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Synopsis

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Concrete pavements and structures subject to severe winter conditions at high elevations in California are being constructed with aggregates which, while meeting the criteria established for performance in the Powers test, probably would not be considered acceptable under ASTM freeze-thaw methods. To date none of the concrete has been exposed to severe weather sufficiently long to justify conclusions as to the validity of the test method and the criteria that have been adopted for acceptance of aggregates.

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PRELIMINARY REPORT
NOT FOR PUBLICATION

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By
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Tests for Freeze-Thaw Durability of Concrete Aggregates

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Sacramento, California

SNYOPSIS

Tests of aggregates in air-entrained concrete have been made by methods suggested by T. C. Powers for freeze-thaw durability. The procedure differs from that of current ASTM methods in important respects. This report describes the apparatus and methods used in testing and presents results of selected aggregates.

Concrete pavements and structures subject to severe winter conditions at high elevations in California are being constructed with aggregates which, while meeting the criteria established for performance in the Powers test, probably would not be considered acceptable under ASTM freeze-thaw methods. To date none of the concrete has been exposed to severe weather sufficiently long to justify conclusions as to the validity of the test method and the criteria that have been adopted for acceptance of aggregates.

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TESTS FOR FREEZE-THAW DURABILITY OF CONCRETE AGGREGATES

This report is intended to outline and discuss results obtained in tests to evaluate the frost resistance of aggregates when incorporated in air-entrained concrete. The concept of the test procedure was provided by T. C. Powers[1][2]. As far as known, the preparation of specifications for the application of these concepts to the purchase of aggregates has not previously been undertaken.

California, although advertized as a region of mild sunny climate, contains the Sierra Nevada range of mountains extending roughly parallel to its eastern boundary for possibly two-thirds of its length. In addition, the Siskiyou Mountains occupy a substantial part of the northern part of the State. Severe winter weather prevails in the passes of these mountain ranges through which roads are constructed. In the past the State has constructed a moderate mileage of concrete highways through such passes with good to poor success with respect to durability. These pavements were constructed before the advent of air-entrainment and their behavior does not yield much information on the performance that could be expected from air-entrained concrete.

In California, Most of the concrete pavements in the State have been constructed at relatively low elevations where freezing weather

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is of rare occurrence. Until recently, the Division of Highways has had little occasion to study the ability of available aggregates to produce frost resistant air-entrained concrete.

One of the Interstate routes, present U.S. No. 40, extends in a generally north and east direction from San Francisco to a point on the eastern border of California near Reno, Nevada. The summit of this road reaches an elevation of 7135 feet at Donner Pass and then drops to an elevation of 5000 feet at the Nevada state line. Precipitation is heavy on the western approach to the summit. The annual snowfall on the road is among the heaviest in the U.S. Temperatures as low as -25°F are not uncommon near the Nevada state line.

A decision to use portland cement concrete on this route over a distance of about 70 miles from the town of Colfax at an elevation of 2500 feet to the state line, necessitated an extensive investigation of aggregates available for concrete.

Since the Division of Highways laboratory was not equipped with apparatus for conducting freezing and thawing tests of concrete, the first step was to reach a decision on the types of tests to be made.

Mr. Powers' paper "Basic Considerations Pertaining to Freezing and Thawing Tests"(1), was studied carefully and was believed to contain a number of proposals of distinct merit. Mr. Powers subsequently spent several days in our laboratory discussing the recommendations in detail and suggesting means by which they could be carried out. A great deal of supplemental theory and test data is given in Mr. Powers' paper "The Physical

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work however, was too great to be considered economical if other, more accessible sources could be shown to be satisfactory.

In order to obtain an aggregate of known poor service history, a sample of limestone from the Rapid formation in Iowa was obtained through the courtesy ~~of Mr. Bert Meyers~~. This material was received as crushed fragments ranging in size from 1-1/2-inch to No. 4. It was combined with the sand from the American River in making concrete for test purposes. Since the material was received in a dry condition it was pre-conditioned before mixing by (a) soaking in water, and (b) vacuum saturation. Tests were made of both air-entrained and non-air-entrained concrete. Figure 10 is a representation of the results obtained in a single cycle of the Powers procedure performed without drying the test specimens. It will be noted that with vacuum saturated aggregate in non-air-entrained concrete, the concrete dilated excessively (off the recorder chart) almost immediately after it reached the presumed freezing point, about 31°F. Water soaked aggregate in non-air-entrained concrete (not shown on the chart) behaved similarly, but the dilation was not so great or so rapid. In air-entrained concrete simple soaking did not produce noticeable dilation. When the aggregate was vacuum saturated however, the air-entrained specimens ceased shrinking at about 31°F. They dilated slightly down to about 14°F and then resumed their normal rate of shrinkage. Expansion relative to the length at 31°F was not great, nevertheless they must be considered to have dilated considerably because with normal shrinkage, the

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length at 14°F should have been some 200 millionths less than actually occurred.

The Iowa limestone thus has provided an example of the type of test result to be expected from an aggregate of known poor service record in highway pavements. In addition, the tests have demonstrated the importance of the degree of saturation at the time the concrete is mixed. The results make it evident that simple soaking of a dry aggregate does not definitely bring it to the ultimate saturation it may have in service and which is necessary in testing to disclose it potentiality for poor performance.

One of the unanswered questions raised by Mr. Powers was concerned with the effect on absorption rate of the concrete produced by simple soaking as compared to freezing and thawing cycles introduced into the procedure during the soaking period. Since data were not available to provide a satisfactory answer to this question, our tests have been conducted by both methods.

As a guide to the number of cycles that would be appropriate in the testing program, temperature records of the experimental test slab at Donner Summit were consulted. Data for the winter of 1956-7 are given in Table II. The freezing point of water in the concrete is somewhat less than 32°F. It was concluded that a freeze-thaw cycle occurred each time the temperature dropped below 23°F and rose above 28°F. The data indicate that an estimate of 50 cycles per year would be amply severe for testing purposes. The great majority of such cycles

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The schedule of drying adopted for these tests was intended to simulate that of pavements constructed in the locality under consideration during the summer or early fall. The tests have shown that drying is of major importance in improving durability. The degree of drying to which the specimens were subjected can be considered to be moderate. Nevertheless the possibility remains of pavement construction so late in the fall that a lesser degree of drying would be afforded before the onset of severe weather. For this reason, it is believed that additional tests should be made with a critical aggregate in which the degree of drying is varied by steps starting with a very small amount which might be that obtained by exposure to room conditions for 8 hours and subsequent conditioning to equilibrium conditions at about 95 percent relative humidity. If it should prove that a practical degree of immunity could be obtained by very minor drying, the evaluation of site conditions by means of test slabs as discussed in this report might be unnecessary.

In the tests which have been discussed in this report, specimens after drying have been immersed at once in water-saturated kerosene for determination of the Powers cooling curve. Considerable concern has been felt as to the possible absorption of kerosene by the partially water-saturated specimens. A few auxiliary tests have indicated the probability that some kerosene has been absorbed. It may be argued that a minor amount of absorbed kerosene would not significantly affect performance

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Test Condition	Dilation Millionths
Not dried, subsequent simple soaking	38
Dried, then simple soaking	7
Dried, then soaked with freeze-thaw cycles	11

Work planned for the future includes tests made on more vulnerable concrete with simple soaking at room temperature, with soaking and freeze-thaw cycles and with cycles involving temperature changes in water above the freezing point (for example, between 40° and 80°F).

Prior to award of contracts for paving on the route of U.S. 40 at high elevations, a number of prospective aggregate sources were tested by both the ASTM method of rapid freezing and thawing in water and by the Powers method. Originally it was hoped that sources could be found which would be durable in laboratory tests performed upon concrete which was not allowed to dry prior to starting freeze-thaw cycles.

A series of ASTM rapid freezing and thawing tests performed upon 4 x 5 x 18-inch prisms yielded durability factors as follows as measured by drop in dynamic E.

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The remaining aggregates in concrete that were given preliminary drying showed good durability but when no drying was permitted, failed rapidly. It is estimated that an expansion of 0.08 percent is equivalent approximately to a reduction in dynamic E of 40 percent.(3)

At this point, it became certain that unless recognition was given in testing to the probable drying of pavement concrete between the time of construction and the onset of winter, the probability of locating acceptable sources of local aggregates was remote.

At this time operating difficulties had developed in the ASTM freezing and thawing equipment and it was necessary to prepare specifications for contract use. The specifications were based entirely upon results obtained in the Powers procedure and were similar to those shown in Appendix I. The nature of the revisions made in the original test method will be discussed later. Attention is called to the following statement in the test requirements.

> "If during any round of Procedure A (Powers) the plotted temperature-elongation curve indicates an elongation in excess of 50 millionths inch per inch during cooling in the range of 32°F to 25°F., the specimen shall be reported to have failed; otherwise the specimen shall be reported to have passed."

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by Powers in his question (b). The other end point suggested was the occurrence of permanent dilation after thawing. The measurement of such an end point introduces complications in routine work, in that the temperature must be raised slowly or held constant for some time at about 40°F. This procedure would require doubling the equipment or halving the capacity of existing equipment. The need for completing a large number of tests in our laboratory has prevented completion of the return cycle on a routine basis. However such a test has been performed on a few specimens and typical results are illustrated in Figure 16. It will be noted that there is no indication of permanent elongation after thawing even though dilations up to 50 millionths were recorded during freezing. These results are indications that the adopted criterion of failure, dilation in excess of 50 millionths during freezing, is amply severe.

Figures 17, 18 and 19 show the measured changes in water content (changes in weight) or length that took place during the testing of samples of aggregate from three sources. Aggregate No. 2 is from a source of known good service performance. Aggregate No. 7 is from an undeveloped pit site. Aggregate No. 8 is from a recently developed commercial pit which was used to supply a recently completed paving project consisting of about 5 miles of 4-lane highway. Test results for these three aggregates have been selected for presentation in this report because they represent the range of results that have been obtained in our work to date. In each case the

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results plotted are the averages of six specimens.

Figure 17 shows the changes in moisture content of the cured concrete during the adopted drying procedure and subsequently during 10 weeks of soaking with intervening cycles of freezing and thawing. It will be noted that during the soaking-freeze-thaw procedure none of the specimens regained completely the amount of water it contained at the end of the 14-day moist curing period.

In Figure 18 overall changes in length, measured at a constant temperature, are shown. The upper graph, representing concrete that had no opportunity to dry at any stage, shows that specimens containing aggregate No. 7 expanded consistently upon exposure to soaking and cycles of freezing and thawing. After 6 weeks of soaking and 30 cycles of freezing and thawing the elongation reached 0.08 percent (800 millionths) a value that is indicative of severe distress(3). After the concrete containing aggregate No. 7 was subjected to drying, subsequent soaking and freeze-thaw cycles produced moderate expansion, but at no time did the length reach that measured at the conclusion of moist curing.

Aggregates 7 and 8, as shown in Figure 18, did not increase beyond the as-cured length although permitted no opportunity to dry. When the concrete was dried, subsequent soaking and freeze-thaw cycles produced only moderate changes in length and at the end of 10 weeks the length was virtually the same as in the as-dried condition. The small amount of drying shrinkage exhibited by aggregate No. 2 compared to

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that produced by aggregates 7 and 8 is noteworthy. It is not believed that an error was made in measuring or recording length changes because each of six individual specimens showed the same trend.

Figure 19 shows the measured dilation during a single freeze at various stages of the test. Concrete containing aggregate No. 7 dilated in excess of 50 millionths at the end of 2 weeks of soaking with 10 cycles of freezing and thawing. At later periods, the dilation tended to increase. These "single-shot" dilation tests are in agreement with the overall change in length as shown in Figure 18. Both aggregates 2 and 8 produced only minor dilation at any stage either with or without drying, a finding that is in agreement with the results shown in Figure 18.

