WATER BATH ACCELERATED CURING OF CONCRETE

by

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(A Cooperative Organization Sponsored Jointly by the Virginia
Department of Highways and the University of Virginia)

Charlottesville, Virginia

September 1970

VHRC 70-R8

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SUMMARY AND CONCLUSIONS

Water bath methods for accelerating the strength development of portland cement concrete were investigated in a two phase study as follows:

Phase I — Participation in a cooperative accelerated strength testing program sponsored by the American Society for Testing and Materials. The three methods studied consisted of; (1) curing immediately after casting in 95°F water for 24 hours, (2) curing in boiling water for 3 1/2 hours, commencing 23 hours after casting, and (3) curing in boiling water for 15 hours commencing after the concrete reached a penetration resistance of 3500 psi (fixed set).

Phase II — A study of the effects on the results of the fixed set accelerated curing methods of curing water temperatures from 95°F to 212°F. Also considered were certain heat transfer parameters relevant to strength development.

The major conclusions were:

Phase I

1. The fixed set boiling method is the most efficient and reliable of those studied.
2. Water bath accelerated curing is more efficient for high than for low strength concretes.
3. Water bath and standard moist curing produce strength results of about equal reproducibility.

Phase II

1. Accelerated curing efficiencies are directly proportional to the total relative amounts of heat released by the concretes during accelerated curing.
2. Boiling (212°F) water is not conducive to optimum curing efficiency.
3. Optimum water bath temperatures for accelerated concrete strength development range approximately from 165° to 180°F.
4. The duration of accelerated curing is not critical for the fixed set boiling method.

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INTRODUCTION

The rapid pace of modern construction activities has led to the evolution of a number of accelerated strength testing methods for portland cement concrete[1]. Still, the great majority of concrete mixtures are evaluated on the basis of a standard compressive strength test (AASHO Designation T22-64) in which the concrete is moist cured for periods of 7 to 28 days before testing. The need for the more rapid test methods is apparent since under current procedures a great deal of inferior concrete can be placed before any strength test results are available. Recognizing the need for rapid test results along with the various independent efforts directed toward the development of a suitable test, Subcommittee II-i of ASTM Committee C-9 initiated a cooperative testing program[2]. For this program, several of the most popular accelerated strength testing methods were selected for study by nine participating laboratories. At the conclusion of this cooperative program, it is hoped that it will be possible to recommend a standardized test capable of giving a reliable estimate of ultimate concrete strength in a much shorter time (say 24 - 36 hours) than is required with the conventional test method.

The Virginia Highway Research Council is one of the participants in the cooperative program with tests for which the writer is responsible. Through this participation, it is believed that a contribution can be made to the overall effort and that at the same time data of particular interest to the Highway Department can be obtained. For example, the establishment of an acceptable accelerated testing method would provide a means for an early check on concrete design strength. Furthermore, accelerated strength testing would be an asset in implementing end result specifications which are being looked upon more favorably since statistical quality control has become of interest to the highway engineer.

Reflection on the concept of accelerated strength testing has led most researchers in the area to impose at least three requirements on an acceptable test method: (1) The test must be reproducible, (2) the test must produce accelerated concrete strengths which can be easily related to a reference strength level (probably the 28 day moist cured strength of the concrete in question), (3) the accelerated strength must be a high percentage of the reference strength (i. e. the test must be efficient). The reasons for requirements one and two are obvious; requirement three is necessary because of certain subtleties associated with concrete strength development. For example, suppose that two concretes are fabricated from the same materials except that one has a high strength and the other a low strength coarse aggregate. Then a low efficiency accelerated procedure might suggest that both have a similar ultimate strength, while in reality the strengths are very different because of limitations placed on one mixture by the aggregate strength. This third requirement is less critical if correlations between 28 day and accelerated strength are established before construction commences.

Utilizing such criteria, most of the curing procedures recently or currently under study[1, 3] have found heated or boiling water as the most effective curing medium. The principles underlying these methods are that optimum moist curing conditions are satisfied by the water surrounding the specimen and that the high temperature of the water enhances the cement hydration process such that high concrete strengths are developed at an early age. On the other hand, when one considers the accelerated curing procedures currently being developed by various agencies it is found that many differences exist in the amounts of heat applied and in the times of application as evidenced by the fact that seven procedures, differing in at least one of the above respects, are to be evaluated in the ASTM cooperative program.

To evaluate the influence of these differences, the present study was initiated. Thus, this report summarizes both the Council participation in the ASTM cooperative program and a satellite study directed toward optimizing accelerated curing procedures through investigation of variables related to heat application and the resultant concrete response.

PURPOSE AND SCOPE

The purposes of the investigation were threefold: (1) to participate in the ASTM cooperative program, (2) within the framework of the cooperative program, to optimize the influence of accelerated curing conditions on the early strength development of concrete, and (3) to achieve a better understanding of the thermal behavior of concrete as it is subjected to high curing temperatures during the accelerated curing. The ultimate objective was to provide information useful to the interpretation of the ASTM program, which might eventually result in a standardized accelerated curing procedure*.

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* Subsequent to this study, subcommittee II-i of ASTM Committee C-9 has developed an accelerated curing method comprising three procedures:

Procedure A — Essentially that designated Procedure A in this study.

Procedure B — Essentially that designated Procedure B in this study.

Procedure C — An autogeneous curing method not included in this study, but investigated at the Research Council and reported in an unpublished thesis by Larry M. Cook.

Included within the study were the "mandatory" ASTM tests and the variations of these tests necessary to arrive at an optimized procedure. Thermocouple instrumentation of concrete cylinders was employed to study the response of the concrete to different curing procedures.

LITERATURE SURVEY

The Early Hydration Processes

Prior to a discussion of the procedures employed in this study it is appropriate to discuss some of the earlier hydration reactions to which those procedures are related.

Dealing with cement pastes, Powers(4) traces the events which occur in the initial stages (usually considered as four) of cement hydration.

During the first stage, beginning when cement and water come into contact, there is a period of rapid dissolution and exothermic chemical reactions, particularly with the anhydrous aluminates (C_3A). At this time heat (called heat of immediate hydration) is rapidly evolved, but no great total amount is developed because of the short time duration of this stage. The end of the first stage comes when the cement-water suspension is still only a few minutes old and is marked by a rapid drop in the rate of heat evolution.

The second stage, known as the dormant period, commences as the rate of heat evolution drops to a very low rate where it remains for approximately one hour.

During the first two stages of the hydration process the gypsum present in cement plays an important part in the nature of the hydration reactions. In Figure 1 a typical heat evolution curve is shown for a cement having the proper gypsum content. Most investigators suggest that the immediate heat evolution is due to the reaction of C_3A and water to produce hydrated calcium aluminates and to a lesser extent by reaction of C_3S and water. Since C_3A is relatively insoluble in the saturated lime-gypsum solution that rapidly develops during the first hydration stage its hydration soon diminishes so that the first descending portion of the curve in Figure 1 develops(5). This same condition prevents the phenomenon referred to as "flash set" of cements that are insufficient in gypsum. Studies(4) have shown that as the dormant period begins the C_3A slowly reacts with the gypsum and that the silicates (C_2S and C_3S) have become coated with their own reaction products. Thus, these silicates are inaccessible to the solution and remain inactive during the dormant period.

As the third stage ("period of set") begins, the heat evolution curve begins its second ascending portion. Also at this time, concrete begins to undergo a rapid change in physical properties as the bleeding gradually ends and the firmness is markedly

40 or 50 (varies with cement)

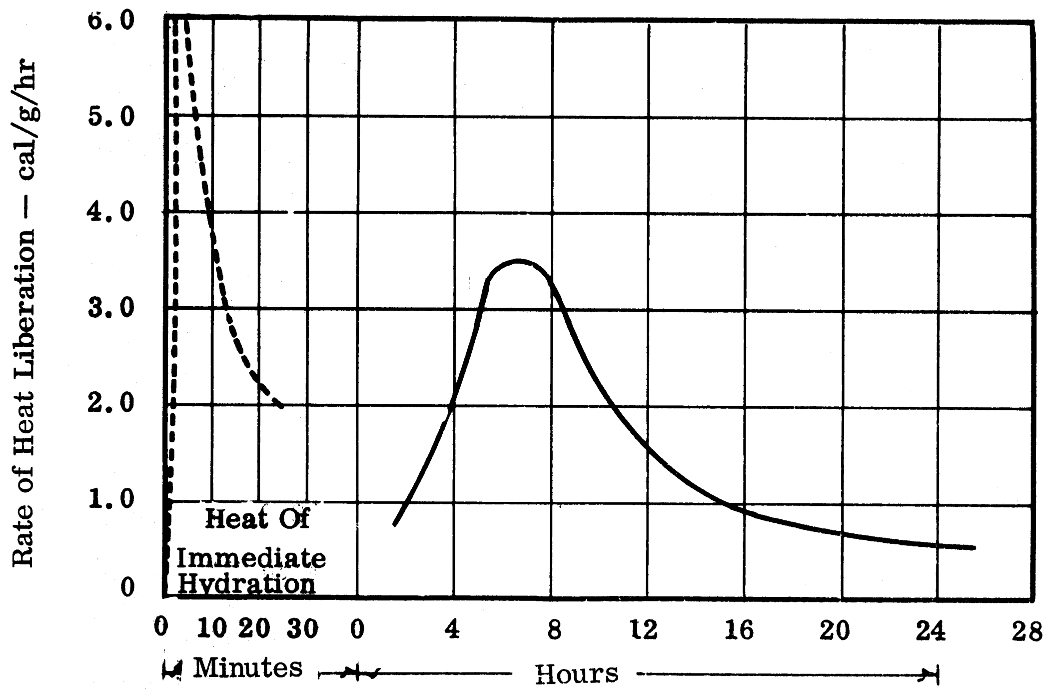


Figure 1. Rate of hydration of a typical cement with a proper SO_3 content. After Lerch.(5)

increased(4). Powers(4) adopts the theory that this stage begins when the calcium silicate gel begins to rupture at scattered points thus permitting renewed access of the aqueous solution to the cement and further reaction to proceed. The renewed reaction itself tends to reseal the ruptured areas so that the reaction rate does not suddenly accelerate to a very high level, but gradually increases as shown in Figure 1 as the process of rupture and resealing continues. Presumably(4) the peak which occurs at an age of 6 - 8 hours indicates that the rupture and resealing process is at an equilibrium condition so that the heat evolution curve momentarily levels off.

Two times of physical significance have been defined during the period of set. These are "initial set" and "final set" (ASTM Designation C403-67T). Powers(4) points out that early investigators apparently noted the rapid change of physical properties that follows the dormant period and defined "initial set time" as that time at which the rapid change is well under way. Similarly, "final set time" appears to indicate the age at which the period of rapid change is drawing to a close.

It has been reported that at the time of final set up to 85 percent of a cement may still be anhydrous. Thus most of the hydration process is completed after final set and after the maximum heat evolution has occurred at about 6 hours of age. A parallel has been found[5] between the heat evolution during the early stage reactions and the early compressive strength. This naturally leads to speculation that if the rate of reaction is accelerated, by external means, during the period of set, advantage can be taken of the already high reaction rate to produce a maximum rate of concrete strength gain.

The fourth stage is comprised of the hydration and hardening subsequent to the period of set.

Temperature Effects

The influence of ambient temperature on the nature of the early hydration reactions has been pointed out by Monfore and Ost[6]. Their findings, derived from calorimeter studies, showed that higher temperatures greatly increase the early rate of heat evolution and cause the peak rate (Figure 1) to occur much earlier. Also, the peak is higher and the total heat evolved at earlier ages is significantly increased. This is equivalent to saying that at higher temperatures the total volume of material hydrated at very early ages is increased.

Additional influences of temperature on early strength development have been pointed out by Verbeck[7], Klieger[8], and others. For example, while high curing temperatures can significantly increase the early strength of concrete, the strength at later ages is detrimentally influenced by high temperatures. Verbeck adopts the theory that rapid early hydration products create a dense zone around the hydrating cement grains so that later hydration and strength development are impaired.

