5, 6[a]	Calaveras (60 C 265)	1-A

[a] - Tests 5 and 6 were alike as to mix composition and mix number, but adiabatic temperature-rise tests for Tests 5 and 6 were started at different starting temperatures; test No. 5 at 69.6° F., test No. 6 started at 46.2° F.

TESTS OF THERMAL PROPERTIES

The various thermal properties of concretes tested in this investigation include specific heat of concrete, thermal diffusivity of concrete, and linear coefficient of thermal expansion of concrete. In addition, tests were made of specific heat of aggregate and calculations were made of thermal conductivity of concrete. Specific-heat specimens were also used to determine the density of concrete, a quantity required in the calculation of thermal conductivity from specific heat and thermal diffusivity data.

Details of test procedures and drawings of apparatus pertinent to test procedures are appended hereto as "Appendix B". While the methods of tests of specific heat, diffusivity, and calculation of thermal conductivity reported here are analagous to those described in the literature,[2, 3] two major differences in procedures were used in order to obtain data believed to be more representative of the thermal properties of the concrete under actual construction conditions.

Specimens for tests of thermal properties of concrete for the Boulder Canyon Project were cast in 8 by 16-inch metal containers. Specimens used for conductivity and specific-heat tests were cast with a 1-1/2 inch hole centered on the axis of the specimen. Specimens used for cooling tests (such as diffusivity) were cast solid, except for a 1/2-inch diameter by 8-3/4 inch deep thermometer well centered on the axis of the specimen. The external metal containers were stripped from the concrete cylincers at an appropriate time interval after casting, and the concrete was cured thereafter at 70°F in a fog room maintained at 100 percent relative humidity.

In the present investigation, the metal casting forms were completely sealed from the outside atmosphere subsequent to casting concrete, and were retained in place throughout both the curing and the testing periods. In the case of selected specimens, the metal containers were removed after testing, and the specimen was retested to determine the effect, if any, of the presence of the container upon test results. Secondly, all concrete specimens were cured along an adiabatic time-temperature curve approximating the experimental curve for the corresponding mix. The applicability of these modifications was demonstrated in research on thermal stress in concrete at the University of California.[4] In this research it was shown that values for specific heat, thermal conducticity, and calculated diffusivity of adiabationally cured concrete varied with curing time and temperature in a manner substantially differen than for a corresponding concrete cured at 70°F. and 100 percent relative humidity.

SPECIFIC HEAT

Values of specific heat were determined both for aggregate from the Oroville dredger tailings deposit and for the concrete of Mixes 1B and 2 as listed in Tables 1 and 5, cured along predetermined adiabatic time-temperature curves, and for Mix 4, cured along a predicted cooling curve.

Specific Heat of Aggregate

The specific heat of aggregate from the Oroville dredger tailings deposit was determined for each of four fractions of material finer than 1-1/2 inch. The four fractions were sand, No. 4 to 3/8 inch, 3/8 inch to 3/4 inch, and 3/4 inch to 1-1/2 inch.

Although the procedure for the determination of specific heat of aggregate is similar in principle to that used for concrete, some modification of the procedure was required to insure adequate circulation of water around and between aggregate particles. The results, determined for the aggregate in the condition received with respect to moisture content, are shown in Table 8, together with values of specific heat corrected to correspond to the oven-dry basis.

It is noted that the difference in specific heat between the sand fraction and the fraction 3/4 in. to 1-1/2 in. is half as great for the oven-dry condition as for the moist condition. A relationship between specific heat and size of aggregate fraction is plotted in Fig. 3. It is apparent that the smaller the size the greater the value of specific heat for sand, being 3 percent higher than that for the coarsest fraction. The accuracy of the test results is estimated at ± 0.3 percent; consequently the observed differences in specific heat are significant. The petrography of the deposit gives no clue as to the reason for the higher specific heat for the finer fractions. However, it is not unreasonable to expect larger amounts of weathered and hydrous material in the finer fractions, and hence relatively higher values of specific heat. Since concrete mix design is based upon aggregate in the saturated-surface-dry condition, a value of 0.21 is assumed for the specific heat of total aggregate in computing the specific heat of concrete at start of test, at age zero and temperature rise zero.

Specific Heat of Concrete

Specific heat was determined for concrete of Mixes No. 1-B (2scy), No. 2 (3-1/2 scy) and No. 4 (6-1/2 scy). Materials used in these mixes are shown in Table 1 and the mix design is given in Table 5. The time-temperature curing curves for the above mixes are shown in Fig. 4.

Mix 1-B: For the mix containing cementing material equal to 2 scy, the temperature cycle of curing followed a stepped curve, starting at 55°F, the curing curve being the average of two adiabatic tests, No. 5 and No. 6 (See Table 7 and Fig. 4). Separate specimens were cast for test at ages 3, 7, 14, and 28 days. In Table 9 there are shown values of specific heat, curing temperature and mean temperature of test for Mix 1-B concrete at four different ages.

Mix 4: For the mix using 6-1/2 sacks of cementing material per cubic yard, the temperature of curing followed a cooling curve furnished by the California Department of Water Resources. This curve, having a starting temperature of 55°F, is shown in Fig. 4. The only specific heat test for this mix was made at age 3 days and the data are given in Table 9.

Mix 2: The major portion of the investigation dealing with specific heat of mass concrete was conducted using this mix (cementing material equal to 3-1/2 scy). The three different curing conditions used (B, C, and D) are shown in Fig. 4 and the specific heat data are tabulated in Table 9.

Curing curve B, starting at 47°F, is a stepped curve approximating the adiabatic curve, shown in Fig. 1, obtained for Mix 3-A (4 scy). Starting from 47°F, curing condition C is an adiabatic curve that is 3°F lower at all times than the time-temperature curve for Test 4 shown in Fig. 1. Curing condition D is a stepped curing curve starting from 55°F and reaching a terminal temperature of 71°F at 3 days.

It will be noted that the mean temperature of test is generally about 10°F above that of the curing temperature. This difference is due to the necessity of imposing a temperature rise of about 20°F above the temperature of the specimen at the time of test in order to evaluate heat input per °F with adequate precision.

For the specimens cured under condition "D", the particular specimen first tested at 3 days was returned to curing following test and was retested at age 7 days and similarly retested at age 28 days. The specimen first tested at age 7 days was returned to curing after test and was retested at age 28 days. The results obtained are listed in Table 10.

Assuming an accuracy of $\pm$ 0.5 percent in test results, values of specific heat are accurate to about $\pm$ 0.001. It is apparent that the effect of the temperature rise of about 20°F utilized in making of specific-heat tests is of significance only for specimens of age less than 7 days.

For standard-cured mass concretes studied in the Boulder Canyon Project[1], it was concluded that:

a. The effect of type of aggregate on specific heat is small.

b. The effect of change in temperature on specific heat was approximately the same for all concretes tested, and for an increase in temperature from 50 to 150°F, the corresponding increase in specific heat was about 20 percent. The increase in specific heat was found to be approximately proportional to the increase in temperature.

In the research conducted by Johnson and Knight[4] at the University of California, it was found that for adiabatically curing concrete, tested in the sealed metal casting forms, the relationship between change in specific heat and change in mean temperature of concrete typical of standard-cured concrete does not hold true. For their tests, a mass concrete mix was employed containing 4 scy of portland cement, but no pozzolan nor air entrainment was utilized in the mix. The cement was Type I, having 53 percent C3S and 8 percent C3A. The results obtained by Johnson and Knight are plotted in Fig. 5.

For the given concrete mix, standard cured, it is noted that there is uniform increase in specific heat with increase in mean temperature of concrete. For the same mix, adiabatically cured from a starting temperature of 53°F, tests of specific heat of the adiabatically curing concrete with increase in age and curing temperature exhibit the plotted relationship. At curing temperature 80°F, specific heat was 0.206 BTU/lb /°F, and values of specific heat corresponding to increased curing temperatures of 97°F, 108°F, 117°F, and 123°F were respectively 0.166, 0.201, 0.220, and 0.260.

It has been pointed out that the principal differences in procedure in determination of specific heat from that used by the U. S. Bureau of Reclamation was first in the tests of specimens undergoing adiabatic curing, and second in making tests on specimens with the sheet-metal casting form sealed from the atmosphere and remaining in place throughout curing and testing. In order to determine whether the presence of the steel mold has an effect upon the value of the specific heat, one specimen was tested with the jacket in place at age 22 days, retested at age 26 days, and the steel mold subsequently removed at age 32 days, and the stripped specimen immediately tested to determine specific heat. The results of these tests are listed in Table 11.

It is noted in Table 11 that the retest value of 0.231 at 26 days agrees exactly with the 28 day value of 0.231 after two retests of specimen 1 of Table 10, but is 0.006 below the value of 0.237 in table 10 for a single retest of specimen 2. Hence we may assume for practical purposes that the reproducibility of tests at later ages, where retest has been made is about ± 0.003. Therefore it would appear that the effect of the steel mold is to increase the value of specific heat by about 0.001 to 0.002. However, in view of the very high conductivity of the steel it is not believed that the difference in the result on removal of the mold (-0.004) is attributable to the presence of the mold, but rather to the precision with which the so-called equilibrium temperature change is chosen at the conclusion of the test.

If the adiabatic temperature rise for a concrete is known, the heat of hydration of the cement paste to any time or corresponding temperature may be computed from the expression:

$$H = \frac{T\,S}{1.8\,C} \tag{1}$$

where $\underline{T}$ is the adiabatic temperature rise in $^{\circ}$F, $\underline{S}$ is the specific heat in BTU/~~hr~~ lb/$^{\circ}$F, and $\underline{C}$ is the proportion of cement in the concrete, by weight. Conversely, if both the adiabatic temperature rise and the heat of hydration are known, the specific heat may be calculated for any age or temperature during the adiabatic curing. Since only the hydrating paste is involved in heat-of-hydration tests, it is required that the water-cement ratio of the paste be close to that of the concrete, yet bleeding of water from the paste must be avoided.

Although heat-of-hydration tests are conducted at constant temperature, it has been observed that for concretes cured adiabatically the computed heat of hydration, using an average value of specific heat, checks quite closely over the whole time-temperature range with values obtained by direct heat-of-hydration tests. In Fig. 5 based on the work of Johnson and Knight[4] is plotted the calculated relationship between specific heat and adiabatic curing temperature for the concrete mix used in the tests, employing the expression:

$$S = \frac{0.173\ H}{\Delta T} \tag{2}$$

where S is the specific heat,

H is the heat of hydration, calories per gram, as determined by the Carlson Vane Calorimeter, and

ΔT is the adiabatic-temperature rise.

Also shown in Fig. 5 is the specific heat calculated for all ingredients of the unmixed concrete. It is observed that there is fair correlation between the observed values of specific heat for adiabatically curing concrete and the curve for computed values. The curve for the calculated relationship between specific heat and curing temperature appears to drop from the value for the unmixed concrete to an undetermined low, then to increase to a maximum value with increase in curing temperature. Subsequently, with increase in curing temperature, the values of specific heat drop to a minimum and then again rise to a maximum of lower magnitude than the maximum at early ages of curing.

All concrete mixes for Oroville Dam contained pozzolan as part of the cementing material. As yet, the determination of heat of hydration of portland-pozzolan blends is difficult and of questionable accuracy; consequently a specific relationship between specific heat and adiabatic temperature rise could not be computed for the Oroville Dam concretes. However, the experimental data are plotted in Fig. 6 both for Mix 1-B (2 scy) and Mix 2 (3 1/2 scy). The specific heat of unmixed concrete was computed using a value of 0.21 for all saturated-surface-dry aggregate and for the cementing material, the specific heat of the unmixed concrete at the starting temperature of adiabatic curing being calculated to be 0.24 BTU/~~hr~~lb/°F. The relationship between specific heat and curing temperature for Mix 2 (3-1/2 scy), determined experimentally, conforms closely to the calculated relationship plotted in Fig. 5. In the temperature range between 70 and 80° F, Mix 1-B (2 scy) appears to be affected considerably less than Mix 2, values of specific heat being substantially lower than for

Mix 1-B. This is to be expected inasmuch as--the specific heat varying proportionally to the cement content--the lower the cement content the lower the specific heat. Further, for very low cement contents, the values of specific heat will be less sensitive to mean temperature of concrete and will be governed by the specific heat of the aggregate.

In view of the rapid changes in adiabatic temperature rise up to about age 14 days and the somewhat rapid changes in specific heat of adiabatically curing concrete at ages earlier than 14 days (40 percent in 14°F between 62 and 76° F as compared to about 5 percent for standard-cured concrete), there is doubt as to the applicability of equation (1) for adiabatically curing concrete. Hence, in order to define more precisely cooling gradients in mass-concrete structures up to ages of about 14 days it is desirable that the diffusivity of adiabatically curing concrete be determined directly by experiment. It follows also that there is doubt as to the accuracy of values either for diffusivity or for thermal conductivity calculated from equation (1) where the specific heat at ages before 14 days is a factor in the equation.

HEAT OF HYDRATION

Although, for Oroville Dam research concretes, the specific heat could not be calculated from adiabatic temperature rise and heat of hydration, equation (2) can be utilized to calculate the heat of hydration for these concretes inasmuch as the quantities T (adiabatic temperature rise in °F), S (specific heat of adiabatically curing concrete), and C (proportion of cementing material in the concrete by weight) are available for mix 1-A, and the required data are available or can be calculated for mix 3-A. Values of specific heat for mix 2 (3-1/2 scy) can be used with the adiabatic temperature rise for mix 3-A (4 scy) to compute a close approximation for heat of hydration of mix 3-A. The results of such calculations are listed in Table 12.

The values calculated for heat of hydration look entirely reasonable, and reflect the influence of the proportion of the pozzolanic replacement for portland cement. It should be borne in mind that the values of heat of hydration in concrete reflect the initial water cement ratio, somewhat higher than that used in conduction calorimeter tests of heat of hydration--that is, 0.436 in concrete as compared to 0.400 for tests in the conduction calorimeter. As has been pointed out heretofore, the heat-of-solution method for determination of heat-of-hydration is not yet adequate for precise determinations of heat of hydration of blends of portland cement and pozzolan.

Inasmuch as there are no significant reactions between pozzolan and portland cement before initial set takes place, values of heat-of-immediate hydration up to 30 minutes can be determined for the portland cements, and the heat-of-immediate hydration of blends with pozzolan calculated on the basis of the proportions of cement and pozzolan, and neglecting any heat of wetting of pozzolan which, in any case, is negligible. Further, the conduction calorimeter is useful in determining the heat of hydration of blended cements with fair precision to age 3 days. The results of tests of heat-of-immediate hydration up to 30 minutes for each of the three portland cements and the blend of the three portland cements are shown in Table 13. The results of tests of heat of hydration for each of the three portland cements blended with pozzolan and for the blend of the three portland cements with pozzolan are shown in Table 14, heats of hydration being determined to age 3 days. For all tests the proportion of portland cement to total cementing material was 0.814 and the water to cementing material ratio was 0.436. For all four tests, Durair was included in amount equal to that used in the concretes.

DIFFUSIVITY

Tests for diffusivity of concrete were made for concretes of Mix 1-B (2 scy), Mix 2 (3-1/2 scy) and Mix 4 (6-1/2 scy). Curing of the mass concretes of Mix 1-B and Mix 2, as in the case of the specific-heat determinations, was adiabatic as indicated hereinafter; and curing of mix 4 was on the cooling curve furnished by the California Department of Water Resources. Again, as in the tests for specific heat, specimens were tested with the casting container in place. However, inasmuch as the value for diffusivity is the principal thermal property of use in calculating cooling gradients in a mass-concrete structure, the effect of the metal container was evaluated by retesting of specimens immediately subsequent to removal of the sealed containers.

Where diffusivity of concrete is determined by calculation from observed values of specific heat, thermal conductivity, and density of standard-cured specimens, the following general relationships have been noted:[2]

Effect of Rock Type - The rock type of the coarse aggregate is the most important consideration in the determination of diffusivity.