The lower graph of Figure 19 shows the dilation produced by 10 weeks of simple soaking at room temperature after the specimens had previously been dried. The dilation is somewhat less than that produced when freeze-thaw cycles are introduced into the soaking procedure.

Figure 20 illustrates the appearance of two cylinders made from the same batch of concrete. Photographs were taken at the conclusion of 10 weeks of soaking with freezing and thawing cycles. The specimen on the right was afforded no opportunity to dry. Aside from the pop-outs readily visible, it contains a crack in the lower right portion. The specimen on the left was subjected to the standard drying procedure and shows virtually no evidence of distress.

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during freezing since the liquid kerosene should develop hydraulic pressure similar to that of unfrozen portions of water. Data have been presented to show that, regardless of the possible presence of absorbed kerosene, the overall effect of water soaking with intervening freeze-thaw cycles was slightly more severe than simple soaking in water for 10 weeks.

Although there appears to be little probability that contact of partially dried specimens with kerosene has reduced the severity of the test, it also appears that there is no necessity of subjecting dried specimens to kerosene until they have had at least two weeks of soaking in water. If the concrete should exhibit excessive dilation after two weeks of soaking, there is little likelihood that one would consider the aggregates acceptable regardless of indicated immunity immediately following the drying.

The test method as revised and as given in the Appendix provides for two weeks of simple soaking in water before immersing the specimens in kerosene for the measurement of dilation by the Powers procedure. This means a reduction from 50 to 40 in the number of cycles of freezing and thawing obtained during the 10-week soaking period. At present no data are available to indicate the effect of this modification.

Sweeping conclusions based upon the data included in this report are not considered to be warranted at this time, primarily because of the lack of service history with many of the aggregates involved. Nevertheless it is felt that the

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results strongly support the beneficial effects of moderate drying of cured concrete with respect to freeze-thaw durability.

ACKNOWLEDGMENT

The work described in this report was performed under the general direction of F. N. Hveem, Materials and Research Engineer. Special credit is due D. L. Spellman, Associate Materials and Research Engineer and D. R. Smith, Assistant Physical Testing Engineer, for their capable development and execution of the tests.

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2. "The Physical Structure and Engineering Properties of Concrete"
   By T. C. Powers,
   Bulletin 90, Research and Development Laboratories, Portland Cement Association, Chicago, Illinois.

3. "Effect of Entrained Air in Strength and Durability of Concrete made with Various Maximum Sizes of Aggregate"
   By Paul Kleiger,
   Proceedings, Highway Research Board, Vol. 31, p. 177-201, Table 15 (1952)

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TABLE I

Relative Humidity within Test Slabs at Start of Severe Winter Weather

Date	Depth Below Surface of Slab, Inch.	Relative Humidity, Percent
	Donner Pass - First Year, 1956	
Nov. 7, 1956	1	83
	2	85
	3	90
	5	98
	7	89
	9 (in subgrade)	82
Nov. 20, 1956	Slab temperature below 32°F. Readings not reliable	
	Yuba Gap - First Year, 1957	
Nov. 22, 1957	3/4	76
	1-1/2	89
	3	74
	5	94
	7	98
	8-1/2 (in subgrade)	89
Dec. 12, 1957	Slab temperature below 32°F. Readings not reliable	

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TABLE II

Summary of Temperature Changes Within Test Slabs

Values shown are number of cycles completed during winter between temperature ranges shown

Temperature Range	Depth of Thermocouple below Surface		
	1/4-inch	4 Inches	8 Inches
Donner Summit, Winter of 1956-7			
Below 28°F Above 33°F	74	41	4
Below 23°F Above 28°F	55	12	5
Below 18°F Above 23°F	30	6	1
Yuba Gap, Winter of 1957-8			
Below 28°F Above 33°F	49	17	0
Below 23°F Above 28°F	23	2	0
Below 18°F Above 23°F	13	0	0

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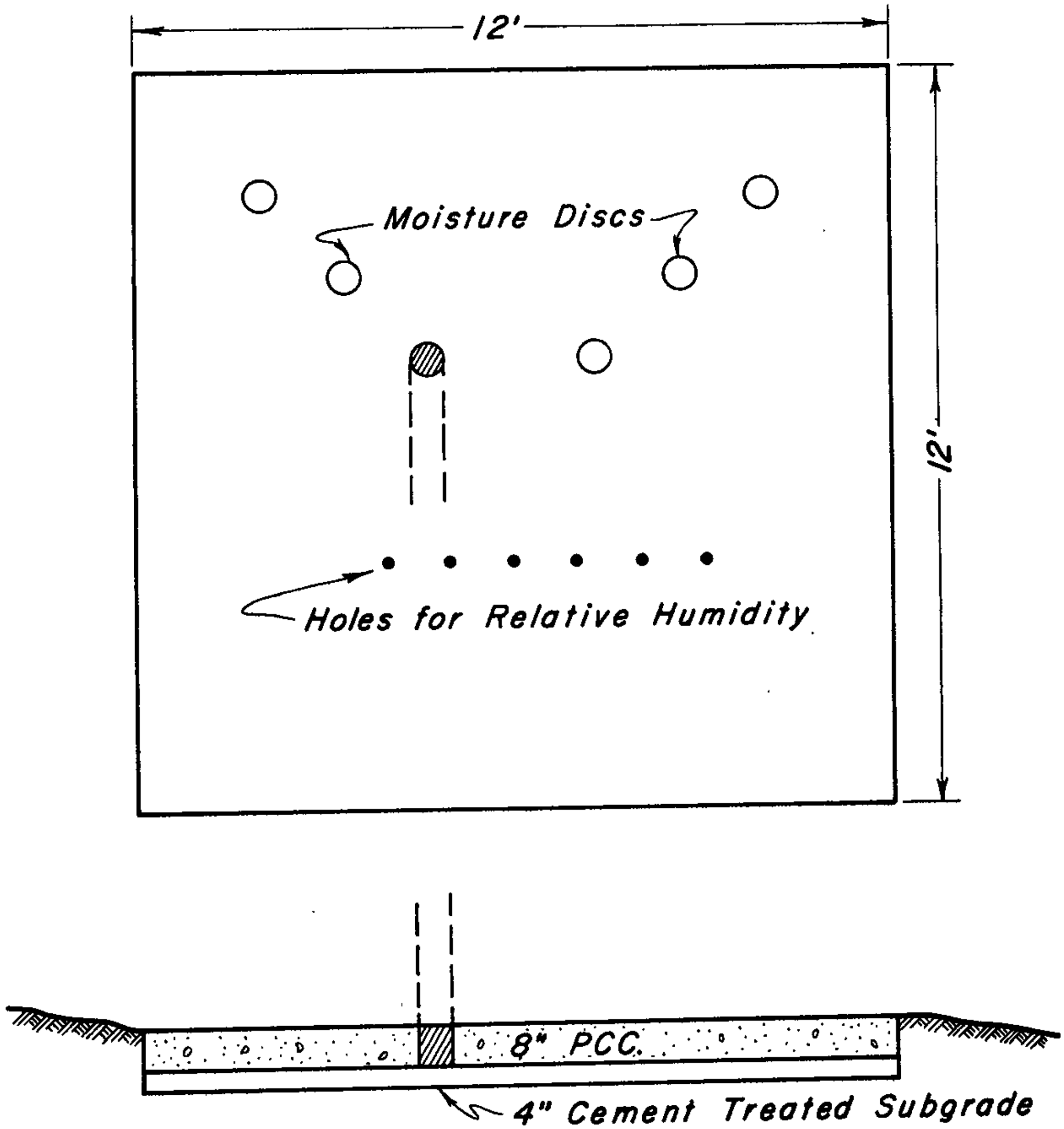

FIGURE 1. TYPICAL TEST SLAB FOR MOISTURE MEASUREMENT

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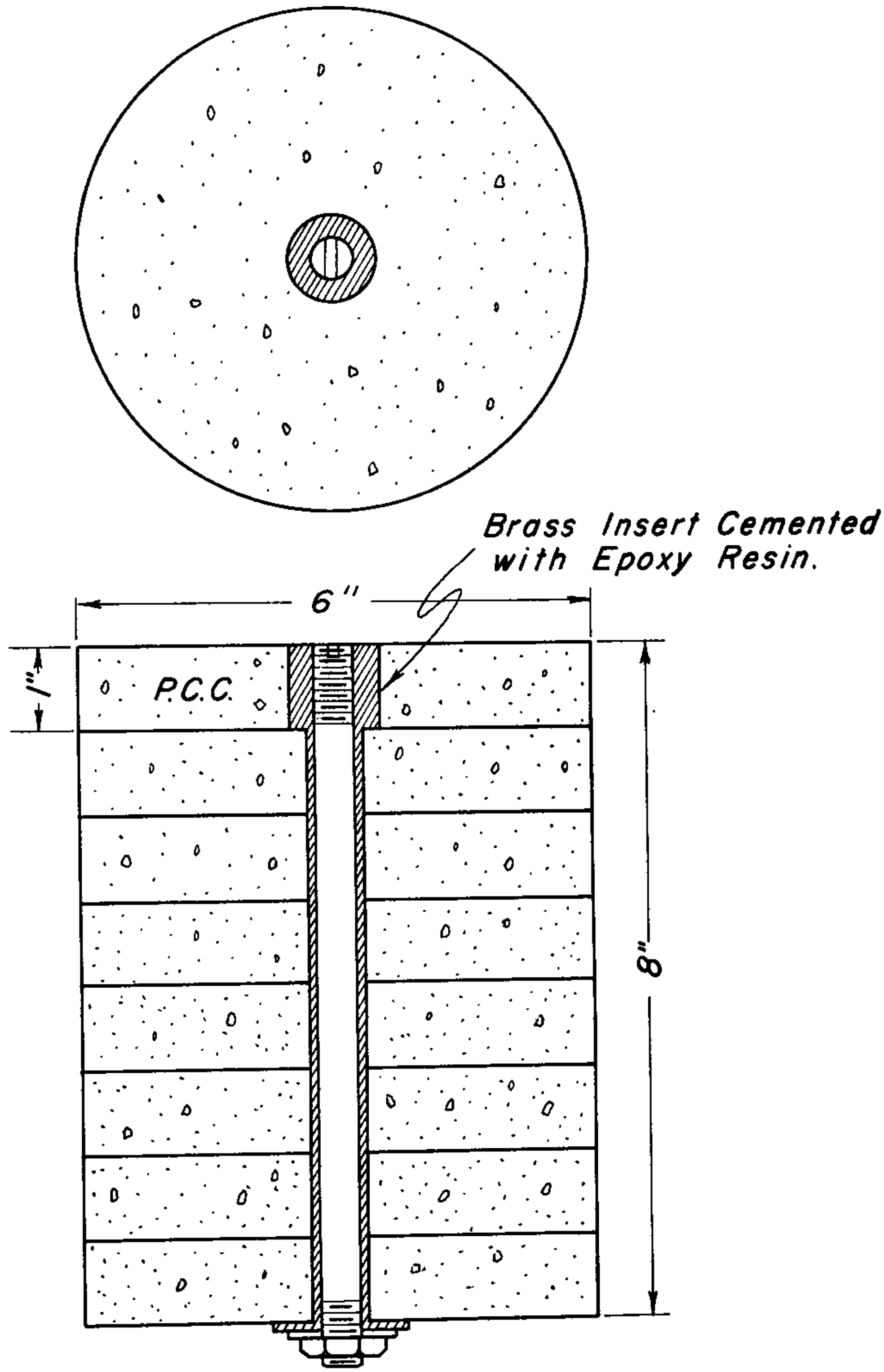