Curing Conditions

Smith and Tiede[1] have thoroughly surveyed the literature concerning the influence of curing conditions on accelerated strength development. From study of the many methods which have been used and based on their own work, these investigators summarize in the following quotation curing requirements as they apply to accelerated strength developments:

> "In order for a procedure to be universally applicable, without first correlating the accelerated strength results to normal 28-day results for the specific concrete mixture in use, it is almost certain that it must contain one of the following essential features:
>
> (i) A long unmeasured delay time. There is evidence that a long initial delay period has the disadvantage that the

ratio of accelerated strength to 28 day strength will be lower and will be only slightly higher than that given by normal curing of the same duration as the accelerated curing. The reason for this may be because the basic gel structure has become well established prior to commencement of acceleration; or

(ii) The delay time required for a particular mixture must be determined. The required delay time can be determined from the degree of set of the concrete using ASTM Method C403; or

(iii) A low rate of temperature rise must be used and the maximum accelerated curing temperature must be below 140°F. The precise limit below this temperature is not known."

MATERIALS AND TEST PROCEDURES

The laboratory testing was conducted in two separate phases; the first of which was the Council participation in the ASTM Cooperative Program[2], the second a related study to help define the influence of accelerated curing temperatures and the time of application of the accelerated curing. These two phases, which involve some differences in procedures, will be discussed separately later.

Materials

Concrete tested in both phases of the study was proportioned from the same materials except that a different lot of Type III cement was used in each phase. These cements were from the same producer and chemical analyses revealed no significant differences in composition.

Cement

The chemical analyses and computed compounds (as determined by ASTM Designation C114-67) of the cements used are given in Table I.

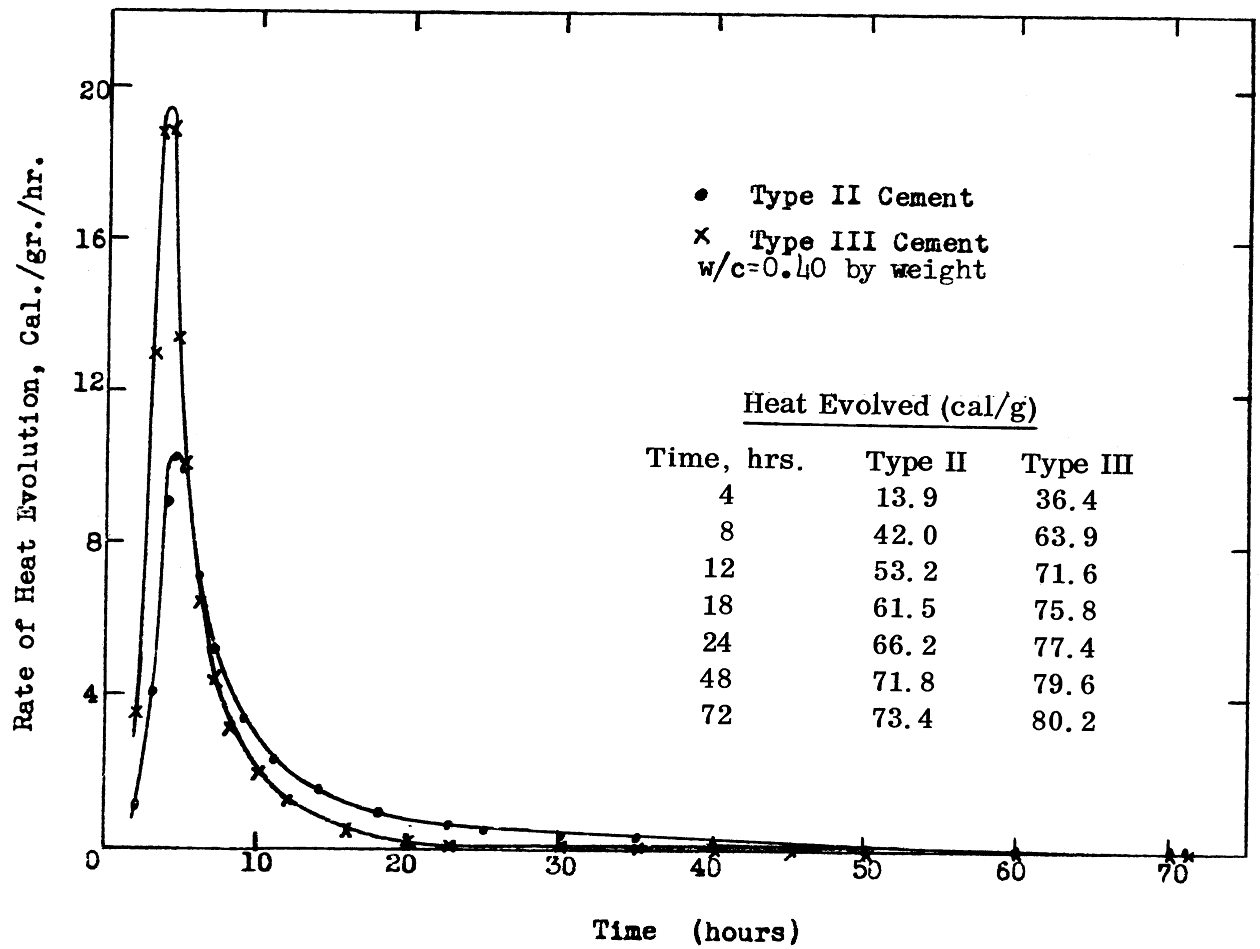
In addition to chemical analyses, heat evolution tests were conducted on the two cements using procedures and equipment developed by Monfore and Ost[6]. The results of these tests are shown graphically in Figures 2 and 3. Note that the figures represent heat evolved for two different ambient temperatures and that they are plotted to different vertical scales. The importance of curing temperature on

TABLE I

CEMENT ANALYSES

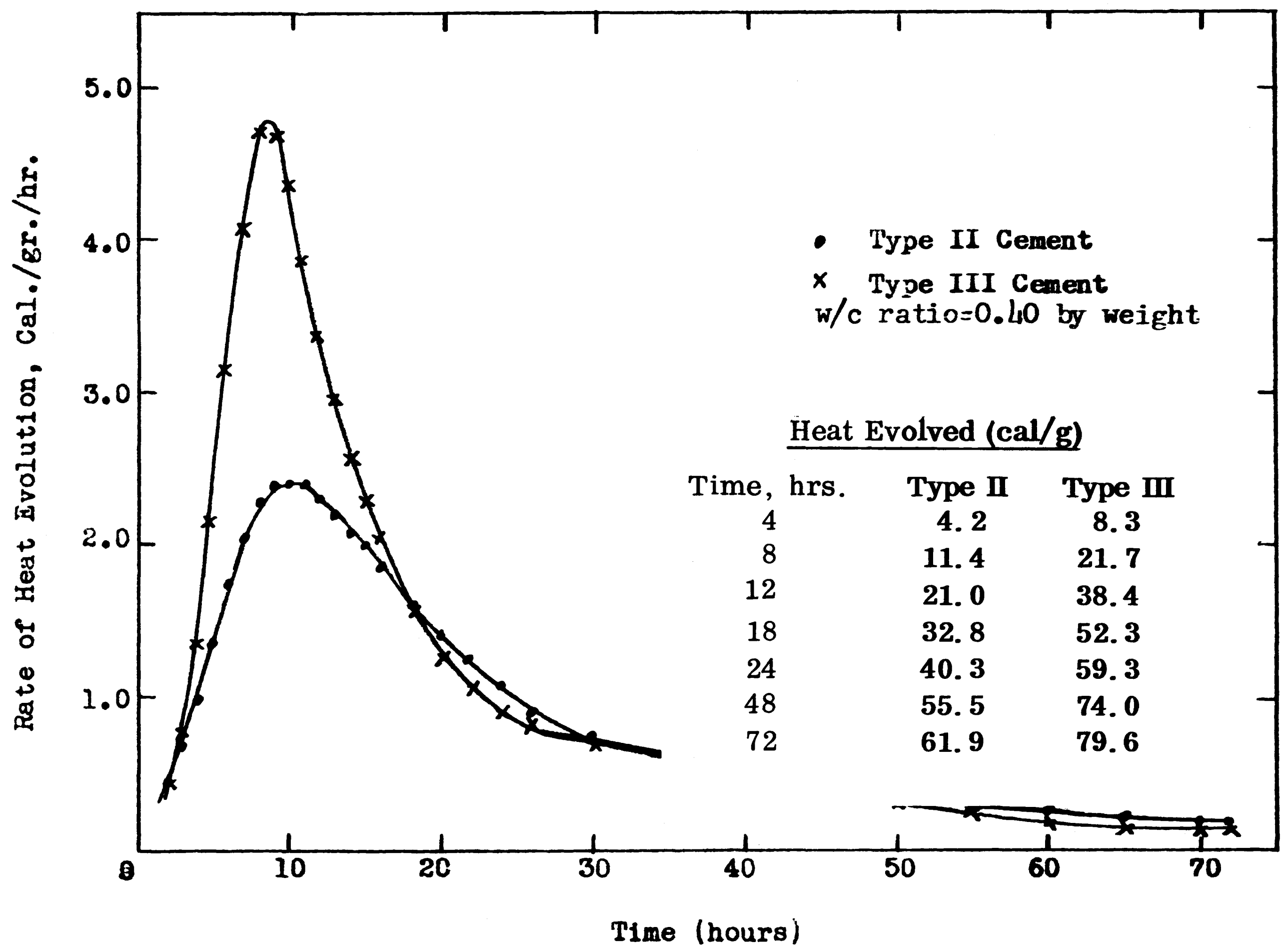
Oxide	Percentage	
	Type III	Type II
SiO_2	21.04	23.05
Al_2O_3	5.44	4.53
Fe_2O_3	2.50	4.46
CaO	63.21	62.90
MgO	2.94	1.73
SO_3	2.94	1.87
Computed Compounds		
C_3S	48.8	38.8
C_2S	23.6	36.8
C_3A	10.2	4.5
C_4AF	7.6	13.5
Specific Surface		
	4780 cm^2/gr	3350 cm^2/gr

the hydration rate is evident in these figures. Note that at the higher temperature the maximum rates of heat evolution are much higher and that these maximums occur at an earlier age. Note also that the maximum heat evolution rate for the Type III cement is about twice that for the Type II, for either temperature level. Finally, note that after about 50 hours of curing at 136.7°F there was no measurable heat evolved, while at 80.1°F the rate is still significant even at 72 hours. Yet, at 72 hours the total heat evolved by the Type III cement seems independent of curing temperature as can be seen by comparing the tabulated values on Figures 2 and 3. At the same time (72 hours), the Type II cement still differs in the total heat evolved at the two temperatures. Thus, Type III cement seems to be influenced more by curing temperature than does the Type II. Analogous behavior of test concretes could be anticipated.



Time, hrs.	Type II	Type III
4	13.9	36.4
8	42.0	63.9
12	53.2	71.6
18	61.5	75.8
24	66.2	77.4
48	71.8	79.6
72	73.4	80.2

Figure 2. **Rate of heat evolution versus time.** Ambient temperature, 136.7°F. **(Courtesy, Portland Cement Association).**



Heat Evolved (cal/g)

Time, hrs.	Type II	Type III
4	4.2	8.3
8	11.4	21.7
12	21.0	38.4
18	32.8	52.3
24	40.3	59.3
48	55.5	74.0
72	61.9	79.6

Figure 3. Rate of heat evolution versus time. Ambient temperature, 80.1°F. (Courtesy, Portland Cement Association).

Mineral Aggregates

A 1-inch maximum size crushed granite gneiss was utilized as coarse aggregate. The aggregate was sieved and recombined to conform to the grading specified in ASTM Standard C33 for the No. 57 concrete aggregate. The fine aggregate was a washed silica sand from the James River Basin conforming to ASTM Designation C33-67.

Chemical Admixtures

A commerical neutralized vinsol resin air entraining agent was used in the amount necessary to entrain 5.5 ± 0.5% air. This admixture was used in all mixtures. In addition, a carboxylic acid water reducing retarder was used in certain of the ASTM program mixtures. These admixtures conformed to the appropriate ASTM specification.

Mixing Procedure

Mixing was done in accordance with ASTM Designation C192-66. All materials entering the mixture were at room temperature and the coarse aggregate was used in a saturated surface dry condition. The admixtures were introduced into the mixer as parts of the mixing water, but in separate portions. Mixing schedules will be discussed later under the discussion of the two separate phases.