Effect of Water Content - For the concretes tested in the Boulder Canyon Project, the effect of water content on diffusivity was much less than the effect of type of coarse aggregate. An increase in the water content from 4 to 8 percent of the weight of the concrete decreased the diffusivity about 17 percent on the average.

Effect of Temperature - Diffusivity decreased with temperature increase, a temperature change of 100 degrees F causing a change of about 20 percent in diffusivity.

Mix 1-B (2 scy) -- The concrete of Mix 1-B containing 2 sacks of cementing material per cubic yard was cured adiabatically at curing condition A (Fig. 4) starting at 50°F. The results of these tests at ages 3, 7, 14, and 28 days respectively are shown in Table 15.

While in general values for diffusivity of this particular concrete decrease with increase in temperature of curing, it is obvious that a maximum value of diffusivity occurs at 7 days at the same time that a minimum value occurs for specific heat, and that the inverse proportionality between diffusivity and specific heat is fairly consistent.

Mix 2 (3-1/2 scy) -- For Mix 2, containing 3-1/2 sacks cementing material per cubic yard, tests for diffusivity of concrete were performed for two different curing conditions. The first curing condition was the stepped adiabatic curing of condition B shown in Fig. 4. For the second curing condition, designated as curing condition D in Fig. 4, the temperature was raised stepwise from the starting temperature of 50°F to 71°F at age 3 days; the specimen was then cured at 71°F continuously.

The results of tests for diffusivity of concretes cured under adiabatic condition B are summarized in Table 15.

One specimen was cured adiabatically to age 35 days (to temperature of 96.0°F), then transferred to curing at 71°F for one day, and then tested at age 36 days to determine the thermal diffusivity. Following the test, without stripping the metal form, the specimen was returned to curing for 1 day at 71°F, then stripped and immediately tested. Upon stripping and testing, the value obtained for thermal diffusivity (age 37 days, Table 15) was higher by 0.001 than when tested with the metal form encasing the specimen (age 36 days, Table 15).

The same concrete, Mix 2, was used also under curing condition D (Fig. 4), where the temperature was raised from the starting temperature of 50°F on the same stepped adiabatic curve as for curing condition B to age 3 days and temperature 71°F. The temperature was maintained at 71°F continuously thereafter to age 101 days, and the specimen was then tested for thermal diffusivity. The value obtained for thermal diffusivity in this test was 0.036. The specimen was returned to curing for 7 days at 71°F, and at age 108 days the metal casing was removed and the stripped specimen again tested. For this test the value of thermal diffusivity was found to be 0.035, or lower by 0.001 than when tested without the metal casing. Considering the two specimens tested both with the metal casing intact and with metal casing removed, it appears that the effect of the metal casing is not significant.

Tests of thermal diffusivity of concrete of Mix 4, containing 6-1/2 sacks cementing material per cubic yard, were conducted for concrete cured on a cooling curve, condition E, shown in Fig. 4. The results of these tests also are listed in Table 15.

The specimens tested in this group, also were cured and tested with sealed metal containers in place. The value for thermal diffusivity, 0.040, was constant for all ages regardless of the curing temperature. It was noted in the test results for Mix 2 that there was less variation in thermal diffusivity with change in temperature than for the very lean concrete of Mix 1-B. For the results shown in Table 15, there was no variation in diffusivity, although the change in curing temperature was greater than for any of the other tests. It appears that the richer the mix in portland cement, the less the effect of temperature change upon values of thermal diffusivity.

It appears that the values of thermal diffusivity of the three concretes of increasing richness of mix -- Mixes 1-B, 2, and 4 -- do not correlate with richness of mix. However, a valid comparison is not possible in view of the difference between adiabatic curing and curing on the cooling curve.

THERMAL CONDUCTIVITY

Thermal conductivity can be determined either directly by experiment or by calculation from the relationship between diffusivity, thermal conductivity, specific heat, and density:

$$K = h^2 p C \qquad (3)$$

where h^2 is diffusivity in $ft^2/hr.$,
p is the density and
C is specific heat in appropriate units.

In the tests here discussed, specific heat and diffusivity were determined experimentally and, for concrete of observed density, the thermal conductivity was calculated.

The computed values of thermal conductivity, for the specimens for which both values of diffusivity and specific heat were available, are summarized in Table 16.

For the quantity p, density, in equation (3) there were employed values of 160 pcf for Mix 1-B having 2 sacks cementing material per cubic yard, for Mix 2 (3-1/2 scy) 156.4 pcf, and for Mix 4 (6-1/2 scy) 157.1 pcf.

It is noted in Table 16 that the leaner the mass-concrete mix, the higher the thermal conductivity. Based on the results obtained for concretes at the U. S. Bureau of Reclamation[2], it appears that the values of thermal conductivity for the Oroville test concretes are relatively quite low.

Considering all the elements involved in equation (3) as studied in this investigation, attention is again called to the decrease in the value of specific heat at the two low points of the curve of Fig. 6, below that computed for all ingredients at the starting temperature, but before mixing. This condition is unrealistic and obviously does not represent the specific heat of the concrete at the given temperature for a stable state. It is reasonable to believe that with rapid temperature rise in lean mixes, the average temperature of the paste will be somewhat higher than the average temperature of the coarse aggregate. Therefore, although the temperature rise in the concrete for a given quantity of heat contributed can be determined for an apparently steady state, the weight of concrete actually involved in the relationship between heat contribution and temperature rise of the mass may be considerably less than the actual weight of the concrete test specimen.

It is concluded therefore that specific-heat determinations are not appropriate for adiabatically curing concrete. However, the conditions present in adiabatically curing concrete which contribute to the widely varying values of specific heat are nevertheless the identical conditions which obtain in mass-concrete construction at the early ages, when cooling gradients change most rapidly near exposed surfaces or at positions where concrete makes contact either with abutments or with foundations. In this respect it is believed that the use of values of specific heat in equation (3) determined for specimens of standard-cured concrete, likewise are inappropriate in calculations of diffusivity of adiabatically curing concrete.

The determination of diffusivity of concrete is relatively simple as compared with determinations of specific heat and thermal conductivity. It has been demonstrated that the specimen may be tested, and reliable values obtained for diffusivity, without removal of the sealed metal casting form. The values of diffusivity obtained for adiabatically curing concrete reflect actual thermal conditions for mass-concrete construction and are useful directly in calculations of cooling gradients. Hence it is believed that such a direct test of adiabatically curing concrete provides improved precision in calculations aimed at evaluating thermal stresses in mass concrete.

Although the computed values of thermal conductivity appear reasonable, it is believed that where this quantity is desired or is necessary for calculations relative to heat concepts it would be most effective to make a direct determination for thermal conductivity in the same manner as utilized in the work of Johnson and Knight[4] at the University of California.

LINEAR COEFFICIENT OF THERMAL EXPANSION

The linear coefficient of thermal expansion was determined for concretes cast in cylinders 8-1/2 in. in diameter and 16 inches in length in accordance with the procedure outlined in Appendix B.

Specimens for test included concretes of Mix 1-B (2 scy) and Mix 2 (3-1/2 scy). Four specimens were cast for each concrete mix. One specimen for each mix was tested at ages 3, 7, 14, and 28 days of adiabatic curing of the type indicated in Table 17 wherein results of tests are summarized.

The thermal expansion specimens were cycled between 40 and 90°F while strains were measured by means of Carlson meters of the so-called "slim" model. The early-age specimens were carried through additional cycling at the time later-age specimens were put through their initial cycling. During such periods when a specimen was not being cycled in the testing procedure it was stored in the cabinet being controlled at the required adiabatic curing temperature.

Below are listed the data obtained for Mix 1-B in the cycling procedures, values being expressed in units of microinches per inch per °F. The values shown in Table 17 are summarized from these data.

3 days of adiabatic curing prior to test				7 days of adiabatic curing prior to test		
	Cycle Limits, °F				Cycle Limits, °F	
70 to 40	40 to 90	90 to 70		70 to 40	40 to 90	90 to 70
5.74	5.95	5.18		5.15	5.76	5.49
5.27	5.89	5.36		5.34	5.54	5.58
5.37	5.42	5.25		5.18	5.44	5.54
5.20	5.55	5.62		5.51	5.58	5.49
5.37	5.54	5.51				
5.64	5.13	5.31				
5.73	5.43					
5.47	5.56	5.37	Cycle average	5.30	5.58	5.53
5.0	7.8	4.7	Max. dev., %	4.0	3.2	0.9
	5.47		Overall average	5.47		

14 days of adiabatic curing prior to test				28 days of adiabatic curing prior to test			
Cycle limits, °F.				Cycle limits, °F.			
70 to 40	40 to 90	90 to 70		70 to 40	40 to 90	90 to 70	90 to 40
5.15	5.29	5.43		5.29	5.35	5.00	5.30
5.34	5.39	5.28		5.00	5.19	5.02	5.05
5.18	5.26	5.28		5.10	5.06		5.06
5.51	5.05			5.09	5.13		
					5.05		
					5.03		
5.57	5.32	5.33	Cycle average	5.12	5.14	5.01	5.14
4.7	5.1	1.9	Max dev., %	3.3	4.1	0.4	3.1
	5.41		Overall average		5.12		

Note: After 28 days of curing, the coefficient is 6% lower than the average of the first three ages.

Similarly, below are shown the data obtained in the cycling procedure for mix 2, also summarized in Table 17.

Temperature Limits of Thermal Cycles, °F.	Average Age, days	Average Linear Coefficient of Thermal Expansion, micro in/in 10 F			
70-50-70	5	4.97			
	7		5.25		
70-50-70	9	5.53		5.18	
70-50-70	10	5.11			
70-50-70	11	5.28	5.13		
70-50-70	12	5.00			5.23
70-50-90-70	32	5.46			
	33			5.29	
70-50-90-70	35	5.12			

From the data shown in Table 17 it appears that the linear coefficient of thermal expansion for mix 1-B (2 scy) at early ages is about 5.5 millionths per °F, and 5.1 at later ages. Similarly, for mix 2 (3-1/2 scy) at early ages the coefficient is of magnitude 5.2 and at later ages 5.3. It is to be noted that while the average value of the coefficient computed from all available data is 5.2 for mix 1-B and 5.4 for mix 2, or an overall average for both mixes amounting to 5.3 the average of all values shown in Table 18 also is 5.3. It is believed that the value of 5.3 millionths per °F. is a representative value for both of the mass-concrete mixes.

CONCLUSION

A considerable portion of the data here reported have been utilized, with the consent of the Department of Water Resources, State of California, in the preparation of a paper on mass concrete to be included in the American Concrete Institute, Committee 207, Symposium on Mass Concrete. The paper, presented at the Annual Meeting of the American Concrete Institute, March 1962 is entitled,

"Thermal Properties, During Adiabatic Curing, of Mass Concrete
For Oroville Dam", by

Alexander Klein, David Pirtz, and Robert F. Adams

SUMMARY

Below there are summarized the observations and conclusions based upon the results of tests of thermal properties of concretes for Oroville Dam. All of the concrete mixes tested in this investigation contained both a pozzolan and an air-entraining agent. The richness of mix varied between nominal limits of 2 sacks of total cementing material per cubic yard of concrete and 6 1/2 sacks of total cementing material per cubic yard of concrete.

RESULTS OF ADIABATIC TEMPERATURE RISE TESTS

The feature of greatest interest in the tests for adiabatic temperature rise was the testing of extraordinarily lean mixes having a total nominal cementing material content of 2 sacks per cubic yard. In this lean mix only about 1 1/4 sacks of portland cement was utilized per cubic yard, the balance being calcined natural pozzolan.

The maximum size of aggregate in the lean mixes was 4 1/2 inches. Because of the large maximum size of aggregate for the size of specimen used and the leanness of the mix, there were effects which, it is believed, while typical of general construction practice for mass concrete were the cause of somewhat unusual temperature rise phenomena. It is believed that the movement of heat generated in the paste was considerably impeded in progressing into the larger sized aggregates. Consequently, both during the heating stages of the adiabatic curing and subsequently during the cooling of such concrete, there was considerable lag in heat movement in the concrete as distributed between paste and aggregate.

These effects are most noteworthy in consideration of starting temperatures. According to the literature it has been found that the lower the starting temperature the higher the temperature rise at age 28 days. On the contrary, for these lean mixes and relatively large size of aggregate, the lower the starting temperature the lower the temp. rise at age 28 days.

The improved calorimeter appears to produce a high degree of precision even with lean mixes. As yet, however, there are inadequate data to determine reproducibility for lean mixes.

SPECIFIC HEAT TESTS OF ADIABATICALLY CURING CONCRETE

Specific Heat of Aggregate. - The specific heat of aggregate from the Oroville dredger tailings deposit was determined for each of four fractions of material finer than 1-1/2 inch. The four fractions were sand, No. 4 to 3/8 inch, 3/8 inch to 3/4 inch, and 3/4 inch to 1-1/2 inch.

It was determined that the smaller the size of the aggregate, the higher the specific heat. For the sand fraction, the specific heat in BTU/lb/°F was determined as 0.215 in the moist condition with the moisture content being 0.8 percent. For the 3/4 in. to 1-1/2 in. fraction, the value of specific heat in the moist condition was 0.203 with the moisture content being 0.1 percent. The difference in moisture contents can account for less than half of the increase of specific heat of the fine fraction.

The petrography of the deposit gives no clue as to the reason for the higher specific heats of finer fractions. It is believed that the relatively higher values of specific heats of finer fractions are related to larger amounts of weathered and hydrous material in the finer fractions.

Specific Heat of Concretes. - Specific heat was determined for concrete of Mixes No. 1-B (2 scy), No. 2 (3-1/2 scy) and No. 4 (6-1/2 scy). For each of these concrete mixes, specific heat was determined at various ages in the course of adiabatic curing according to predetermined time-temperature curing curves. The metal cylinder employed in the casting of specific-heat specimens was retained in place both during the curing and testing of individual specimens. Subsequently, the effect of the metal cylinder on values of specific heat was evaluated for selected specimens.

For Mix No. 1-B (2 scy) separate specimens were cast for tests at ages 3, 7, 14, and 28 days, cured adiabatically on a stepped curve starting at 55°F and concluding at a temperature of 80°F at 28 days. The values of specific heat, in BTU/lb./°F observed at ages 3, 7, 14, and 28 days were 0.225, 0.222, 0.234, and 0.227 respectively.

For Mix No. 2 (3-1/2 scy), the effects of three different curing conditions were evaluated at various ages of test. Separate specimens were cast for tests at ages of 1, 3, and 7 days for concretes adiabatically cured on a stepped curve starting at 50°F and concluding at a temperature of 89.3°F at age 7 days. The values of specific heat, in BTU/lb./°F observed at ages 1, 3, and 7 days were 0.205, 0.283, and 0.236 respectively. The second condition of curing for concretes of this mix consisted of adiabatic curing at a temperature 3°F less than the true adiabatic temperature, the starting temperature being 47°F and the concluding temperature at age 28 days being 106.5°F. Values of specific heat, in BTU/lb./°F observed at ages 7, 14, 21, and 31 days were 0.235, 0.261, 0.249, and 0.246 respectively. The third condition of curing consisted in adiabatically curing stepwise from a starting temperature of 50°F to a temperature of 71°F at age 3 days, and thereafter maintaining the temperature at 71°F to age 28 days. Separate specimens, tested at ages 3, 7, and 28 days had observed values of specific heat, in BTU/lb./°F of 0.221, 0.235 and 0.241 respectively.

In addition to the use of separate test specimens for each of the ages and curing conditions noted above, retests were made for specimens of this mix and curing condition. The specimen of age 3 days, was returned to curing and subsequently retested at ages 7 days and 28 days. The specimen of age 7 days was returned to curing after test and subsequently retested at age 28 days. Further, a separate specimen was prepared, cured and tested at ages 22 and 26 days with the metal form in place, then retested at age 32 days with the metal form removed prior to testing.

For Mix No. 4 (6-1/2 scy), curing was on a cooling curve provided by the Department of Water Resources. Specific heat was determined at only 1 age of curing, 3 days, the value obtained amounting to 0.232 BTU/~~hr~~lb./°F.