FIGURE 2. ASSEMBLY OF MOISTURE DISCS

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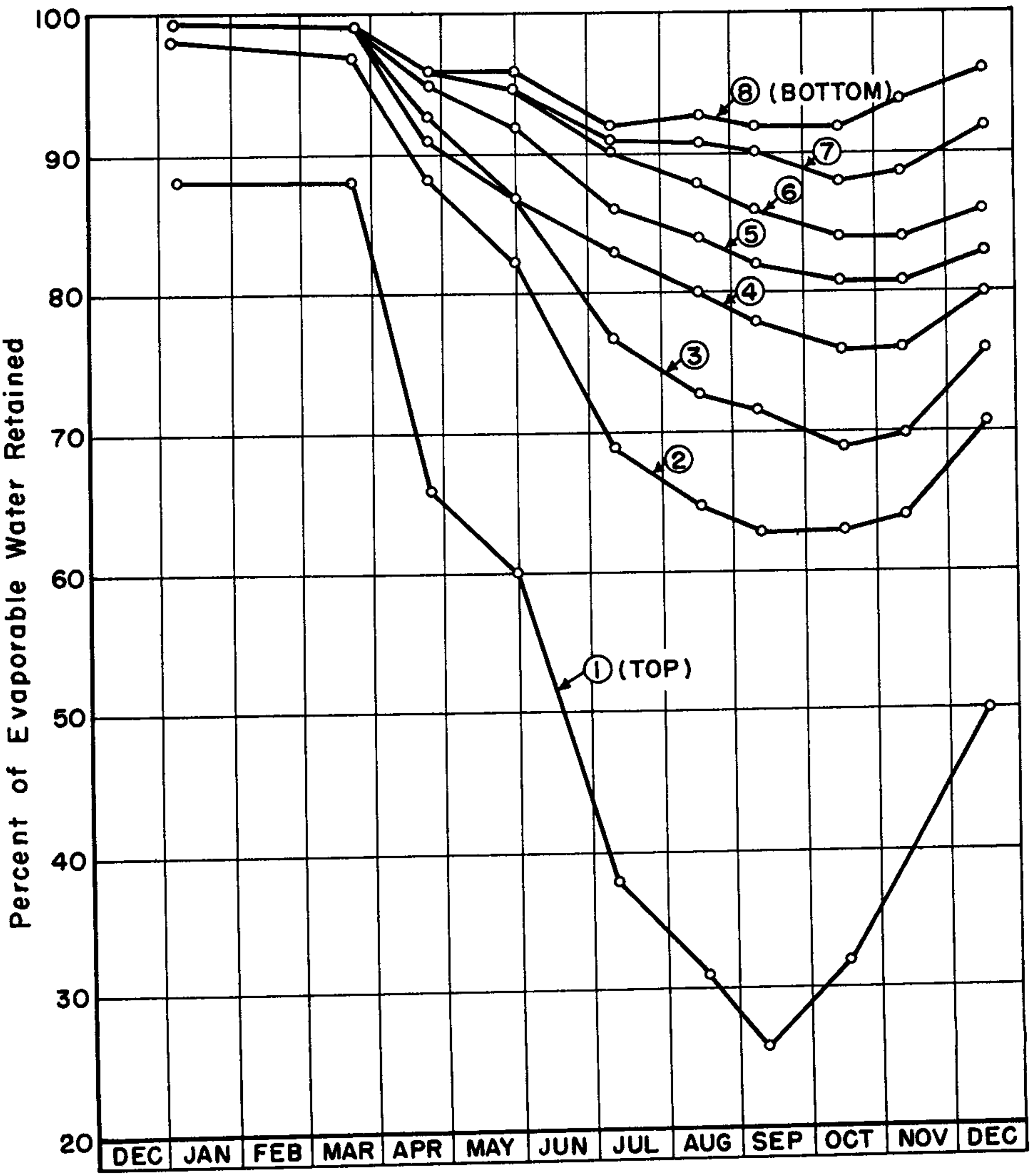

3' - 8" x 5' - 6" x 8"

FIGURE 3. TEST SLABS AT SACRAMENTO

Placed Nov., 1953

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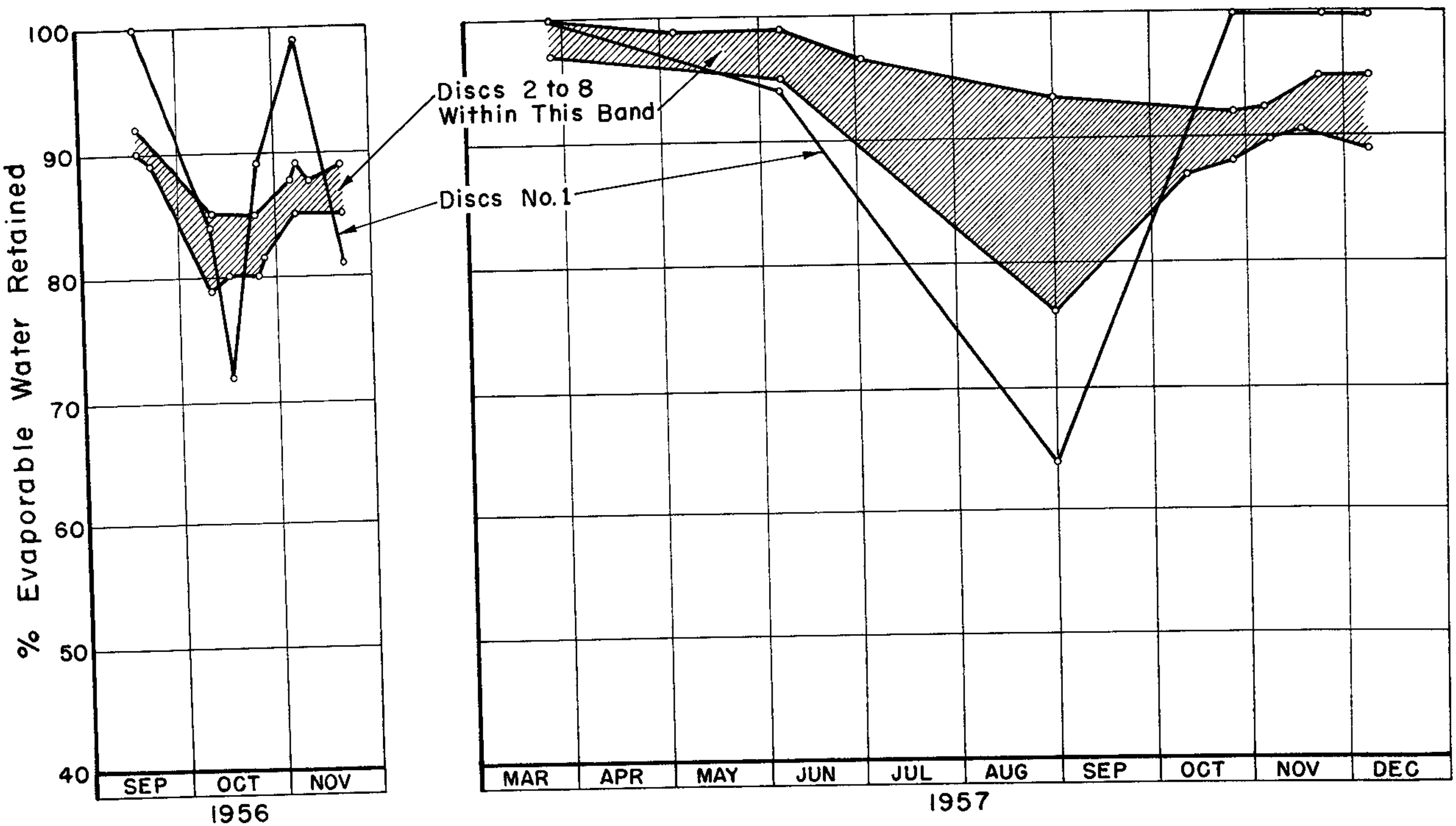

FIGURE 4. TEST SLAB AT DONNER SUMMIT

Placed Aug 9, 1956

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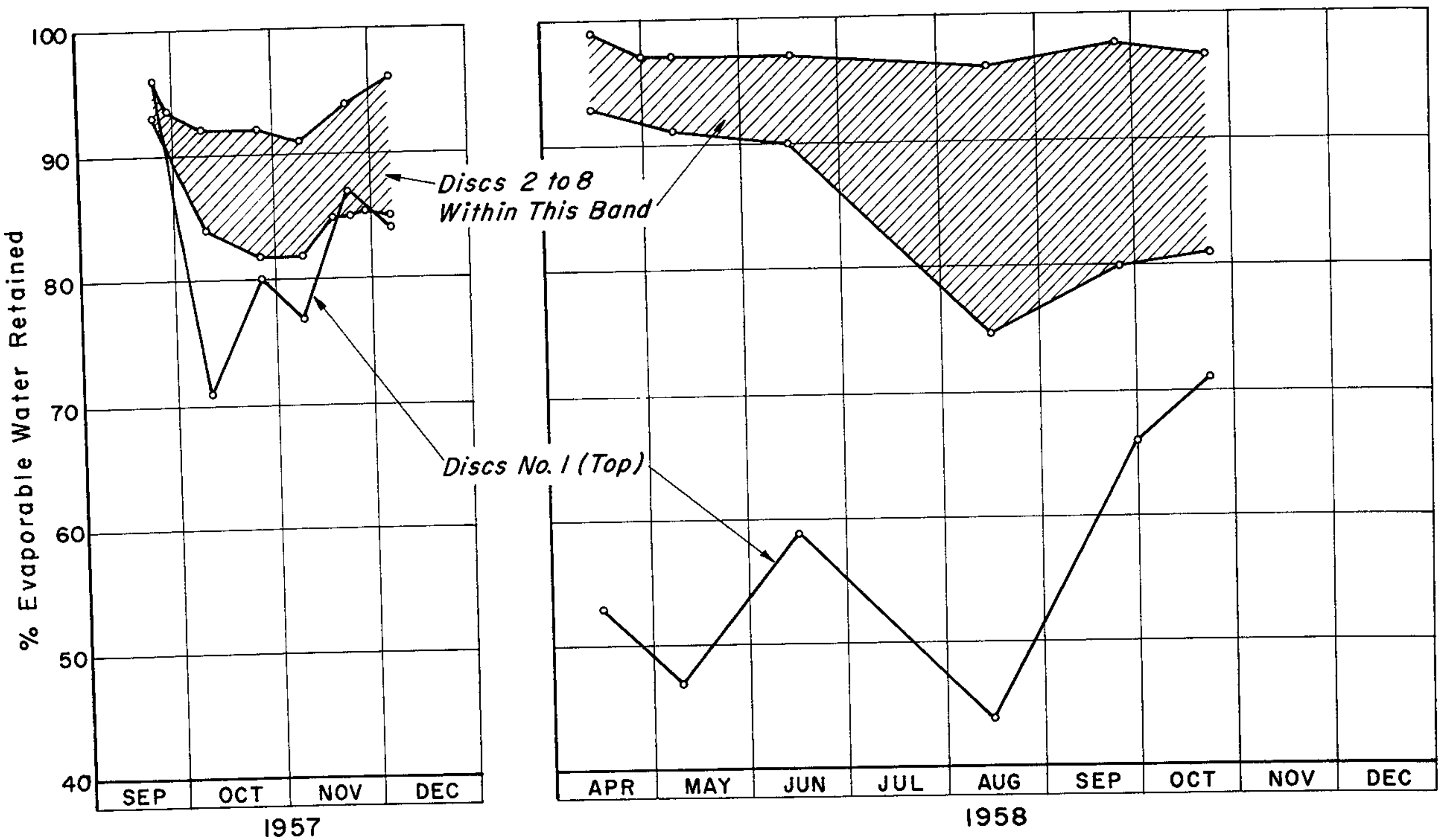

FIGURE 5. TEST SLAB AT YUBA GAP, ELEVATION 5700 FT.