Required Mixture Characteristics

The ASTM Cooperative Program on accelerated strength testing established certain tolerances which must be met by fresh concrete to be used in the program. These requirements, which were applied to both phases of the study, are as follows (see also Appendix A):

1. All mixes must have an air content of 5.5 ± 0.5% (ASTM C231-62).
2. All mixes must have a slump of $2\frac{1}{2} \pm \frac{1}{2}$ inch (ASTM C143-58).
3. Temperature of the test mixtures must be held within 23 ± 1.7°C (73.4 ± 3°F).
4. Materials from the slump test shall be returned to the mix and remixed and material from the air determination shall be discarded as required by ASTM Designation C192-65. Material from the time of set test shall also be discarded.

PHASE I

ASTM Cooperative Program

The cooperative program included three mandatory accelerated curing procedures which all participants were to perform. A brief description of these procedures follows:

Procedure A - Accelerated curing while immersed in 35 ± 2°C (95°F) water. Curing commences immediately after concrete is cast in metal molds and continues for 24 hours, testing is 2 hours later.

Procedure B - Accelerated curing while immersed in boiling water. Curing commences 23 hours after casting in metal molds and continues for $3\frac{1}{2}$ hours, testing is at an age of $28\frac{1}{2}$ hours.

Procedure C - Accelerated curing while immersed in boiling water. Curing in metal molds commences 20 minutes after the Proctor penetration resistance (ASTM C403) reaches 3500 psi and continues for 15 hours, testing is 2 hours after removal from boiling water.

Number of Test Mixtures

Each of the three accelerated curing procedures was applied to test mixtures employing the following variables:

1. Two types of Cement (Type II and Type III)
2. Three cement factors (450, 550, and 650 lb/cu. yd.)
3. Admixtures (1) AEA only (5.5 ± 0.5% air)
   (2) AEA and Water Reducing Retarder (manufacturer's recommended dosage)
4. Duplicate batches for each variable.
5. Total mixtures per procedure: 2 x 2 x 3 x 2 = 24

Thus, the entire cooperative program required 72 batches of concrete having the characteristics and mixed as described in earlier sections of this report. From each of these batches six 6 in. x 12 in. cylinders were cast to be tested; 2 after accelerated curing, 2 after 28 days of conventional moist curing, and 2 after 1 year of conventional moist curing.

Results and Discussion

Strength Relationships

Figures 4, 5, and 6 show graphically the relationship between accelerated strengths and 28 day moist cured strengths for procedures A, B, and C respectively. Each point on the graphs represents the average values of four accelerated and four 28 day compressive strengths. The lowest point represented by a given symbol indicates a 450 lb./cu. yd., the intermediate, a 550 lb./cu. yd., and the highest a 650 lb./cu. yd. cement factor. Note that all groups of data are to the right of the line of equality, but Procedure C (which depends on setting time) is least displaced and thus is most efficient. For a 100 percent efficient test method the data points would all lie along the line of equality. Regression analyses resulted in the linear equations of best fit and limits of uncertainties shown around the groups of data. If a large number of tests incorporating the variables found in this study were run, 95 percent of the data points for a given procedure could be expected to fall within the limits shown by the broken lines. Note that procedure C, the most efficient, also is least variable as evidenced by the narrower band around the regression line.

From procedure C, for example, a fair estimate of the 28 day strength could be obtained in one day by application of the regression equation $\sigma_{28} = 0.945\ \sigma_a + 2280$. Typical results, assuming that accelerated strengths have been determined from tests, are shown in Table II. Note that the procedure is much more efficient for the higher than for the lower 28 day strength levels. The same can be shown for all of the procedures and is due to the fact that the highest strength levels (for the materials used in this study) contained Type III cement, which is more responsive to high early temperatures.

Published results, including those developed in the ASTM Cooperative Program, show that the correlation equation varies with specific combinations of materials. During initial use of the accelerated curing procedures, correlations will need to be developed for each specific combination of materials.

In the case of the 3000 psi design strength concrete often used in Virginia, none of the accelerated curing tests conducted to date are very indicative. More tests, utilizing concrete proportioned for a lower strength, would be needed to properly define this lower portion of the various strength relationships. Clearly, the true relationships take the form of curved lines because it is unreasonable to suggest, as Figures 4, 5, and 6 do, that the accelerated strengths all would be zero for 28 day strengths of less than about 3000 psi.

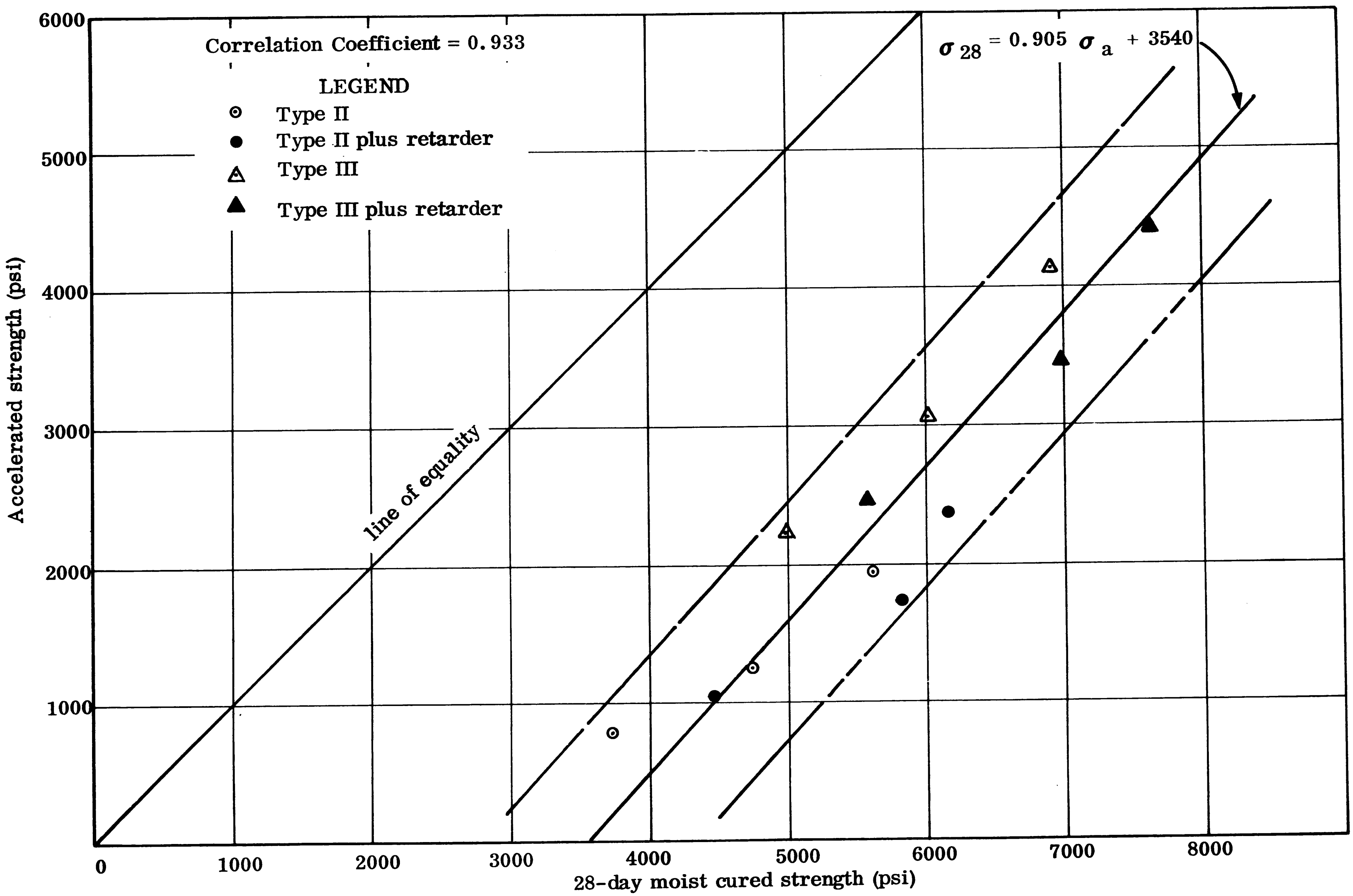


Figure 4. Accelerated versus moist cured strengths. Procedure A.

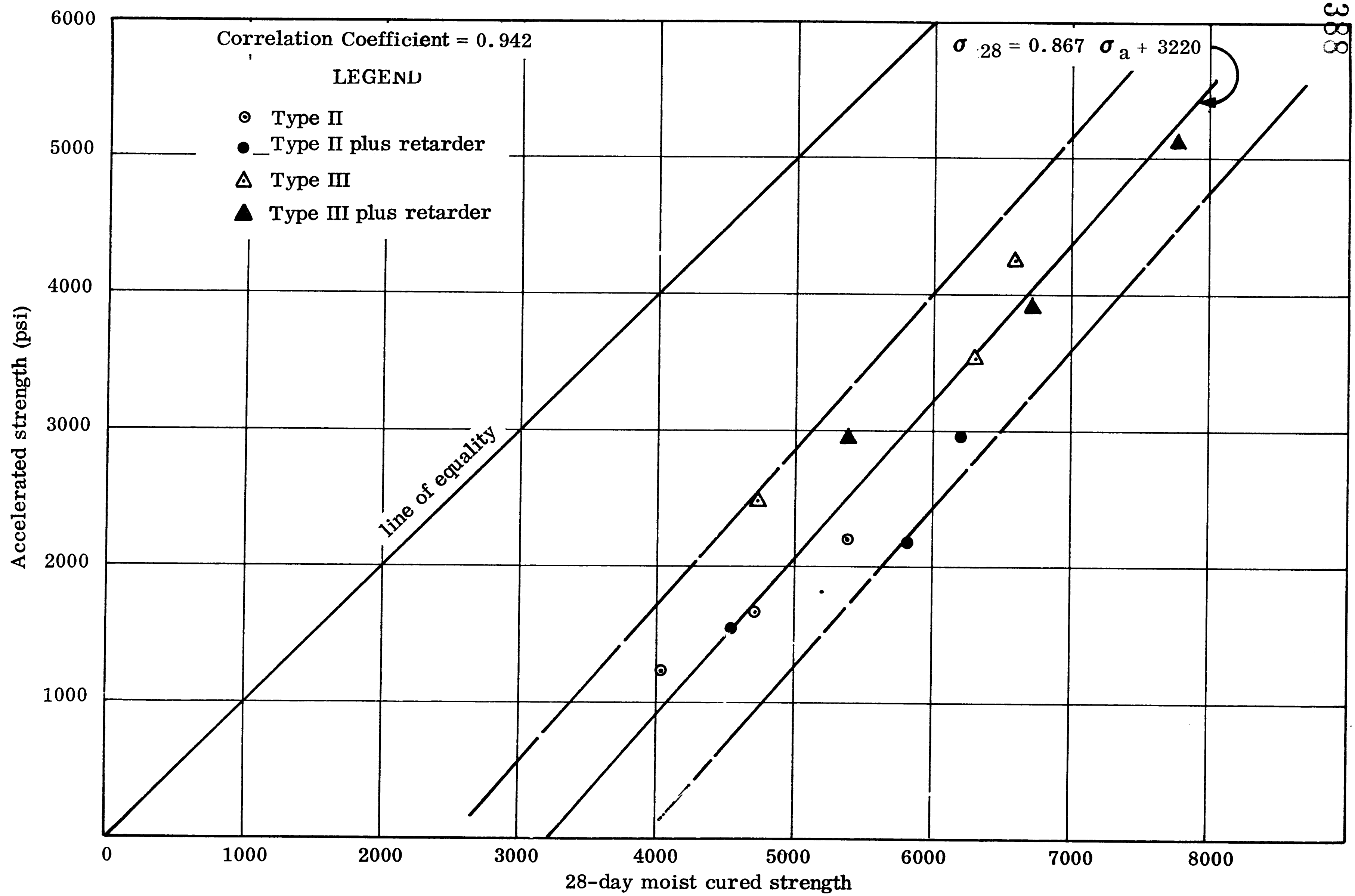


Figure 5. Accelerated versus moist cured strengths. Procedure B.