Due to the necessity of imposing a temperature rise of about 20°F above the temperature of the specimen at the time of test in order to evaluate heat input per °F with adequate precision, the mean temperature of test in determinations of specific heat was about 10°F above that of the adiabatic curing temperature. Since the values of specific heat as determined are calculated to be accurate to about ± 0.001, the effect of the temperature rise of about 20°F utilized in making of specific heat tests is of significance only for specimens of age less than 7 days.

It was established that the presence of the metal form during tests of specific heat of concrete had no significant effect upon the values of specific heat; hence the effect of adiabatic curing upon values of specific heat may be directly considered in comparisons with values of specific heat for concretes standard cured. In general, it has been determined that for standard cured concretes, there is uniform increase in values of specific heat with increase in mean temperature of concrete. This is not the case with concrete cured adiabatically, the values of specific heat being relatively very high at early ages, and at relatively low temperatures of concrete.

All the concrete mixes included in this investigation contain pozzolan. For such mixtures of pozzolan and portland cement, heats of hydration cannot yet be determined with sufficient accuracy to allow calculation of reliable values of specific heat from the relationship between heat of hydration, adiabatic temperature rise, content of cementing material, and specific heat.

In the light of the findings of this part of the investigation, relative to applicability of values of specific heat determined either for adiabatically cured concrete, or for standard cured concrete having the mix designs studied in this investigation, it is believed that it is desirable that the diffusivity of adiabatically curing concrete be determined directly by experiment, in order to define more precisely cooling gradients in mass-concrete structures prior to age 14 days.

Likewise, inasmuch as values of thermal conductivity calculated from the relationship of diffusivity, specific heat, and density of concrete would reflect the unreliability of the specific-heat values in these mixes, it is believed that where determinations of thermal conductivity are desired, values should be determined by the direct method.

DIFFUSIVITY OF ADIABATICALLY CURING CONCRETES

Tests for diffusivity of concrete were made for concretes somewhat corresponding to the same mixes and the same curing conditions as listed above for tests of specific heat. Again, as in the tests for specific heat, specimens were tested with the casting container in place. However, inasmuch as the value for diffusivity is the principal thermal property of use in calculating cooling gradients in a mass-concrete structure, the effect of the metal container was evaluated by retesting of specimens immediately subsequent to removal of the sealed containers.

For Mix No. 1-B (2 scy) specimens were cast for tests of diffusivity at ages 3, 7, 14, and 28 days, for concrete cured adiabatically in the sealed casting container on a stepped curve starting at 55°F and concluding at a temperature of 80°F at 28 days. The values of diffusivity, in ft^2/hr, observed at ages 3, 7, 14, and 28 days were 0.047, 0.048, 0.045, and 0.044 respectively. The maximum value of diffusivity at age 7 days is consistent with the observed minimum value of specific heat for the corresponding concrete at age 7 days.

For Mix No. 2 (3-1/2 scy), tests for diffusivity of concrete were performed for two different curing conditions.

For adiabatic curing on a stepped curve starting at 50°F and concluding at a temperature of 96°F at age 14 days, and continued curing at 96°F to age 37 days, concrete specimens were cast and cured in sealed containers for tests of diffusivity at ages 3, 7, 15, and 29 days. The values of diffusivity, in ft^2/hr. observed at the test ages of 3, 7, 15, and 29 days were 0.036, 0.037, 0.037, and 0.037 respectively. A retest of diffusivity with the casting container in place, at age 36 days, provided a value of 0.038 ft^2/hr. A retest of the same specimen a day later, age 37 days, after stripping away the casting container, provided a value for diffusivity of 0.039 ft^2/hr.

Also for Mix No. 2, having 3-1/2 scy cementing material, specimens were cast for tests of diffusivity for a curing temperature starting at 50°F, the temperature raised gradually to 71°F at age 3 days, and the temperature held constant at 71°F thereafter. The age of concrete at the time of test with the casting form in place was 101 days, and the age of retest with the casting form removed was 108 days. The value for diffusivity observed at 101 days with the casting form in place was 0.036 ft^2/hr. and that observed at 108 days with the casting form removed was 0.035 ft^2/hr. Since for the specimens of the first curing condition, the value of diffusivity was increased by 0.001 ft^2/hr. and for the specimen of the second curing condition was decreased by 0.001 ft^2/hr., and since it is believed that the precision of these tests is only within ± 0.001 ft^2/hr., it is concluded that the metal container has no significant effect upon observed values of diffusivity.

For Mix No. 4 (6-1/2 scy), curing was again conducted on the same cooling curve, provided by the Department of Water Resources, as was utilized in the curing of specific heat test specimens for this mix. Ages of test, with casting container in place were 2 days, 7 days, and 14 days. For all tests the value observed for diffusivity was 0.040.

It is apparent that for adiabatically curing concretes, values of diffusivity are likely to be highest at early ages under conditions where specific heats are relatively low. At later ages, values of diffusivity become relatively constant. Further, the richer the mix, the lower the value of diffusivity whether the concrete be cured adiabatically or cured on the particular cooling curve furnished by the Department of Water Resources.

LINEAR COEFFICIENT OF THERMAL EXPANSION OF ADIABATICALLY CURED CONCRETES

The linear coefficient of thermal expansion was determined for concretes cast in cylinders 8-1/2 in. in diameter and 16 inches in length. Length changes were measured by means of Carlson strain meters, of the so-called "slim" model.

Thermal expansion specimens were cycled between 40 and 90°F. Early-age test specimens were carried through additional cycling at the time later-age specimens were put through their initial cycling. During such periods when a specimen was not being cycled in the testing procedure it was stored in the cabinet being controlled at the required adiabatic curing.

Linear coefficients of thermal expansion were determined for Mix No. 1-B (2 scy) at ages 3, 7, 17, and 28 days for specimens cured adiabatically (except for cycling periods) on a stepped curing curve starting at 55°F and concluding at a temperature of 80°F at age 28 days. The average linear coefficient of thermal expansion, in "millionths per °F ", was found to be 5.5 at ages 3 days and 7 days, 5.4 at age 14 days, and 5.1 at age 28 days.

Also, linear coefficients of thermal expansion were determined for Mix No. 2 (3-1/2 scy) at ages 7, 11, and 33 days for specimens cured adiabatically (except for cycling periods) on a curing curve starting at 47°F and concluding at a temperature of 104°F at age 33 days. The average linear coefficient of thermal expansion, in "millionths per °F ", was found to be 5.25 at age 7 days, 5.13 for age 11 days, and 5.29 at age 33 days.

Taking into consideration all data for all cycles, it is considered that a linear coefficient having a value of 5.2 for Mix No. 1-B (2 scy) and 5.4 for Mix No. 2 (3-1/2 scy) would be appropriate and representative for use in calculations involving thermal properties of these concretes.

ACKNOWLEDGEMENTS

This research program was sponsored by the State of California, Department of Water Resources, and was administered at the University of California by Professor J. M. Raphael.

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TABLES

TABLE 1. MATERIALS

Mix No.	Nominal Cementing Material, scy	Max. Size of Agg., Inch	Cement (Type II), Brand	Pozzolan	Aggregate		Agent	Tests Conducted
					Fine	Coarse		
1-A	2	4 1/2	Calaveras 60C-265	Basalt 60C-290	Dry Creek 60C-147	Oroville Dredger Tailings 59C-194-4	Durair 58C-126 WRA-Orzan KRL-40-60C	Adiabatic Test Nos. 5 and 6
1-B	2	2 1/2	Ditto	Ditto	Ditto	Ditto	Ditto	Specific Heat Thermal Diffusivity Thermal Expansion
2	3 1/2	3	Blend Permanente 58C-109 Calaveras 59C-93 Ideal 59C-36	Basalt 59C-II	Oroville Dredger Tailings 59C-295	Ditto	Durair 59C-369	Ditto
3-A	4	4 1/2	Ditto	Ditto	Ditto	Ditto	Durair 58C-126	Adiabatic Test No. 1
3-B-I	4	4 1/2	Permanente 58C-109	Ditto	Ditto	Ditto	Ditto	Adiabatic Test No. 2
3-B-II	4	4 1/2	Calaveras 59C-93	Ditto	Ditto	Ditto	Ditto	Adiabatic Test No. 3
3-B-III	4	4 1/2	Ideal 59C-36	Ditto	Ditto	Ditto	Ditto	Adiabatic Test No. 4
4	6 1/2	2 1/2	Calaveras 60C-290	Basalt 60C-290	Dry Creek	Oroville Dredger Tailings	Durair 60C-121 KRL-40 60C-490	Specific Heat Thermal Diffusivity Thermal Expansion

TABLE 2. GRADATION OF AGGREGATES

Percentages by Weight Retained on Each Sieve

Mix Number	1-A	1-B	2	3A and 3B	4
Nominal Cementing-Material Factor, scy.	2	2	3-1/2	4	6-1/2
Coarse Aggregate					
Sieve Size					
Maximum size, in.	4-1/2	2.5	3	4-1/2	2-1/2
4-1/2 in.	-	0	0	-	0
3 in.	27	0	0	27	0
1-1/2 in.	26	35.6	35.6	26	29
3/4 in.	25	34.2	34.3	25	36
3/8 in.	17	20.6	20.5	15	22
No. 4	5	9.6	9.6	7	13
Sand					
Sieve Size					
No. 4	0	0	0	0[a]	0
No. 8	15	15	11	13	15
No. 16	16	16	16	14	16
No. 30	26	26	31	31	26
No. 50	29	29	25	25	29
No. 100	11	11	14	14	11
Pan	3	3	3	3	3
Fineness Modulus	2.86	2.86	2.76	2.78	2.86

Note: Dry Creek sand was used in mixes 1-A, 1-B, and 4. Sand from Oroville dredger tailings was used in mixes 2, 3-A, and 3-B.

a - Sand gradation designated as "gradation G" by Department of Water Resources

TABLE 3. CHEMICAL PROPERTIES OF PORTLAND CEMENTS AND POZZOLANS

	Portland Cements Type II				Basalt Pozzolan
	Permanente	Ideal	Calaveras		
Oxides, percent by weight	58C 109	59C 36	59C 93	60C 265	60C 290
$Si0_2$	24.20	21.37	23.59	23.09	73.3
Al_20_3	2.92	5.53	4.73	63.69	----
Fe_20_3	2.92	4.73	2.75	2.79	----
$Al_20_3 + Fe_20_3$	----	----	----	----	23.3
Ca0	65.61	63.69	64.66	64.24	----
Mg0	0.52	1.75	1.56	1.70	0.65
$S0_3$	1.94	1.94	1.90	1.96	0.01
Na_20	0.11	0.28	0.41	0.45	----
K_20	0.17	0.00	0.18	0.24	----
Total alkalies as Na_20	0.22	0.28	0.53	0.61	----
Insoluble residue	0.04	0.07	0.13	0.26	----
Loss on ignition	1.57	0.75	0.94	1.17	0.34
Compound Composition percent by weight					
C3S	54	48	45	46	----
C2S	29	26	34	31	----
C3A	3	7	7	7	----
C4AF	9	14	8	8	----

TABLE 4. PROPERTIES OF PORTLAND CEMENTS AND POZZOLANS

Property	Portland Cements				Pozzolans	
	Permanente Type II 58C 109	Ideal Type II 59C 36	Calaveras		Basalt	
			Type II 59C 93	Type II 60C 265	58C 11	60C 290
Specify Gravity	3.16	3.25	3.17	--	2.48	2.48
Fineness, Air permeability, cm^2/gram	3626	3280	2960	3131	12,840	13,100
Mean particle diameter, microns	5.24	5.63	6.39	--	1.88	1.85
Precent passing No. 325 sieve	--	--	--	--	10.0	8.0
Normal Consistency, percent	24.4	22.2	23.2	24.0	50.0	--
Set Time Initial Set Hr.:min.	4:35	1:40	3:45	4:35	--	--
(Gillmore) Final Set Hr.:min.	5:35	3:40	5:00	5:45	--	--
Autoclave Expansion, percent	-0.019	+0.063	+0.006	+0.008	--	--
Air Entrainment of Mortar, percent	10.06	9.20	9.85	8.75	--	--
Compressive Strength(b), psi (2-in. cubes, 1:2.75 mortar) Age 3 days	2250	1980	1720	1980	--	--
Age 7 days	2930	2960	2740	2700	--	--
Age 28 days	4130	5540	4230	4330	--	--
Compressive Strength(a), (2-in. cubes 1:2.75 mortar) Age 28 days Central, psi	--	--	--	--	4650	4090
Pozzolan Cement, psi	--	--	--	--	4340	3950
Percent of control	--	--	--	--	99.3	96.5
2-in. by 4-in. cylinders 2:1:9 Pozzolan-lime-sand Age 28 days	--	--	--	--	1283	1190
Water requirement, precent of control	--	--	--	--	106.7	106.3
Reduction in reactive expansion, percent	--	--	--	--	96.4	84.5

a - ASTM Method C402-58T except as noted.
b - ASTM Method C109-58T.
c - USBR Method of December 15, 1956.

TABLE 4

TABLE 5. MIX PROPORTIONS BY WEIGHT

Mix No.	1-A	1-B	2	3-A	3-B	4
Cementing Material, scy.	2	2	3-1/2	4	4	6-1/2
Cementing Material	1.00	1.00	1.00	1.00	1.00	1.00
Cement	0.63	0.63	0.79	0.81	0.81	0.85
Pozzolan	0.37	0.37	0.21	0.19	0.19	0.15
Aggregate						
Sand	4.71	4.71	2.28	1.98	1.88	1.54
Coarse	16.81	16.81	9.61	8.30	8.40	3.99
Sand, percentage of total aggregate						
by weight	21.9	21.9	19.2	19.3	18.3	27.9
by volume	23.8	23.8	20.6	20.6	19.8	30.0
Ratio, cementing material to total aggregate	1:21.5	1:21.5	1:11.9	1:10.3	1:10.3	1:5.5
Ratio, water to cementing material	0.81	0.80	0.50	0.43	0.43	0.38