Placed Aug. 7, 1957

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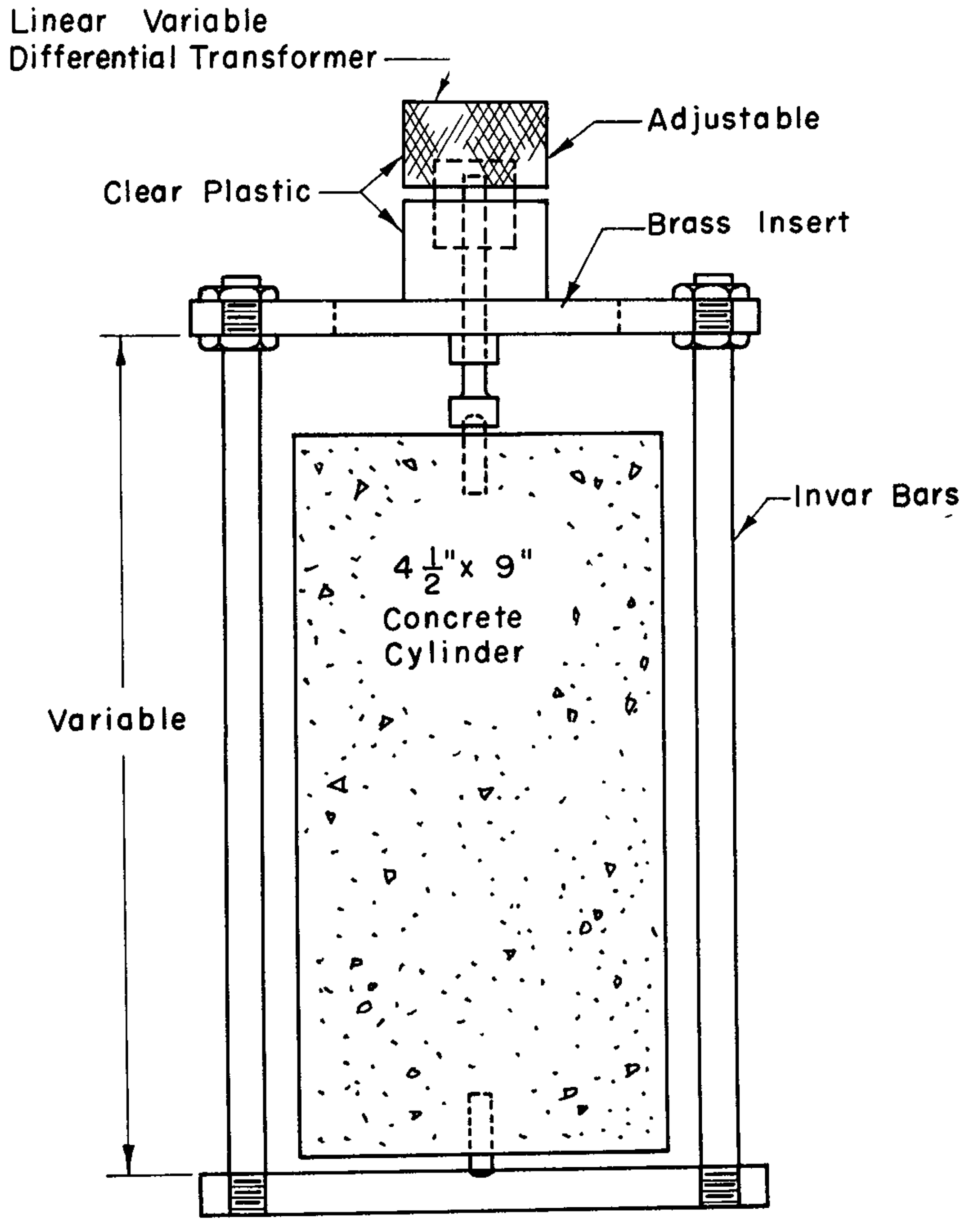

FIGURE 6. DEVICE FOR CONTINUOUS MEASUREMENT OF LENGTH CHANGE

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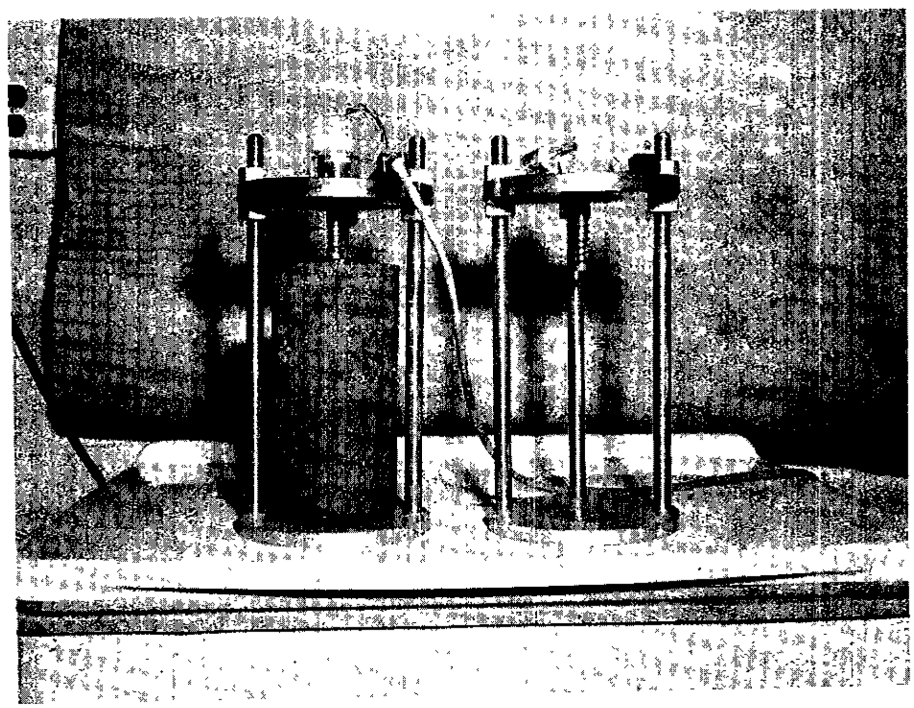

FIGURE 7. FRAMES FOR POWERS TEST

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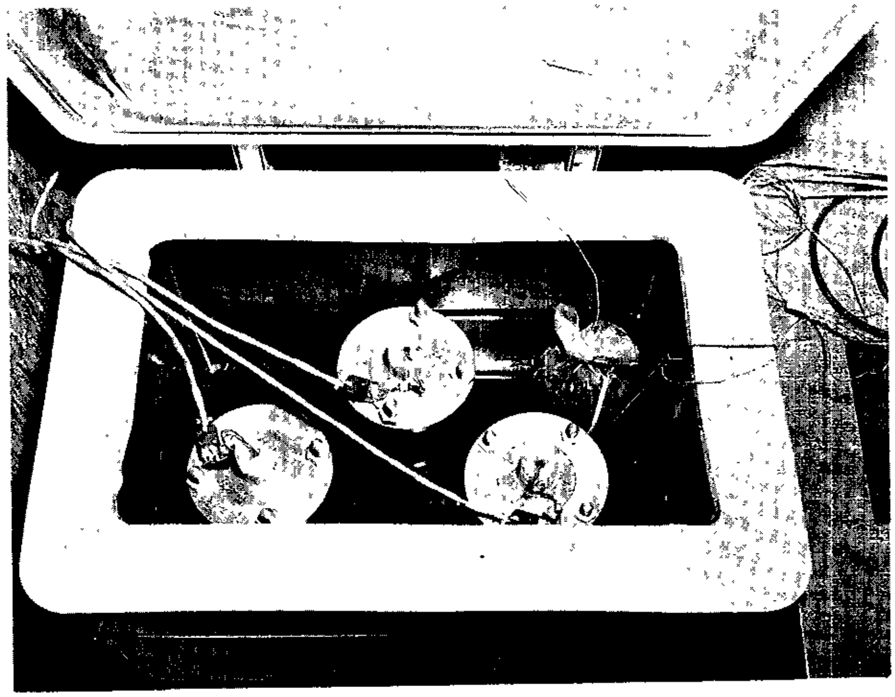