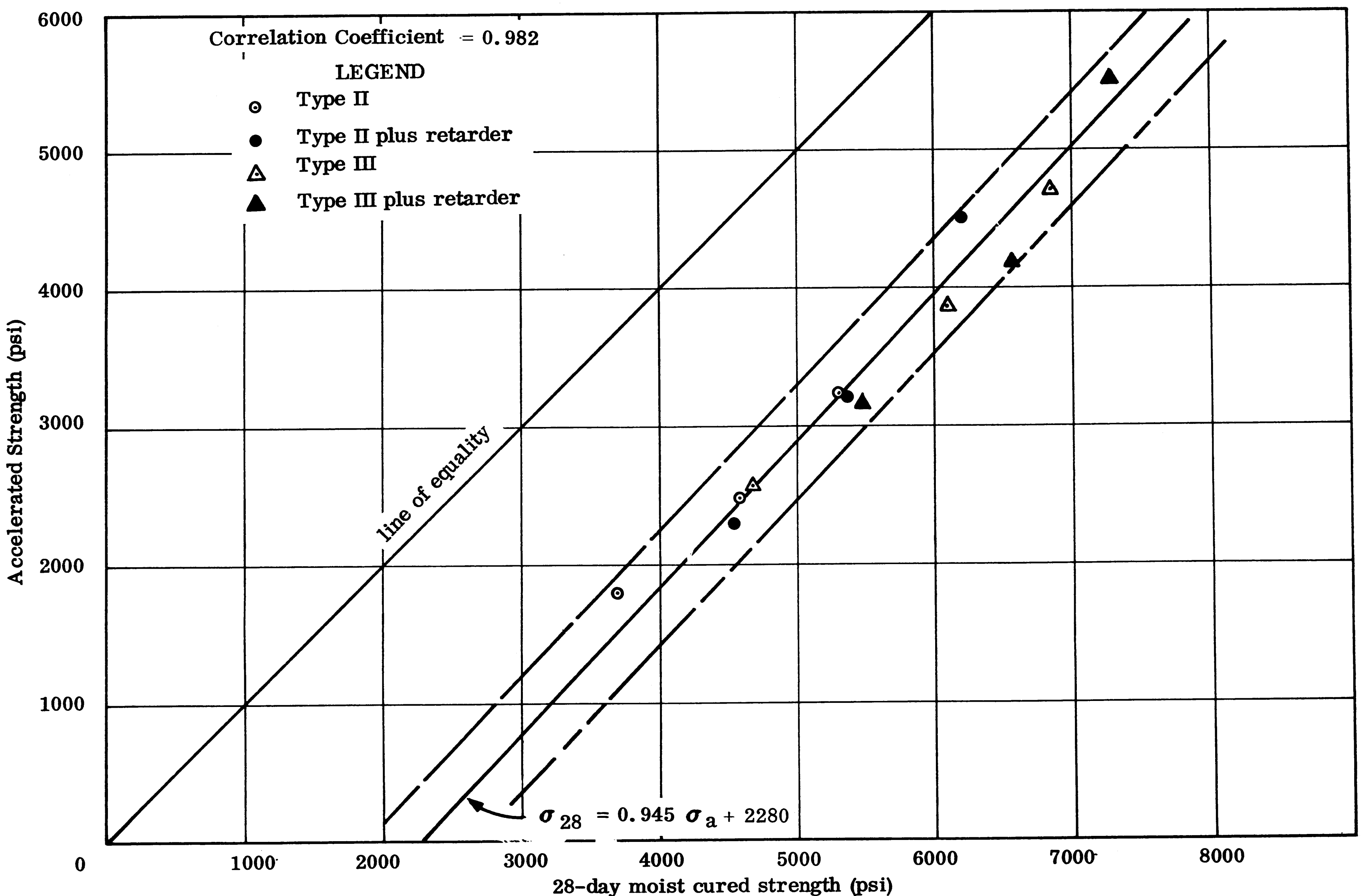


Figure 6. Accelerated versus moist cured strengths. Procedure C.

TABLE II

ESTIMATE OF 28 DAY STRENGTH FROM RESULTS OF PROCEDURE C

Assumed Accelerated Strength	Estimated 28 day Strength	Estimated Efficiency of Cure
2,000 psi	4170 psi	48%
3,000 psi	5120 psi	59%
4,000 psi	6060 psi	66%
5,000 psi	7010 psi	71%

The efficiencies for all mixtures tested are tabulated in Table III. Each tabulated value is the average of four strength tests.

TABLE III

RATIO OF ACCELERATED TO NORMAL STRENGTH (a/x)

	Procedure	450#/yd^3			550#/yd^3			650#/yd^3		
		a	a/28	a/364	a	a/28	a/364	a	a/28	a/364
Type II Cement: AEA	A	790	.21	.18	1260	.27	.22	1930	.34	.28
	B	1240	.31	.26	1670	.35	.33	2200	.41	.33
	C	1800	.49	.41	2480	.54	.45	3240	.61	.50
Type II Cement: AEA + Retarder	A	1060	.24	.20	1740	.30	.25	2380	.39	.34
	B	1540	.34	.29	2190	.38	.31	2960	.48	.40
	C	2300	.55	.52	3220	.63	.57	4510	.69	.60
Type III Cement: AEA	A	2240	.45	.44	3070	.51	.48	4130	.60	.53
	B	2470	.52	.48	3540	.56	.51	4250	.65	.57
	C	2570	.51	.43	3860	.60	.49	4720	.73	.56
Type III Cement: AEA + Retarder	A	2460	.44	.43	3450	.49	.48	4420	.58	.49
	B	2940	.55	.51	3930	.59	.53	5140	.66	.62
	C	3170	.58	.54	4190	.64	.57	5530	.76	.65

Reproducibility of Test Results

The reproducibility of test results is always of great importance when a new or different test method is under evaluation. Statistical analysis (ACI Manual of Concrete Practice, Part 1, 1967) of the strength test results listed in the Appendix revealed the findings shown in Table IV.

TABLE IV

REPRODUCIBILITY OF STRENGTH TESTS

Curing Condition	Within Batch Coefficient (%)	Overall Coefficient (%)
Procedure A	1.2	6.5
Procedure B	1.4	3.8
Procedure C	2.3	5.3
Moist (28 day)	2.4	4.5

The coefficients of variation are offered as the statistical parameters in this discussion because of the various strength levels under consideration. Thus, the results may be presented on the basis of percentages rather than absolute values. The relatively small number of tests conducted for each variable yielded insufficient data for adequate statistical analysis so that while calculated separately for each variable, the tabulated coefficients of variation have been averaged for accelerated and moist cured concretes. There were no obvious differences in variation between the accelerated curing methods nor between different concretes cured by different methods. Similarly, there appear to be no significant differences between the coefficients shown in the table for accelerated and moist cured concretes. The coefficients all are within the ACI (ACI 214-65) recommended limits for good to excellent control of laboratory concrete. Thus, from the standpoint of reproducibility of test results, the accelerated procedures and standard moist curing appear equally reliable.

PHASE II

INFLUENCE OF CURING TEMPERATURE AND HEAT EVOLUTION

Materials and Test Procedures

The purpose of Phase II was to study the accelerated strength development of selected concretes as related to the temperature variations manifested by the concretes during accelerated curing in a constant temperature water bath. Thus, concrete temperatures were monitored during accelerated curing and accelerated strengths were compared to the strengths of reference concretes cured in the standard manner (28 days of moist curing at $72 \pm 3^{o}F$).

Mixture proportioning, specimen preparation, and curing procedures were within the framework of the ASTM Cooperative Program (Phase I) so that the results could have application to the interpretation of the ASTM results. However, in order to reduce the number of test variables the following changes from the ASTM program were necessary:

1. Only high and low cement factors were utilized as opposed to high, medium, and low for the ASTM program.
2. No cylinders for testing at an age of one year were included in this study.
3. All accelerated curing in this study was in accordance with the method designated by ASTM as "Fixed Set Boiling" (Procedure C) except that temperatures below boiling were included.

Thus, the only difference between accelerated curing methods for a given concrete mixture employed in Phase II was in curing temperature ($95^{o}F$, $130^{o}F$, $167^{o}F$, and $212^{o}F$). These temperatures were also under study in the ASTM program but there the effects of temperature differences were obscured by other variables, such as time of application or duration of accelerated curing, which did not exist in Phase II.

Because of the interest in hydration heats, it was desirable to use two cements differing in heat evolution potential. This was accomplished through use of the same Type II and Type III (ASTM C150-67) cement used in Phase I. This variable along with others and the proportioning requirements of the ASTM program are tabulated in Table V. Details concerning materials and procedures are discussed in the following sections.

TABLE V

VARIABLES AND PROPORTIONING DATA

Accelerated Curing Temperatures:	$95^{o}F$, $130^{o}F$, $167^{o}F$, $212^{o}F$
Heats of Hydration:	Low, High
Cement Factors:	450 lb/c.y., 650 lb/c.y.
Air Content:	5.5 ± 0.5%
Slump:	$2\frac{1}{2} \pm \frac{1}{2}$ in.
Maximum Aggregate Size:	1 in.

Mixing Schedule and Procedure

Mixing was done in accordance with ASTM Designation C 192-66. All materials entering the mixture were at room temperature and the coarse aggregate was used in a saturated surface dry condition. The air entraining agent was introduced into the mixer as a part of the mixing water.

For each proportioning variable and curing temperature, replicate concrete mixtures were produced so that a total of 40 batches was included as indicated in Table VI. Mixtures not meeting the criteria established in Phase I were rejected and satisfactory replacements produced. In order to minimize bias due to personnel changes or variations in laboratory conditions, the mixing order was completely random within a given temperature level, as established by a random numbering system.

Specimen Preparation

Two specimens for accelerated curing and testing, one for 28 day conventional curing and testing, and one for thermocouple instrumentation were cast from each batch. Replicate batches yielded a total of four specimens for accelerated strength and two for thermal behavior for each combination of cement type and curing temperature. This procedure also provided forty 28 day reference cylinders for which curing temperature was not a variable.

Immediately after molding, three of the cylinders were placed in a standard moist curing room (two of the three to await accelerated curing) while the fourth was instrumented with two thermocouple wires. Both thermocouples were located at a

TABLE VI

MIXING VARIABLES AND NUMBER OF BATCHES

Cement Type	Cement Factor (lb/c.y.)	Curing Temperature (°F) 72	95	130	167	212	Total
II	450	2	2	2	2	2	10
II	650	2	2	2	2	2	10
III	450	2	2	2	2	2	10
III	650	2	2	2	2	2	10
Totals		8	8	8	8	8	40

depth of six inches into the cylinder, with one at the center and the second on the perimeter of the mold. The wires were inserted through a heavy metal plate which served as a cover for the cylinder. Finally, this cylinder was placed in a container of water at room temperature and the thermocouples were connected to a multipoint temperature recorder.

At the time of cylinder molding, specimens also were made and tested in accordance with ASTM C403-67T "Time of Setting of Concrete Mixtures by Penetration Resistance". These tests were used to determine the time for starting the accelerated cure (ASTM Program).

Accelerated Curing and Temperature Monitoring

While the time-of-set test for a given mixture was in progress, a continuous record of the thermocouple readings for its companion cylinder was made by the temperature recorder.

At the time of final set (3500 psi penetration resistance), the thermocouple instrumented cylinder and the two cylinders for accelerated strength testing were placed in the hot water tank. The two tanks used may be seen in Figure 7. The large tank at the right was used for 72°F and 95°F curing, while it was necessary to use the small, better insulated tank (shown at left) to maintain constant higher temperatures (130°F, 167°F, 212°F). Also seen in the photograph is the temperature recorder and a thermocouple instrumented cylinder.

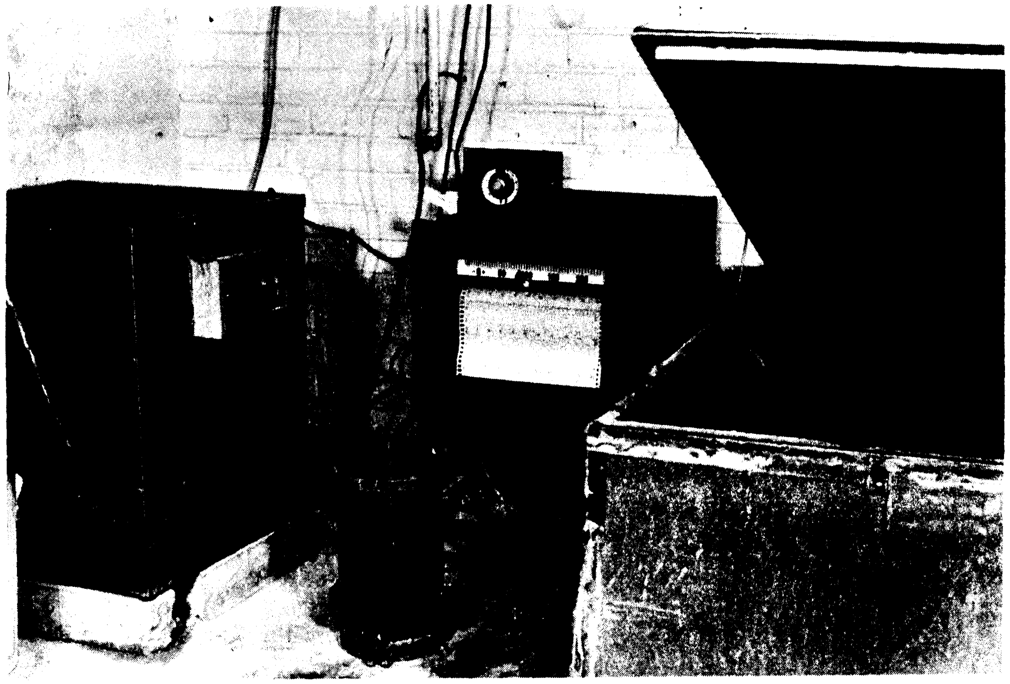


Figure 7. Accelerated curing tanks and temperature recorder.

