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FINAL REPORT

AUTOGENOUS ACCELERATED CURING OF CONCRETE CYLINDERS

Part I

Strength Results

by

Larry M. Cook
Highway Engineer Trainee

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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PREFACE

The Research Council's studies of early determination of compressive strength of concrete stored in water baths at elevated temperatures were initiated in 1967 as a part of the State funded research program. The results of this research were presented by K. H. McGhee in his report entitled "Water Bath Accelerated Curing of Concrete".

Under the work plan by L. M. Cook entitled "An Investigation of the Moisture-Temperature Relationships — Autogenous Accelerated Curing for Early Determination of Concrete Strength Potential", the study was extended to autogenous curing. The extended study was approved for financing under Federal Highway Planning and Research Funds on May 14, 1969. The objectives of this project were:

1. To extend knowledge of the thermal and moisture behavior of concrete subjected to high curing temperatures during autogenous curing.
2. To examine the influence that variables such as cement type, cement factor, water-cement ratio, and admixtures have on moisture and temperature.
3. To correlate the accelerated strengths of autogenously cured cylinders with those of 28 and 91 day old moist cured cylinders.

Concurrently with the Council's research project, ASTM Committee C-9 was developing standard methods of testing. Several questions raised during the ASTM efforts were closely related to the Council's work. As a result of a discussion with Federal Highway Administration personnel in October, 1969 a limited study of the curing container characteristics and the influence of initial mixture temperatures on the strength results was undertaken.

The project ultimately involved preparation of approximately 300 batches of concrete in the laboratory with all of the necessary testing. Calibration of moisture measuring instrumentation and continuous recording of temperature and moisture for the test specimens resulted in voluminous data.

For maximum intelligibility and usefulness, the report on this project has been subdivided into five parts as follows:

Part I. Strength Results

Part II. Development of a Moisture Measuring Method

Part III. Temperature Relationships

Part IV. Moisture Relationships

Part V. The Influence of Container and Storage Characteristics and Initial Mixture Temperature

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Each report contains sufficient background information to enable it to stand alone as coverage of the aspect of the project reflected in its title. The titles, in general, reflect the project objectives. Taken together, these five reports represent the final report on the study of Autogenous Accelerated Curing of Concrete Cylinders.

SUMMARY

Forty-eight different concrete mixes were designed to investigate the influence of cement types (II, III, and V), cement contents (450, 550, and 650 lb. per cu.yd.), water-cement ratios (0.4, 0.5, and 0.6), admixtures (accelerator, retarder, and air entraining agent), and initial mixture temperatures (50°F, 70°F, and 90°F) on the strengths of autogenous accelerated cured concrete cylinders.

A total of 940 cylinders were made incorporating autogenously cured cylinders, 28 day, 91 day, and 1 year moist cured cylinders, and autogenously cured cylinders instrumented for moisture and temperature measurements.

The project involved routine testing for slump, unit weight, air content, time of set, and compressive strengths. Additional measurements of moisture movement and temperature development were made.

The project also encompassed the design and fabrication of the autogenous curing containers and the AC ohmmeter used in moisture measurements.

The report lists fourteen observations and conclusions along with recommendations for further research.

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INTRODUCTION

At the present time, the evaluation of most concrete is based on the results of compressive strength tests on cylinders that are conventionally moist cured for 7, 14, or 28 days before testing.

The rapid pace at which concrete is being placed and the trend toward "end result" specifications have emphasized the need for an accelerated test to determine the compressive strength of concrete.

Strength data obtained at the earliest possible time after placement would aid in achieving greater uniformity, which would result in savings in cost and improvements in concrete performance. It would also provide a rapid means of evaluating material sources.

The Research Council has evaluated several methods in which the acceleration of strength development is accomplished by external heat with water baths. These studies were reported by McGhee.(1)

It has been shown that curing a concrete cylinder autogenously (by a self-generated increase in curing temperature) inside a container sufficiently insulated to prevent heat and moisture loss will provide accelerated strengths comparable to those obtained by applying external heat. This method has been used experimentally in Canada.(2)

An acceptable accelerated curing procedure should fulfill the following requirements:(2, 3)

1. Possess a high degree of repeatability and reproducibility.
2. Provide an acceptable correlation with ultimate strength values.
3. Possess a high efficiency (i.e., accelerated strength must be a high percentage of ultimate strength).
4. Involve simple procedures and equipment.

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5. Require no overtime work.

6. Permit curing to be complete as soon as possible.

The results reported to date suggest that all of the accelerated curing methods provide about the same degree of reliability and predictive capacity so that the choice will ultimately be based upon simplicity, rather than technical considerations. By reason of its simplicity, the autogenous method offers many advantages and thus was selected for further study as reported herein.

OBJECTIVES

The objectives of this investigation were as follows:

1. To examine the influence that concrete mixture variables such as cement type, cement factor, water-cement ratio, and admixtures have on the strength of autogenously cured concrete cylinders.

2. To examine the influence of initial mixture temperature over a range from 50°F to 90°F on the strength as related to the concrete mixture variables.

3. To correlate the accelerated autogenous curing strengths with those of moist cured cylinders tested at 28 days and 91 days.

4. To design the autogenous curing container used in this investigation and to evaluate its efficiency.

The scope of the investigation was restricted to the autogenous accelerated curing method.(2) Earlier work by McGhee(1) had developed similar data for methods utilizing water baths.

AUTOGENOUS CURING CONTAINER

Design and Fabrication

One main advantage of the autogenous curing method is the simplicity of the equipment needed to conduct the test. The insulated container has no moving parts, which makes it much easier to maintain than the elaborate water curing tanks and moist rooms. The autogenous container also serves as a safe means of handling, shipping, and storing cylinders prior to testing.

After studying the work of Smith and Tiede(2,4) on autogenous curing, the investigator postulated that if a container could be designed having better insulating properties, then the accelerated strengths should increase. The subsequent strength increase would increase the efficiency, i.e., the ratio of accelerated strength to 28-day moist cured strength, and the increased efficiency would greatly enhance the probability of wide acceptance by operating units.

The basic guide lines for the construction of autogenous containers are contained in the Canadian "Provisional Specification for Autogenous Concrete Cylinder Curing Containers"(5). A container was designed by the investigator and manufactured by Dacar Chemical Company, Pittsburgh, Pennsylvania, under the supervision of Dr. J. N. Datesh. The dimensions of the container are shown in Figure 1.

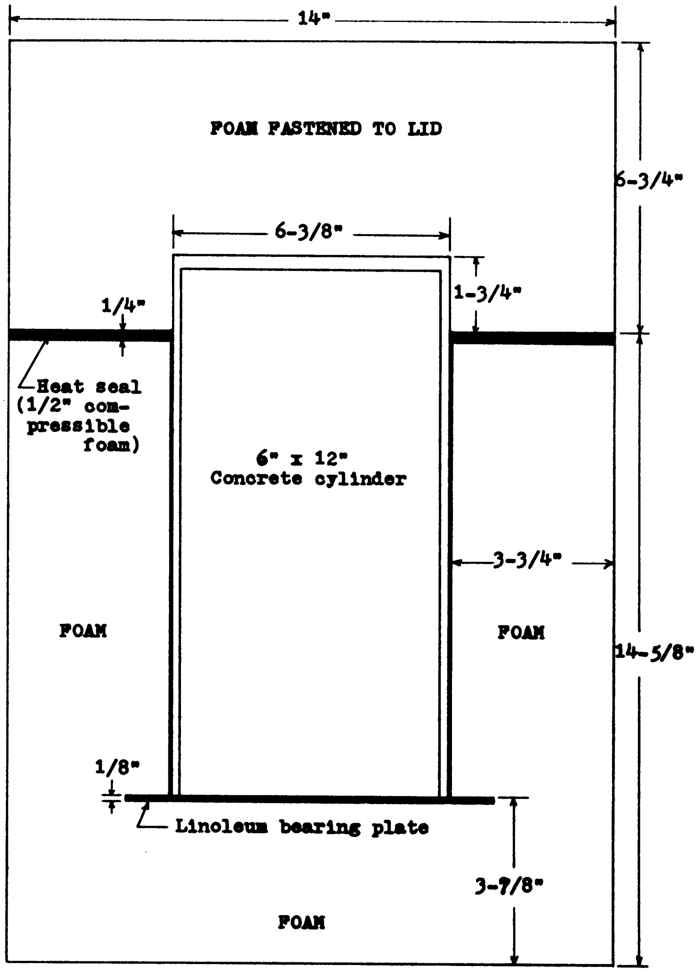
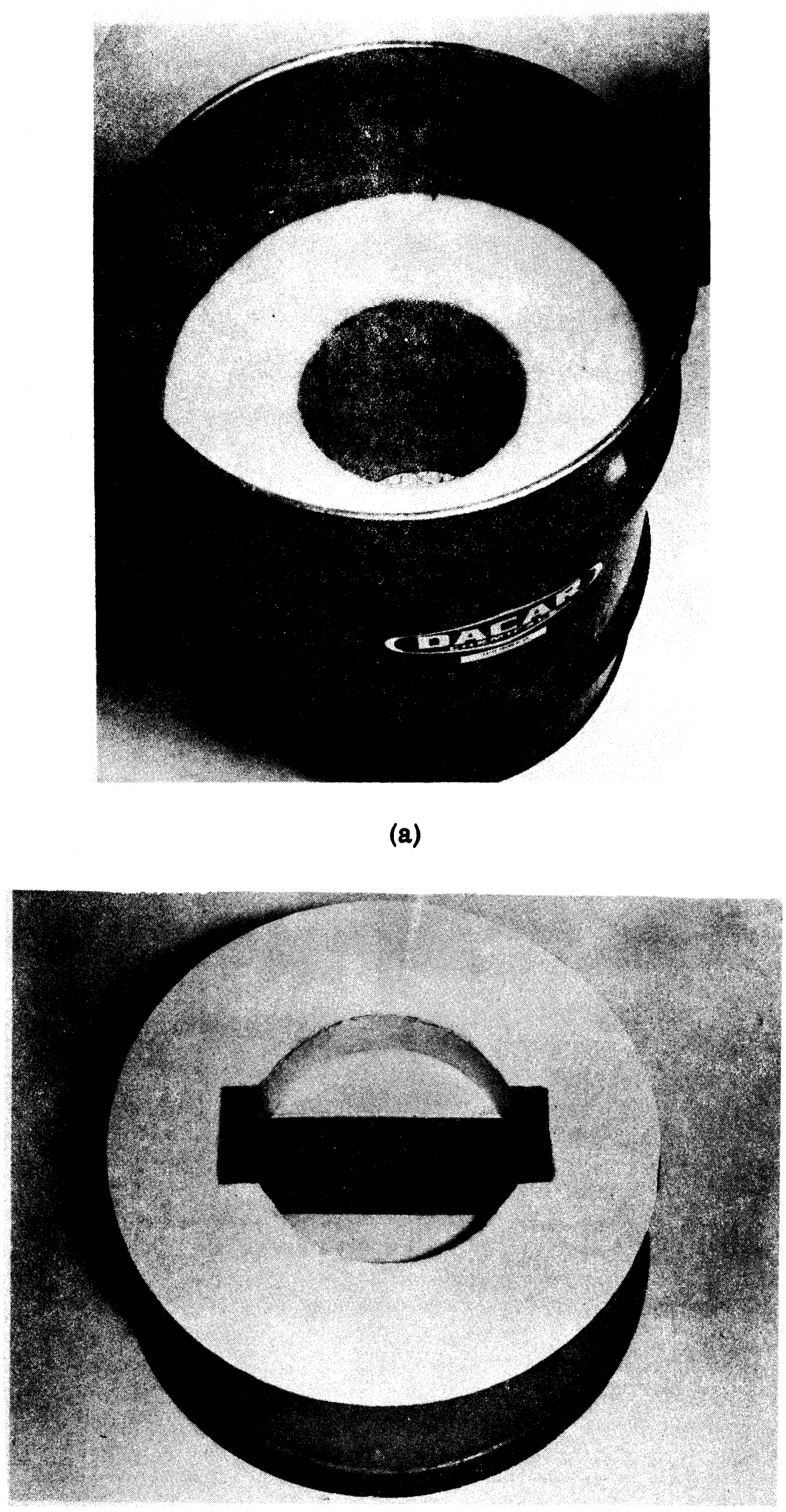


Figure 1. Cutaway front view of autogenous curing container.