FIGURE 8. SPECIMENS IN COOLING UNIT

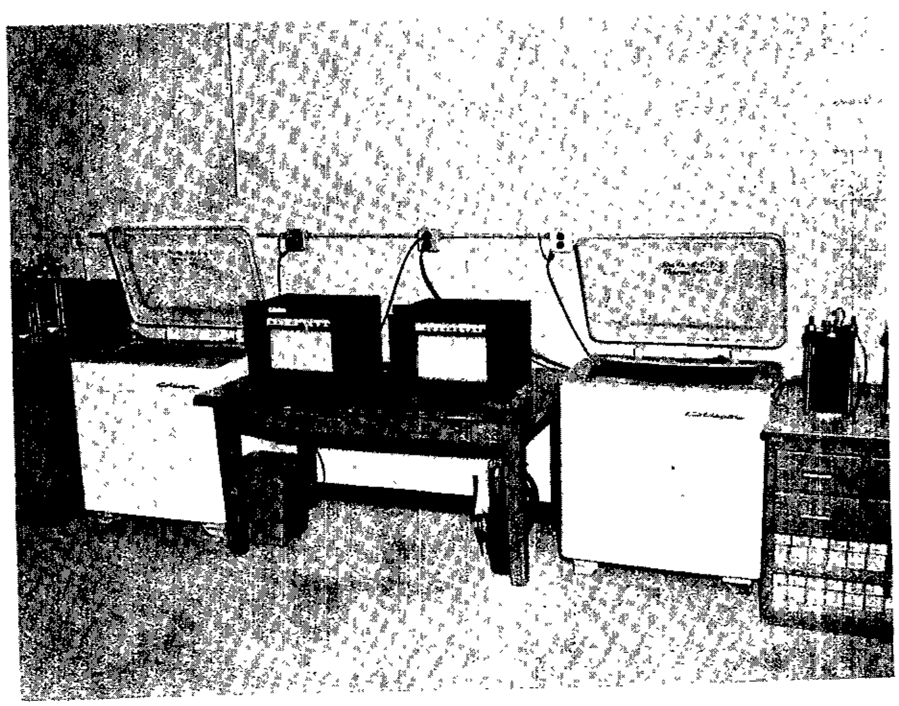

FIGURE 9. COOLING UNITS AND RECORDERS

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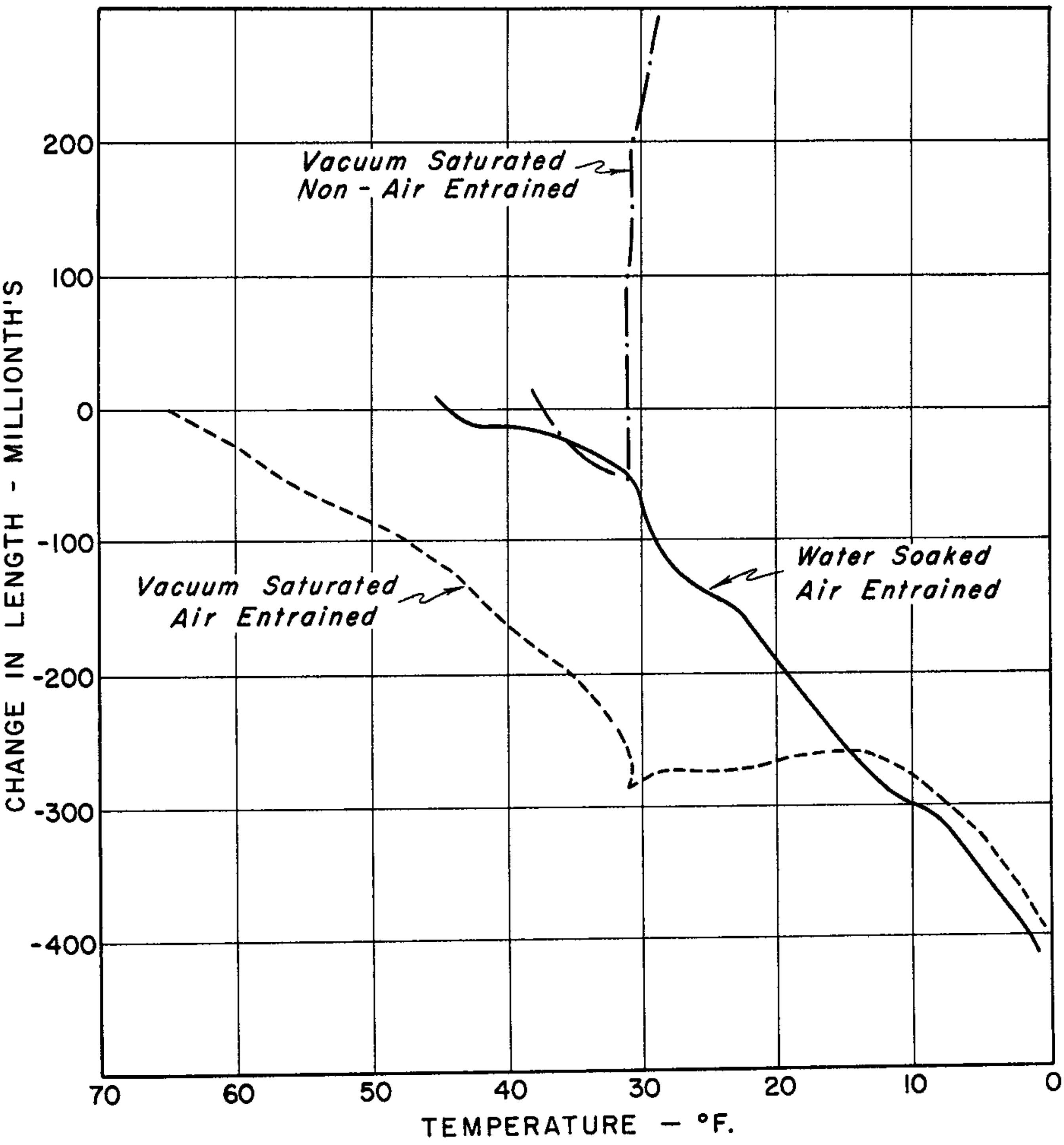

FIGURE 10. IOWA LIMESTONE RAPID FORMATION AND AMERICAN RIVER SAND

—CONCRETE NOT DRIED—

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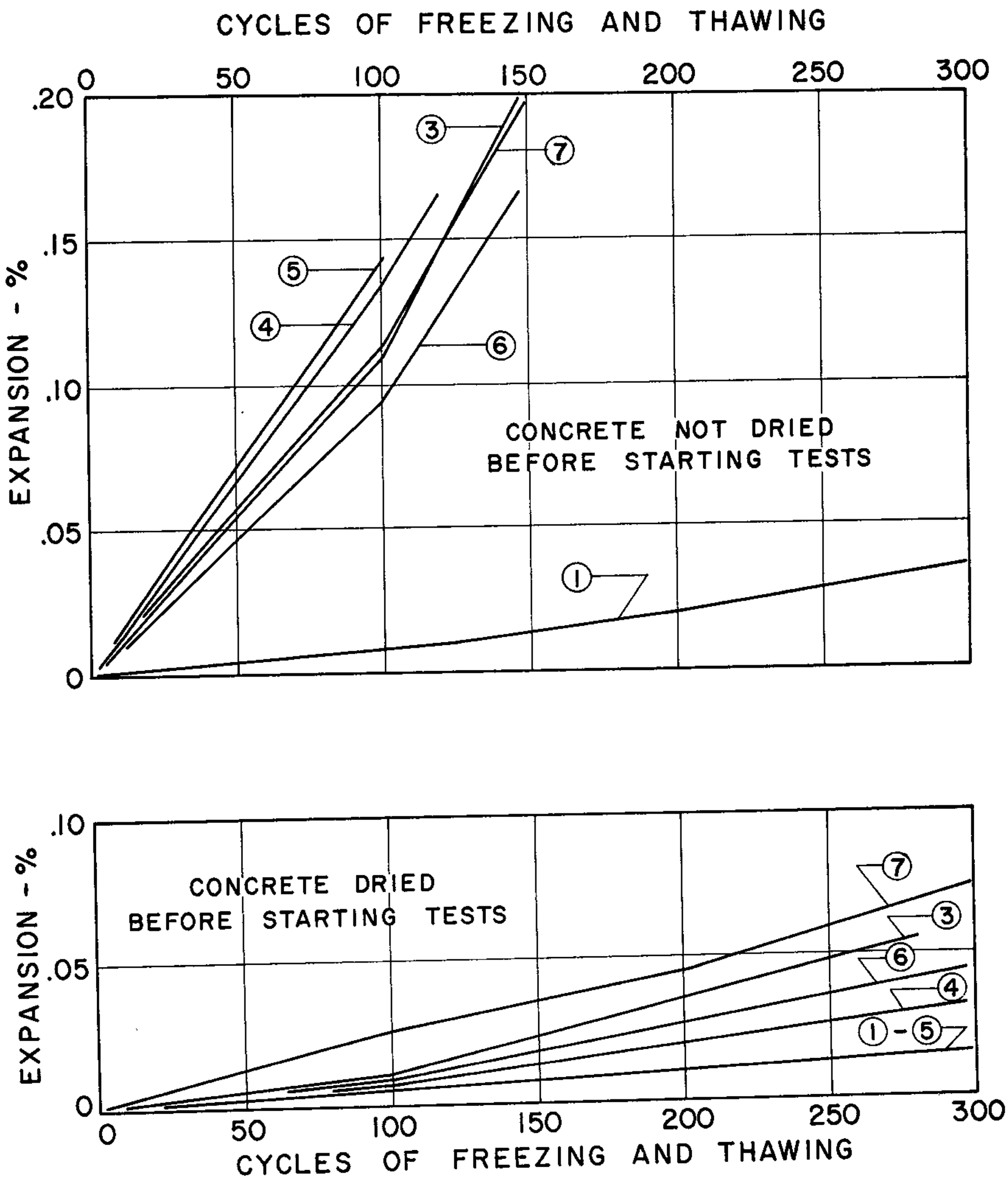

FIGURE 11. RAPID FREEZING AND THAWING IN WATER
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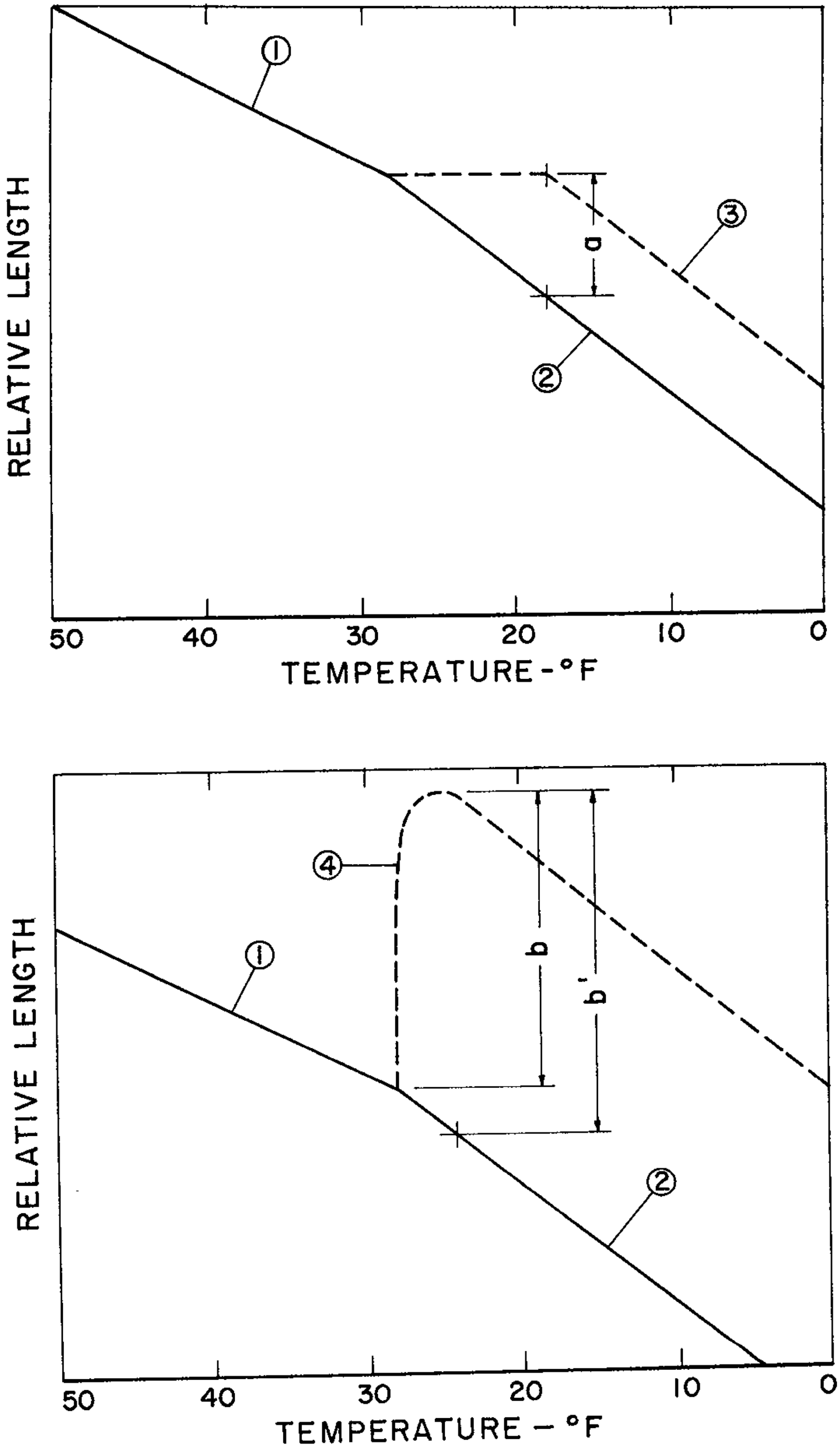