Accelerated curing continued for a period of 15 hours at a constant elevated temperature. During this curing period, a continuous temperature record was made for the imbedded thermocouples and for the curing water. This was accomplished through use of the multipoint temperature recorder, having a range of -25 to 225°F, which scanned all thermocouples on a 6-minute cycle. The least reading of the temperature recorder was 1°F but the estimation of temperatures to within ¼°F was possible.

At the end of the accelerated curing period the two strength cylinders were removed from the hot water and the molds removed. At the same time, the instrumented cylinder was disconnected, stripped from its mold, and placed in moist storage. After one hour of cooling, the strength cylinders were capped and one hour later tested to rupture in compression.

Results and Discussion

Introduction

The following discussion of results is presented in four major divisions as follows:

1. Time-of-set Tests
2. Strength Test Results
3. Concrete Temperature Observations
4. Relationship of Accelerated Strength to Concrete Heat Release

The first three of these divisions are of an observational nature and discuss the procedures prior to the beginning of accelerated curing, the strength test results, and the observed concrete temperatures before and during accelerated curing. Finally, the fourth section explores the reasons for the observed behavior in strengths and concrete temperatures. Here an attempt is made to bring together the first three sections and to explain the strength-curing temperature relationships in terms of the heat evolution of the concrete.

Time-Of-Set Tests

Typical time-of-set tests for the four mixtures are illustrated by the four curves in Figure 8. As would be expected the setting time was significantly influenced by both the cement type and the cement factor with the Type III high cement factor mixture setting fastest and the Type II low cement factor mixture setting slowest. While this behavior was anticipated[9] it serves to point out the significant differences between mixtures and why setting time was used as the criterion for the beginning of accelerated curing.

The detailed results of time-of-set tests are tabulated in Table A-1, appended. It is of interest that, within a given mixture, the average coefficient of variation of final set was only 5.9%. This suggests that if a long series of accelerated curing tests involved the same mixture, one might be able to justify only an occasional time-of-set test. Nevertheless, in this study the time-of-set was determined for each mixture and accelerated curing begun immediately after reaching a penetration resistance of 4000 ps

Effects of Curing Temperature

The results of compressive strength tests (expressed as efficiencies) on each of the four test mixtures are shown graphically in Figure 9 as a function of curing temperature. Detailed strength data are tabulated in Tables A-2 through A-5, appended.

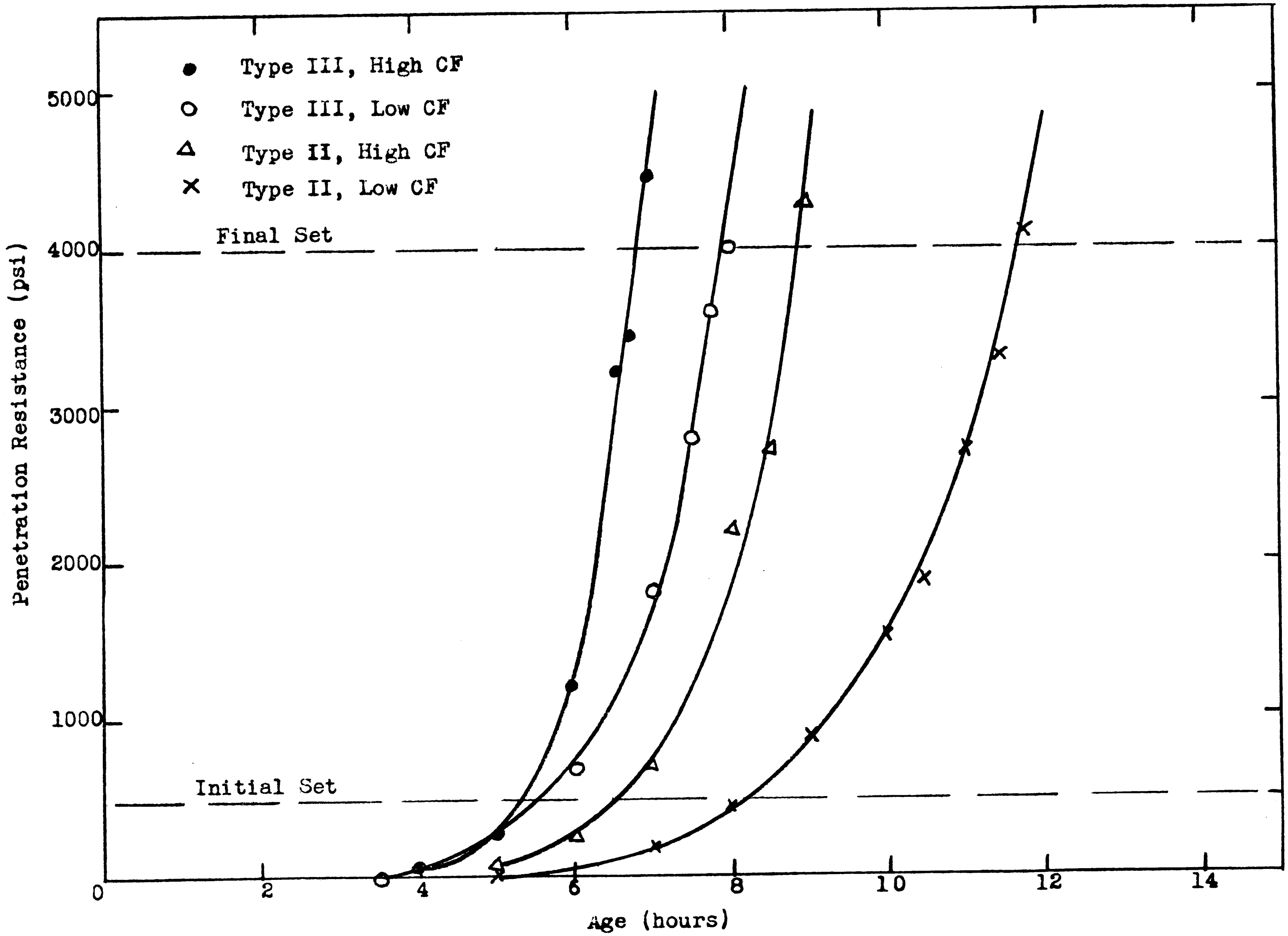


Figure 8. Penetration resistance versus age. (Typical curves.)

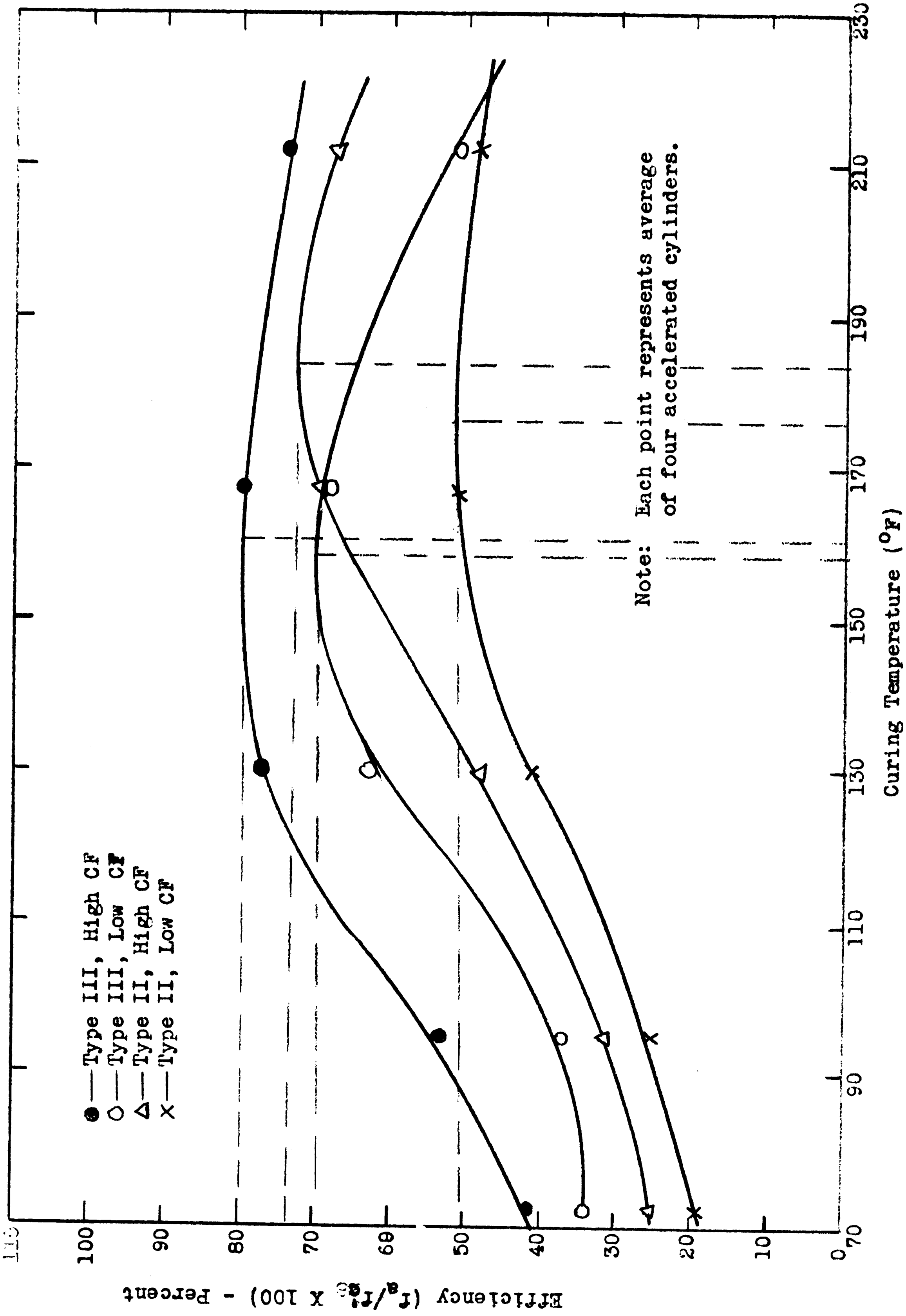


Figure 9. Efficiency versus curing temperature.

Note that maximum efficiencies of 70 to 80 percent were obtained for all mixtures except that containing Type II cement at a low cement factor. This very lean mixture attained a maximum efficiency of about 52 percent at a curing temperature of 167°F. It is clear from Figure 9 that, under the conditions used in this study, the efficiency of the accelerated curing method is dependent upon (1) the type of cement, and (2) the cement factor. It is also clear that no advantage is realized from curing at very high temperatures. In fact, boiling water seemed to have a detrimental effect on strength development. This effect can be seen to be small in the case of concretes containing Type II cement, while the Type III concretes seem to have been significantly influenced. Thus, for the present a water curing temperature of about 165 - 180°F seems to represent an optimum for all four of the mixtures tested.

Interestingly, approximately 165°F is also the optimum temperature level reported by many investigators for use in the atmospheric pressure steam curing of concrete(10). Furthermore, steam cured concrete usually is of the order of 5000 - 6000 psi design (28 day) strength with about 80 percent of the design strength realized after a 24-hour steam curing cycle. Such apparent similarities between optimum steam curing and optimum accelerated curing procedures lead to speculation that the two types of curing really differ only in the curing medium used.

Some of the reasons for the findings illustrated in Figure 9 will be discussed later. While the trends seen are more marked in the present study they are not too different from those observed by others(1).