TABLE 6. ADIABATIC TEMPERATURE AND ADIABATIC TEMPERATURE RISE OF CONCRETES WITH DIFFERENT BRANDS OF CEMENT

Test No.	1		2		3		4	
Mix No.	3-A		3-B (I)		3-B (II)		3-B (III)	
Cement	Blend		Permanente II		Calaveras II		Ideal II	
Age of Specimen, Days	Temp., deg. Fahr.		Temp., deg. Fahr.		Temp. deg.Fahr.		Temp., deg. Fahr.	
	Actual	Rise	Actual	Rise	Actual	Rise	Actual	Rise
0	40[a]	--	40[a]	--	40[a]	--	40[a]	--
0	51.7[b]	0	48.3[b]	0	49.0[b]	0	50.7[b]	0
1	68.8	17.1	65.2	16.9	65.1	15.3	62.6	11.9
2	74.7	23.0	73.0	24.7	72.9	23.1	70.4	19.7
3	78.7	27.0	76.7	28.4	77.9	28.1	76.1	25.4
4	82.2	30.5	79.3	31.0	82.1	32.3	80.9	30.2
5	84.9	33.2	81.3	33.0	85.4	35.6	84.7	34.0
6	87.2	34.5	83.0	34.7	88.0	38.2	87.7	37.0
7	89.3	37.6	84.5	36.2	90.5	40.7	90.4	49.7
8	91.1	39.4	85.7	37.4	92.7	42.9	92.8	42.1
9	92.6	40.9	86.8	38.5	94.6	44.8	94.9	44.2
10	93.9	42.2	87.8	39.5	96.2	46.4	96.7	46.0
11	95.0	43.3	88.7	40.4	97.6	47.8	98.2	47.5
12	96.0	44.3	89.5	41.2	98.7	48.9	99.5	48.8
13	96.8	45.1	90.3	42.0	99.6	49.8	100.5	49.8
14	97.5	45.8	90.9	42.6	100.5	50.7	101.4	50.7
15	98.2	46.5	91.6	43.3	101.1	51.3	102.2	51.5
16	98.8	47.1	92.1	43.8	101.7	51.9	102.8	52.1
17	99.3	47.6	92.6	44.3	102.2	52.4	103.4	52.7
18	99.8	48.1	93.1	44.8	102.6	52.8	103.9	53.2
19	100.2	48.5	93.5	45.2	103.0	53.2	104.3	53.6
20	100.7	49.0	93.9	45.6	103.4	53.6	104.7	54.0
21	101.1	49.4	94.3	46.0	103.7	53.9	105.0	54.3
22	101.4	49.7	94.6	46.3	104.0	54.2	105.3	54.6
23	101.7	50.0	94.9	46.6	104.2	54.4	105.5	54.8
24	102.0	50.3	95.2	46.9	104.5	54.7	105.8	55.1
25	--	--	95.5	47.2	104.7	54.9	105.6	54.9
26	102.1	50.4	95.7	47.4	104.9	55.1	106.1	55.4
27	102.3	50.6	(96.0)[c]	(47.7)[c]	105.1	55.3	106.3	55.6
28	(102.4)[c]	(50.7)[c]	(96.1)[c]	(47.8)[c]	105.3	55.5	106.5	55.8

a - Material storage temperature

b - Temperature at time of placement

c - Estimated value

TABLE 7. EFFECT OF STARTING TEMPERATURE ON ADIABATIC TEMPERATURE AND ADIABATIC TEMPERATURE RISE OF CONCRETE

Test No.	5		6	
Mix No.	1-A		1-A	
Cement	Calaveras II		Calaveras II	
Age of Specimen, Days	Temp., deg. Fahr.		Temp., deg. Fahr.	
	Actual	Rise	Actual	Rise
0[a]	----	----	40	----
0[b]	69.6	0	46.2	0
1	77.1	7.5	50.5	4.3
2	81.2	11.6	55.0	8.8
3	83.6	14.0	57.5	11.3
4	85.4	15.8	59.3	13.1
5	86.7	17.1	60.5	14.3
6	87.7	18.1	61.5	15.3
7	88.7	19.1	62.5	16.3
8	89.7	20.1	63.4	17.2
9	90.4	20.8	63.9	17.7
10	91.0	21.4	64.3	18.1
11	91.6	22.0	64.6	18.4
12	92.0	22.4	64.8	18.6
13	92.4	22.8	65.0	18.8
14	92.8	23.2	65.1	18.9
15	93.2	23.6	65.3	19.1
16	93.5	23.9	65.4	19.2
17	94.0	24.4	65.5	19.3
18	----	----	65.6	19.4
19	----	----	65.7	19.5
20	94.0	24.4	65.7	19.5
21	94.3	24.7	65.8	19.6
22	94.5	24.9	----	----
23	94.6	25.0	65.8	19.6
24	94.8	25.2	----	----
25	----	----	----	----
26	----	----	----	----
27	95.4	25.8	----	----
28	95.2	25.6	(66.0)[c]	(19.8)[c]

a - Material storage temperature

b - Temperature at time of placement

c - Estimated value

TABLE 8. SPECIFIC HEAT OF AGGREGATE FROM OROVILLE DREDGER TAILINGS DEPOSIT

Size Fraction	Moisture Content, percent	B.T.U. per lb. per °F	
		Moist Condition	Corrected to Oven-Dry Basis (220°F)
Sand, Grading "G"[a]	0.8	0.215	0.209
No. 4 to 3/8 in.	0.4	0.209	0.208
3/8 in. to 3/4 in.	0.2	0.206	0.204
3/4 in. to 1-1/2 in.	0.1	0.203	0.203

a - Sand gradation designated as "gradation G" by Department of Water Resources

TABLE 9.--SPECIFIC HEATS OF CONCRETES

For Method of Test, see Appendix B

Nominal Cementing-Material Factor, sacks/cu.yd.	Curing[a] Condition	Age, Days	Mean Temperature of Test, °F	Curing Temperature at Time of Test, °F	Specific Heat, B.T.U. per lb. per °F
2 (Mix No. 1-B)	A Adiabatic, (average of tests 5 and 6)	3	80.4	70.0	0.225
		7	83.4	74.7	0.222
		14	88.4	78.2	0.234
		28	88.7	80.0	0.227
	B Stepped Curve to Adiabatic Curing, Test 1	1	76.8	65.0	0.205
		3	82.5	77.9	0.283
		7	97.8	88.9	0.236
3 1/2 (Mix No. 2)	C Adiabatic, Test 4 Less 3°F	7	95.0	86.4	0.235
		14	106.1	98.1	0.261
		21	109.4	101.7	0.249
		31	111.3	104	0.246
	D Stepped Curve to Standard Curing at 71°F	3	78.4	71	0.221
		7	81.2	71	0.235
		28	81.0	71	0.241
6 1/2 (Mix No. 4)	E Cooling Curve Provided by Department of Water Resources	3	106.4	97.0	0.232

[a] See Fig. 4 for curing conditions.

TABLE 10. EFFECT OF SPECIFIC HEAT TESTS UPON SPECIMENS RETURNED TO CURING

Age of Specimen at Time of Test, days	Specific Heat,[d] BTU/lb. /°F		
	Specimen 1	Specimen 2	Specimen 3
3	0.221		
7	0.230[a]	0.236	
28	0.231[b]	0.237[c]	0.241

a - First retest of spec. 1 previously tested at age 3 days.

b - Second retest of spec. 1 previously tested at age 7 days.

c - First retest of spec. 2 previously tested at age 7 days.

d - Curing Condition D (Fig. 4); Curing Temperature 71°F.

TABLE 11. EFFECT OF STEEL FORM ON RESULTS OF SPECIFIC HEAT TESTS

Age of Concrete at Time of Test, days	Specific Heat,[a] BTU/lb. per °F	Specimen
22	0.227	with form
26	0.231	with form
32	0.227[b]	without form

a - Curing Condition D, curing temperature 71°F.

b - Steel mold removed at age 32 days, just prior to test.

TABLE 12. HEATS OF HYDRATION AS CALCULATED FROM SPECIFIC HEAT AND ADIABATIC TEMPERATURE RISE OF CEMENTING MATERIALS FOR USE IN OROVILLE DAM CONCRETES[a]

Cementing Material	Age, days	Specific Heat, "S"	Adiabatic Temperature Rise, °F, "T"	Heat of Hydration cal/gram
Portland Cement Pozzolan, Durair, 2 sacks/cu. yd. Ratio of Portland Cement to total cementing material, "C", = 0.628 Curing Condition A	3	0.225	11.3	33
	7	0.222	16.3	49
	14	0.234	18.9	58
	28	0.227	19.8	59
Portland Cement, Pozzolan, Durair, 4 sacks/cu. yd.[b] Ratio of Portland Cement to total cementing material, "C", = 0.814 Curing Condition C (see Fig. 4)	7	0.235	37.6	58
	14	0.261	45.8	78
	21	0.249	49.4	80

a - Heat of Hydration, calories per gram = $\frac{TS}{1.8\ C}$

b - Specific-heat values are for mix 2 (3-1/2 scy), Cured under Condition C, on adiabatic-curing cycle for mix 3-A (4 scy) minus 3°F.

TABLE 13. HEATS-OF-IMMEDIATE HYDRATION FOR CEMENTING MATERIALS FOR USE IN OROVILLE DAM CONCRETES

Cementing Material	Calories per Gram					
	Age of Paste, minutes					
	1	3	5	10	20	30
Portland Cements:						
Blend 51C-159	3.0	4.6	5.2	5.8	6.6	6.9
Ideal 59C-36	2.3	3.0	3.5	4.2	4.8	5.3
Permanente 58C-109	1.3	1.5	1.6	2.3	2.9	3.3
Calaveras 59C-93	1.7	2.7	2.7	3.2	3.5	3.8
Portland Cements Blended with Pozzolan: Computed						
2-Sack Mix R = 0.628[a]						
Blend 51C-159	1.9	2.9	3.3	3.7	4.1	4.3
Ideal 59C-36	1.5	1.9	2.2	2.6	3.0	3.3
Permanente 58C-109	0.8	0.9	1.0	1.4	1.8	2.1
Calaveras 59C-93	1.1	1.7	1.9	2.0	2.2	2.4
4-Sack Mix R = 0.814[a]						
Blend 51C-159	2.4	3.7	4.2	4.7	5.4	5.6
Ideal 59C-36	1.9	2.4	2.8	3.4	3.9	4.3
Permanente 58C-109	1.1	1.2	1.3	1.8	2.4	2.7
Calaveras 59C-93	1.4	2.2	2.2	2.6	2.9	3.1

[a] - R = ratio of portland cement to total cementing material

TABLE 14. HEAT OF HYDRATION, BY CONDUCTION CALORIMETER, OF BLENDS OF PORTLAND CEMENTS, POZZOLAN, AND DURAIR FOR USE IN OROVILLE DAM CONCRETES

Cementing Material,[a] Pozzolan, Durair, and	Calories per Gram		
	1 day	2 days	3 days
Blended portland cements, 59C-159	32	40	44
Ideal portland cement, 59C-36	28	38	45
Permanente portland cement, 58C-109	32	42	47
Calaveras portland cement, 59C-93	31	38	42

a - Ratio of portland cement to total cementing material for all tests, 0.814

Water to cementing material ratio for all tests, 0.436

TABLE 15. THERMAL DIFFUSIVITY OF CONCRETES

For Method of Test, See Appendix B

Nominal Cementing-Material Factor, sacks/cu.yd.	Curing[a] Condition	Age, Days	Curing Temperature at Time of Test, °F	Thermal Diffusivity h^2, ft^2 per hr.
2	A Adiabatic, (average of tests 5 and 6)	3	70.0	0.047
		7	74.7	0.048
		14	78.2	0.045
		28	80.0	0.044
3 1/2	B Stepped Curve to Adiabatic Curing, Test 1	3	77.9	0.036
		7	88.9	0.037
		15	96.0[d]	0.036
		29	96.0[d]	0.037
		36[b]	69.4	0.038
		37[c]	70.0	0.039
	D Temperature Raised from Starting Temperature of 50° to 71°F at Age 3 Days; Then Cured Continuously at 71°F Thereafter	101	71	0.036
		108[e]	71	0.035
6 1/2	E Cooling Curve Provided by Department of Water Resources	2	101.8	0.040
		7	62.7	0.040
		14	57.0	0.040

[a] See Fig. 4 for curing conditions.

[b] Specimen cured adiabatically for 35 days, moved to 71°F, tested at age 36 days.

[c] Specimen of note (b) above, stripped of metal form, returned to 71°F, tested at age 37 days.

[d] Specimen cured adiabatically to age 14 days, then stored at 96°F.

[e] Specimen tested at age 101 days with steel form in place, returned to curing at 71 F, and retested at age 108 days after stripping steel form.

TABLE 16--COMPUTED VALUES OF THERMAL CONDUCTIVITY

Nominal Cementing-Material Factor sacks/cu.yd.	Curing[a] Condition	Age, Days	Diffusivity, h^2	Specific Heat, C	Temperature for Age Shown, °F	Computed Thermal Conductivity, K, B.T.U. per sq. ft. per hr. per °F per ft.[b]
2 (Mix No. 1-B)	A Adiabatic (Average of tests 5 and 6)	3	0.047	0.225	70.0	1.69
		7	0.048	0.222	74.7	1.71
		14	0.045	0.234	78.2	1.69
		28	0.044	0.227	80.0	1.60
3 1/2 (Mix No. 2)	B Stepped Curve to Adiabatic Curing, Test 1	(1)	0.040[c]	0.205	65.0	1.28
		3	0.036	0.225	77.9	1.27
		7	0.037	0.240	88.9	1.39
		14	0.036	0.262	96.0	1.48
		21	0.0365[d]	0.249	101.7	1.42
		29	0.037	0.246	103.3	1.42
6 1/2 (Mix No. 4)	E Cooling Curve Provided by Department of Water Resources	3	0.040	0.232	97.0	1.46

[a] See Figs. 1, 2, and 3 for curing conditions.

[b] Thermal conductivity computed from relationship, $K = C \cdot h^2 \cdot d$ where d is density in pounds per cubic foot, C is specific heat, and h^2 is diffusivity.

[c] Value obtained by extrapolation from h^2 vs curing temperature relationship.

[d] Value obtained by interpolation between h^2 for 14 and 29 days.

TABLE 17 --LINEAR COEFFICIENT OF THERMAL EXPANSION

Nominal Cementing-Material Factor, sacks/cu.yd.	Curing[a] Condition	Age	Curing Temperature at Age of Test, °F	Average Linear Coefficient of Thermal Expansion, Millionths per °F	
		Days Curing prior to testing			
2 (mix No. 1-B)	A	3	70.0	5.5	5.2[c]
		7	74.7	5.5	
		14	78.2	5.4	
		28	80.0	5.1	
		Average Age, days			
3 1/2 (mix No. 2)	C	7	86.4	5.25	5.4[c]
				5.18[b]	
		11	95.1	5.13	
		33	104	5.29	

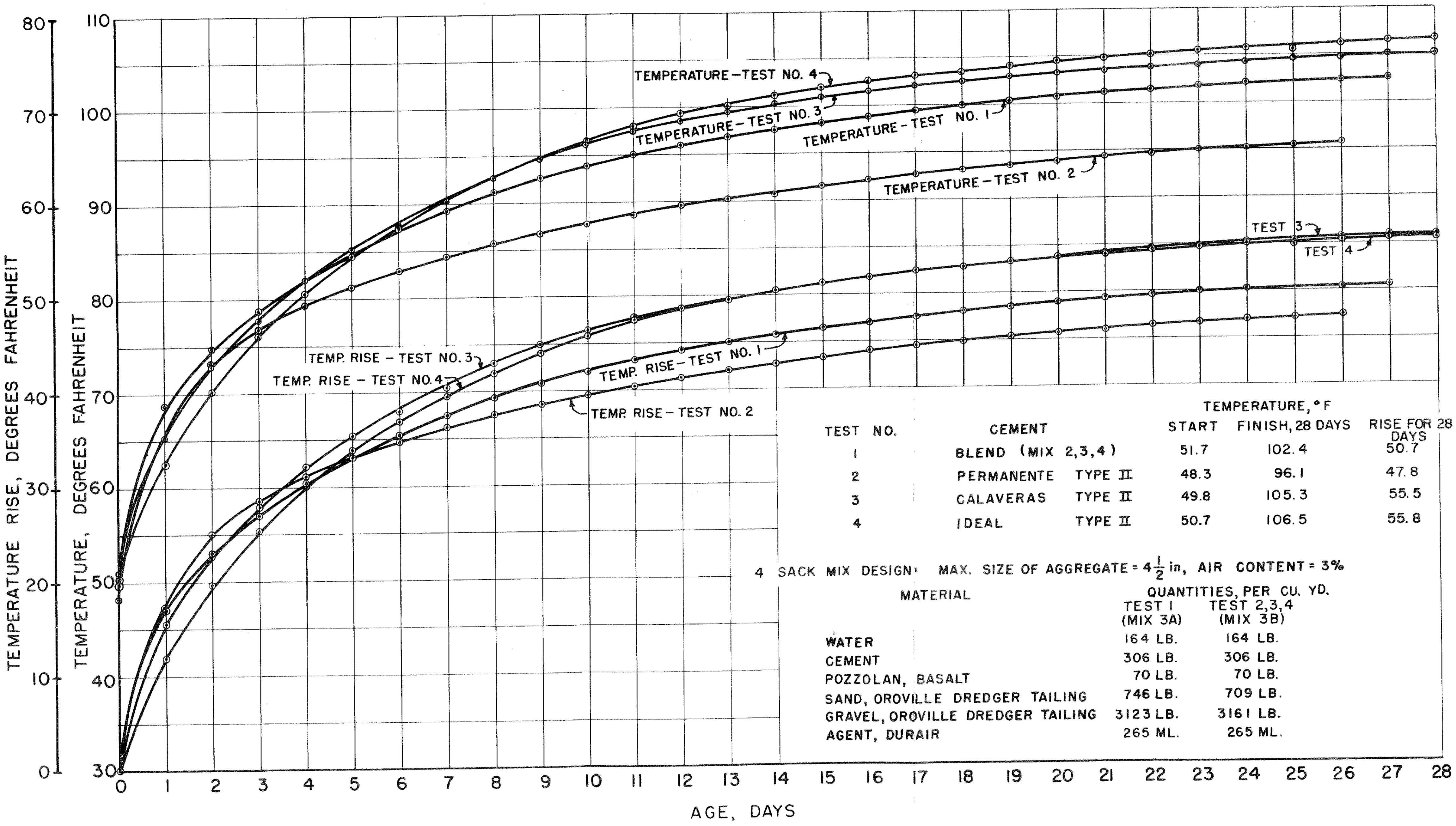
---

[a] See Fig. 4 for curing conditions.