FIGURE 12. IDEALIZED COOLING CURVES

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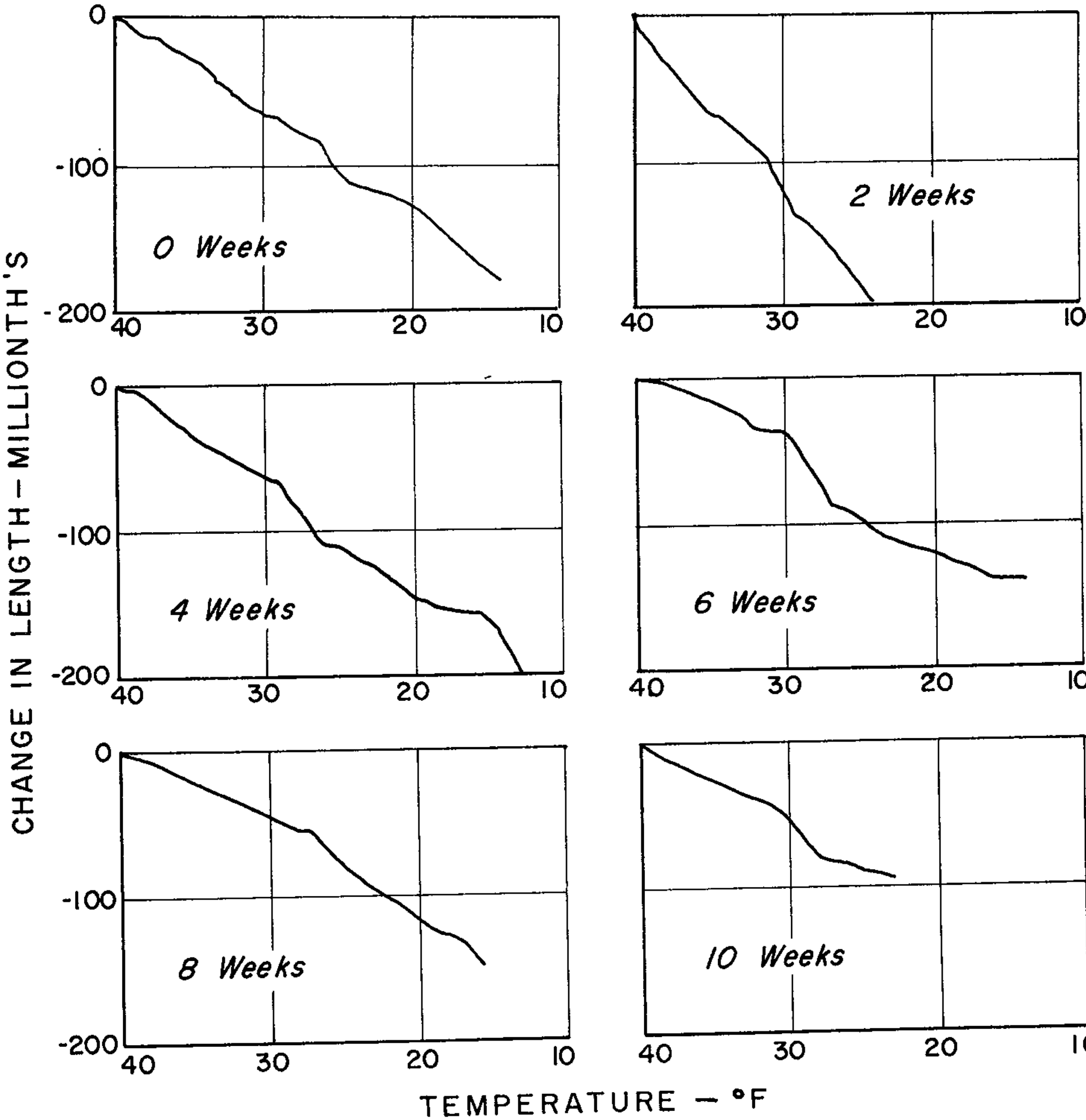

Aggregate No. 1 Good Service Record

Specimen dried, then soaked with intervening freeze thaw cycles, 5 per week, for period indicated.

FIGURE 13. POWERS COOLING CURVES

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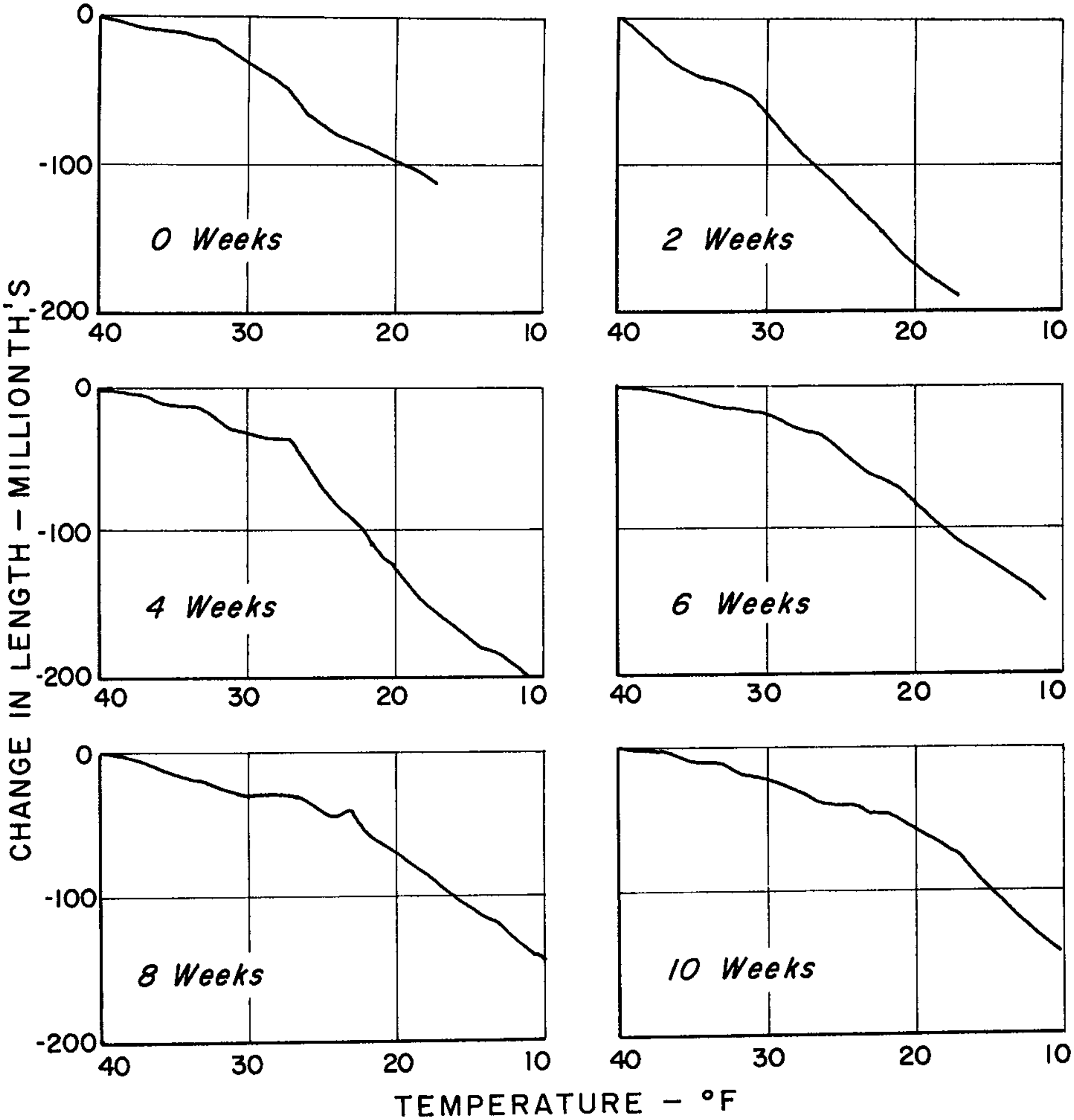

Aggregate No. 2 Good Service Record

Specimen dried, then soaked with intervening freeze thaw cycles, 5 per week, for period indicated.

FIGURE 14. POWERS COOLING CURVES

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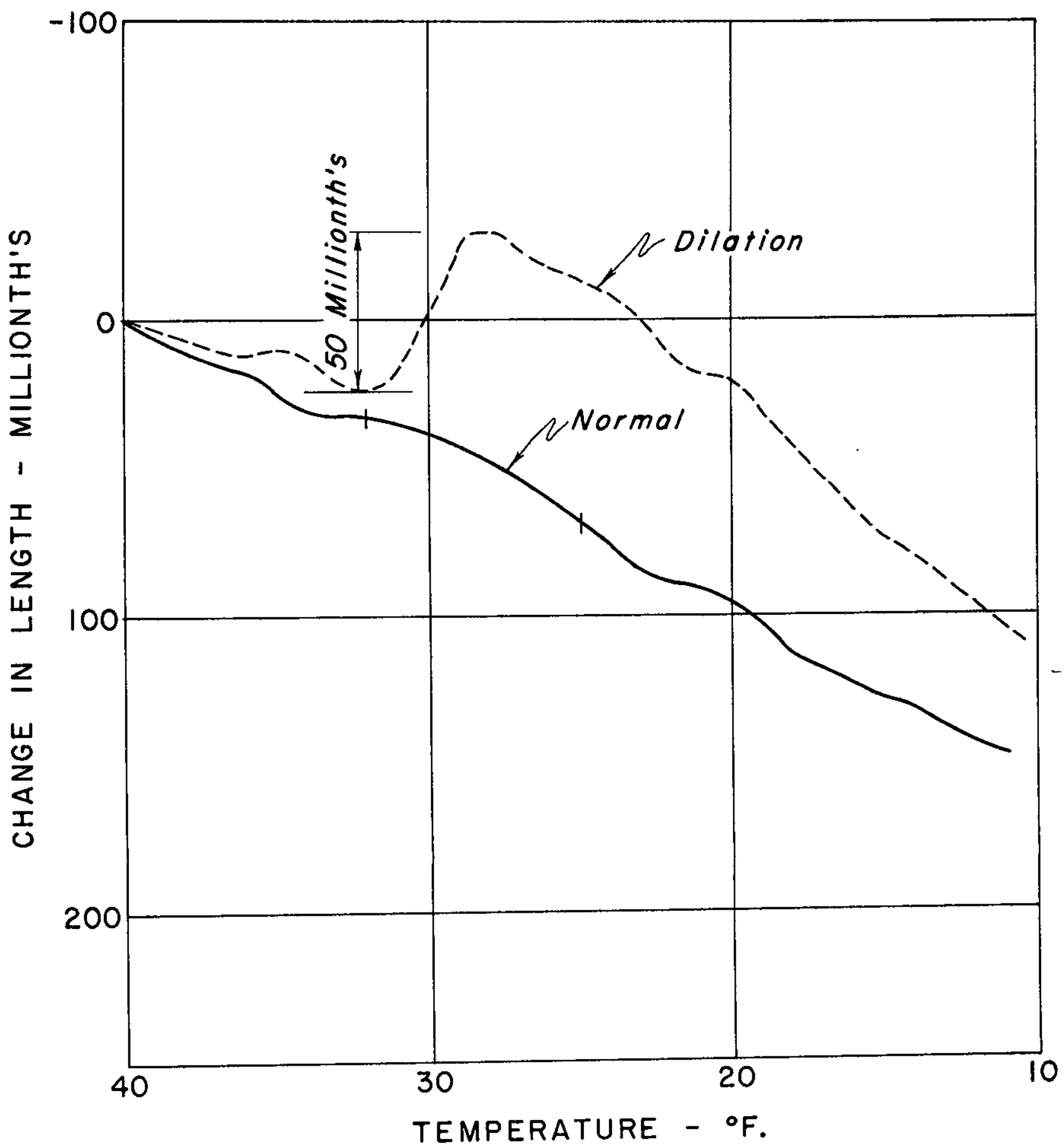