The outer container is a ribbed, 20-gauge steel drum, 14 in. in diameter and 22 in. high, with straight sides and a lever-lock, ring type lid, as shown in Figure 2.

Figure 2. [illegible] container.

The flat lid lifts completely off to provide full access to the inner container (Figure 3(a)). The lid has a compressible rubber seal around its perimeter, as pictured in Figure 3(b). A piece of 1/16 in. thick linoleum forms the inner lining and bottom of the container (Figure 3(a)) and is securely fastened to the foam to prevent damage to the insulation. The area around and below the inner lining (Figure 3(a)) is filled with foamed polyurethane having a density of 3 lb./cu.ft. On top of this polyurethane foam is a 1/2 in. thick compressible polyurethane foam gasket having a density of 2 lb./cu.ft., which is used as a heat seal. The heat seal was placed at this depth inside the container to prevent the heat or hot air from having a direct horizontal avenue of escape. This location of the heat seal, rather than its being fastened to the lid, also protected it from being damaged or becoming contaminated with dirt and other foreign materials which would have reduced its effectiveness in retaining heat. The lid has $6\frac{3}{4}$ in. of foam fastened to it, which is protected by a 20-gauge steel band, as shown in Figure 3(b). A well, $6\frac{3}{8}$ in. in diameter



(a)

(b)

Figure 3. Lid and interior of autogenous curing container.

by 1-$\frac{3}{4}$ in. deep, was formed in the top (Figure 3(b)) to accommodate the top portion of the concrete cylinder mold; then the top was sealed with thin, white, high impact polystyrene plastic, as shown in Figure 3(b). A thermometer well was also formed in the lid and was filled in with a dark colored foam, as shown in Figure 3(b).

Some of the containers were modified by a hole drilled in the outer container at the level of the heat seal to accommodate a thermocouple wire which could be inserted into the concrete cylinder.

A total of 25 containers were purchased at an individual cost of $34.50 FOB, Carnegie, Pennsylvania.

In order to assure completely random, unbiased numbering (the reasons for which will become apparent in the following paragraphs), the packing containers were given consecutive numbers from 1 to 25 as they were removed from the freight truck. These numbers were also subsequently painted on the respective autogenous containers therein. The numbers of the containers to be used for a special study of temperature and moisture were selected prior to arrival of the containers.

Tests for Heat Retention

The Canadian Provisional Specification(5) states the maximum heat loss requirements as follows:

> 5.3 Heat Retention
>
> A watertight container with internal dimensions of 12 in. high and 6 in. diameter shall be filled to the brim with hot water at a temperature of 180°F (82°C) while within the autogenous curing container. A thermocouple shall be installed in the water and the temperature of the water shall be measured by an electrical potentiometer. The water container shall then be sealed with a plastic cap or bag at the top. The autogenous curing container shall then be closed.
>
> When the autogenous curing container is standing in an ambient temperature of 70°F (21°C) ± 2°F (1°C), in still air, the following drop in temperatures of the water shall not be exceeded:
>
> After 12 hrs. from 180°F (82°C) to 150°F (66°C)
> 24 hrs. from 180°F (82°C) to 130°F (54°C)
> 48 hrs. from 180°F (82°C) to 115°F (46°C)
> 72 hrs. from 180°F (82°C) to 95°F (35°C)

Because of the strict controls under which the containers were manufactured, it was decided that checking one-fifth of the total number of containers for heat retention would be sufficient, provided the temperature differential among all five containers for the same conditions was less than an arbitrarily selected value of 3°F. Before the autogenous containers were received, numbers 1, 6, 11, 16, and 21 were selected for testing. The numerical results of the heat retention tests are presented in Table I and show that the temperature differentials among the 5 containers were 1°F for 12 hours and 24 hours and 2°F for 48 hours and 72 hours. Since the temperature differential values obtained were less than the allowable 3°F, additional containers were not tested for heat retention. The actual and provisional heat retention curves are shown in Figure 4.

TABLE I

RESULTS OF TEMPERATURE TESTS FOR HEAT RETENTION CAPABILITIES OF AUTOGENOUS CONTAINERS

Container Number	Temperature reached at —			
	12 hr.	24 hr.	48 hr.	72 hr.
1	159°F	148°F	130°F	113°F
6	160	148	128	113
11	159	149	128	113
16	160	149	128	114
21	160	148	128	112
Average	159.6	148.4	128.4	113

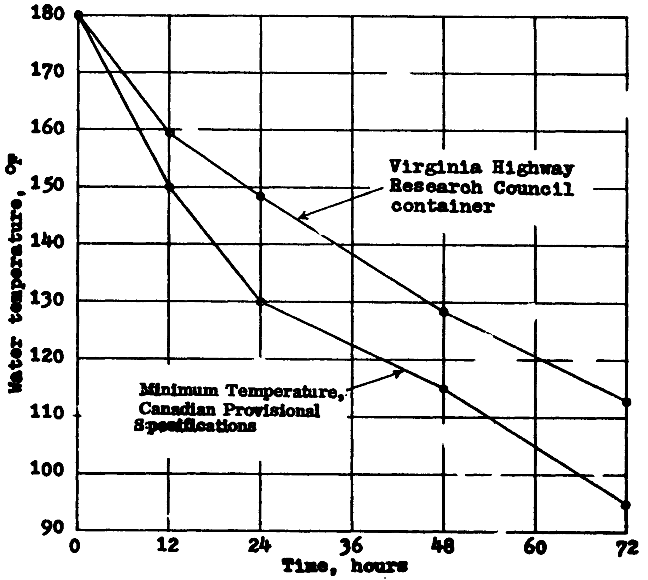


Figure 4. Heat retention curves for autogenous containers.

EXPERIMENTAL TEST MATERIALS AND PROCEDURES

Variables

Table II lists the concrete mixture variables investigated in the experiment to determine their influence on autogenous strength development. The air content was held constant at 5.5 ± 0.5 percent for all mixtures.

TABLE II

CONCRETE VARIABLES INVESTIGATED

Initial mixture temperatures...	50°F, 70°F, 90°F
Heats of hydration............	Low, medium, high
Cement factors...............	450 lb/cu yd, 550 lb/cu yd, 650 lb/cu yd
Water-cement ratios..........	0.4, 0.5, 0.6
Admixtures..................	Accelerator, retarder

Materials

Cements

In order to provide a range of heat liberation during curing, three types of portland cement were used in this experiment. The chemical analysis and computed compound compositions of the cements used (as determined by ASTM C 114-67(6) and ASTM C 150-68,(7) respectively) are listed in Table III. One of the three cements met each of the specifications for types II, III, or V portland cement as set forth in ASTM C 150-68.

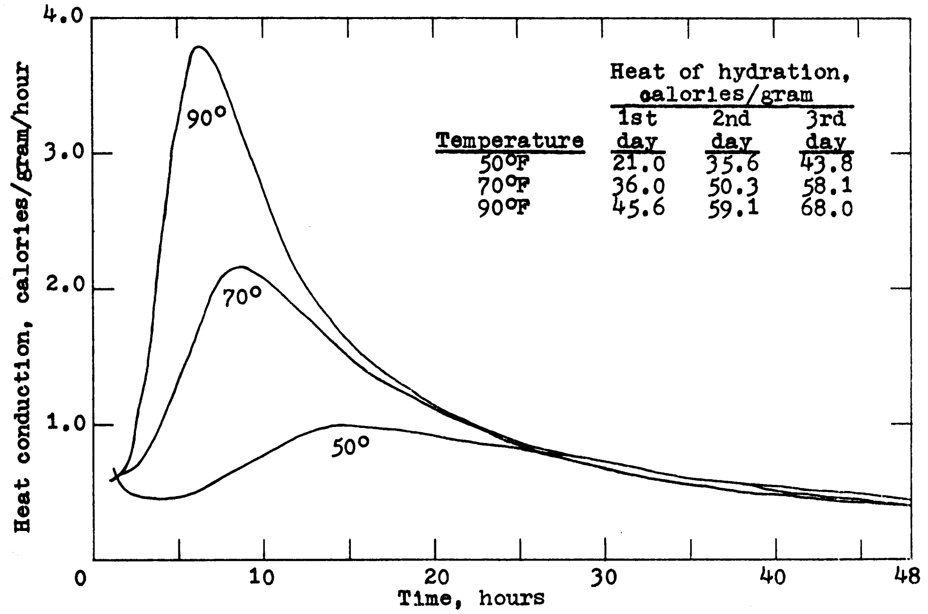
Heat evolution tests were conducted by the Portland Cement Association on all three cements at temperatures of 50°F, 70°F, and 90°F using a conduction calorimeter,(8) and the results of these tests are shown in Figures 5, 6, and 7.

TABLE III

CHEMICAL ANALYSIS OF PORTLAND CEMENTS

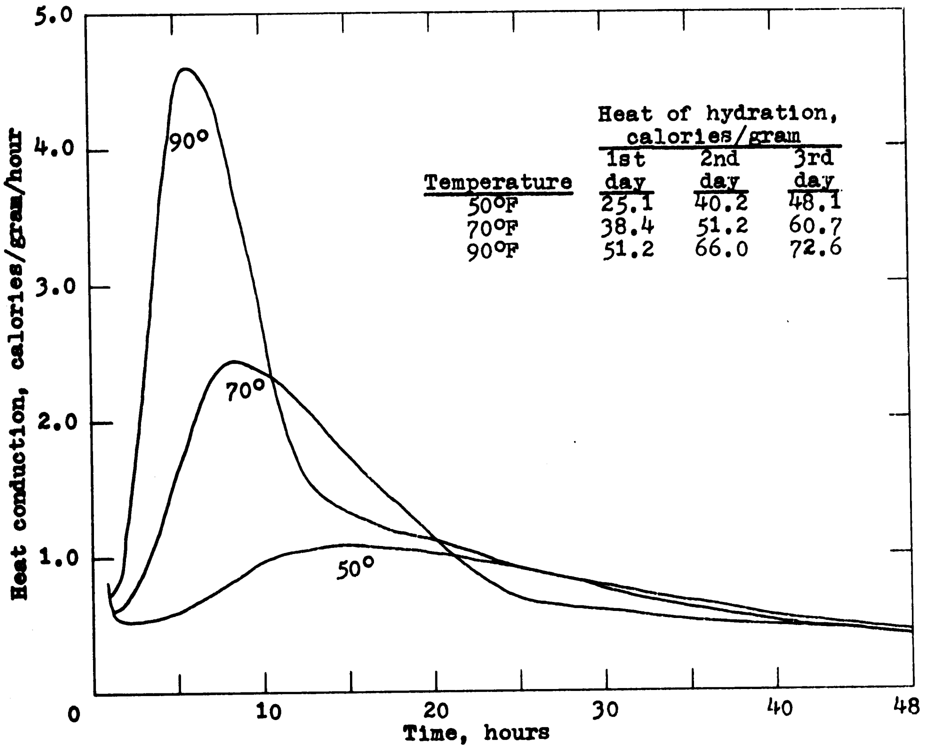
Chemical analysis	Percentage of portland cement		
	Laboratory number, Cement type		
	69-18, Type V	69-16, Type II	69-17, Type III
Oxides:*			
SiO_2	23.50%	22.00%	20.88%
Al_2O_3	3.68	4.60	5.64
Fe_2O_3	3.50	4.10	2.22
MgO	1.45	2.90	2.54
SO_3	1.88	1.80	3.34
Loss on ignition	0.93	0.80	0.93
Insoluble residue	0.19	0.17	0.32
Computed compounds:			
C_2S	30.78	26.86	21.00
C_3S*	48.50	48.00	51.60
C_3A	3.80	5.20	11.19
C_4AF	10.65	12.48	6.75
	Surface area, cm^2/gm		
Fineness* (Blaine)	3,830	3,580	4,815

*Data from cement manufacturer's test report.