[b] Average value of data from 5 to 12 days, considered representative of value for age 9 days.

[c] Average value for all data obtained for each curing condition.

FIGURES

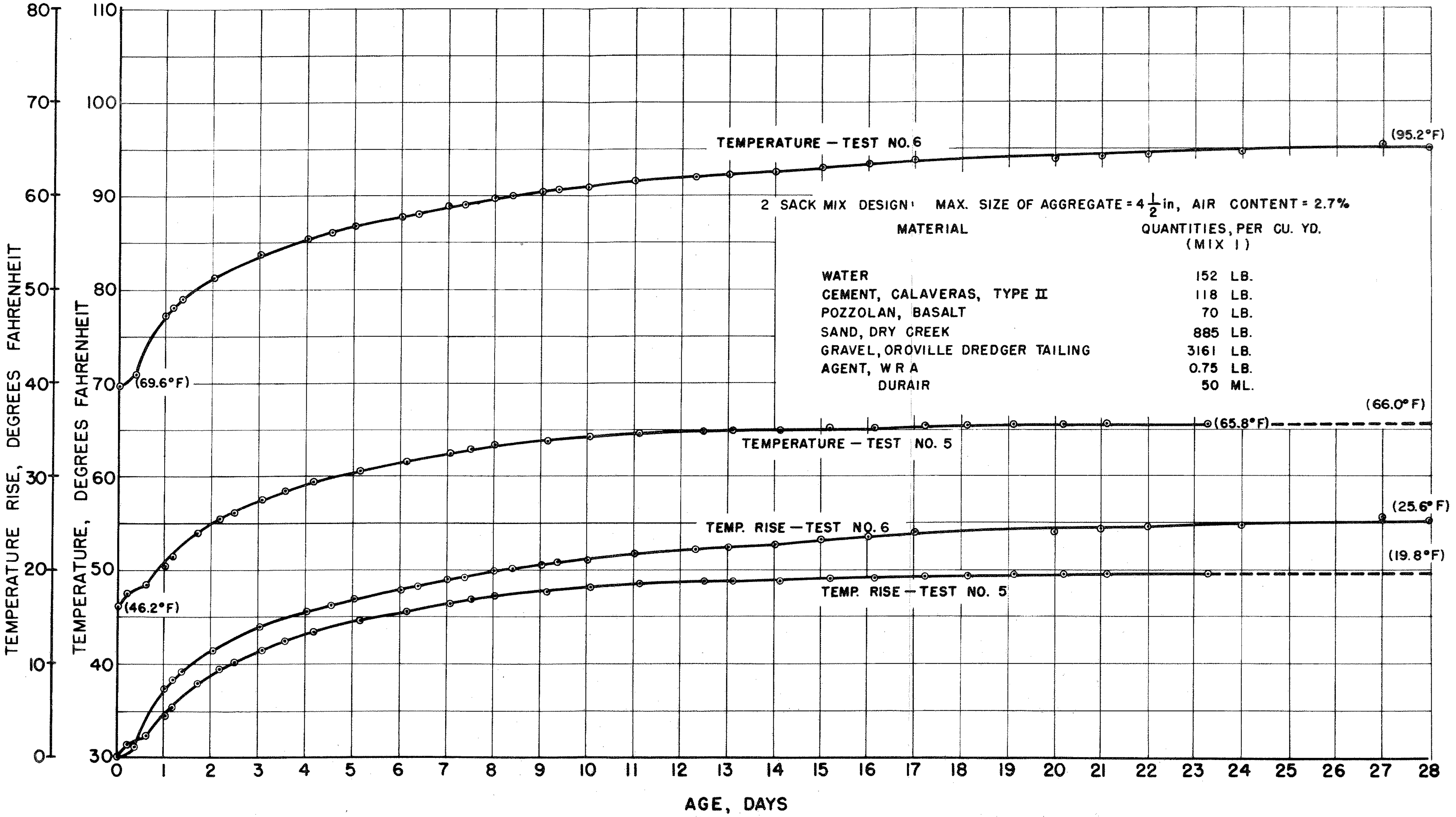


TEST NO.	CEMENT		TEMPERATURE, °F START	TEMPERATURE, °F FINISH, 28 DAYS	RISE FOR 28 DAYS
1	BLEND (MIX 2,3,4)		51.7	102.4	50.7
2	PERMANENTE	TYPE II	48.3	96.1	47.8
3	CALAVERAS	TYPE II	49.8	105.3	55.5
4	IDEAL	TYPE II	50.7	106.5	55.8

4 SACK MIX DESIGN: MAX. SIZE OF AGGREGATE = $4\frac{1}{2}$ in, AIR CONTENT = 3%

MATERIAL	QUANTITIES, PER CU. YD. TEST 1 (MIX 3A)	QUANTITIES, PER CU. YD. TEST 2,3,4 (MIX 3B)
WATER	164 LB.	164 LB.
CEMENT	306 LB.	306 LB.
POZZOLAN, BASALT	70 LB.	70 LB.
SAND, OROVILLE DREDGER TAILING	746 LB.	709 LB.
GRAVEL, OROVILLE DREDGER TAILING	3123 LB.	3161 LB.
AGENT, DURAIR	265 ML.	265 ML.

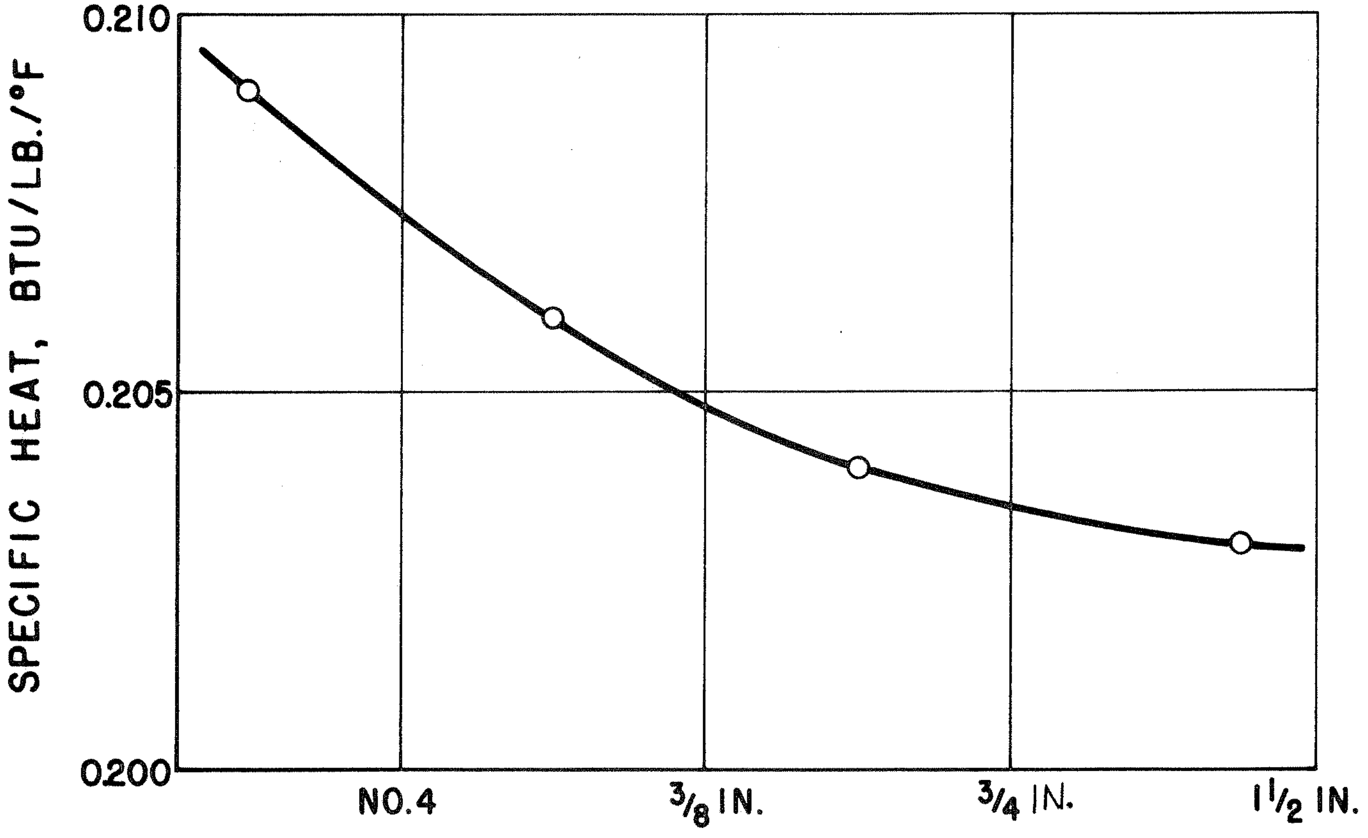
FIG. 1 ADIABATIC TEMPERATURE AND ADIABATIC TEMPERATURE RISE OF CONCRETES WITH DIFFERENT BRANDS OF CEMENT.



2 SACK MIX DESIGN: MAX. SIZE OF AGGREGATE = $4\frac{1}{2}$ in, AIR CONTENT = 2.7%

MATERIAL	QUANTITIES, PER CU. YD. (MIX 1)
WATER	152 LB.
CEMENT, CALAVERAS, TYPE II	118 LB.
POZZOLAN, BASALT	70 LB.
SAND, DRY CREEK	885 LB.
GRAVEL, OROVILLE DREDGER TAILING	3161 LB.
AGENT, WRA	0.75 LB.
DURAIR	50 ML.

FIG. 2 — EFFECT OF STARTING TEMPERATURE ON ADIABATIC TEMPERATURE AND ADIABATIC TEMPERATURE RISE OF CONCRETE.



SIZE OF AGGREGATE, FRACTION

FIG. 3 SPECIFIC HEAT VS SIZE OF AGGREGATE, FRACTION.

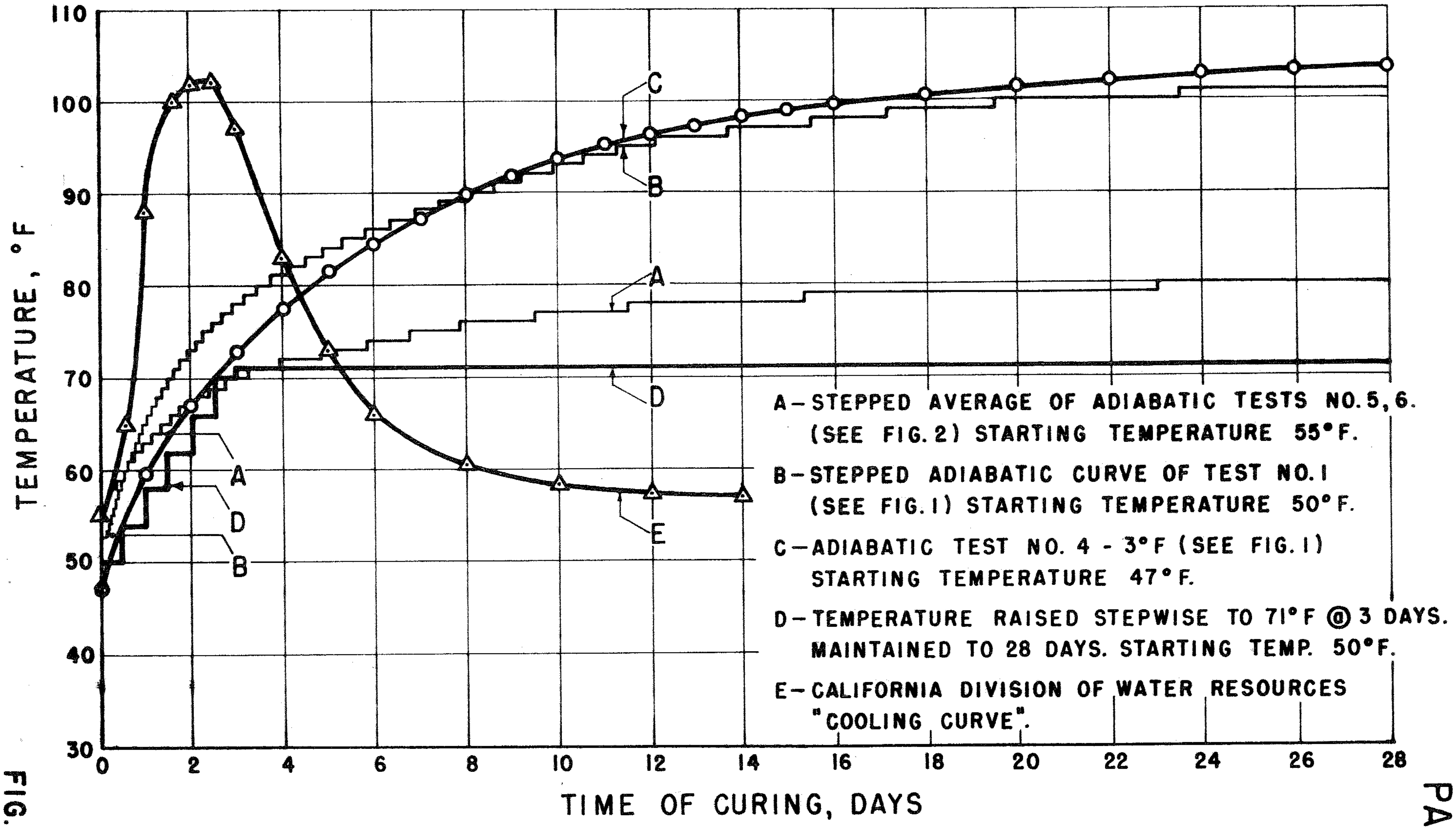


FIG. 4 TIME-TEMPERATURE CURING CONDITIONS FOR SEALED SPECIMENS.