Temperatures Observed During Accelerated Curing

At the time of final set the thermocouple instrumented cylinder and the two cylinders for accelerated strength testing immediately were placed into the accelerated curing tank containing water at the temperature specified for the given test. Then, as before accelerated curing, a continuous record of the temperature at the interior and the side of the thermocouple cylinder and of the curing water was obtained through use of the temperature recorder. This record covered the entire period of accelerated curing up to removal of the concrete from the water tank after 15 hours.

Figure 10 is a typical plot of the time-temperature relations observed during accelerated curing. While only one case is shown in this figure, all were of the same character and differed only in the curing temperatures and the relative concrete temperatures. Note that both the interior and exterior concrete temperatures reach maximum temperature levels substantially above those of the curing water.

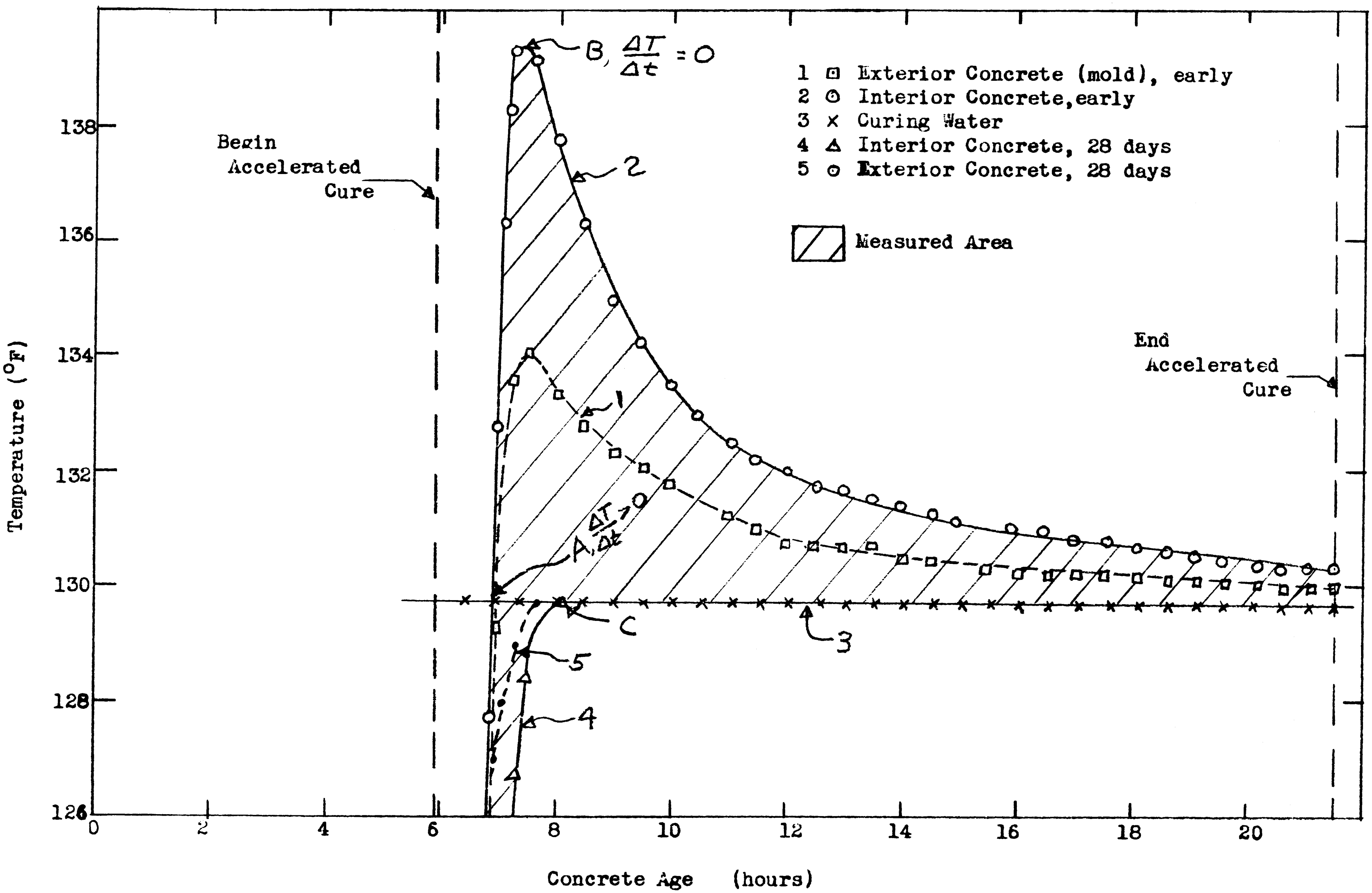


Figure 10. Typical time-temperature history for concrete during accelerated curing. Type III cement, high cement factor, $T_o = 130^o$ F. curing.

The shapes of the concrete time-temperature curves are clearly dependent on the amount and rate of heat evolved by the concrete. Otherwise, the concrete temperature could never exceed the curing water temperature. This is evidenced by the fourth and fifth curves on Figure 10, which are the time-temperature records for the same thermocouple cylinder placed in the curing water after about 28 days of moist curing. Note that under these conditions the concrete temperature climbs from room temperature to equilibrium with the curing temperature and does not at any time exceed the curing temperature. Thus, any hydration occurring at this later age is of insufficient magnitude to measurably influence the concrete temperature.

Figure 10 will be referred to throughout the following discussion, at which times features of the figure which have not been mentioned here will be discussed.

Relationship of Accelerated Strength to Concrete Heat Release

General

It has been well established in the literature, and in the previous sections of this report, that temperature increases accelerate the rate of chemical reactions in general and of the portland cement hydration process in particular. A first inclination might be that for an exothermic reaction, which tends to evolve heat, the addition of external heat would tend to slow the reaction. However, this is not the case. Both exothermic and endothermic reactions are accelerated as temperatures increase(11).

Lerch(5) observed a relationship between cement hydration heat for early ages and concrete compressive strength at similar ages for normally cured concretes. A working hypothesis of this discussion is that such a relationship also exists for concretes cured by accelerated methods. In applying such a hypothesis to the strength (or efficiency) results as reflected in Figure 9 it was necessary to make the following simplifying assumptions, necessitated by the impracticality of purchasing certain calorimetric equipment or of curing under adiabatic conditions (which would not have been applicable to the ASTM Cooperative Program):

(1) It was assumed that for conditions of constant curing temperature, the differences in heat loss between concretes due to differences in concrete temperatures would be negligible.

(2) It was assumed that the specific heats of the test concretes could be estimated from information given in the literature,(12) and

(3) It was assumed that the thermal conductivities, and thus the heat transfer capabilities, of all concretes were equal because the same amount and type of coarse aggregate was used in each case(12).

Overall Heat Release

Referring to the typical time-temperature record shown in Figure 10, consider the interior concrete temperatures (T) both during accelerated curing (curve 2) and for the same time interval 28 days later (curve 4). The curing temperature (T_o) was nearly constant. In order for the concrete, which was immersed in the curing water, to have a temperature $T \neq T_o$ it was necessary for heat (Q) to be transferred. Initially the concrete was at room temperature $T_f < T_o$ and in increasing the cylinder temperature from $T = T_r$ to $T = T_o$ the quantity of heat received by the concrete of mass (m) is given by the equation(12):

$$Q = -mc \Delta T = -mc (T_r - T_o)$$

where, for the present, the variations of temperature within the cylinder are ignored.

In going from T_r to T_o the mechanism by which the heat is furnished makes no difference in the quantity received by the concrete. However, the time-temperature path is dependent on the source of heat. As pointed out previously, both the fresh and the older concretes reach the curing water temperature (points A and C, Figure 10) but by different paths because the fresh concrete is itself a heat source while the older concrete receives all its heat from the curing water.

Equation 1 ($Q = -mc \Delta T$) shows that when $T > T_o$ heat must be transferred from the concrete to the water. Yet, between points A and B (Figure 10) the slope ($\frac{\Delta T}{\Delta t}$) of the time-temperature curve is positive ($\Delta T/\Delta t > 0$) so that hydration heat is causing the temperature of the concrete to increase faster than heat loss to the (cooling) water is causing temperature to decrease. At point B, $\frac{\Delta T}{\Delta t} = 0$ and the effects of hydration heat and heat loss are in equilibrium. Beyond point B, $\frac{\Delta T}{\Delta t} < 0$ and heat loss is the dominant effect. However, even beyond the peak concrete temperature (B), hydration heat is still an important factor. Without hydration heat, the time-temperature curve beyond point B would decrease as a mirror reflection of the temperature increase for 28 day old concrete between T_r and T_o, as dictated by Newton's law of cooling(13). This law states that the rate of transfer of heat between a thermally inactive body and its surroundings varies strictly as the difference in temperature between that of the body and that of the surroundings. Thus, hydration heat is causing a significant delay in the cooling of the concrete beyond point B. Note that during the time the concrete temperature exceeds the curing water temperature the water temperature is maintained at a constant level partially by hydration heat and partially by heat from the electrical elements.

A measure of the relative quantities of heat released by the various concretes during the curing period can be obtained by integration of the difference between the concrete and the water time-temperature curves shown as shaded area in Figure 10(14). This includes the small area below the water temperature and between the early and the 28 day interior concrete temperature curves, used to partially account for hydration heat evolved during the period of temperature rise. A planimenter was used to determine the areas under each curve from an average of two traverses.

Analyses revealed a linear relationship between accelerated curing efficiency and relative concrete heat release for a given curing temperature. However, when all curing temperatures were considered together, a family of straight lines resulted. The reason for this is apparent upon reconsideration of Equation 2 ($Q = -mc \Delta T$) where heat transferred is a function of both temperature difference and specific heat. It has been shown[12] that c is directly temperature dependent. Thus, more hydration heat is required to raise the concrete temperature one degree above the water temperature at 130°F (c = 0.260) for example, than at 95°F (c = 0.240)[15]. Then, in order to compare results between temperature levels it is necessary to introduce a different specific heat for each curing temperature. This was accomplished through use of the relationship $A = A_m c\,(T_o)\,m$ where:

A = adjusted area (BTU x hrs)

A_m = measured area (°F x hrs)

$c(T_o)$ = specific heat at temperature T_o (BTU/°F lb)

m = mass (30 lbs.) of concrete specimen.

In Figure 11 the curing efficiencies are plotted as functions of the adjusted areas shown in Table A-6. This figure includes all four accelerated curing temperatures. It can be seen that the curing efficiency is linearly related to the heat release of the concrete. Although there is considerable scatter of the data, it is of particular interest that the strengths generally fall close to the regression line regardless of cement type, cement factor, or of curing temperature, and that again the correlation coefficient is high (0.890). Thus, it may be concluded that for the mixtures studied here, accelerated concrete strength (or efficiency) is a linear function of the total heat evolved by the concrete during accelerated curing. An equivalent statement would be that higher early strengths result from a higher degree of early hydration.

The influence of curing temperature on the relative amount of heat evolved during accelerated curing is shown graphically in Figure 12. Note that for 212°F curing the strength reductions noted in Figure 9 are paralleled in the lower areas under the concrete temperature curves. Clearly, the implication is that despite the higher temperature, 212°F curing is not conducive to maximum strength development because less hydration occurs at this temperature. Reasons for this apparent retardation of the hydration process for 212°F curing are difficult to define clearly. In fact, the reduction in gypsum solubility at higher temperatures[16] and the subsequent release of unhydrated C_3A suggests that the hydration process should be even more accelerated than most chemical reactions by high ambient temperatures. Thus, the retardation observed in this study does not appear to be a chemical phenomenon in the usual sense.