Temperature	Heat of hydration, calories/gram 1st day	 2nd day	 3rd day
50°F	21.0	35.6	43.8
70°F	36.0	50.3	58.1
90°F	45.6	59.1	68.0

Figure 5. Rate of heat evolution plotted against time for type V cement and water-cement ratio of 0.4.



Temperature	Heat of hydration, calories/gram 1st day	 2nd day	 3rd day
50°F	25.1	40.2	48.1
70°F	38.4	51.2	60.7
90°F	51.2	66.0	72.6

Figure 6. Rate of heat evolution plotted against time for type II cement and water-cement ratio of 0.4.

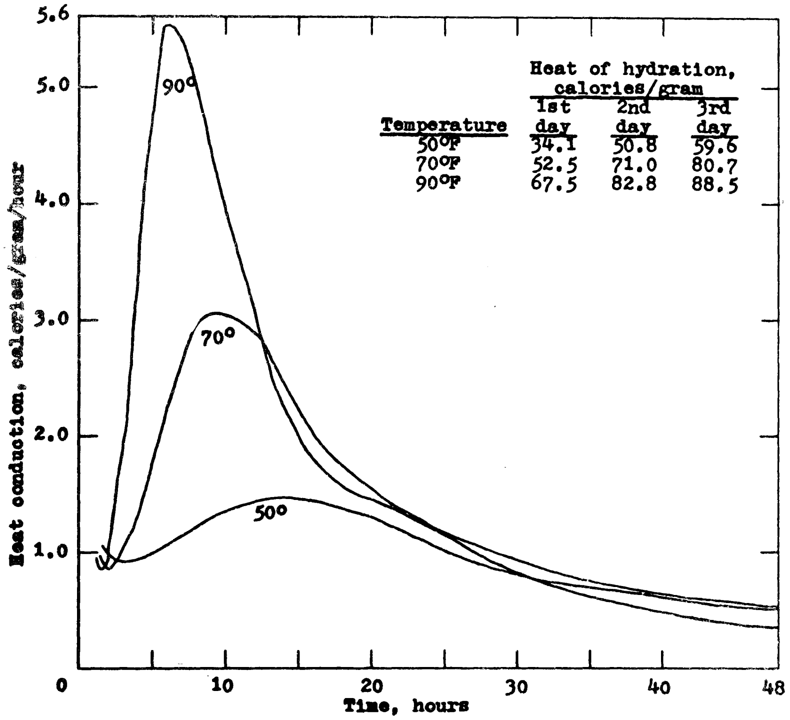


Figure 7. Rate of heat evolution plotted against time for type III cement and water-cement ratio of 0.4.

Aggregates

A crushed granite gneiss having a maximum size of 1 in. was used as coarse aggregate. The same type of aggregate, graded artificially, and recombined in quantities necessary for a single batch, was used throughout the experiment. The coarse aggregate gradation, in conformance with ASTM standard C 136-67(7), was as follows:

Coarse aggregate, number 57

	Sieve size	Percent retained	Cumulative percent retained
Coarse aggregate gradation used in concrete	1 in.	0	0*
	$\frac{3}{4}$ in.	20	20
	$\frac{1}{2}$ in.	37	57*
	$\frac{3}{8}$ in.	33	90
	#4	10	100
	#8	100	100
	#16	100	100
	#30	100	100
	#50	100	100
	#100	100	100
	Fineness modulus		7.10

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*Not included in fineness modulus.

Specific gravity = 2.84

All coarse aggregate was utilized in the saturated, surface-dry condition.

The fine aggregate was a washed, natural silica sand conforming to ASTM standard C 33-67.(7) The fine aggregate gradation was as follows:

Fine aggregate

Sieve size	Percent retained	Cumulative percent retained
4	1.91	1.91
8	11.00	12.91
16	15.72	28.63
30	23.25	51.88
50	24.66	76.54
100	19.80	96.34

Fineness modulus = 2.68

Specific gravity = 2.59

The same type and gradation of fine aggregate was used for the entire project.

Admixtures

The air-entraining agent was commercially marketed neutralized vinsol resin conforming to ASTM C 260.(7)

The retarding admixture was a water-reducing, retarding, nonair-entraining, metallic salt of hydroxylated carboxylic acid conforming to ASTM C 494, Type D.(7) The following proportions were used:

Above 85°F: 4 fl. oz. per bag of cement
65° to 85°F: 3 fl. oz. per bag of cement
Below 65°F: 2 fl. oz. per bag of cement

Calcium chloride ($CaCl_2$) flakes conforming to ASTM C 494, Type E and ASTM D98, Type 1 were used as the accelerator. The dosage rate used in the experiment was 1.7 percent by weight of cement.

Water

The mixing water was from the Charlottesville, Virginia, water supply and was used at various temperatures as necessitated by the several initial mixture temperatures.

Concrete Mixture Design

The recommended practice for selecting proportions for concrete (ACI 613-54)(9) was used for the proportioning of all mixtures. The concrete mixture schedules and specimen preparation schedules for this experiment are presented in Appendices A and B, respectively.

Mixing and Testing Procedures

Mixing and testing were in accordance with ASTM C 192. Mixing was accomplished in a Lancaster pan mixer as follows:

1. Fine aggregate and cement were placed in the mixer and mixed for 30 seconds.
2. Water was added and mixed for 1 minute.
3. Coarse aggregate was added and mixed for 2 minutes. Thus, the total initial mixing time was $3\frac{1}{2}$ minutes.

When a retarding or accelerating admixture was used, part of the mixing water contained the retarder or accelerator and the remaining water contained the air-entraining admixture. Immediately after initial mixing, the temperature of the concrete was recorded, then tests for slump, air content, and density were conducted in accordance with ASTM C 143, C 231, and C 138, respectively.(7) If the results of these tests did not meet the requirements previously established for the project, the batch was discarded. Provided the requirements were met, the concrete from the slump test was returned to the mixer and the concrete was remixed for 1 minute. Concrete used in the air test was always discarded.

All cylinders were made according to ASTM C 192 procedures. The two cylinders from each batch for autogenous curing were cast simultaneously so that fluctuations in temperature would be the same for both. The cylinders designated for moist curing were stored in a moist room meeting the requirements of ASTM C 511 and were cured according to ASTM C 192 procedures. For Phases I and III, test specimens were made at the time of cylinder molding for use in conducting time-of-set tests in accordance with ASTM C 403 procedures.

The cylinders for autogenous curing were formed in single-use molds, sealed with metal lids, and then placed inside three plastic bags. The plastic bags were used to ensure no moisture loss, to reduce further the volume of air between the cylinder and inner lining of the autogenous container, and to act as a handle for removing the cylinder from the autogenous container.

The cylinder, in the plastic bags, was lowered into the autogenous container, and the plastic bags were sealed with a wire tie. As soon as the plastic bags were sealed, the autogenous container was closed and sealed with the lever-lock ring. All autogenous curing containers were sealed in less than 30 minutes after time ZERO* and were then stored

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*Time "ZERO" is the time at which the mixing water is added to the cement.

in a room in which the ambient temperature was the same as the initial mixture temperature of the concrete. For Phase III the room temperature was kept at 50°F, 70°F, or 90°F, to correspond to the respective initial mixture temperature.

Autogenous cylinders were cured for 47 hours, then were removed from the containers and allowed to cool at room temperature for 1 hour before capping. The cylinders were capped at 48 hours and tested in compression at 49 hours, according to ASTM C 617 and C 39 procedures, respectively. At the prescribed time of test, the standard moist cured cylinders were removed from the moist room, capped, and tested according to ASTM C 617 and C 39.

Temperature Monitoring

A pilot study was undertaken to determine the number of thermocouples needed in each cylinder to describe accurately the autogenous adiabatic temperature rise. Seven cylinders were made in metal single-use molds for investigation of various facets of temperature and moisture in concrete cylinders.

Two of these cylinders were instrumented with six thermocouples each, as shown in Figure 8. The initial concrete temperature was 67°F, and the tests were conducted at a room temperature of 72°F. The only difference between the two cylinders was that one was cured in still air while the other was cured in the draft of a low speed fan at a distance of approximately 7 feet from the fan, which represented a more severe curing condition. Temperature data were recorded for 2 days, and the results showed an average differential of 0.9°F between the interior and exterior thermocouples in the draft cured cylinder. The range in differential temperatures was from 0°F to 2.5°F. The maximum concrete temperature was 80°F, and the maximum difference between the bottom and top thermocouples was 1.5°F. The temperature in the top of the cylinder was less than in the bottom, and the bottom temperature was less than that in the middle of the cylinder.

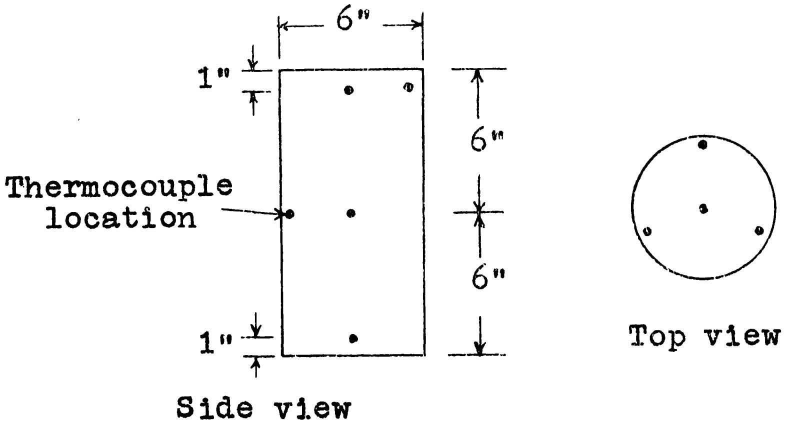

Figure 8. Locations of thermocouples in concrete cylinders used in temperature pilot study.

In the cylinder cured in still air, the maximum temperature differential between the interior and exterior was 0.2°F, with a range from 0°F to 1°F. Again, the maximum concrete temperature was 80°F, and the maximum difference between the top and bottom of the cylinder was 1.5°F. The temperatures in the top and bottom of the cylinder were equal but below the temperature in the middle of the cylinder.

As a result of this pilot study, one copper-constantan thermocouple located in the center of the cylinder at a depth of 6 in. into the cylinder was used to record temperatures for the main investigation. The test results from the pilot study also showed that the temperature readings taken every hour would be sufficient; but since the temperature readings were recorded automatically, the interval was set for every half-hour.

All 96 thermocouples used in the experiment were tested under various controlled temperature conditions to check fabrication and variability. The maximum variability as recorded by the Honeywell multipoint temperature recorder was $\pm\frac{1}{4}$°F.

RESULTS

The purpose of this section is to analyze the relationships between strengths of accelerated autogenously cured cylinders and those of moist cured cylinders at 28 days and 91 days, and to examine the influence that variables such as cement type, cement factor, water-cement ratio, admixtures, and initial mixture temperature have on these strengths.

Variability

In order to reduce the within-batch and between-batch variabilities, 74 batches of concrete were discarded for failing to meet the requirements previously established for the project. This procedure reduced the variation resulting from improper proportions, mixing procedures, and other factors. Testing variations for air content and slump determination were minimized by employing the same operators for each test throughout the project. The initiation of autogenous and moist curing procedures and the times for removing, capping, and testing cylinders were all within ±15 minutes of the designated times.

The precision statement for ASTM proposed "Tentative Method of Accelerated Strength Testing" for Procedure C (autogenous curing method) is as follows:

> Z.1 The single-laboratory coefficient of variation (1S%) has been determined as 3.6 percent for a pair of cylinders cast from the same batch. Therefore, results of two properly conducted strength tests by the same laboratory on the same materials should not differ by more than 10.0 percent of their average.

Z. 2 The single-laboratory, multi-day coefficient of variation (1S%) has been determined as 8.7 percent for the average of pairs of cylinders cast from single batches mixed on two days. Therefore, results of two properly conducted strength tests by the same laboratory on the same materials should not differ by more than 25.0 percent of their average (D2S%).