FIGURE 15. POWERS COOLING CURVES ILLUSTRATING DILATION AS MEASURED

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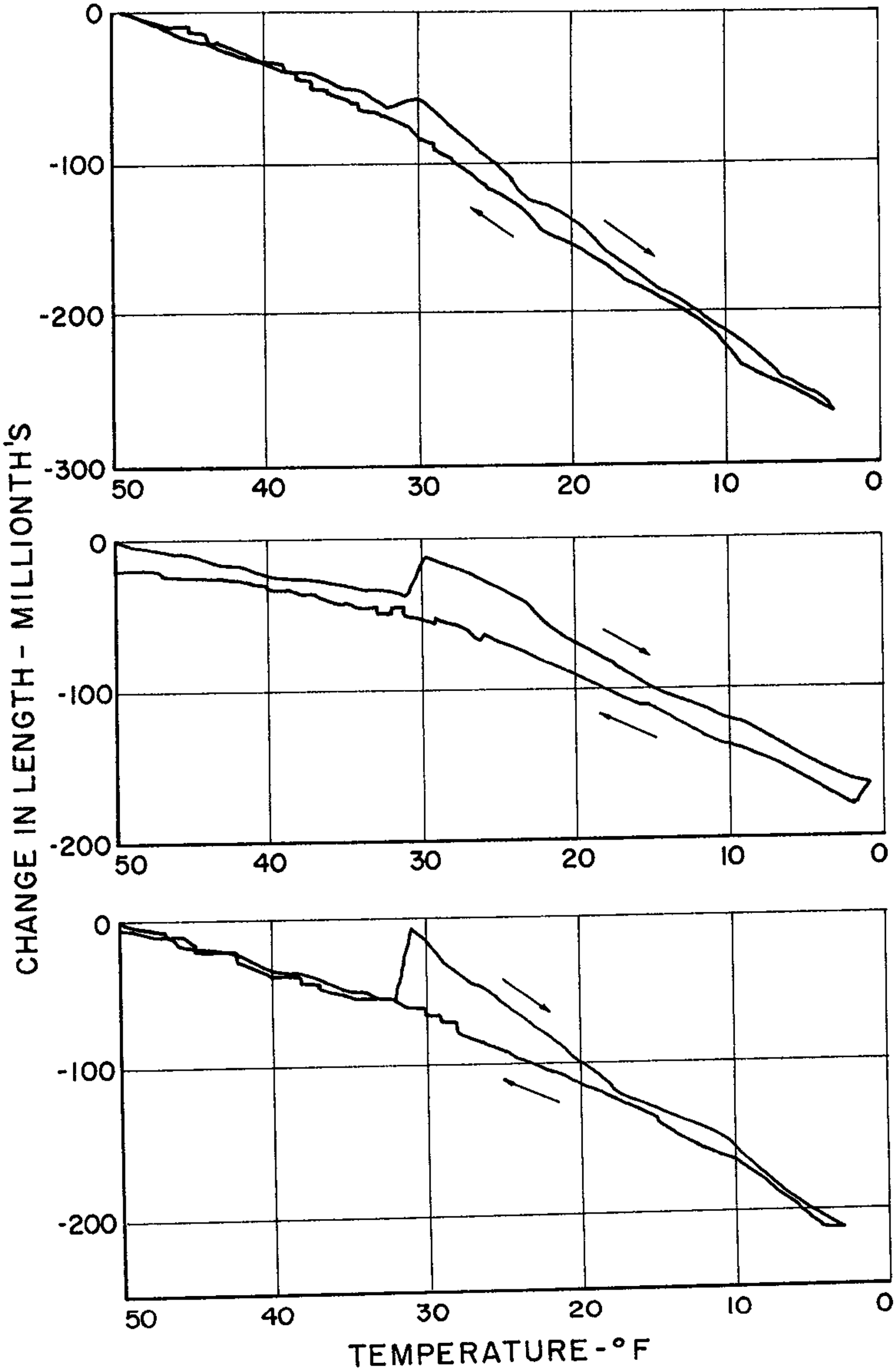

FIGURE 16. POWERS COOLING AND WARMING CURVES

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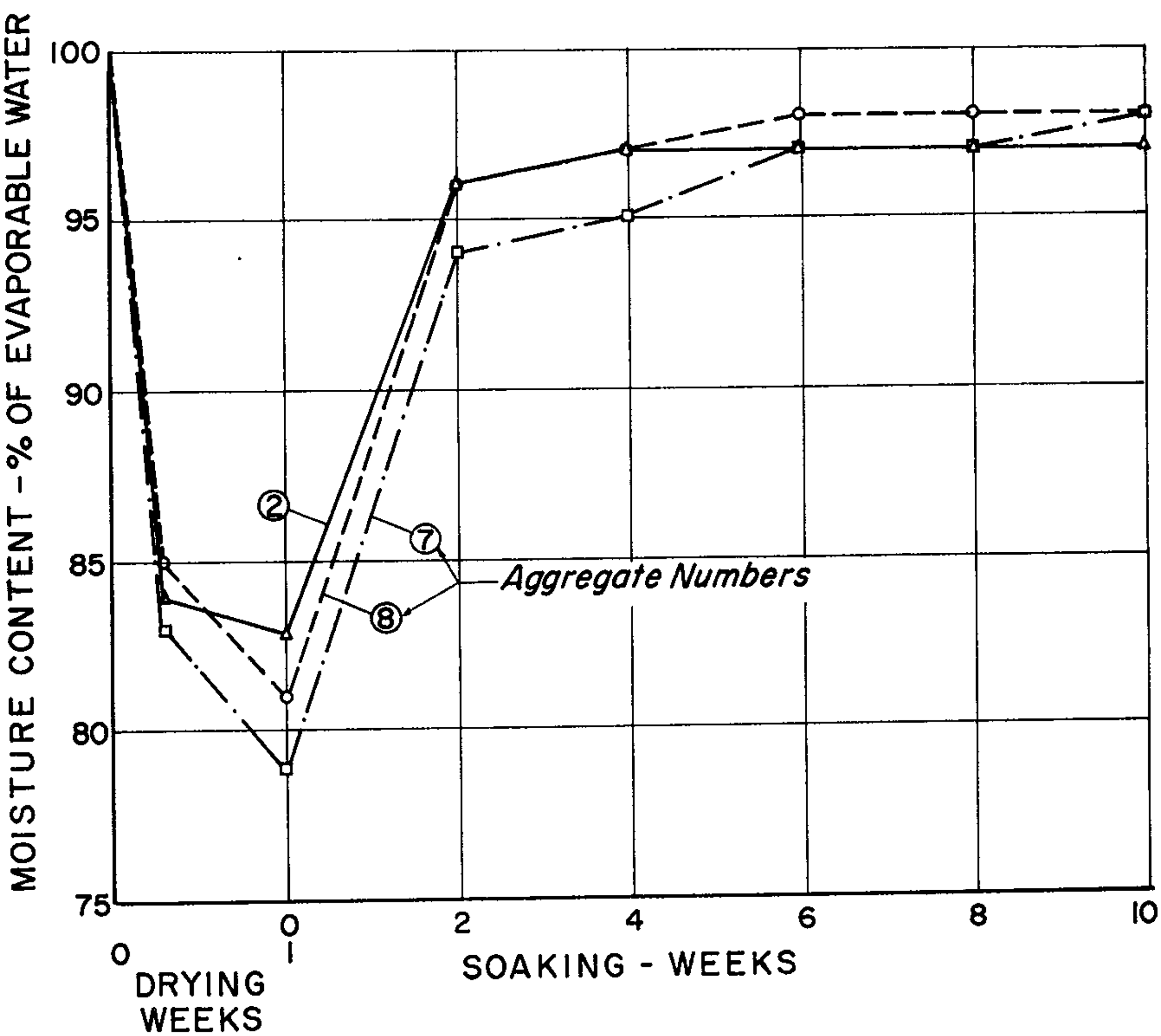

NOTE: Specimens cured in fog room for 14 days, then dried at 73°F and 50% rel. humidity for 48 hrs. then in closed container over saturated sodium acetate solution for 5 days, then soaked in water with intervening freezing to 0°F repeated 5 times per week. Each plotted point represents average change of 6 specimens.

FIGURE 17. CHANGES IN MOISTURE CONTENT DURING POWERS FREEZE-THAW TEST

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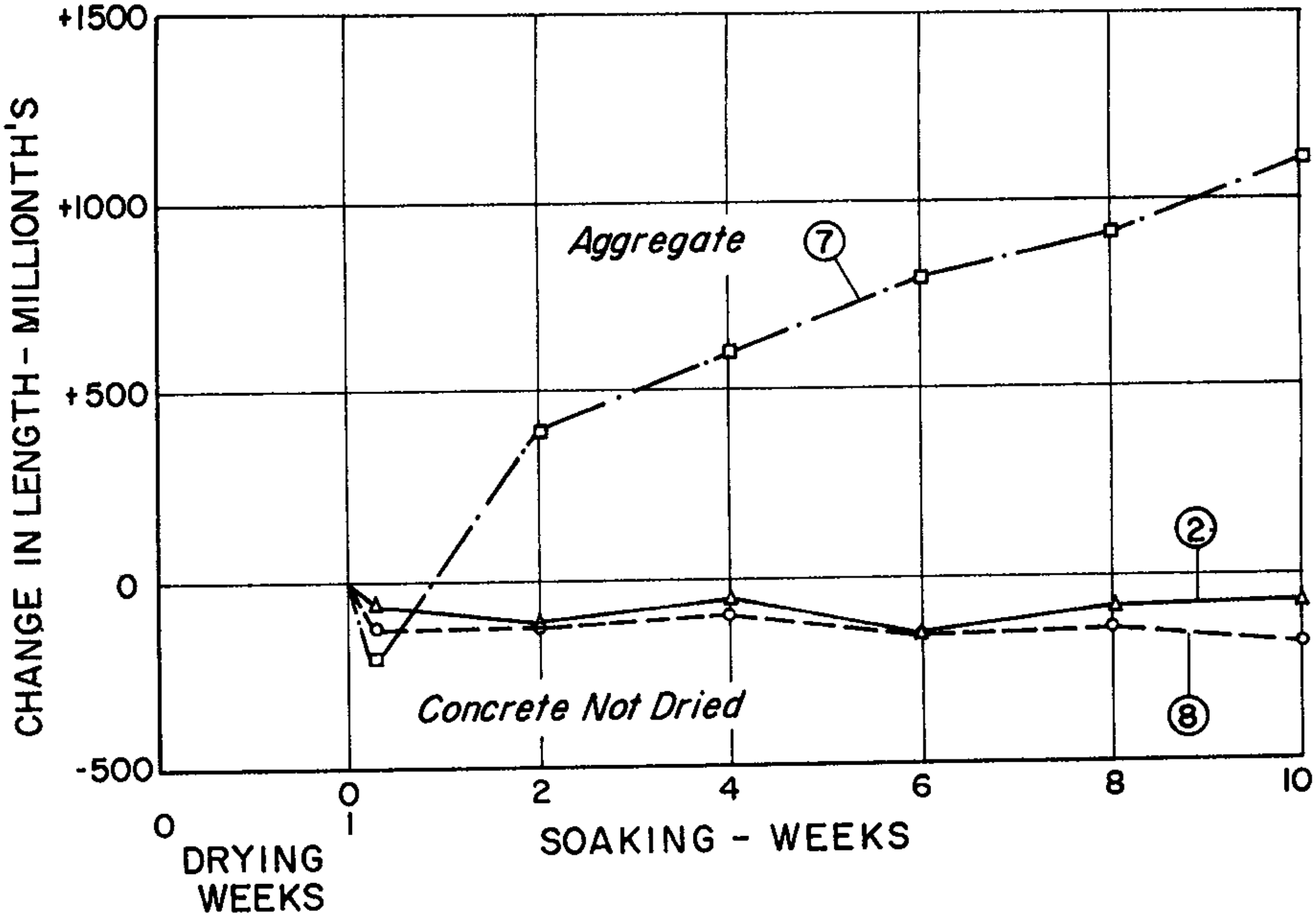