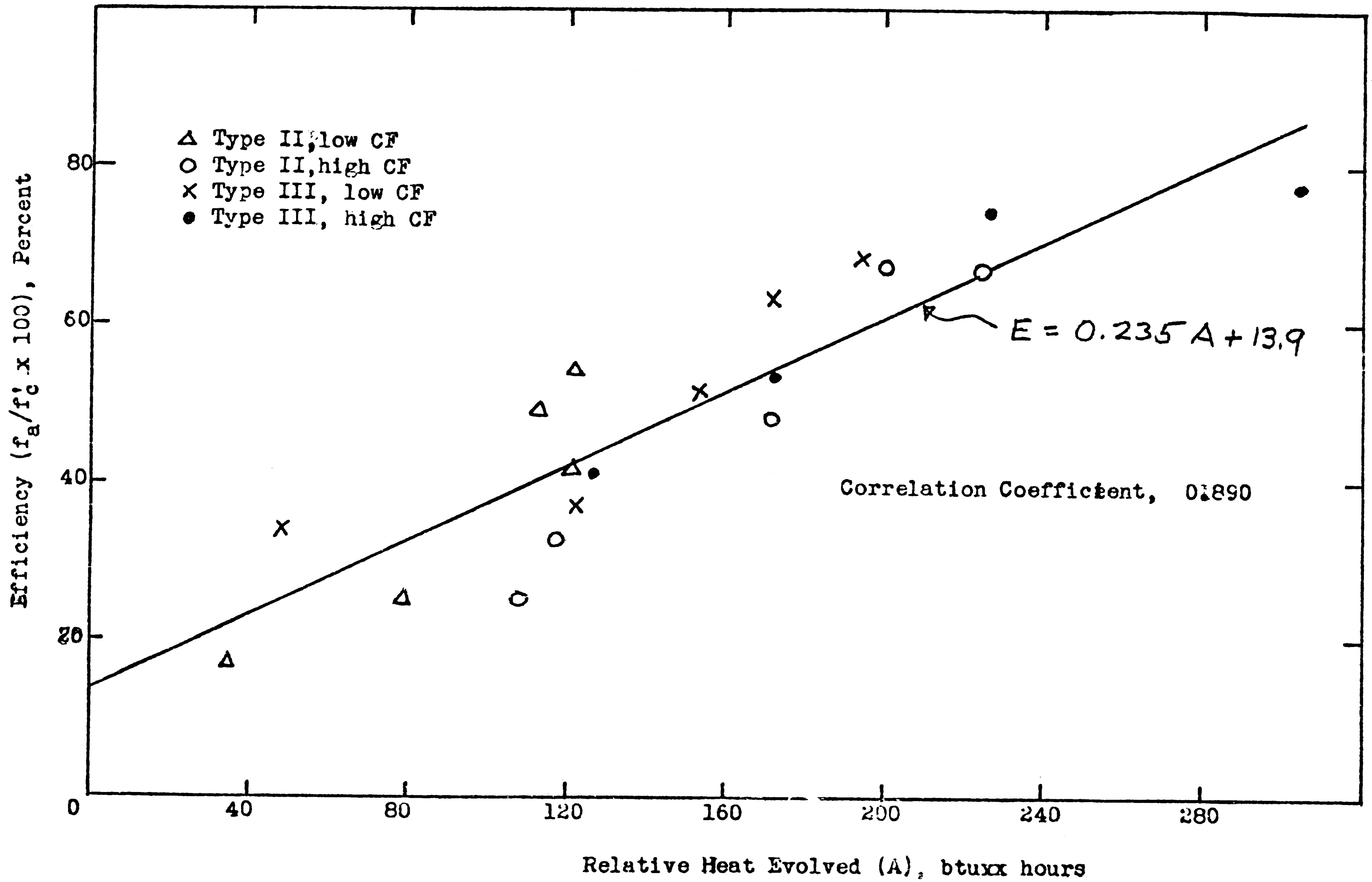


Figure 11. Efficiency versus relative total amounts of heat evolved during accelerated curing.

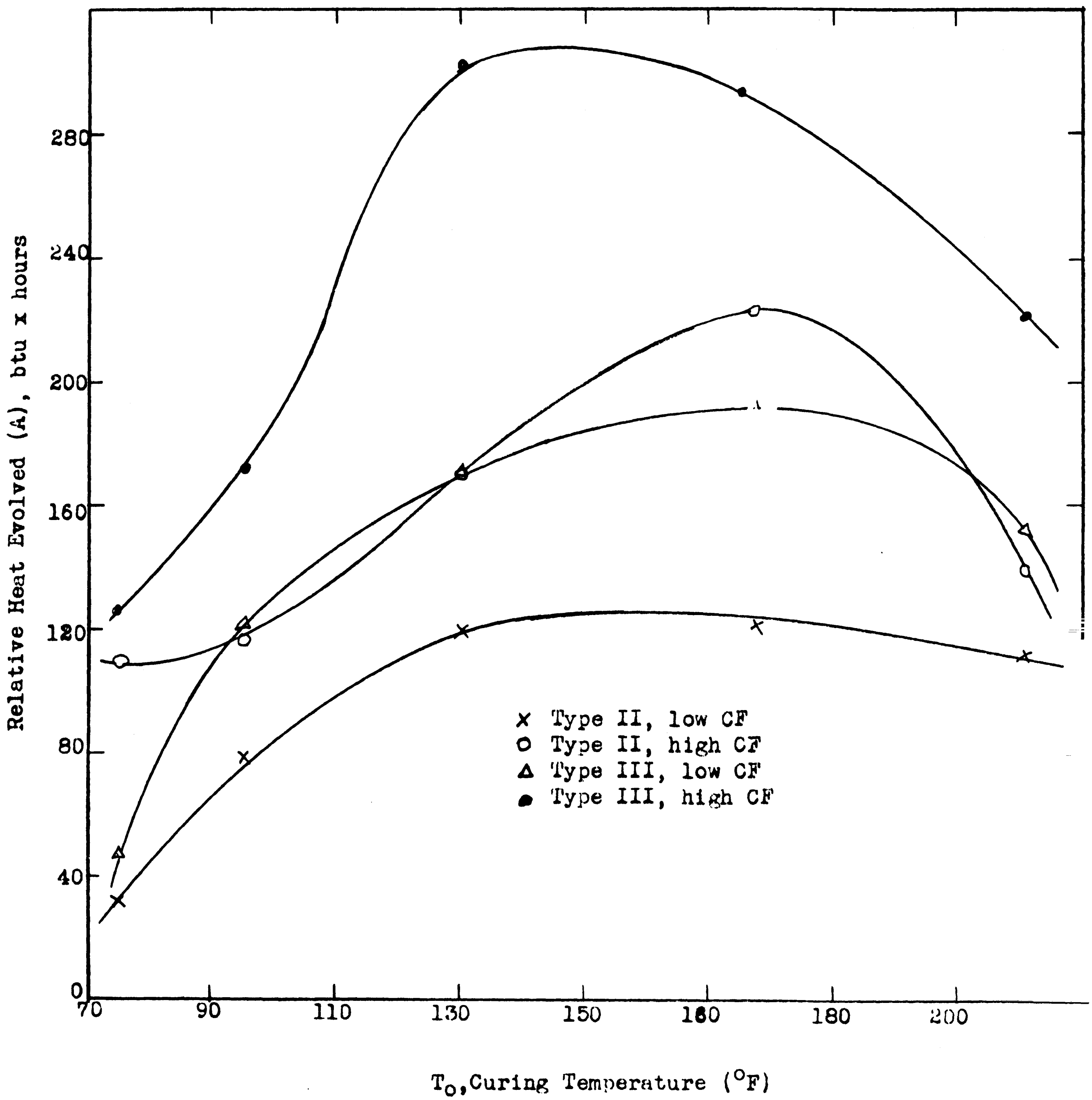


Figure 12. Relative total amounts of heat involved versus curing temperature.

Verbeck[7] offers a physical interpretation of a high temperature hydration phenomenon which leads to lower ultimate strength, although early strengths may be relatively high. In this theory, the rapid early hydration which is induced by high temperatures causes a dense zone of hydration products to form around the cement grains such that subsequent hydration is significantly retarded.

There is circumstantial evidence that the above "encapsulation" phenomenon may have occurred in the present study. This evidence may best be discussed through reference to Figure 13, which shows the time-temperature curves (above curing temperature) for the Type III, high cement factor mixtures at four curing temperatures. The areas and efficiencies shown are the averages for the two batches representing the particular curing temperature. Note the profound effect on the peak temperature differences of increasing the curing temperature from 95°F to 130°F. On the other hand, temperature increases above 130°F were much less effective in causing differences in temperature between the concrete and the curing water. In fact, 167° and 212°F curing temperatures resulted in almost identical peak differences. Such a result suggests that something happened, during the temperature rise time, to retard the influence of high curing temperatures. As the concrete temperature begins to fall toward the curing water temperature, further evidence of something like Verbeck's encapsulation phenomenon begins to appear. For example, note that as the curing temperature is increased, the slopes of the descending portions of the curves become steeper. This could not happen if hydration (heat evolution) was occurring at a similar rate for each of the three higher curing temperatures which produce essentially equal peak temperature differences. Thus, it is clear that hydration is occurring at a much lower rate at 212°F than at 130°F, for example. A logical cause could be encapsulation of the cement grains so that the aqueous solution has progressively more difficulty in gaining access to the grains as the curing temperature goes up.

Finally, note that as curing the temperature is increased, the concrete temperature more nearly approaches the curing water temperature within the 15 hour curing period and that for 212°F curing the concrete temperature is not measurably different from the curing temperature after 10 to 12 hours of accelerated curing. This was interpreted to mean that after 10 to 12 hours the hydration rate for 212°F curing would be very low and that little concrete strength gain could be expected after that time. Furthermore, it was noticed that even after 4-5 hours of 212°F curing little apparent hydration occurred and that the strength obtainable in 15 hours should be essentially developed in 5 hours. As a check on this hypothesis, one extra mixture was produced with the Type III, high cement factor proportions. From this mixture, cylinders were subjected to 212°F accelerated curing for 5, 10, and 15 hours and tested as before. The results are shown in Table VII, where it can be seen that the relative accelerated strengths were much as would be predicted from Figure 13. This, again, was evidence that encapsulation was fairly advanced at an early age for a high curing temperature.

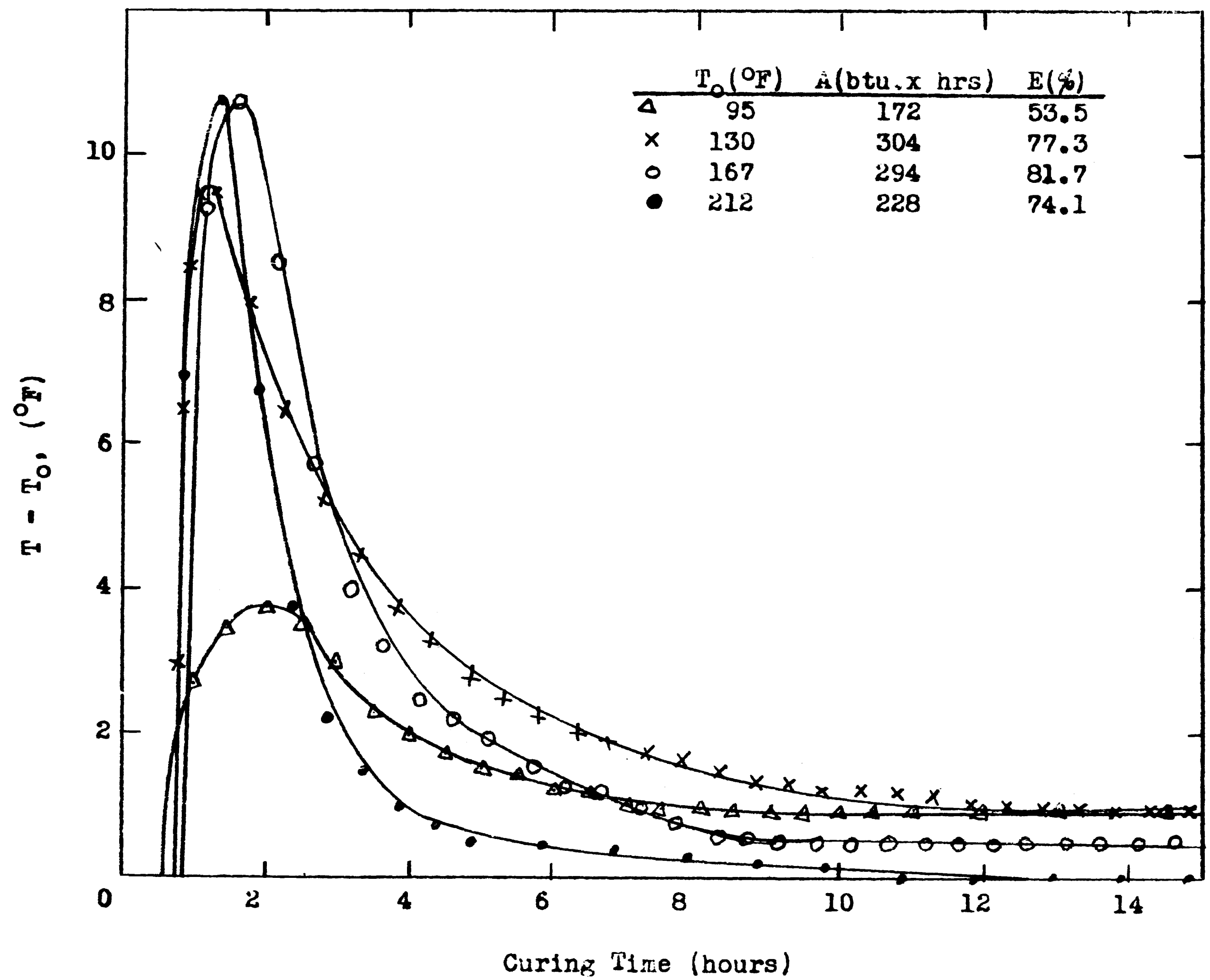


Figure 13. Difference between interior concrete and curing water temperatures as a function of time. Type III, high CF mixture, typical curves.