The format for this precision statement was taken from the proposed "Recommended Practice for Preparing Precision Statements for Test Methods for Construction Materials", which supplements ASTM Recommended Practice E-177, "Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material".(7) The numerical values were established from the round robin testing program conducted by Subcommittee II-i of ASTM Committee C-9.

The maximum allowable range for within-batch variation is $\bar{\bar{X}} \pm E\bar{\bar{X}}$, where E = 10.0 percent, which is the error of the average of the sample, and $\bar{\bar{X}}$ = the average strength value; the maximum allowable range for between-batch variation is $\bar{\bar{X}} \pm E\bar{\bar{X}}$, where E = 25.0 percent.

Table IV lists the ranges of E values and the average E values obtained for each of the three phases in the experiment.

The within-batch variations for the autogenously cured cylinders and the 28-day moist cured cylinders are shown in Table V. It is interesting to note the variability between the autogenous and 28-day cylinders. The 28-day strengths are approximately 2.3 times as variable as the autogenous strengths inasmuch as the curing time is greater for the 28-day moist cured cylinders; the longer curing period allowed more time for variations in curing conditions to take place. In Table V the error of the average (E) used in Table IV is expressed in pounds per square inch instead of percent. For example: For a total of 24 batches (batches 1 and 2 for the 12 mixtures) in Phase 1, the actual average range (E) was ±25 psi, with the values of E ranging from ±0 psi to ±110 psi.

It is evident from Tables IV and V that the variability resulting from experimental procedures was held to a minimum.

TABLE IV

STATISTICAL VARIATION OF CONCRETE STRENGTHS FOR PHASES I, II, AND III

Phase	Actual values of E, percent					
	Within batch				Between batch	
	Batch 1		Batch 2			
	Average[a]	Range	Average[a]	Range	Average[a]	Range
I	0.6	0 - 0.9[b]	1.0	0 - 2.3	1.8	0.3 - 2.0[c]
II	1.4	0 - 3.3	0.8	0 - 2.1[d]	4.6	0.1 - 13.8[e]
III	0.8	0 - 2.3	1.7	0 - 3.3[f]	2.5	0.3 - 6.2

[a] "Average" value includes exception value, but "Range" does not.

[b] One exception, 3.4%.

[c] One exception, 4.8%.

[d] One exception, 4.3%.

[e] One exception, 24.6%.

[f] One exception, 4.7%.

TABLE V

WITHIN-BATCH VARIATIONS FOR AUTOGENOUSLY CURED CYLINDERS AND 28 DAY MOIST CURED CYLINDERS IN TERMS OF ERROR OF AVERAGE (E), EXPRESSED IN POUNDS PER SQUARE INCH FOR PHASES I, II, AND III

Phase	Error of average, $\bar{X} \pm E$	Cylinder strength, psi	
		Autogenous cured	28-day moist cured
I 24 batches	Average E	±25	±60
	Range E	±0 to ±110	±5 to ±145
II 36 batches	Average E	±38	±85
	Range E	±0 to ±135	±0 to ±540
III 36 batches	Average E	±32	±77
	Range E	±0 to ±115	±5 to ±275

Correlation Between Autogenous Cured Strengths and Moist Cured Strengths for 28 and 91 Days

Since different concretes have different strength potentials, it is meaningful to present the strength test results in terms of the efficiency (strength ratio) of the autogenous curing method rather than in terms of actual strengths. The efficiency is defined as the ratio of accelerated strength to moist cured strength.

The 28-day efficiencies obtained are shown in Table VI for all phases of the experiment. The range of efficiencies for the experiment was from 30.7 to 76.7 percent, with an average of 62 percent for all mixture variables, including initial mixture temperature.

TABLE VI

INFLUENCE OF MIXTURE VARIABLES ON EFFICIENCY OF AUTOGENOUS CURING

Initial mixture temperature, °F	Cement type	28-day efficiency, percent								
		Cement content, lb/cu yd			Water-cement ratio			Admixtures		
		450	550	650	0.4	0.5	0.6	A	A-R	A-A
50	V		31.1	30.7						
	II		35.3	38.3						
	III		66.1	66.6						
70	V		47.0	47.9						
	II	49.8	62.1	70.6	66.3	64.2	59.9	59.7	66.5	70.2
	III	70.3	72.4	74.3	74.1	72.2	70.2	69.6	71.7	75.2
90	V		51.6	51.9						
	II		56.6	58.9						
	III		68.9	64.6						

For an increase in cement content and a decrease in the water-cement ratio, the efficiency increased. For the type V cement the efficiency increased as the IMT increased; for types II and III there was an increase in efficiency between 50°F and 70°F, but a decrease occurred between 70°F and 90°F. The efficiency increased as the admixtures were changed from air only to air plus retarder to air plus accelerator. The efficiencies for the type III cement were the least affected by the mixture variables.

The efficiency of the autogenous method of curing was higher than the efficiencies of the three water-bath accelerated curing methods applied to similar mixtures by McGhee.(1) For comparable mixtures, the efficiencies for each of the four accelerated methods are shown in Table VII.

TABLE VII

EFFICIENCIES OF FOUR METHODS OF ACCELERATED CURING

Method	Curing temperature	Age accelerated curing began	Duration of accelerated curing	Efficiency, percent
A	Water 95°F	Immediately	24 hours	40
B	Water 212°F	23 hours	$3\frac{1}{2}$ hours	48
C	Water 212°F	4 to 6 hours	15 hours	61
D	Autogenous	$\frac{1}{2}$ hour	$46\frac{1}{2}$ hours	67

As noted earlier, selected cylinders were instrumented for continuous measurement of temperature during the autogenous curing period. These temperature data are discussed in Part III of this report.(10) Because of their important influences on the measured strengths, two aspects of the temperature data, i.e., maximum autogenous temperature and the total heat generated, will be discussed here. A typical time-temperature curve is shown in Figure 9, on which the following important parameters are defined:

A = Maximum autogenous temperature, °F
B = Autogenous temperature increase (+ ΔT), °F
C = Autogenous temperature decrease (- ΔT), °F
D = Time to maximum temperature, hours
E = Initial rate of temperature rise, °F per hour
F = Average time of initial rate of temperature rise, hours
G = Final rate of temperature rise, °F per hour
H = Average time of final rate of temperature rise, hours
I = Change from initial to final rate of temperature rise, hours
J = Rate of temperature rise between initial and final set, °F per hour
K = Total heat generated, i.e., measured area, °F x hours

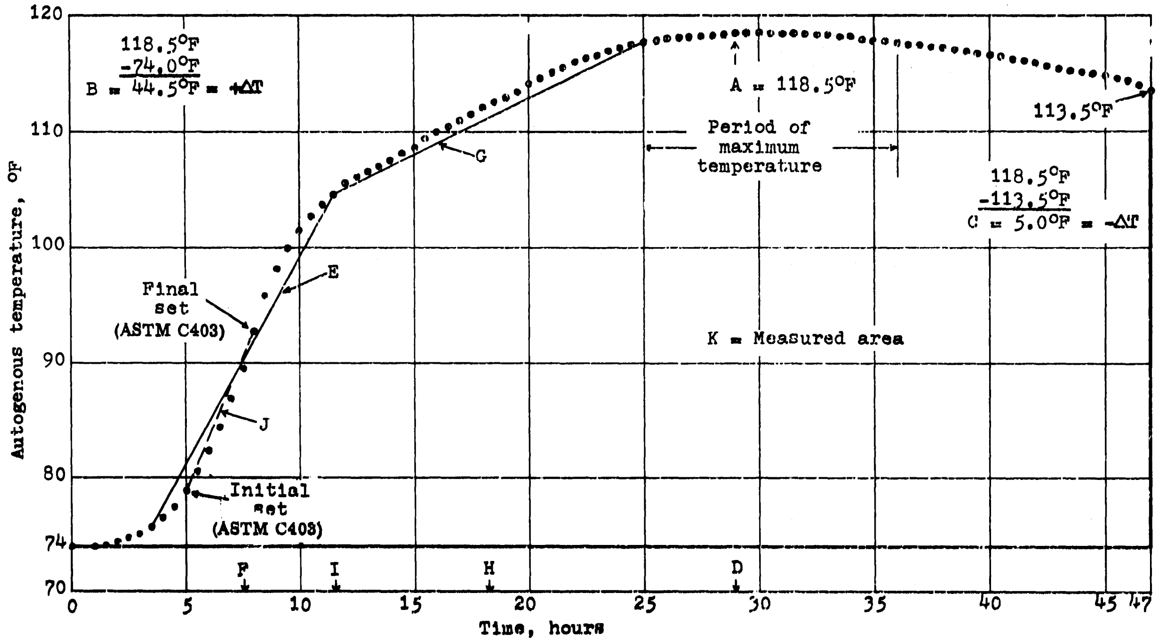

Figure 9. Typical temperature-time curve for autogenously cured concrete cylinder.

The data points in Figures 10 through 15 are the average of either two or four values, as follows:

Average of 2 values	Average of 4 values
Maximum autogenous temperature	28-day efficiency
Autogenous temperature increase	28-day strength
Total heat generated	91-day efficiency
	Autogenous strength

Figures 10 and 11 show typical results for two temperature parameters, maximum autogenous temperature and total heat generated; the remaining temperature parameters were closely related to these two, as can be deduced from Figure 9.

The efficiencies for this experiment reached maximum values and showed a trend toward decreasing for subsequent increases for various temperature factors. From the data presented in Figure 10, it is estimated that the 28-day efficiency reaches a maximum value of approximately 75 percent ± 5 percent at a maximum autogenous temperature of 145°F ± 5°F. This temperature level was not attained in Phase II. The same maximum efficiency value is reached for a total heat generated from 45 to 50 square inches (2,250°F x hr. to 2,500°F x hr.), as shown in Figure 11.

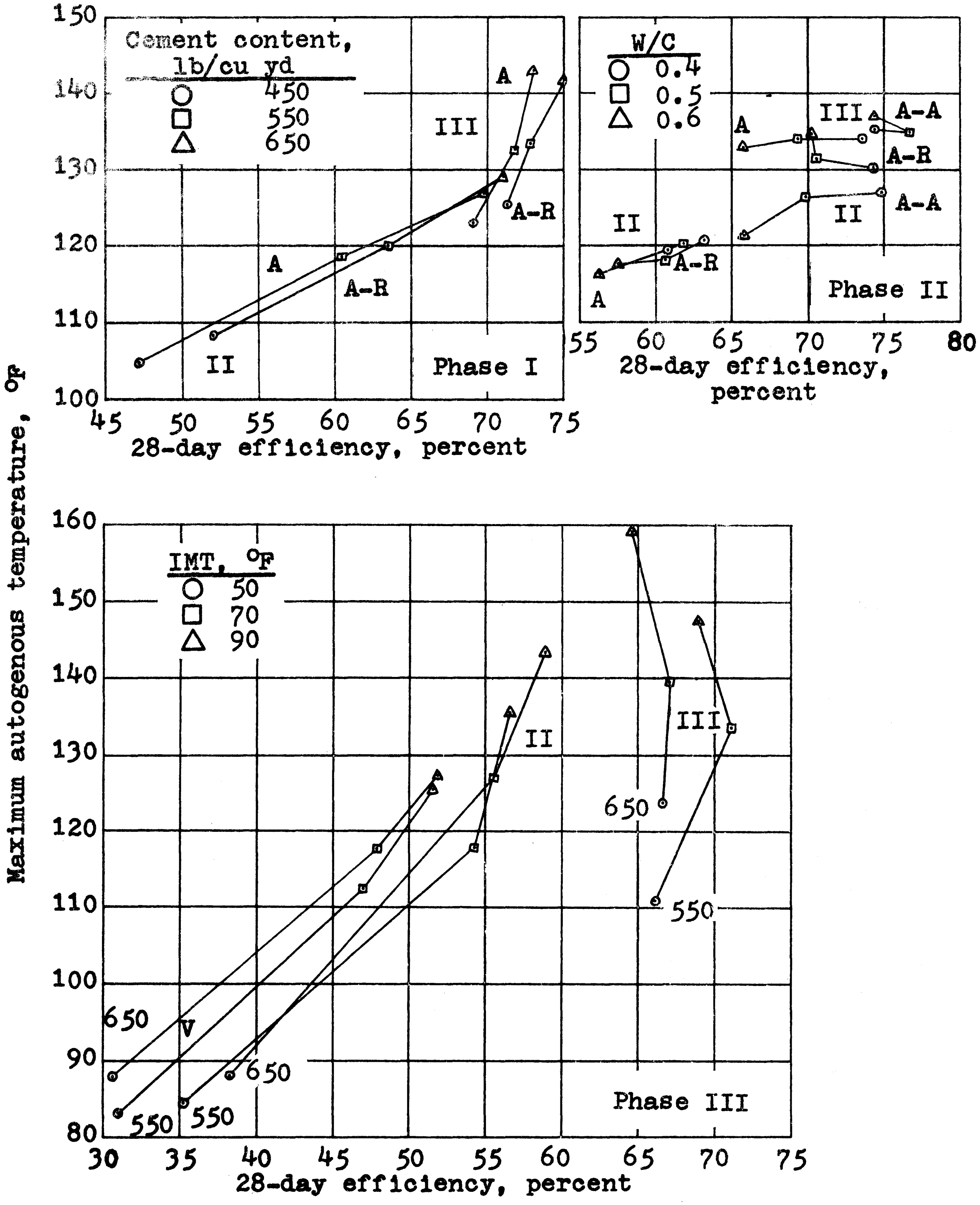

Figure 10. Relationship between maximum autogenous temperature and 28-day efficiency for all phases.