FIG. 4

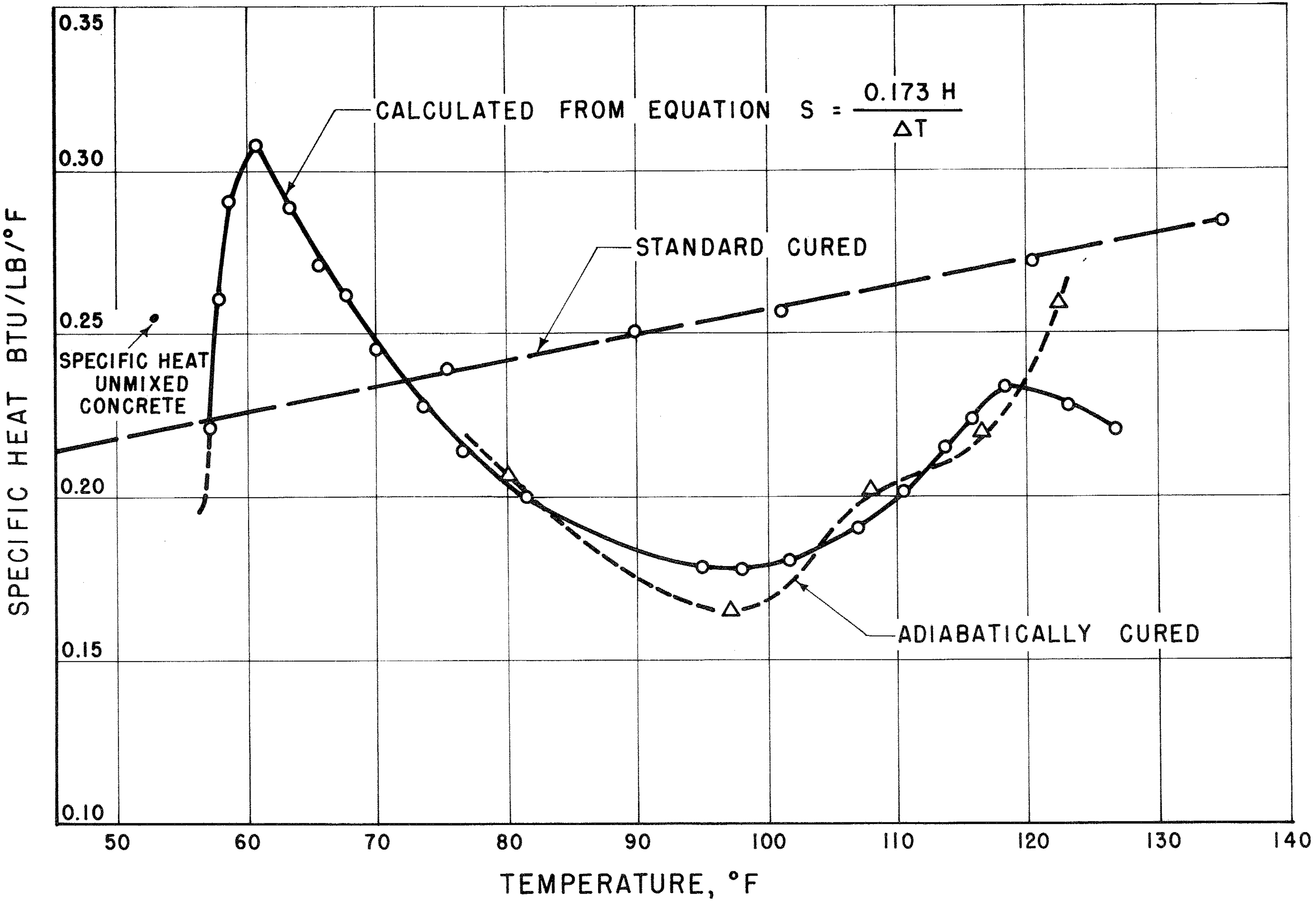


FIG. 5

FIG. 5 ADIABATIC CURING TEMPERATURE (AFTER JOHNSON & KNIGHT).

FIG. 6

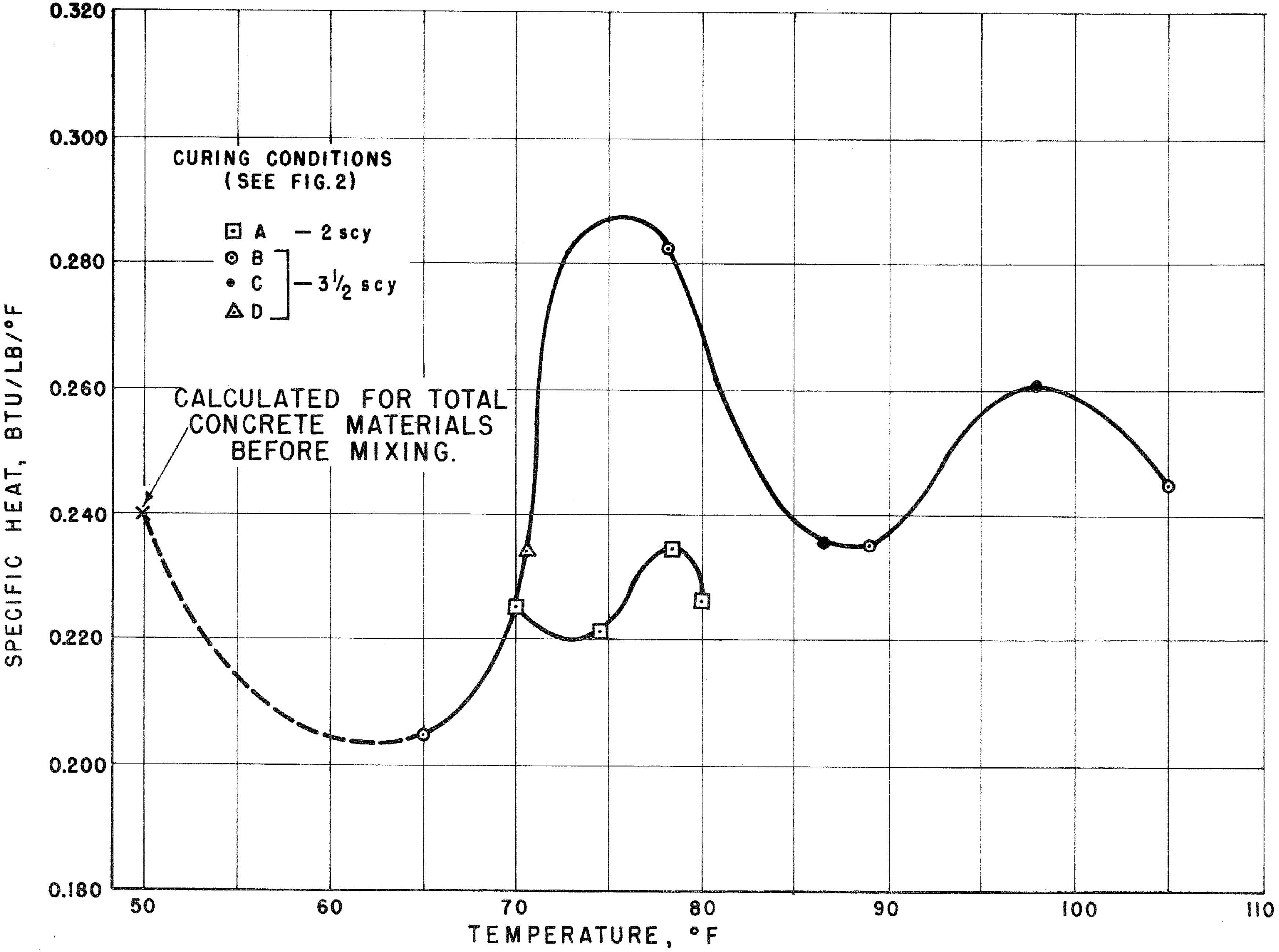


FIG. 6 ADIABATIC CURING TEMPERATURE FOR OROVILLE DAM CONCRETES.

APPENDIX

APPENDIX

Section A

Procedure for Adiabatic Calorimeter Tests

A new improved adiabatic calorimeter was designed to perform these tests. The two basic improvements incorporated in the calorimeter were as follows:

(1) The calorimeter consists of an inner chamber and an outer chamber. The outer chamber is maintained at a controlled difference in temperature below that of the inner chamber in order to dissipate the heat generated by stirring of air in the inner chamber and in order that only a small amount of heat need be added in the inner chamber to maintain the desired temperature.

(2) A row of eight precise fast-response resistance thermometers is mounted across the section and its immediately surrounding insulation, at mid-height of the concrete specimen, so that the temperature in the concrete specimen can be maintained with desired precision. The temperature of the air in the inner chamber is maintained in a manner such that ideally no heat generated by the concrete is absorbed by the specimen container and by the surrounding insulation. In other adiabatic calorimeters additional cement and water are added to the concrete mix to compensate for the heat absorbed by the container and by one-half of the insulation surrounding the specimen. With the improvement noted above, it is unnecessary to add additional cement and water to the concrete mix.

Calorimeter Rooms

Essentially, the calorimeter is a chamber within a chamber as illustrated in Fig. A1. The outer chamber has a concrete slab floor, reinforced concrete walls, and a ceiling which is lined with cork slab, 3 in. thick, coated with aluminum paint. Access is through a double door, the outer half of which is a standard cold-locker door. Six resistance heaters ranged around the walls and a blower in the cold-air vent are alternately energized by an appropriate control circuit to provide the desired temperature.

The inner chamber, which is the calorimeter proper, is shown in Fig. A1. It is essentially a box 4 1/2 ft. square by 7 1/2 ft. high outside.

The walls and ceiling consist of foamed styrene 4 inches thick, faced on both sides with plywood. Access is through a door of the same construction at the front of the box. The interior corners are beveled at 45° by means of foamed styrene covered with plywood inserts in order to streamline the flow of air within the chamber. Two fans, positioned as shown in the illustration, serve to maintain a uniform temperature throughout the box. The fan motors are mounted outside the inner chamber in view of preliminary measurements which showed that their heat output could not be accommodated in the interior. A 600-watt heater cone and a 90-ohm coil fixed to a lower fan provide a controllable heat source for the interior of the inner chamber.

Container for Specimen

The container for the concrete, as shown in Fig. A1, consists of a 27-in. diameter by 30-in. high cylinder made from 24-gage black-iron sheet metal. The side and bottom seams are made with double-lapped joints and are soldered to avoid any leaks. A 1/2-in. flange is provided at the top of the sides so that a lid can be attached by soldering. The lid of the container has five neoprene "0" ring seals, as shown in Fig. A2, so that the resistance thermometers placed within the concrete can be sealed and can be removed from the specimen at the conclusion of the test.

Instrumentation

Resistance thermometers of the Carlson (fast-acting) type are used in all cases to sense temperature. Each thermometer is wound with No. 33 BWG copper wire to give a resistance of 46.00 ohms at 70 F so that a temperature change of 1.00 F produces a change in resistance of 0.10 ohms. The Mueller Bridge (Leeds and Northrup No. 8067) used to measure thermometer resistance yields values reproducible to four decimal places, or a least reading of 0.0001 ohms. It is possible, therefore, to measure temperature to the nearest 0.001 F.

All thermometers to be used in a given test are calibrated simultaneously against the same mercury thermometer over the range 60 F to 100 F using the Mueller Bridge measuring circuit. Subsequent temperature readings are interpreted accordingly.

Inner chamber temperature control for a heating circuit only is accomplished by means of a temperature-difference controller (Leeds and Northrup MICROMAX) driven by an amplified unbalanced bridge signal from a pair of thermometers, one at the center of the concrete specimen under test and the other in the air of the inner chamber. The controlling and heating circuits are shown schematically in Fig. A3. Amplification of the driving signal is achieved by means of a portion of the circuit of the null indicator (Brown ELECTRONIK).

Outer-chamber temperature control is similarly accomplished by a second temperature-difference controller driven directly by the unbalanced bridge signal resulting from the resistance difference between a second pair of thermometers, one each in the inner and in the outer chambers. In this controller no amplifier is used for the galvanometer signal. This controller operates both heating and cooling circuits.

Each controller drives a strip chart which provides a record of the temperature difference between the two controlling thermometers. A third strip chart recorder is used to provide a continuous record of the temperature of the inner chamber and may be used as a qualitative check on the overall operation of the system.

Control

The following variables are subject to direct control:

(a) Power input to inner-chamber heaters.

(b) Temperature difference between inner and outer chambers.

(c) Power input to outer-chamber heaters.

(d) Cool-air supply to outer chamber.

(e) Temperature difference between specimen and inner chamber.

The first four of these variables influences both cycling rates and amplitudes of variation. Conditions are reduced to minimum operating values as soon as possible in the course of each test, in order to minimize the hazards of equipment failure. The last variable, temperature difference, is adjusted from time to time throughout each test to maintain minimum cumulative error.

Operational Procedure

First, all of the resistance thermometers are calibrated. The thermometers and a calibrated mercury thermometer are taped together and placed within a vacuum jar that is stored in the inner chamber of the calorimeter. A mercury regulator which controls the 600-watt heater in the inner chamber is set at 80 F; thereafter thermometer resistances are observed by means of a Mueller Bridge, until equilibrium is reached. The thermometers are left in the room for about 8 hours before the top of the vacuum jar is sealed. Final adjustment is then made by adding a small amount of No. 14 copper wire at the terminal strip within the inner chamber. All thermometers are calibrated to have the same resistance within ±0.0005 ohms so that temperatures can be computed rapidly. Thermometers then are calibrated at 60 F, 100 F, and again at 80 F.

Five thermometers constructed as shown in Fig. A2 are placed through the lid and then into the concrete container, as shown in Fig. A1. The bottoms of the thermometers are held in position by thin wires attached to the container. Particular care is taken during placement and vibration of the concrete to insure that the embedded thermometers are not disturbed or displaced.

Concrete is placed and vibrated into the container, taking care to insure uniform distribution of material. The lid is then soldered on, and the thermometer system is sealed by means of the "0" rings.

The container is tested for leaks. Testing for leaks is important, since any small amount of moisture that escapes may procuce an appreciable cooling effect through evaporation.

Thereafter, the two thermometers at positions 2 and 7, as shown in Fig. 1, are attached to the outside of the container in a manner to insure a good thermal contact. The outer sheet-metal jacket is placed in position. Expanded vermiculite is then placed and is covered with plywood to prevent its being blown out by the upper fan. The two thermometers at positions 1 and 8 are then attached to the outer sheet-metal jacket.

As a rule, temperatures are measured daily with each of the thermometers. During the initial phases of each test, and at times of equipment malfunction, more frequent measurements are made. Control variables are adjusted as necessary after each set of temperature measurements.

The controls for the heating and cooling of the outer chamber are so adjusted that a minimum amount of heat is required to maintain the desired temperature in the inner chamber. The amount of heat required in the inner chamber will depend upon the rate of temperature rise of the specimen; and therefore, the temperature difference between the inner and outer chambers will vary since the rate of temperature rise is not a constant. For any one test the temperature of the outer chamber varies between 3 and 5 degrees Fahrenheit below that of the inner chamber. The amount of heating or cooling of the outer chamber is so controlled that its temperature varies approximately ± 0.02 F from the set temperature, and the cycling rate is approximately 10 minutes.

The controls for the inner chamber consist of 0.01-ohm decades in the thermometer circuit, compensator "S_1" in the bridge circuit, and a variable transformer to adjust the voltage for the 90-ohm heating coil. After the first day of test the amount of heat required in the inner chamber is between 40 and 60 watts which is on only approximately one-half of the time. The temperature of the air in the inner chanber is set in such a manner that there is a minimum temperature gradient across the concrete specimen. The temperature of the air as recorded by the controller varies ± 0.01 F from the set point, and its cycling rate is approximately 2 minutes.

Probable Error

A procedure was devised to determine the error in the observed temperature rise at the center of the specimen for a unknown change of the air temperature in the inner chamber. At the age of 28 days, the air temperature in the inner chamber was raised 1.00 F, a known amount, above that of the center of the specimen. Temperatures were observed daily at all thermometer locations until equilibrium was achieved. It was deemed that equilibrium existed at a time when all thermometers showed the same temperature rise per day. The temperature rise of the specimen was then caused both by the generated adiabatic temperature rise and by the 1.00°F imposed temperature difference. It was assumed that the adiabatic temperature rise per day was constant between ages 28 days and 32 days. By subtracting this daily temperature rise from the actual temperature rise at the center of the specimen, the temperature rise due to the 1.00°F imposed temperature difference was computed. The value determined as temperature rise due to the imposed 1.00 F was found to be 0.26 F per day. Then further, assuming the error in controlling the air temperature in the inner chamber to be ±0.05 F, the consequent error in temperature rise would be 1/20 of 0.26 F, or 0.013 F per day. Thus, the error for 28 days would be 28 x 0.013, or approximately 0.3 F.

In the preliminary design of this calorimeter, it was thought that the air temperature in the inner chamber would need to be maintained at a slightly higher temperature than the concrete temperature in order to obtain a zero temperature gradient within the concrete. This difference was in order that no heat generated by the concrete would be lost in raising the temperature of the container or of the insulation around the specimen. In the six tests performed with this calorimeter, the temperature of the air in the outer chamber was on the average lower than that of the concrete and was roughly inversely proportional to the rate of temperature rise of the concrete. This relationship could be due to the heat generated by the additional paste that is concentrated near the edge of the specimen because of the boundary effect of the container. This effect would increase with the maximum size of aggregate used in the concrete mix.