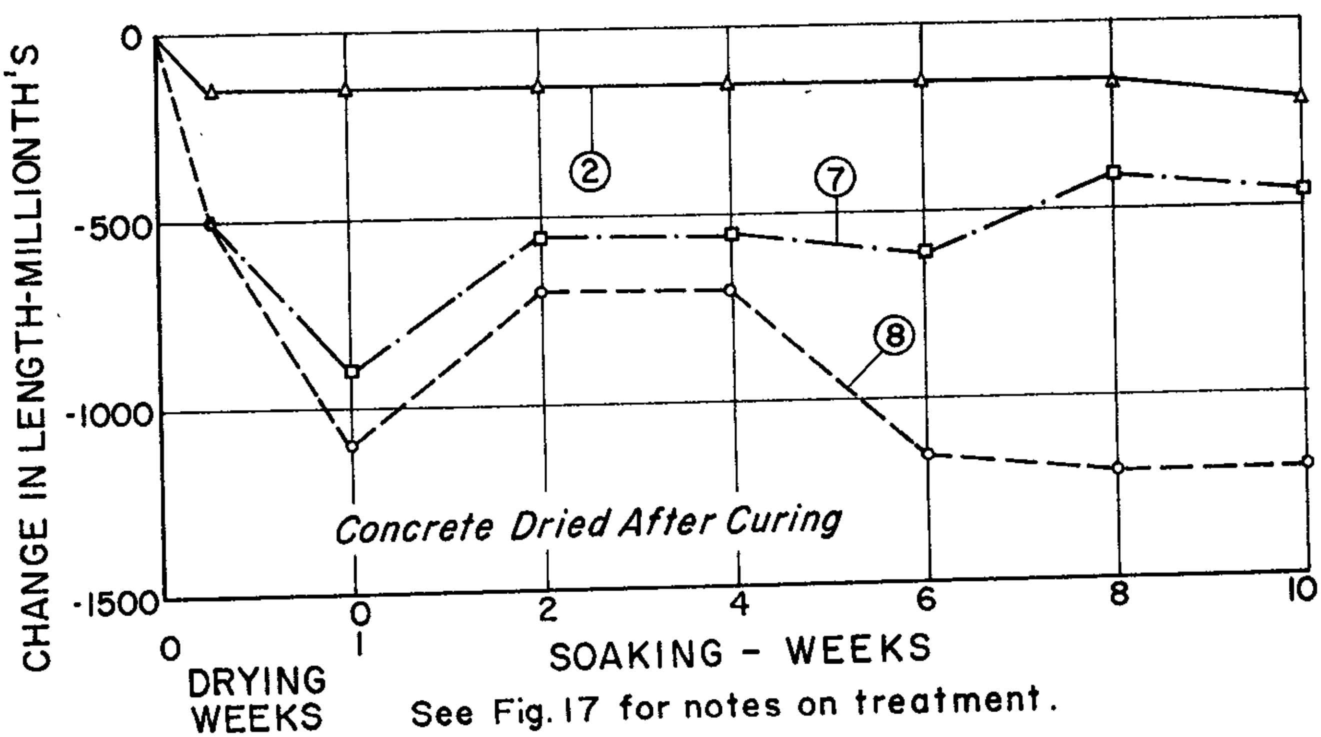

See Fig. 17 for notes on treatment.

FIGURE 18. CHANGES IN LENGTH DURING POWERS FREEZE - THAW TEST

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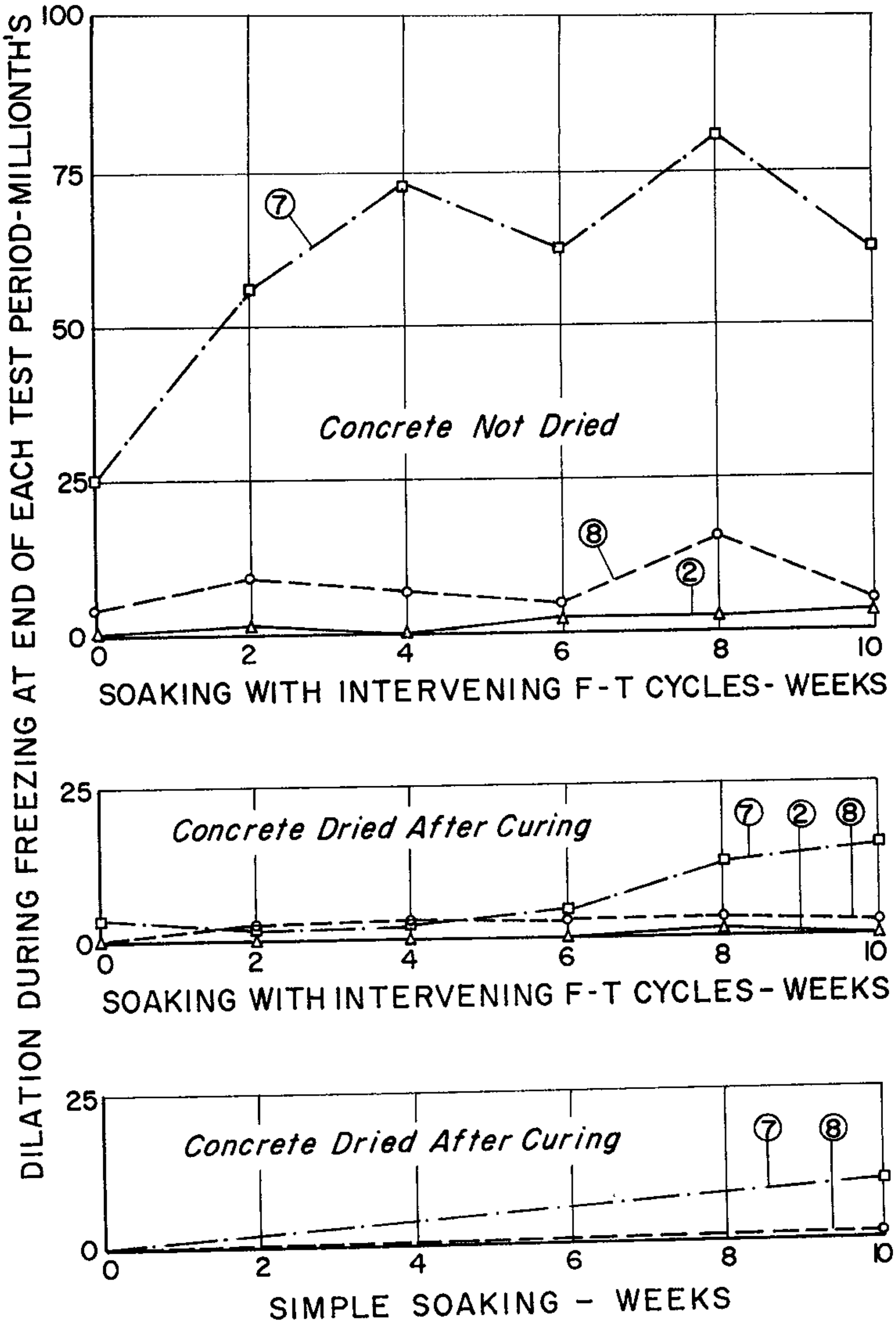

See Fig. 17 for notes on treatment.

FIGURE 19. EFFECT OF TREATMENT ON MEASURED DILATION AT END OF EACH TEST PERIOD

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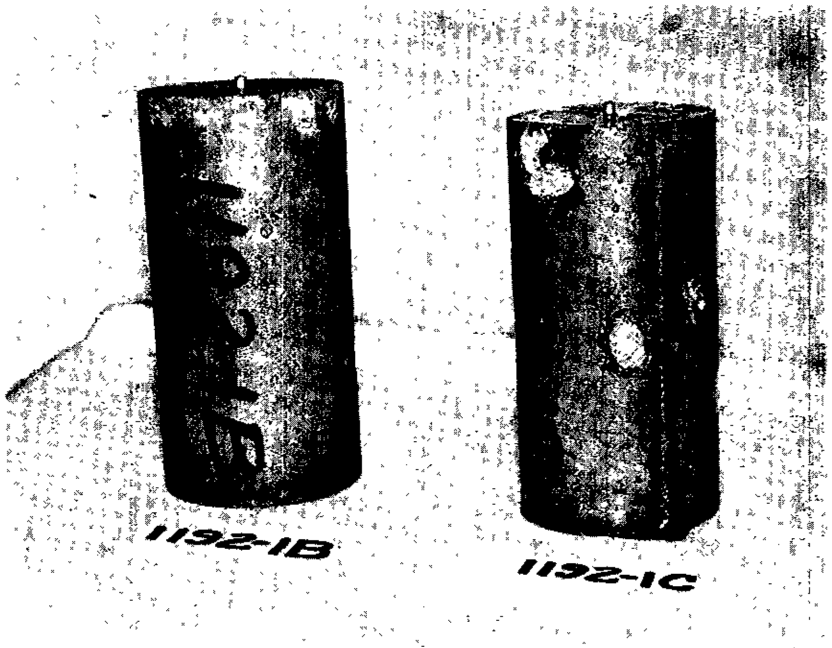

FIGURE 20. EFFECT OF DRYING CONCRETE ON CONDITION OF SPECIMENS SUBJECTED TO FREEZE - THAW.

1192 - 1B DRIED AFTER MOIST CURING.
1192 - 1C NOT DRIED.

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APPENDIX

METHOD OF TEST FOR FREEZE-THAW RESISTANCE OF AGGREGATES IN AIR-ENTRAINED CONCRETE

October 30, 1958

Fine and Coarse Aggregates

In addition to the tests required by the Standard Specifications and these special provisions, fine and coarse aggregates for portland cement concrete to be used in the construction of reinforced concrete structures, pavement and curbs and gutters shall pass the freezing and thawing test described below.

This freezing and thawing test is intended to determine the resistance of aggregates in air-entrained concrete to a prescribed series of freezing and thawing cycles.

Except when it is proposed that the aggregates be furnished in a dry condition, they shall be so sampled and shipped to the laboratory that absorbed moisture present in the pit or in stockpiles of washed aggregate is retained in the sample. Stockpiles shall be sampled only at locations where surface moisture is visibly present. In the laboratory the samples shall be maintained in a saturated condition during processing and until they are incorporated in mixed concrete. When it is proposed that the aggregates be dried after manufacture and before use, samples shall be taken after discharge from the drying equipment and shall be placed in sealed containers. In the laboratory they

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shall be handled in such a manner that contained moisture if present is retained up to the time the aggregates are incorporated into mixed concrete.

The aggregates shall be mixed with portland cement and water in the proportions specified for concrete on the project. During mixing, an air-entraining agent shall be added in an amount to result in 4.0 ± 0.5 percent entrained air.

Two or more 4-1/2 x 9-inch test cylinders shall be molded from each batch of freshly mixed concrete. Stainless steel studs one inch long shall be embedded in the fresh concrete to project 1/8-inch at each end of the longitudinal axis of the cylinders.

For each aggregate or combination of aggregates to be tested, at least three batches of concrete shall be mixed, each on a different day.

The test specimens shall be cured in moist air under standard conditions to the age of 14 days. They shall then be exposed to freely circulating air at 70-75°F and 50-60 percent relative humidity for 48 hours. They shall then be placed over a saturated solution of sodium acetate in a sealed container at a temperature of 70-75°F for five days. They shall then be immersed in water at room temperature for 14 days. At the conclusion of this period, they shall be subjected to Procedure A.

Procedure A.

A recording extensometer capable of recording changes in length to the nearest 0.00005 inch shall be mounted to engage

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the studs of the specimen. The specimen shall be placed in a bath of kerosene saturated with water and shall remain at approximate constant temperature above 50°F until equilibrium has been established between the temperature of the bath and that of the specimen. A similar specimen containing a thermocouple at its approximate center shall also be placed in the bath. The thermocouple leads shall be connected to a recording thermometer. The temperature of the test specimen shall be considered to be that of the companion specimen containing the thermocouple. The temperature of the bath shall then be lowered at a rate not exceeding 5°F per hour until the temperature of the specimen reaches 0°F. The recorded change in length shall be plotted against the recorded change in temperature. The specimen shall then be subjected to Procedure B.

Procedure B.

The specimen shall be immersed in a water bath maintained at 40-50°F for two hours. It shall then be placed in water-saturated kerosene at 40°F and the temperature shall be lowered to 0°F at a rate not exceeding 5°F per hour. Ten such freezing and thawing cycles shall be repeated at the rate of one per day during a two-week period. The specimens shall be immersed in water at all times except during the freezing cycle in kerosene. One two-week period as described above shall constitute one round of Procedure B.

Alternate rounds of Procedures A and B shall be continued until 10 weeks have elapsed since the specimen was

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first immersed in water.

If during any round of Procedure A the plotted temperature-elongation curve indicates an elongation in excess of 50 millionths inch per inch during cooling in the range of 32 to 25°F, the specimen shall be reported to have failed; otherwise, the specimen shall be reported to have passed.

The aggregate or combination of aggregates shall be reported to have failed in the freezing and thawing test if one-half or more of the individual specimens fail during any round of Procedure A. If more than one-half of the individual specimens pass during all rounds of Procedure A, the aggregate or combination of aggregates in the moisture condition in which sampled shall be reported to have passed the freezing and thawing test.

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