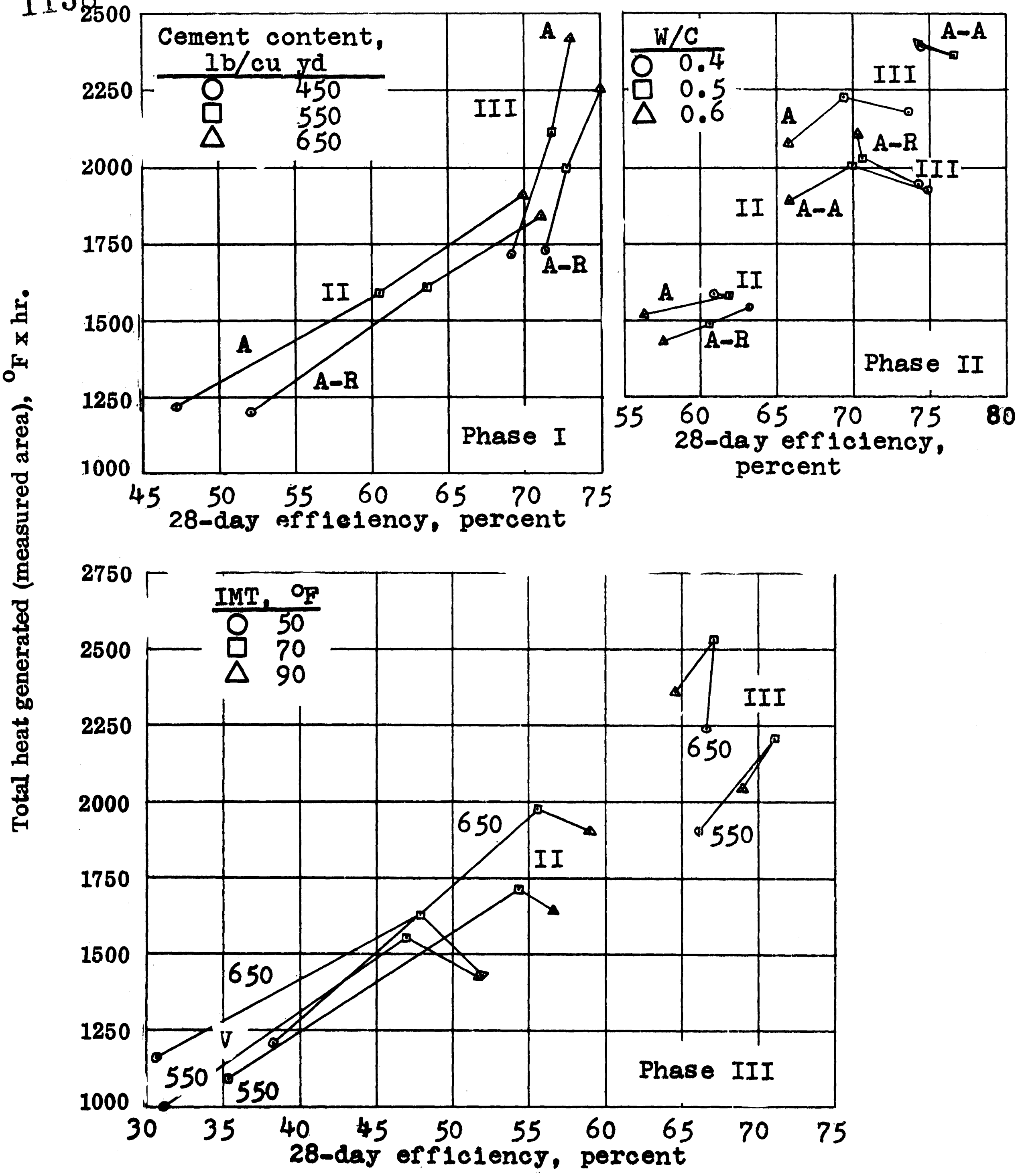

Figure 11. Relationship between total heat generated (measured area) and 28-day efficiency for all phases.

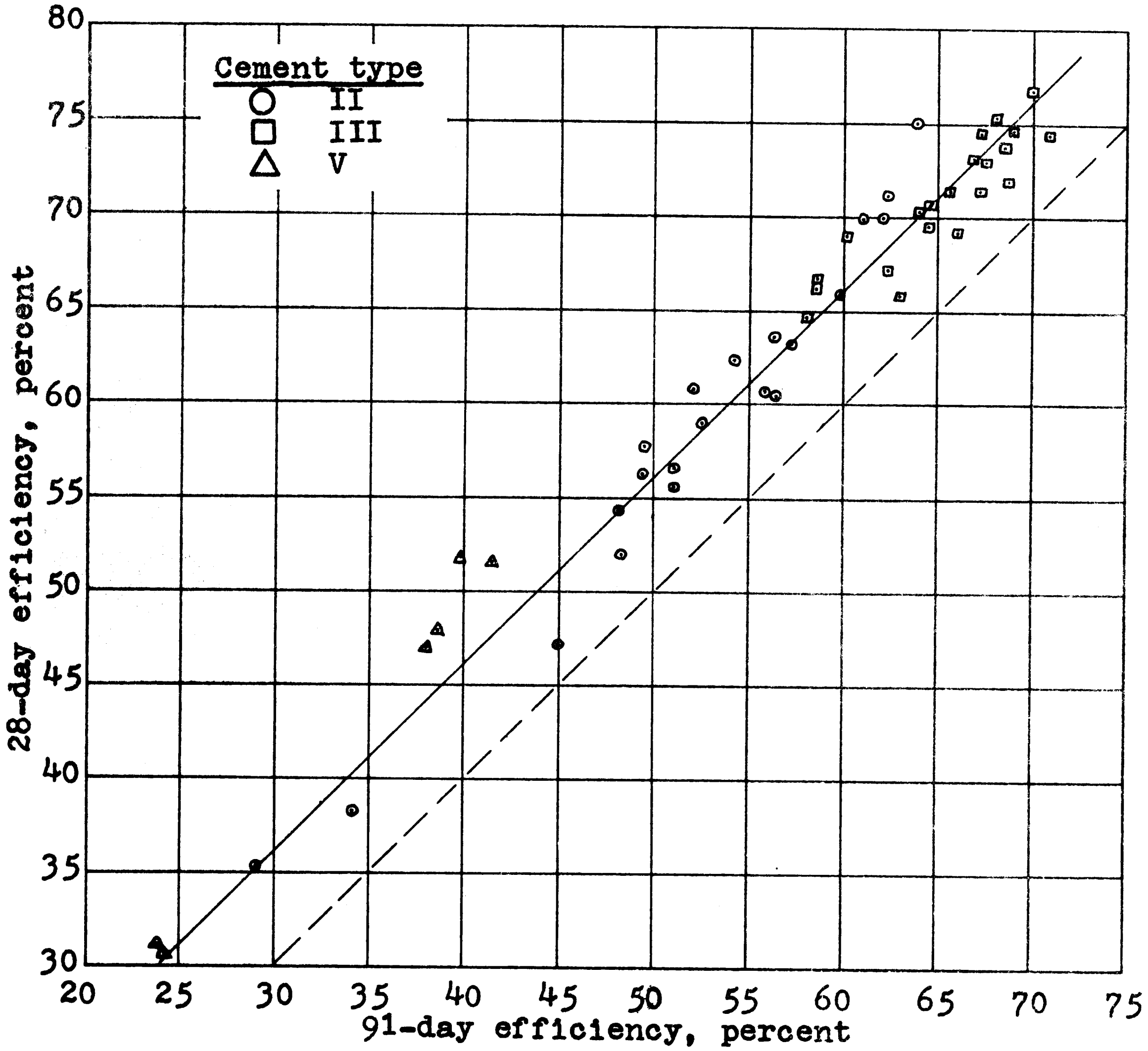

Figure 12. Relationship between 28-day and 91-day efficiencies for all phases.

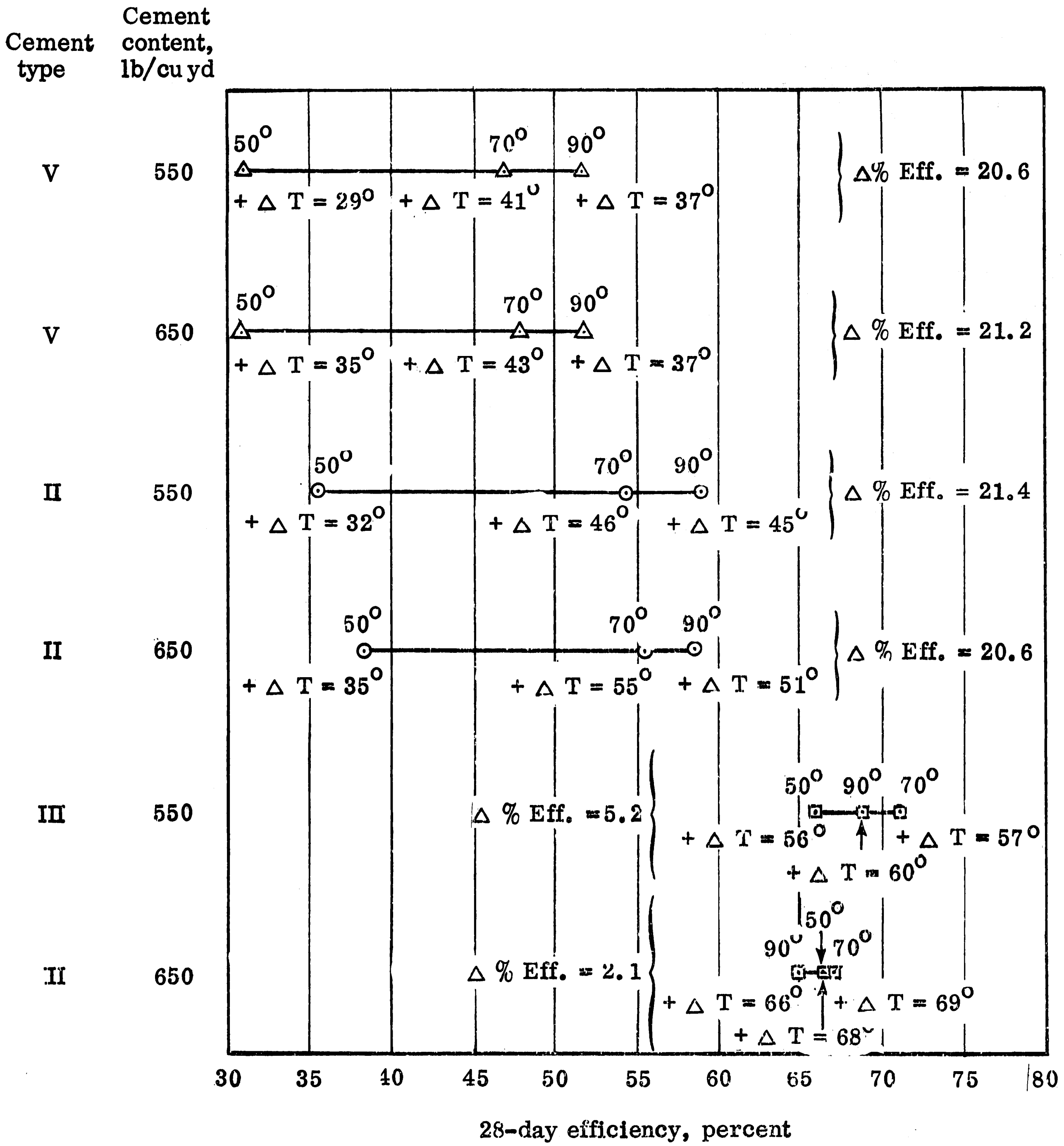

Figure 13. Relationship of autogenous temperature increase (+ Δ T), 28-day efficiency, and initial mix temperature to three cement types used in Phase III.