For the test in which the air in the inner chamber was maintained at a temperature of +1.00 F above that of the center of the specimen, the temperature gradient between the center of the specimen and thermometer locations 3 and 6 (for location see Fig A1) was +0.10 F. Therefore, an average temperature gradient of 0.01 F at thermometer locations 3 and 6 would produce an error in the actual total adiabatic temperature rise for a period of 28 days of (0.10) (0.26) (28) = 0.7 F. Previous tests had shown that a gradient of 0.10 F at this distance (10 1/2 in.) from the center produced an error of 0.26 F per day at the center of the specimen. Taking into consideration the plus and minus values, a more probable value for the error in adiabatic temperature rise for the whole period of 28 days would be 0.4 F.

APPENDIX

Section B

Procedures and Apparatus for Tests of Thermal Properties of Mass Concretes During Adiabatic Curing

Specific Heat of Concrete

The specimens for the determination of specific heat of concrete were cast in 8 1/2 by 16-inch tin-plate cylindrical molds having an axial copper tube, 16 inches long and of inside diameter 1 1/2 inches, soldered through a hole in the bottom. After vibration, the friction lid with a central hole for the copper tube was affixed and was temporarily sealed with tape. The specimen was then placed in a room the temperature of which was controlled to follow the previously determined adiabatic time-temperature curve for the particular mix. After one day, the central copper tube was soldered to the lid and the lid was soldered to the can to provide a completely sealed specimen.

The calorimeter in which the specific-heat tests were performed consisted of an inner and an outer chamber (see Fig. B-1).The outer chamber was of double-wall construction having 3 1/2 inches of mineral wool as insulation. The inner chamber, centrally positioned inside the outer chamber, consisted of two galvanized-iron cans separated from one another by a 1-inch dead air space.

About 1 hour prior to commencing the test, the specimen was removed from adiabatic curing and was placed centrally in the inner of the two concentric galvanized-iron containers. Sufficient water at specimen temperature was poured in to submerge the specimen completely, and the weight of water was recorded. A heater-stirrer assembly was then inserted in the hollow central portion of the specimen. The lids of the two concentric cans were positioned. The stirrer shaft, then projecting above the cover of the outer chamber, was belted to a motor which caused the stirrer to propel the water down the central passage in the specimen to maintain uniform temperature distribution.

An electric heater, pans of ice, and a fan in the annular space between the inner and outer chambers were used to maintain adiabatic conditions between the inner and outer chambers.

The temperature of the water was read by means of a thermopile consisting of four thermocouples placed in the water at the specimen mid-height and spaced equally around the periphery. Four thermocouples similarly spaced around the outer of the two concentric cans formed a thermopile from which the temperature could be determined at this surface. The cold junctions for these thermopiles were maintained in a Dewar flask at 32°F (see Fig. B-2).

By means of suitable switching, the output of either the inner or the outer thermopile could be read on a precision potentiometer. Additionally, these thermopiles could be connected in series-opposition so that during the test the temperature gradient existing between the specimen and the air in outer annular space could be observed and be maintained at zero.

After approximately 1 hour for equilibrium to be assured, the heater in the hollow central part of the specimen was energized and the power supplied was indicated by means of sensitive watt-hour meter. As the water temperature rose, the heat input to the air surrounding the concentric cans was proportionally increased so that no temperature difference would exist between the water and the air. After 2 1/2 hours, the current to the water heater was shut off; and the test was completed when the water temperature stabilized. At this time the specimen and the water had come to the same temperature and the specimen temperature was obtained by reading the thermopile in the water.

The difference between the initial and final watt-hour meter reading gave the electrical energy supplied during the test period. The weights of the inner can and lid, the mold, the center tube, and the heater-stirrer assembly multiplied by the appropriate values of specific heat, added to the weight of water used multiplied by its specific heat of one, gave the water equivalent of materials other than the specimen. This value, multiplied by the temperature rise, gave the heat storage. When the heat storage was subtracted from the net energy supplied to the system, the quantity of heat in BTU's absorbed by the concrete was obtained. This value divided by the product of the specimen weight and the temperature rise gave the specific heat of the concrete.

Specific Heat of Aggregate

The procedure for the determination of specific heat of aggregate was similar to the one used for concrete but with the following exceptions. A disc of bronze fly-screen was supported about 1 inch above the bottom of the inner can to provide a reservoir for better circulation of water when the weighed charge of aggregate was placed directly into the can around the central copper tube. Since there was no annular space existing between the inner can wall and the specimen as in the case of the concrete specimens, the thermocouples were contained in a glass tube midway between the top and bottom surfaces of the aggregate mass.

For the sand, a mold similar to those used to cast concrete specimens and complete with the central copper tube was filled with a weighed amount of sand. This test was run without the mold lid, in the same manner as that used for the concrete specimens.

Thermal Diffusivity of Concrete

Concrete specimens were cast in 8 1/2 by 16-inch tin-plate cans. A brass rod over which rubber tubing had been slipped was axially positioned and terminated at the center of the specimen. After the concrete had been vibrated, the can lid, having a central hole for a #6 1/2 rubber stopper, was placed on the can and sealed with tape. The rubber stopper, through which the brass rod extended, sealed the hole in the lid.

The specimen was then subjected to adiabatic curing. After 1 day the lid was soldered to the can. The brass rod was then withdrawn, leaving a central hole of diameter approximately 3/8 inch. The hole in the lid was closed with a solid rubber stopper, and thus a completely sealed specimen was obtained.

The diffusivity apparatus made use of the outer chamber described for the specific heat test. In addition, provision was made by means of an external heat exchanger, circulating pump, and valves to provide a temperature-controlled well-circulating water bath (see Fig. B-3). An immersion heater with a variable transformer balanced the cooling effect from the heat exchanger to provide $\pm$ 0.1°F temperature control.

About 1 hour prior to the diffusivity determination, the rubber stopper was replaced with one through which a long-stemmed thermometer, reading to 0.2°F, projected its bulb to the center of the specimen. Mercury was used to fill the annular space between the concrete and the thermometer to provide good thermal coupling.

At the start of the test the specimen temperature was read by means of the thermometer, and the specimen was submerged in the water bath controlled at 40°F. Readings of specimen temperature were taken at 5-minute intervals until the temperature had dropped to about 1°F above the bath temperature.

Reduction of the data consisted in calculating, for the various time intervals, the ratio of temperature difference existing between the specimen and the bath to the initial temperature difference. Entering Table 12, U. S. Bureau of Reclamation Boulder Canyon Project Final Reports, Bulletin 1, entitled "Thermal Properties of Concrete", with these values of the part of original temperature difference remaining gave a value for h^2t/D^2. Knowing the elapsed time t in hours and the specimen diameter D in feet, the equation could be solved for the thermal diffusivity h^2. The average of the last 5 diffusivity values (sometimes 4, 6, or 7) where equilibrium was obtained and where the part of the original temperature remaining had declined to the smalled value was reported.

To determine the effect of the tin-plate mold upon thermal diffusivity, a brass collar was glued to the top of the concrete specimen with epoxy resin cement. The rubber stopper carrying the thermometer was seated in this collar, the mold was stripped off, and the test was run as previously described.

Thermal Coefficient of Expansion

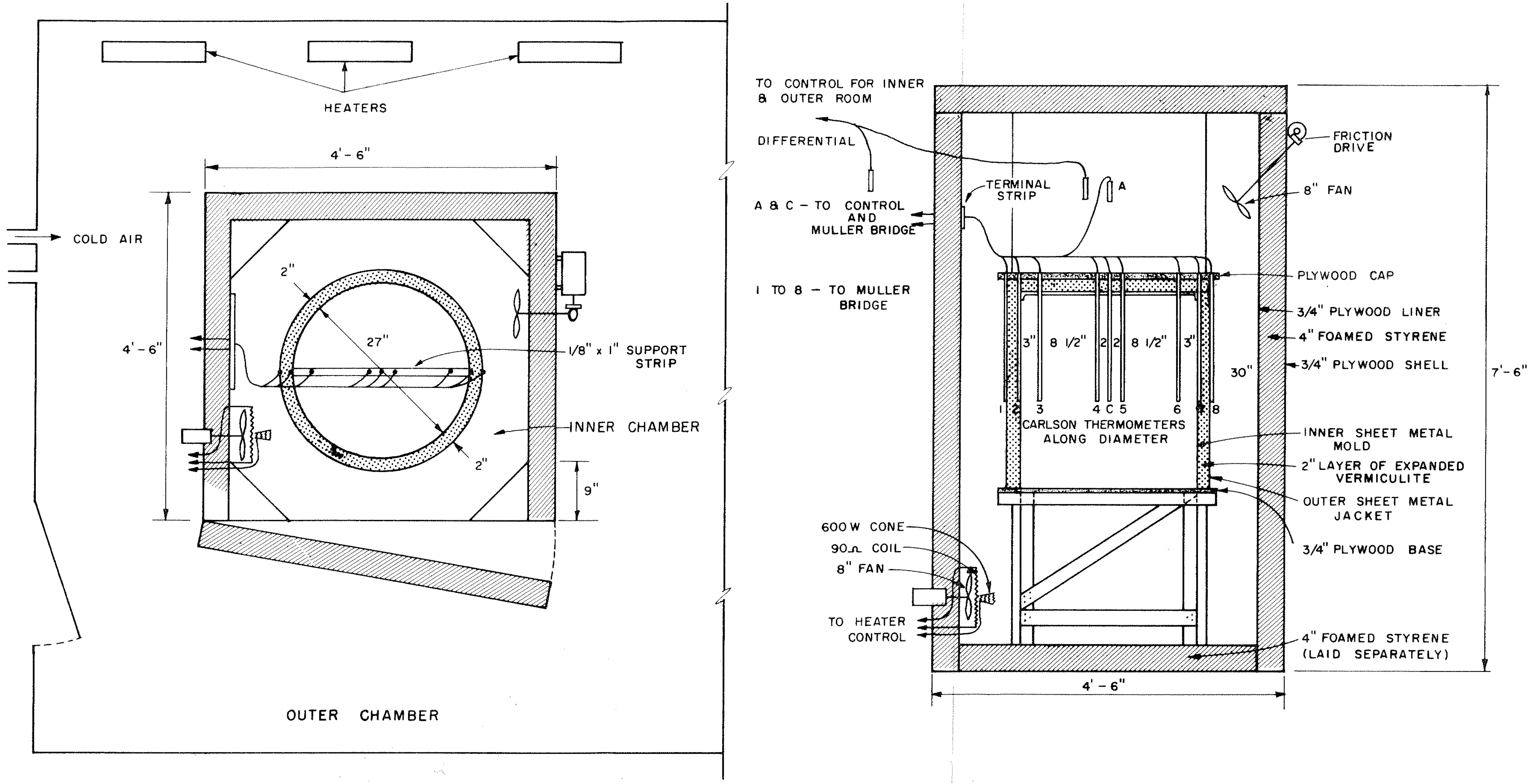
Concrete specimens were cast in 8 1/2 by 16-inch tin-plate cans with slip covers like those used for the specific-heat and the diffusivity specimens. Prior to casting, a 10-inch slim-style Carlson strain meter was positioned midway along the axis of the mold with the lead wire brought out through the can bottom through a watertight fitting. After concrete placement and vibration, the cover was put on and sealed with tape, and adiabatic curing was started. After 1 day, the tape was removed and the can lid was soldered in place.

The three thermal-coefficient specimens for the 3 1/2-scy cement blend mix were cured along Curve C for three days and subjected to thermal cycling between 71 and 50°F air temperature. When equilibrium had been reached at each temperature as indicated by the embedded Carlson meter, the gross thermally induced strains were read. The net concrete strain per °F was then calculated by correcting for the thermal strain of the meter itself.

The specimens were returned to storage at 71°F until the next age at which thermal data were to be taken. They were then subjected to the same thermal cycling except that the temperature range for the 30-day observations was from 50 to 90°F.

Four specimens of the 2-scy mix were cast and cured along Curve A. At 3 days one specimen was cycled in water baths between 40 and 90°F. At 7 days a new specimen was cycled together with the 3-day specimen. This procedure was repeated at ages of 14 and 28 days, with storage at the adiabatic temperature when the specimens were not undergoing temperature cycling.

FIGURES



PLAN VIEW

VERTICAL SECTION OF INNER CHAMBER

FIG. A-1 — ADIABATIC CALORIMETER

FIG. A-1
ADIABATIC
CALORIMETER

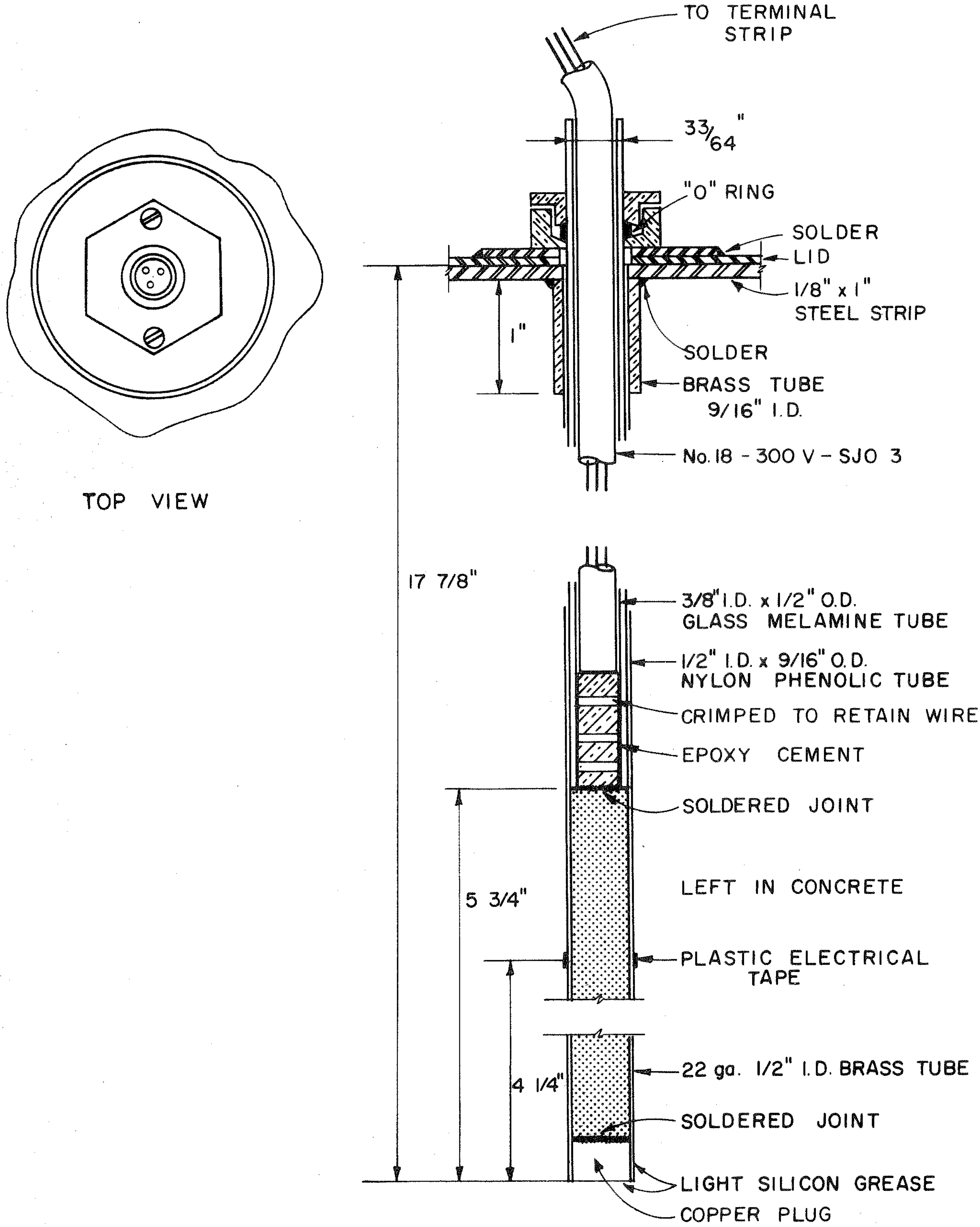


FIG. A-2—THERMOMETER INSTALLATION DETAILS.