TABLE VII

ACCELERATED STRENGTHS FOR DIFFERENT LENGTHS OF 212°F CURING

Type III, 650 lb/c.y. Mixture

Length of Cure (Hrs.)	Accelerated Strength (PSI)
5	3660
10	3990
15	3870

As a final factor which possibly contributes to the nature of the results found in this study, there is microscopic evidence(7) that acceleration of the early hydration results in a nonuniform distribution of the reaction products within the paste structure and therefore prevents full strength development. This effect can be expected to be even more pronounced as the curing temperature is progressively increased, and may have contributed to the lower strengths found for 212°F curing.

CONCLUSIONS

Based upon the laboratory investigations and pertinent technical literature, the conclusions offered below appear justified. The reader is cautioned that the conclusions offered apply only to the materials and conditions as set forth in this report and may or may not be applicable under different circumstances.

Phase I

ASTM Cooperative Program

1. The fixed set boiling method (procedure C) is the most efficient and most reliable of the accelerated curing methods studied.
2. Water bath accelerated curing is much more efficient for higher strength concretes than for those of lower strength.
3. The water bath accelerated curing methods yield approximately equally reproducible results as evidenced by statistical analysis. Similarly, the results of all methods (accelerated and standard)

have variation coefficients within the American Concrete Institute's (ACI 214-65) recommended limits for good to excellent control of laboratory concrete.

Phase II

Influence of Curing Temperature and Heat Evolution

The following conclusions are applicable to the fixed set method of accelerated strength testing:

1. Accelerated curing efficiencies are directly proportional to the total relative amounts of heat released by the concretes during accelerated curing. This is true regardless of the cement factor, cement type, or curing temperature employed for a given concrete.

2. Boiling (212°F) water is not conducive to optimum curing efficiency. It is conjectured that at this temperature the reaction rate during temperature rise is so high that the cement grains become encapsulated in a dense shell of hydration products such that hydration during most of the accelerated curing time is significantly retarded.

3. Optimum water bath temperatures for accelerated concrete strength development range approximately from 165 to 180°F. Based on the ratio of accelerated strength to moist cured strength, the above temperatures provide a curing environment which (on a 24-hour cycle) is from 55 to 80 percent efficient, depending upon the cement type and the cement factor of the concrete under consideration.

4. The duration of accelerated curing is not critical for the fixed set boiling method, where tests indicate that the accelerated strength has been achieved in from 5 to 10 hours.

ACKNOWLEDGEMENTS

The work described in this report was performed under the general direction of Mr. Jack H. Dillard and the late Dr. Tilton E. Shelburne, State Highway Research Engineers. Especial appreciation is expressed to Mr. Howard H. Newlon, Jr., Assistant State Highway Research Engineer, for his valuable technical assistance; and to Mr. Clyde Giannini, Highway Materials Technician, who conducted much of the laboratory testing. Also of great assistance were Mr. George Verbeck, Director of Research, Portland Cement Association, and Mr. W. J. McCoy, Director of Research, Lehigh Portland Cement Company, who conducted heat of hydration tests.

The work was financed from state research funds provided by the Virginia Department of Highways.

REFERENCES

1. Smith, P., and H. Tiede, Earlier Determination of Concrete Strength Potential, Ontario Department of Highways, January 1967.

2. ASTM, Subcommittee II-i, Committee C-9, "Cooperative Accelerated Strength Testing Program", November 1966.

3. Malhotra, V. M., N. G. Zoldners, and R. Lapinas, Accelerated Test for Determining the 28-Day Compressive Strength of Concrete, Department of Mines and Technical Surveys, Ottawa, 1964.

4. Powers, T. C., "Some Physical Aspects of the Hydration of Portland Cement", PCA Bulletin No. 125, 1961.

5. Lerch, William, "The Influence of Gypsum on the Hydration and Properties of Portland Cement Pastes", PCA Bulletin No. 12, 1946.

6. Monfore, G. E., and Borje Ost, "An Isothermal Conduction Calorimeter for Study of the Early Hydration Reactions of Portland Cements", PCA Bulletin 201, 1966.

7. Verbeck, George, "Cement Hydration Reactions at Early Ages", Journal of the PCA Research and Development Laboratories, September 1965.

8. Klieger, Paul, "Effect of Mixing and Curing Temperature on Concrete Strength", PCA Bulletin 103, 1962.

9. American Society for Testing and Materials, STP 169-A, Concrete and Concrete Making Materials, 1966.

10. Brown, H. E., "An Investigation of the Effect of the Gypsum Content and Steam Curing Variations on the Compressive Strength of Portland Cement Concrete", Masters Thesis, University of Virginia, 1963.

11. Pauling, Linus, College Chemistry, W. H. Freeman, San Francisco, 1952.

12. United States Bureau of Reclamation, Bulletin 1, Thermal Properties of Concrete, 1940.

13. Worthington, A. G., and D. Halliday, Heat, John Wiley and Sons, Inc., New York, 1948.

14. Budnikov, P. P., and E. Ya. Erschler, USSR, "Studies of the Processes of Cement Hardening in the Course of Low-Pressure Steam Curing of Concrete", HRB Special Report 90, 1966.

15. McGhee, K. H., "An Investigation of Accelerated Curing Procedures for Portland Cement Concrete", Masters Thesis, University of Virginia, June 1968.

16. Steinour, Harold H., "The Setting of Portland Cement, A Review of Theory, Performance and Control", PCA Research Bulletin 98, November 1958.

TABLE A-1

CHARACTERISTICS OF FRESHLY MIXED CONCRETES

	Mixture Type			
	Type II		Type III	
	450 lb/c.y.	650 lb/c.y.	450 lb/c.y.	650 lb/c.y.
Batches	1 - 10	11 - 20	21 - 30	31 - 40
Water Content (%)	7.7 ± 0.9	7.9 ± 0.7	7.6 ± 0.6	7.8 ± 0.8
Air Content (%)	5.4 ± 0.4	5.2 ± 0.4	5.6 ± 0.6	5.3 ± 0.4
Slump (in.)	2.2 ± 0.4	2.4 ± 0.6	2.3 ± 0.4	2.6 ± 0.6
Unit Weight (lb/c.f.)	144.0 ± 1.6	145.0 ± 2.0	143.8 ± 2.0	145.5 ± 2.6
Time of Set (hrs.)	11.44 ± 1.50	8.84 ± 1.58	7.85 ± 0.76	6.82 ± 0.50
Water-Cement Ratio gal/bag	7.50 ± 1.0	5.4 ± 0.8	7.4 ± 0.7	5.3 ± 0.7
Coarse Aggregate lb/c.y.	1830	1830	1830	1830
Fine Aggregate lb./c.y.	1300	1150	1300	1150

TABLE A-2

COMPRESSIVE STRENGTHS OF TYPE II, 450 LB/C.Y. C. F. MIXTURES

Accelerated Curing Temperature	Batch	24 Hour Accelerated Strength (psi)	28 Day Moist Strength (psi)	Average Efficiency (%)
72°F	1	450 440	2690	16.7
	2	530 490	2480	20.6
95°F	3	870 870	3300	26.4
	4	870 820	3550	23.9
130°F	5	1290 1310	3030	42.8
	6	1230 1220	3120	39.4
167°F	7	1520 1560	3090	49.8
	8	1890 1930	3280	58.8
212°F	9	1640 1670	3230	51.7
	10	1700 1670	3560	47.5

TABLE A-3

COMPRESSIVE STRENGTHS OF TYPE II, 650 LB./C.Y. C.F. MIXTURES

Accelerated Curing Temperature	Batch	24 Hour Accelerated Strength (psi)	28 Day Moist Strength (psi)	Average Efficiency %
$72^{o}F$	11	1190		
		1140	4860	24.1
	12	1090		
		1090	3960	26.6
$95^{o}F$	13	1570		
		1520	5160	30.1
	14	1550		
		1540	4750	32.6
$130^{o}F$	15	2130		
		2140	4420	48.4
	16	2250		
		2210	4670	47.8
$167^{o}F$	17	3090		
		3080	5150	60.0
	18	3730		
		3930	5170	74.0
$212^{o}F$	19	3210		
		3180	4950	65.0
	20	3410		
		3320	4840	69.5

TABLE A-4

COMPRESSIVE STRENGTHS OF TYPE III, 450 LB/C.Y. C. F. MIXTURES

Accelerated Curing Temperature	Batch	24 Hour Accelerated Strength (psi)	28 Day Moist Strength (psi)	Average Efficiency %
$72^{\circ}F$	21	1060		
		1140	3470	31.7
	22	1360		
		1330	3630	37.2
$95^{\circ}F$	23	1640		
		1620	4180	39.0
	24	1530		
		1570	4390	35.3
$130^{\circ}F$	25	2070		
		2040	3170	65.0
	26	1910		
		2070	3230	61.7
$167^{\circ}F$	27	2410		
		2430	3470	69.7
	28	2860		
		2870	4210	68.1
$212^{\circ}F$	29	2310		
		2300	4490	51.3
	30	1940		
		1990	3770	52.3

TABLE A-5

COMPRESSIVE STRENGTHS OF TYPE III, 650 CL/C.Y. C.F. MIXTURES

Accelerated Curing Temperature	Batch	24 Hour Accelerated Strength (psi)	28 Day Moist Strength (psi)	Average Efficiency %
$72^{o}F$	31	2000 2030	5390	37.4
	32	2320 2340	5150	45.2
$95^{o}F$	33	2560 2580	5190	49.7
	34	2830 2830	4930	57.3
$130^{o}F$	35	3860 4010	5320	74.2
	36	4050 4100	5080	80.3
$167^{o}F$	37	4190 4040	5130	80.2
	38	4470 4700	5510	83.2
$212^{o}F$	39	3950 3930	5350	75.0
	40	4600 4560	6270	73.2

TABLE A-6

THERMAL ANALYSIS DATA

Batch	Mixture Type	Curing Temperature (^oF)	Specific Heat (Btu/lb ^oF)	A (Btu x hr)	Efficiency $(\frac{f_a}{f'_c} \times 100)$
1	II (Low)	72	0.228	33	16.7
2				—	20.6
3		95	0.240	78	26.4
4				80	23.9
5		130	0.260	103	42.8
6				138	39.4
7		167	0.284	—	49.8
8				122	58.8
9		212	0.315	134	51.7
10				91	47.5
11	II (High)	72	0.228	120	24.1
12				95	26.6
13		95	0.240	81	30.1
14				153	32.6
15		130	0.260	193	48.4
16				148	47.8
17		167	0.284	224	66.0
18				—	74.0
19		212	0.315	200	65.0
20				—	69.5

TABLE A-6 (Cont.)

Batch	Mixture Type	Curing Temperature (^oF)	Specific Heat (Btu/lb ^oF)	A (But x hr)	Efficiency ($\frac{f_a}{f'_c}$ x 100)
21	III (Low)	72	0.228	50	31.7
22				45	37.2
23		95	0.240	126	39.0
24				117	37.2
25		130	0.260	165	65.0
26				179	61.7
27		167	0.284	194	69.7
28				—	68.1
29		212	0.315	153	51.3
30				—	52.3
31	III (High)	72	0.228	112	37.4
32				140	45.2
33		95	0.240	163	49.7
34				181	57.3
35		130	0.260	270	74.2
36				337	80.3
37		167	0.284	294	80.2
38				—	83.2
39		212	0.315	236	75.0
40				209	73.2