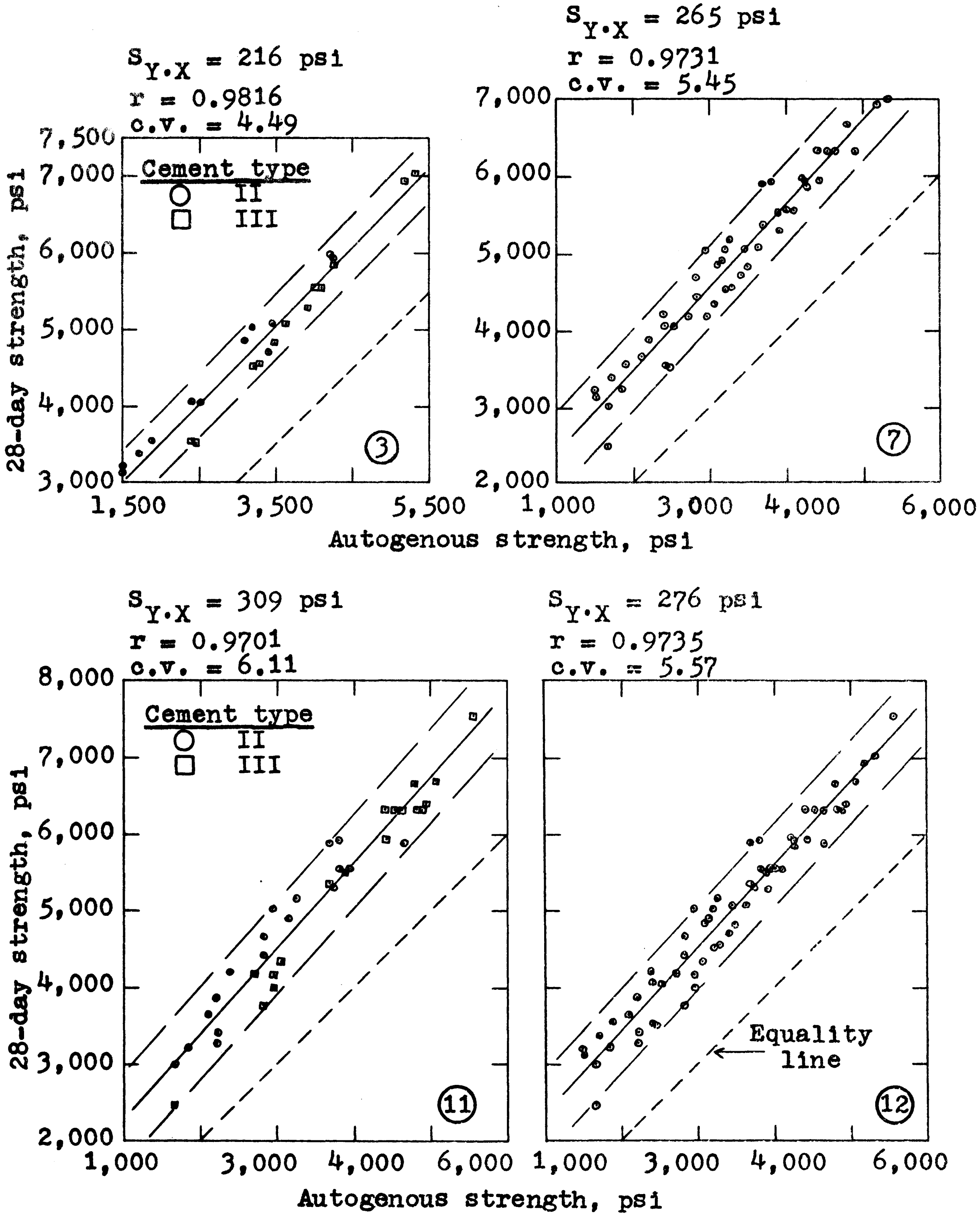

Figure 14. Relationship between autogenous and 28-day strengths for Phases I and II — Computer Runs ③ , ⑦ , ⑪ , and ⑫ of Table VIII.

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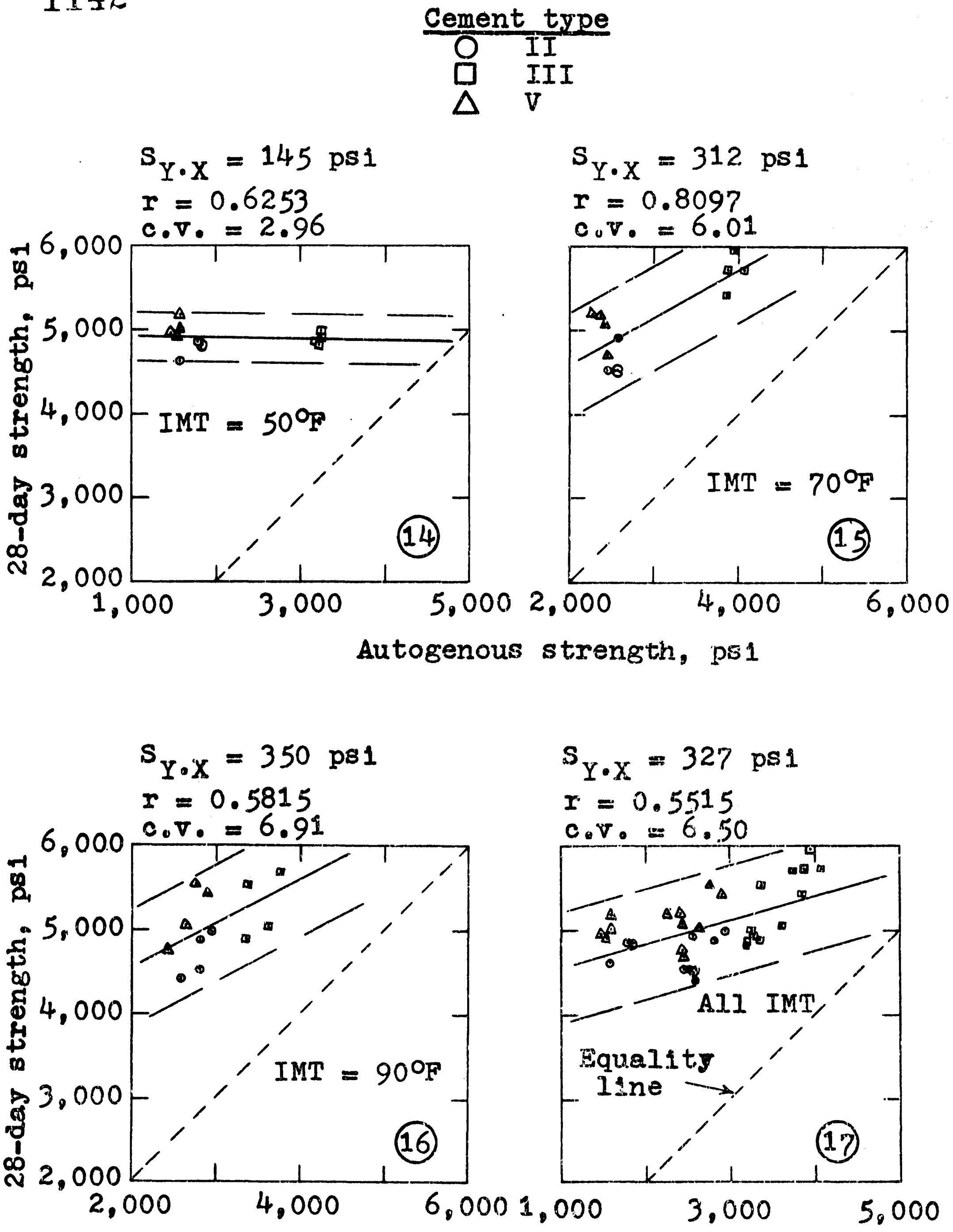

Figure 15. Relationship between autogenous and 28-day strengths for Phase III — Computer Runs ⑭ through ⑰ of Table VIII.

This same maximum efficiency value of 75 percent was reached for the following temperature and moisture variable values as discussed in detail in Parts III and IV of this report.(10, 11)

Initial rate of temperature rise: 6°F per hour
Autogenous temperature increase ($+\Delta T$): 65°F
Time to maximum autogenous temperature: 10 to 15 hours
Total water fixed: approximately 2.9 percent

The 75 percent efficiency value corresponded to an autogenous cylinder strength level from 5,000 to 5,500 psi. The investigator postulates that for concrete mixes designed for higher strengths than those tested, the maximum efficiency would be reached at a somewhat higher strength level than obtained in this experiment but that the 75 percent efficiency level will not fluctuate substantially.

The water-bath methods, as reported by McGhee, showed that a water-bath curing temperature between 165° and 180°F represented an optimum curing temperature for the mixtures tested.(1) For the autogenous method, the optimum maximum autogenous temperature was between 140°F and 150°F for the mixtures tested.

The existence of an optimum temperature is not unexpected and may be the result of several mechanisms. One would be the result of the reduced solubility of the gypsum as the curing temperature increases. As the concrete curing temperature rises, the setting process is accelerated by the high curing temperatures, which results in increased strength. This increased rate of reaction requires, for the proper retardation of the C_3A, that the availability of gypsum be increased beyond that necessary for the proper setting of normal moist cured concrete.(12) Nevertheless, with increasing temperatures the solubility of gypsum decreases rather than increases.(12, 13) Brown(12) showed that the solubility of gypsum reaches a maximum at approximately 100°F and begins to decrease rapidly at approximately 150°F. In addition to the insolubility of the gypsum, the reduction in strength is further aggravated by the formation of a thick, dense layer, or shell, around the cement grains (C_2S and C_3S), which retards the subsequent hydration and strength development.(14)

The relationship between autogenous cylinder strength and 28- and 91-day moist cured strengths is shown in Figure 12 in terms of the relationship between 28- and 91-day efficiencies. The range of 91-day efficiencies for all phases was from 23.8 to 70.0 percent with an average of 55.8 percent, which is 6.2 percent below the average efficiency for 28-day strengths.

Figure 13 shows the relationships among autogenous temperature increase ($+\Delta T$), 28-day efficiency, and IMT for the three cement types and two cement contents used in Phase III. It can be seen that low initial mixture temperatures have a significant influence on the efficiency (strength ratio) at 28 days. As shown in Figure 13 the type III cement is the least affected by temperature parameters in that the range of autogenous temperature increase ($+\Delta T$) is only 4°F for the different IMT's, as compared with 12°F and 20°F for types V and II, respectively. The differential in efficiency ($\Delta\%$) for type III is 5.2 percent, as compared with 21.2 and 21.4 percent for types V and II, respectively.