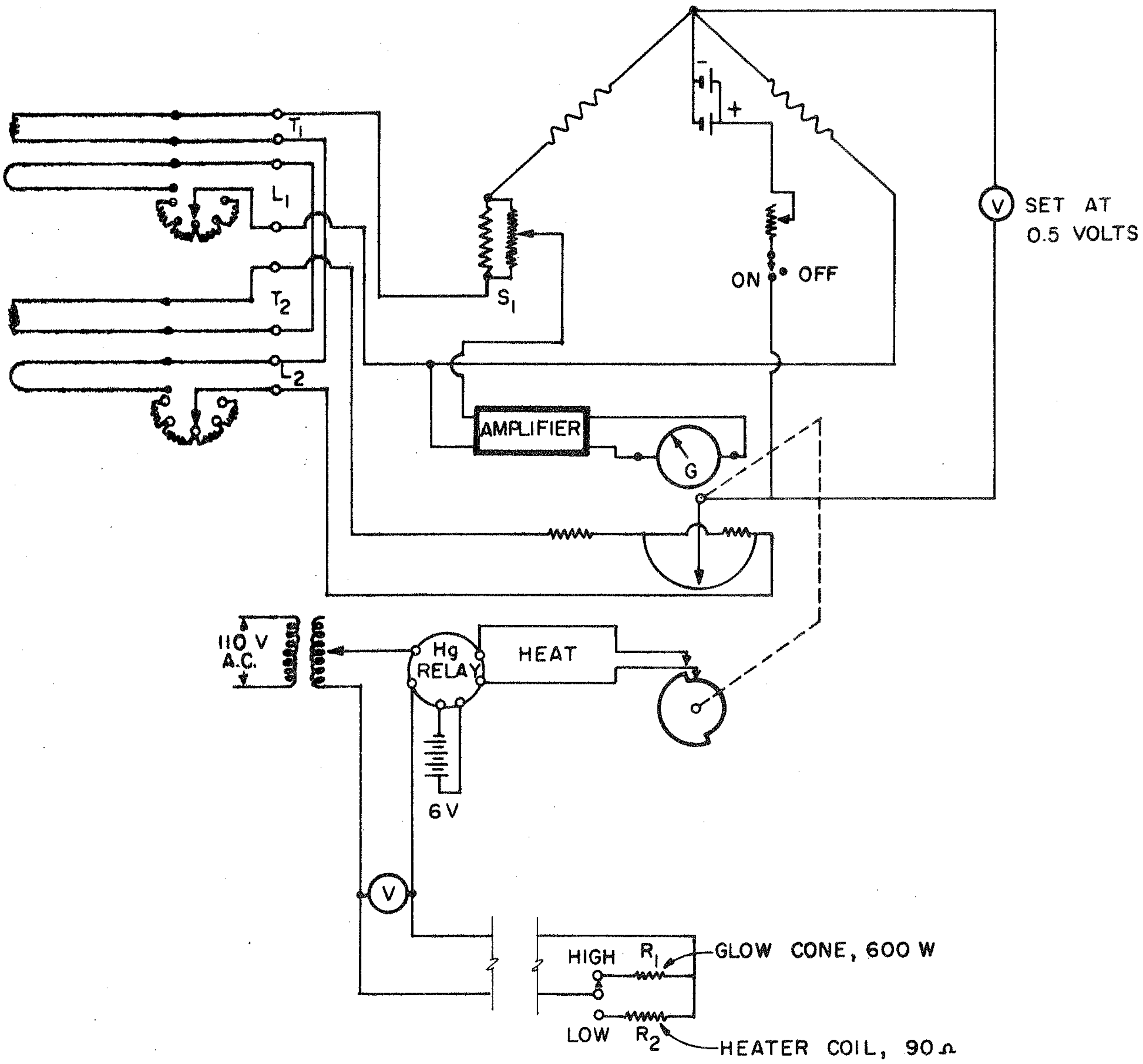
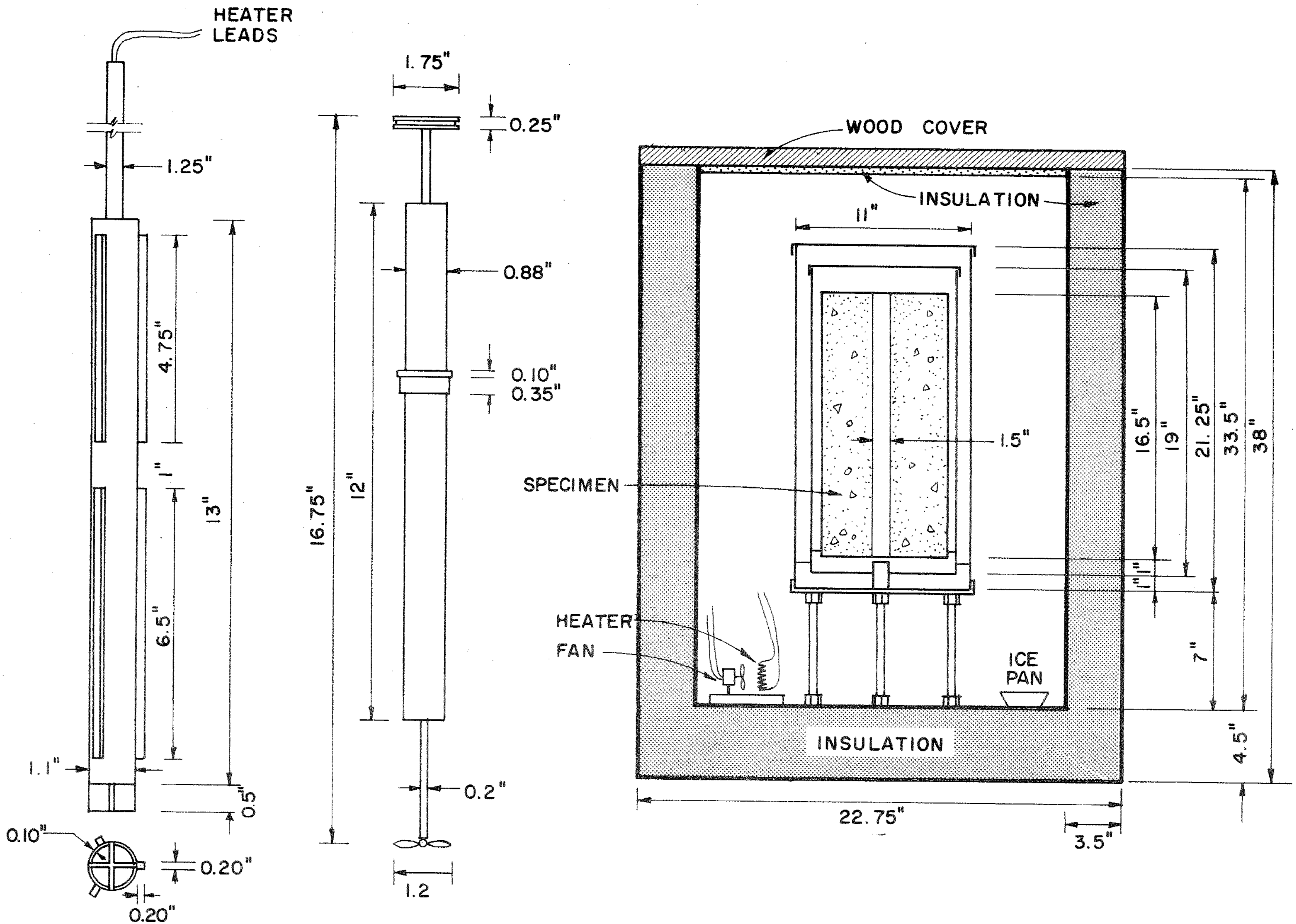


FIG. A-3 – CONTROL AND HEATING CIRCUIT



IMMERSION HEATER

STIRRER

FIG. B-1 – CALORIMETER AND HEATER-STIRRER ASSEMBLY FOR DETERMINING SPECIFIC HEAT OF CONCRETE.

FIG. B-1

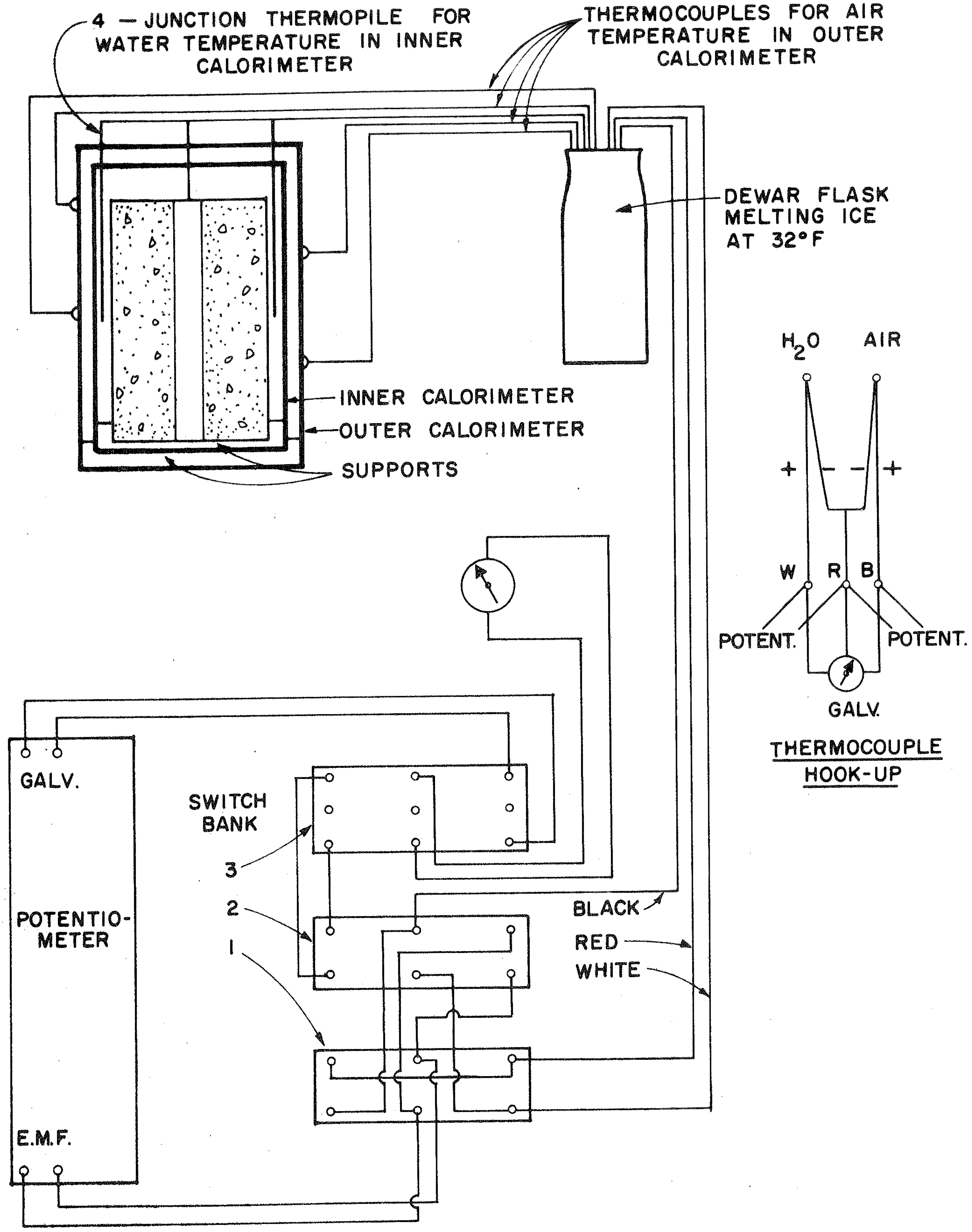


FIG. B-2 — THERMOCOUPLE ARRANGEMENT FOR DETERMINING SPECIFIC HEAT OF CONCRETE.

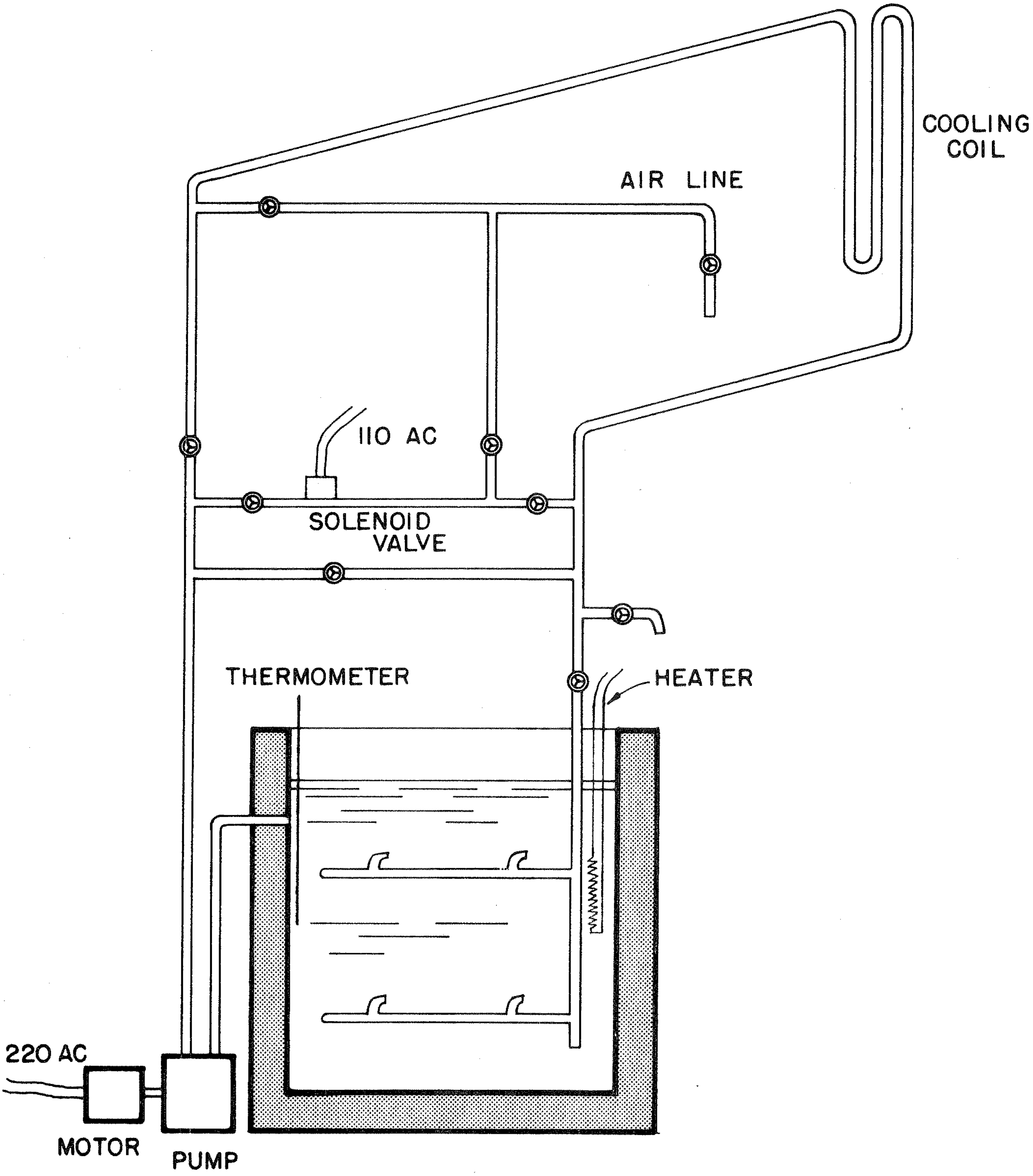


FIG. B-3 – CONTROLLED TEMPERATURE BATH USED IN THE DETERMINATION OF THERMAL DIFFUSIVITY OF CONCRETE.