Also, for the type III cement, the efficiency reaches a maximum and then decreases, as shown by the fact that the IMT data points no longer are in ascending order. For type III cement and a cement content of 550 lb/cu yd, the 90°F IMT point falls between the 50°F and 70°F points; but as the $+\Delta T$ increases from approximately 58°F to approximately 68°F (cement content, 650 lb/cu yd), the 90°F IMT point drops below both the 50°F and 70°F points. This phenomenon was explained in the discussion of Figures 10 and 11.

Strength results can also be considered in terms of the correlation between accelerated and 28-day concrete strengths. Standard statistical methods(9, 15, 16, 17) were used to determine the line of best fit for predicting standard moist cured 28-day strengths from autogenous 48-hour strengths. Computer regression analysis furnished the solid straight line through the data points presented in Figures 14 and 15.

Table VIII shows the breakdown of data used in correlating the strength results from all phases of the experiment, and the results of the regression analyses.

The correlation between the autogenous and 28-day moist cured strengths is highly significant. Even the results of Phase III (computer run number 13, Table VIII), which displayed relatively wide dispersion, yielded a significant correlation (this dispersion of Phase III data is attributable to the different initial mix temperatures). This high degree of correlation for data from all phases reduces the severity of the effect of IMT on strength when comparisons are made with the range of correlation coefficients obtained by other investigators using various accelerated curing methods. The ranges of correlation coefficients and standard errors, as reported in references 1, 2, 3, and 20, are 0.52 to 0.98 and 200 to 600 psi, respectively.

Figure 14 shows the relationships between autogenous and 28-day strengths for Phases I and II. These are very similar to those presented by others.

Figure 15 shows the relationships between autogenous and 28-day strengths for Phase III, in which the effect of the IMT on strength is evident. For an IMT of 50°F there is no relationship between the two measures of strength. This resulted from the fact that the IMT influenced the autogenous strength of the concrete but had no influence on the 28-day strengths since they were cured at 73°F. At an IMT of 70°F, the relationship between strengths was similar to those relationships shown in Figure 14. Note that in Figure 15 the IMT's of 50°F and 70°F had little influence on the 28-day strengths for cement types II and V but there was an influence on the 28-day strengths of the type III cement. When the IMT was increased from 50°F to 70°F, there was an increase in 28-day strength for the type III cement of approximately 900 psi. For an IMT of 90°F the influence of the IMT on the strength relationship was the same for both autogenous cured and 28-day cured cylinders. Figure 15 also shows the strength relationship for all IMT data combined and indicates that changes in initial mix temperature tend to decrease the slope of the regression curve.

TABLE VIII

BREAKDOWN OF DATA USED IN CORRELATING STRENGTHS FROM ALL PHASES AND THE RESULTS OF THE REGRESSION ANALYSES

Computer run number	Phase	Mixture*	Regression curve,** $Y = aX + b$	Standard error of Y on X, $S_{Y \cdot X}$ = psi	Correlation coefficient, r	Coefficient of variation for σ_{28}	Number of values
1	I	a - f	$\sigma_{28} = 0.9995 \sigma_A + 1658$	138	0.9913	3.12	12
2	I	g - l	$\sigma_{28} = 1.2309 \sigma_A + 548$	60	0.9987	1.15	12
3	I	a - l	$\sigma_{28} = 1.0244 \sigma_A + 1458$	216	0.9816	4.49	24
4	II	a, b, d, e, g, h	$\sigma_{28} = 1.3697 \sigma_A + 769$	133	0.9911	2.95	12
5	II	j, k, m, n, p, q	$\sigma_{28} = 1.2574 \sigma_A + 561$	187	0.9903	3.50	12
6	II	runs 4 and 5	$\sigma_{28} = 1.1409 \sigma_A + 1198$	290	0.9709	5.89	24
7	I, II	runs 3 and 6	$\sigma_{28} = 1.0795 \sigma_A + 1338$	265	0.9731	5.45	48
8	II	c, f, i, l, o, r	$\sigma_{28} = 1.2014 \sigma_A + 636$	225	0.9881	4.22	12
9	II	a, d, g, j, m, p	$\sigma_{28} = 1.1485 \sigma_A + 1113$	251	0.9796	5.54	12
10	II	b, e, h, k, n, q	$\sigma_{28} = 1.0900 \sigma_A + 1440$	333	0.9568	6.27	12
11	II	a - r	$\sigma_{28} = 1.1214 \sigma_A + 1157$	309	0.9701	6.11	36
12	I, II	All mixtures	$\sigma_{28} = 1.0852 \sigma_A + 1273$	276	0.9735	5.57	60
13	I, II, III	All mixtures	$\sigma_{28} = 0.7945 \sigma_A + 2491$	542	0.8319	10.87	96
14	III	b, c, e, f, h, i	$\sigma_{28} = 0.0110 \sigma_A + 4922$	145	0.6253	2.96	12
15	III	k, l, n, o, q, r	$\sigma_{28} = 0.5566 \sigma_A + 3472$	312	0.8097	6.01	12
16	III	t, u, w, x, z, z1	$\sigma_{28} = 0.5355 \sigma_A + 3465$	350	0.5815	6.91	12
17	III	runs 14, 15, and 16	$\sigma_{28} = 0.2821 \sigma_A + 4264$	327	0.5515	6.50	36

*See Tables X - XII.

** σ_{28} = Estimated 28-day moist cured strength

σ_A = 2-day autogenous cured strength

The influence of the IMT on autogenous strength in terms of the percent change in strength as the IMT increases from one level to a higher level is shown in Table IX. The positive (+) values indicate an increase in strength, whereas the negative (-) values indicate a decrease. In other words, at lower temperatures the magnitude of the strength increase is inversely proportional to the potential of the mixture to evolve heat. The strength increase for the type V cement was one-quarter as great from 70°F to 90°F as it was from 50°F to 70°F. For the type II cement, the autogenous strength increase from 70°F to 90°F was one-seventh as great as it was from 50°F to 70°F, and for the type III cement there was a 22 percent increase from 50°F to 70°F and an 11 percent decrease in strength from 70°F to 90°F.

TABLE IX

INFLUENCE OF INITIAL MIXTURE TEMPERATURES ON AUTOGENOUS STRENGTHS IN TERMS OF PERCENT CHANGE IN STRENGTH AS INITIAL MIXTURE TEMPERATURE INCREASES

Cement type	Cement content, lb/cu yd	Percent change in strength as initial mixture temperature increases from —	
		50°F to 70°F	70°F to 90°F
V	550	+53.8	+17.2
	650	+54.4	+ 7.4
II	550	+53.7	+ 3.5
	650	+36.3	+10.1
III	550	+22.7	- 7.0
	650	+20.4	-14.0

Figure 16 presents a comparison of correlating curves developed for some of the more widely used accelerated strength testing procedures. Curve ① represents the line of equality equal to an efficiency of 100 percent. Curve ② is that of Smith and Tiede for autogenous accelerated curing(2), and curve ③ represents the results obtained by the investigator for all data of Phases I and II (computer run 12, Table VIII), which are comparable to that obtained by Smith for an IMT of 73°F. The remaining curves in Figure 16 are as follows:

④ — ASTM, Committee C-9, average of round robin results (autogenous)

⑤ — Thompson (24 hours hot water at 95°F: cubes)

⑥ — Akroyd modified boiling (24 hours normal curing + 3½ hours boiling: cubes)

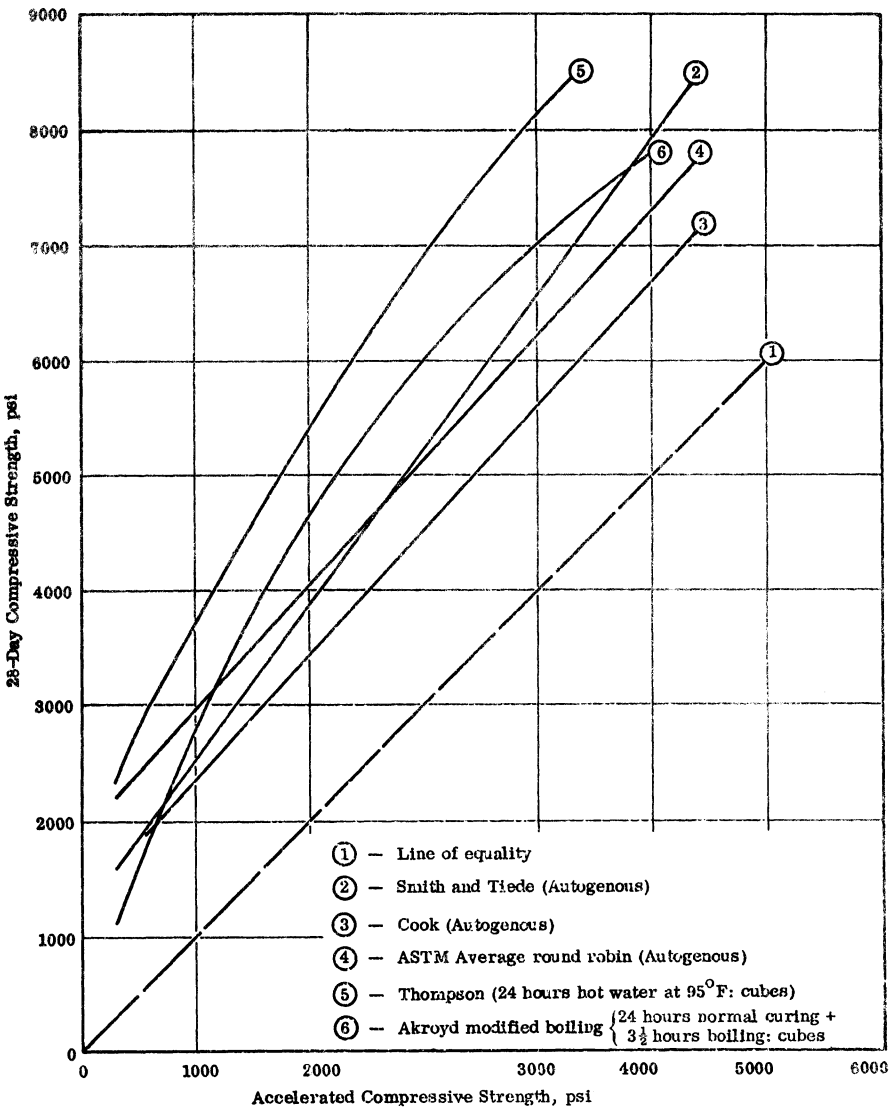

Figure 16. Comparison of some of the more promising or widely used accelerated strength testing procedures.

The efficiency indicated by curve ③ is considerably higher than those reflected by the other curves. In comparing curves ② and ③ , the difference in efficiencies probably is due primarily to the increased insulating properties of the autogenous containers used in this experiment and not necessarily to the methods and/or materials used in making the concrete cylinders. For an accelerated compressive strength of 1,000 psi the efficiency of both curves ② and ③ is approximately 41 percent but at 5,000 psi the efficiencies for curves ② and ③ are 63 percent and 75 percent, respectively. Since the heat evolved in curing 5,000 psi concrete is much greater than that of 1,000 psi concrete, the influence of the insulating ability of the autogenous container to retain the heat evolved is more prevalent for 5,000 psi concrete than for 1,000 psi concrete. In fact, the range of efficiencies is less among all the curves for an accelerated strength of 1,000 psi concrete than it is for 5,000 psi concrete.

Influence of Mixture Variables and Curing Parameters on Strength

The influence of mixture variables and temperature parameters on autogenous strength is presented in Part III of this report(10) and the influence of moisture parameters on autogenous strength is presented in Part IV.(11)

OBSERVATIONS AND CONCLUSIONS

1. The range of efficiencies (ratio of accelerated strength to 28-day moist cured strengths) obtained in this investigation for autogenous curing for all mixtures was from 30.7 to 76.7 percent, with an average of 62 percent.

2. The range of efficiencies for all tests at an initial mixture temperature of 70°F was from 47.0 to 76.7 percent, with an average of 65.6 percent.

3. The efficiency of the autogenous method of curing was higher than the efficiencies of the various water-bath accelerated curing methods investigated by McGhee and others.(1, 2, 3, 4, 18, 19, 20)

4. For given materials the efficiencies were not constant. For an increase in cement content or a decrease in water-cement ratio, the efficiency with respect to 28-day moist cured cylinders increased, the cement content having the predominant influence. For the type V cement the efficiency increased as the initial mixture temperature increased; for types II and III there was an increase in efficiency between initial mixture temperatures of 50°F and 70°F, but a decrease occurred between 70°F and 90°F. The efficiencies for the type III cement were the least affected by the mixture variables.

5. The autogenous accelerated curing method resulted in a very high degree of correlation with the 28-day moist curing method. As shown in Table VIII, the correlation coefficients, for the initial mixture temperature of 70°F, ranged from 0.9568 to 0.9987, with an average value of 0.9804.

6. As the initial mixture temperature increased from 50°F to 70°F, the autogenous temperature increase $(+\Delta T)$, total heat generated, and autogenous strength increased. But as the initial mixture temperature increased from 70°F to 90°F, these three parameters decreased. This reduction in strength as temperature increases beyond 70°F can be attributed primarily to the reduced solubility of the gypsum and the encapsulation of the cement grains.

7. For comparable concretes, greater strengths were obtained with the autogenous container used in this investigation than those obtained in Canadian studies.(2, 4) These increases in strength resulted from the container's increased ability to retain the heat of hydration and was not a result of differences in laboratory procedures or materials.

8. The time of initial set can be used to predict the time to maximum autogenous temperature within ±20 percent for test procedures similar to those used in this investigation.

9. There is evidence to show that the 28-day efficiency, at least for the autogenous containers used in this experiment, reached a maximum value of approximately 75 percent at the corresponding values for moisture and temperature variables, as follows:

   Maximum autogenous temperature = 145°F ± 5°F

   Total heat generated (measured area) = 2,250°F x hr. to 2,500°F x hr.

   Initial rate of temperature rise = 6°F per hour

   Autogenous temperature increase ($+\Delta T$) = 65°F

   Time to maximum temperature = 10 to 15 hours

   Total water fixed = 2.9 ± 0.4 percent

   Autogenous cylinder strength level = 5,000 to 5,500 psi

   It is postulated that for concrete mixtures proportioned for higher strengths than those tested, the maximum efficiency would be reached at a somewhat higher strength level than was obtained in this experiment but that the maximum efficiency level will not fluctuate substantially from 75 percent.

10. For increases in initial mixture temperature, the autogenous strength increase was one-quarter as great from 70°F to 90°F for the type V cement as it was from 50°F to 70°F. For the type II cement the autogenous strength increase from 70°F to 90°F was one-seventh as great as it was from 50°F to 70°F, and for the type III cement there was a 22 percent increase from 50°F to 70°F and an 11 percent decrease in strength from 70°F to 90°F.

11. The reduction of the total length of time for autogenous curing by at least 8 hours seems feasible.

12. The correlation coefficient for all phases of the experiment and for all initial mixture temperatures investigated was 0.8319, which is significant. This high degree of correlation for all phases reduces the severity of the effect of initial mixture temperature on strength when compared with the range of correlation coefficients obtained by other investigators using various accelerated curing methods. However, the results of the regression analysis (computer runs 14, 15, 16, and 17) on the data from Phase III shown in Figure 15 indicated that a nonlinear curve would be desirable if one general regression equation were to be used for a large range of initial mixture temperatures, including temperatures (Fahrenheit degrees) in the high 40's and low 50's.

13. The investigator found the autogenous method to provide very uniform curing with regard to moisture and temperature gradients within the curing cylinders. The autogenous test results are highly reproducible and the equipment is relatively maintenance free. As a result of the interrelation of rate of temperature rise, temperature increase above initial mixture temperature, maximum autogenous temperature reached, and total heat generated on the concrete strength developed, it is concluded that a more efficient autogenous container could be developed which would more nearly utilize the optimum values of the aforementioned temperature parameters.

14. The autogenous curing procedure, as followed in this investigation, is a simple, efficient, and reliable method to accelerate the curing of concrete for the purpose of estimating the strength of concrete at later ages.

RECOMMENDATIONS FOR FURTHER RESEARCH

With regard to development of an optimum autogenous curing container, the following questions should be answered:

1. For a constant maximum autogenous temperature, what is the range of times to maximum temperature?

2. Which variables change the time to maximum temperature? How? Why?

3. What degree of influence do the maximum temperature, temperature increase, and total heat generated have on autogenous strength development?

4. How can the autogenous container be designed to utilize the maximum potential of each temperature variable to develop the highest degree of efficiency?

5. What factors cause the autogenous temperature decrease ($-\Delta T$) defined in Figure 9? Are these factors related to the concrete or the autogenous container?

6. For the same maximum autogenous temperature, why do different temperature decreases result?

7. What is the influence of autogenous temperature increase ($+\Delta T$) and time to maximum temperature on the autogenous temperature decrease ($-\Delta T$)?

8. What is the influence of autogenous temperature decrease ($-\Delta T$) on strength?

Other recommendations for further research are as follows:

1. An investigation of the influence of extended curing periods (greater than 47 hours) on strength to determine if the additional curing time causes an increase in strength.

2. An investigation of the effect of the curing period between maximum temperature and 47 hours on strength development to determine if the total curing period can be shortened. The possibility of reducing the total length of time for autogenous curing by at least 8 hours seems feasible.

3. A more exhaustive study of the influence of initial mixture temperature on autogenous strength.

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APPENDIX A

Mixture Schedules

The experiment was divided into three phases.(21) Phase I was patterned after the ASTM Cooperative Testing Program(22) so that the results of this investigation could be related to the ASTM results. Phases II and III were designed such that the main variables were water-cement ratio and initial mixture temperature, respectively.

The constants in Phase I were

Initial mixture temperature = 73°F

Slump = 2 to 3 in.

Air content = 5 to 6 percent

The mixture schedules for Phase I are given in Table X.

TABLE X

MIXTURE SCHEDULES FOR PHASE I

Type II cement			Type III cement		
Mixture Number	Cement, lb/cu yd	Admixtures*	Mixture Number	Cement, lb/cu yd	Admixtures*
I-a	450	A	I-g	450	A
I-b	450	A-R	I-h	450	A-R
I-c	550	A	I-i	550	A
I-d	550	A-R	I-j	550	A-R
I-e	650	A	I-k	650	A
I-f	650	A-R	I-l	650	A-R

*A = Air-entraining agent; R = Retarder.

The constants in Phase II were

Initial mixture temperature = 73°F

Cement factor = 550 lb/cu yd

Air content = 5 to 6 percent

The mixture schedules for Phase II are given in Table XI.

TABLE XI

MIXTURE SCHEDULES FOR PHASE II

Type II cement			Type III cement		
Mixture Number	W/C ratio	Admixtures*	Mixture Number	W/C ratio	Admixtures*
II-a	0.4	A	II-j	0.4	A
II-b	0.4	A-R	II-k	0.4	A-R
II-c	0.4	A-A	II-l	0.4	A-A
II-d	0.5	A	II-m	0.5	A
II-e	0.5	A-R	II-n	0.5	A-R
II-f	0.5	A-A	II-o	0.5	A-A
II-g	0.6	A	II-p	0.6	A
II-h	0.6	A-R	II-q	0.6	A-R
II-i	0.6	A-A	II-r	0.6	A-A

* A = Air only;
A-R = Air and retarder;
A-A = Air and accelerator.

The constants in Phase III were

Water-cement ratio = 0.5

Admixture = Air only

Air content = 5 to 6 percent

The mixture schedules for Phase III are given in Table XII.

TABLE XII

MIXTURE SCHEDULES FOR PHASE III

Initial mixture temperature	Cement type					
	II		III		V	
	Mixture number	Cement, lb/cu yd	Mixture number	Cement, lb/cu yd	Mixture number	Cement lb/cu yd
50°F	III-a	450*	III-d	450*	III-g	450*
	III-b	550	III-e	550	III-h	550
	III-c	650	III-f	650	III-i	650
73°F	III-j	450*	III-m	450*	III-p	450*
	III-k	550	III-n	550	III-q	550
	III-l	650	III-o	650	III-r	650
90°F	III-s	450*	III-v	450*	III-y	450*
	III-t	550	III-w	550	III-z	550
	III-u	650	III-x	650	III-z1	650

*The mixtures having a cement factor of 450 lb/cu yd were so stiff (Slump = 0) that it was impossible to make properly formed cylinders. In order to use a cement factor of 450 lb/cu yd different aggregate gradations would have to be used and the mixtures redesigned. Since aggregate gradation was a constant, mixtures III-a, d, g, j, m, p, s, v, and y were not made.

The temperature of the mixtures was reduced to 50°F by substitution of ice for a portion of the mixing water. The temperature of the mixtures was raised to 90°F by using water heated to 170° F.

APPENDIX B

Specimen Preparation Schedules

Phase I comprised the following:

Total number of mixtures = 12

Total number of batches = 36

Total cylinders per mixture = 20

Total cylinders = 240

The schedule for specimen preparation for Phase I is shown in Table XIII. There were three batches for each mixture.

TABLE XIII

SPECIMEN PREPARATION SCHEDULE FOR PHASE I

Type of curing	Number of Cylinders per batch			Total cylinders per mixture	Total cylinders, Phase I
	Batch 1	Batch 2	Batch 3		
Autogenous	2	2		4	48
28-day standard*	2	2		4	48
91-day standard	2	2		4	48
1-year standard	2	2		4	48
2-day standard			2	2	24
Autogenous temperature**			2	2	24
Time-of-set test***			-	-	—
Totals	8	8	4	20	240

*"Standard" means normal moist curing conditions.

**"Autogenous temperature" denotes cylinders instrumented for temperature measurements. A total of 24 thermocouples were used. Results of the temperature study are presented in Part III of this report.(10)

***Cement-sand mortar for time-of-set test, in accordance with ASTM C 403,(7) was taken from the third batch of each mixture. A total of 12 time-of-set tests were conducted.

Phase II comprised the following:

Total number of mixtures = 18

Total number of batches = 54

Total cylinders per mixture = 20

Total cylinders = 360

The schedule for specimen preparation for Phase II is shown in Table XIV. There were three batches for each mixture.

TABLE XIV

SPECIMEN PREPARATION SCHEDULE FOR PHASE II

Type of curing	Number of cylinders per batch			Total cylinders per mixture	Total cylinders, Phase II
	Batch 1	Batch 2	Batch 3		
Autogenous	2	2		4	72
28-day standard	2	2		4	72
91-day standard	2	2		4	72
1-year standard	2	2		4	72
Autogenous moisture*			2	2	36
Autogenous temperature			2	2	36
Totals	8	8	4	20	360

*"Autogenous moisture" denotes cylinders instrumented for moisture measurement. Two moisture gages were embedded in each cylinder; there were a total of 72 moisture gages used in Phase II. A total of 36 thermocouples were needed for Phase II. Results of the moisture study are presented in Part IV of this report.(11)

Phase III comprised the following:

Total number of mixtures = 18

Total number of batches = 54

Total cylinders per mixture = 20

Total cylinders = 340

The schedule for specimen preparation for Phase III is shown in Table XV. There were three batches for each mixture.

TABLE XV

SPECIMEN PREPARATION SCHEDULE FOR PHASE III

Type of curing	Number of cylinders per batch			Total cylinders per mixture	Total cylinders, Phase III
	Batch 1	Batch 2	Batch 3		
Autogenous	2	2		4	72
28-day standard	2	2		4	72
91-day standard	2	2		4	72
1-year standard	2	2		4	72
Autogenous moisture*			2	2	16
Autogenous temperature			2	2	36
Time-of-set test			-	-	—
Totals	8	8	4	20	340

*Autogenous moisture cylinders were made only for mixtures III-f, k, l, n, o, q, r, and x, requiring a total of 32 moisture gages. A total of 36 thermocouples were needed for Phase III.

To summarize, the totals for Phases I, II, and III were

Total number of mixtures = 48

Total number of batches = 144

Total number of cylinders = 940

A total of 218 batches of concrete were made in the laboratory, of which 74 batches did not meet the air content or slump requirements established for the project.