FINAL REPORT

AUTOGENOUS ACCELERATED CURING OF CONCRETE CYLINDERS

Part V

ASTM Cooperative Testing Program with Additional Emphasis on the Influence of Container and Storage Characteristics

(Supplemented by Data on Water Bath Curing From an Earlier Council Project)

by

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

Virginia Highway Research Council
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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 storage conditions was undertaken to supplement the major project effort.

The total 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	—	ASTM Cooperative Testing Program with Additional Emphasis on the Influence of Container and Storage Characteristics (Supplemented by Data on Water Bath Curing From an Earlier Council Project)

In Part V, it was deemed desirable to include data from the earlier study by McGhee so as to give a comprehensive picture of the Council's portion of the ASTM Cooperative Testing Program. While some of the work reported in Part V was not a part of the autogenous curing study, most of it was done as a part of the project so that its inclusion in the project report seems logical.

Each part of the 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

Concomitant with the Research Council's studies of accelerated curing for strength testing, Subcommittee II-i of ASTM Committee C-9 was developing and refining accelerated methods for standardization. This development included a cooperative testing program in which nine U. S. and Canadian laboratories, including the Research Council, applied various methods to their mixtures and materials. The Council's work was conducted as a part of two different projects. Procedures employing water bath curing were evaluated and subsequently the autogenous procedure was studied.

This report combines the information from these two investigations with data from limited scope studies of containers and storage conditions. The curing procedures evaluated were:

(1) $95^{\circ}F$ water bath immediately for 24 hours (Procedure A)

(2) $212^{\circ}F$ water bath after 23 hours for $3\frac{1}{2}$ hours (Procedure B)

(3) $212^{\circ}F$ water bath after initial set (approximately 4 - 6 hours) for $\approx$ 15 hours (Procedure C)

(4) Autogenous curing immediately in special containers (Procedure D)

Based upon the data developed, the following conclusions are drawn.

(1) Each of the four accelerated procedures is capable of predicting strengths at later ages with accuracy equivalent to that currently achieved with moist curing.

(2) Procedure A gives the lowest strength ratios (i.e., accelerated strength to that at later ages) while Procedures C and D give the highest ratios. Procedure B is intermediate.

(3) The variability of test results from accelerated tests is of the same order as that from conventional procedures.

(4) The four procedures are comparatively insensitive to the presence of retarding admixtures at normal dosages. Procedure C appeared to be affected by the presence of the admixture more than by changes in cement type.

(5) Differences in results among the procedures and the influence of other factors such as initial mixture temperatures are greatest for mixtures at lower initial temperatures and with a low potential for heat evolution.

(6) Variations of initial mixture temperatures above 60°F do not significantly influence results. Temperatures below 60°F may give slightly lower strength ratios than do higher temperature mixtures.

(7) For the Autogenous Procedure, D, a fairly wide range of heat retention characteristics between container types ($\approx$ 25°F at 48 hours) had no significant influence on strength ratios. It is postulated that a minimum heat retention value is necessary but that limits on maximum values are not necessary.

(8) Minor variations in storage conditions and/or lengths of curing do not significantly affect results for either Procedure B or D although Procedure B is slightly more influenced than Procedure D.

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Concomitant with the Research Council's studies of accelerated curing for strength testing, Subcommittee II-i of ASTM Committee C-9 was developing and refining standards for accelerated curing methods. The development included a cooperative testing program in which nine U. S. and Canadian laboratories, including the Research Council, applied various procedures to their mixtures and materials (ASTM — 1966). The Council's participation in the ASTM Cooperative Testing Program was in two parts. Procedures using water as the curing medium have been reported by McGhee (1970). For completeness, portions of McGhee's work have been included in this report as Phase A even though his study was not a part of this project. Procedures based on autogenous curing are reported by Cook in Parts I - IV of this report (Cook — 1970a, 1970b, 1971c, and 1971d). That portion of Cook's work relating to the ASTM Cooperative Testing Program is designated as Phase B in this Part but was designated as Phase I in Parts I - IV.*

PURPOSE

The purpose of this report is to present the results of those portions of the Research Council's studies of accelerated strength testing which pertain specifically

*McGhee's investigation of the methods using water as a curing medium was financed from state research funds, while Cook's study of the autogenous method was financed by federal HPR Funds.

to the standardizing of the methods by ASTM. These include:

(1) The strength ratios and correlations between the results from accelerated and conventional tests, and

(2) the influence on results of the autogenous container characteristics and storage conditions.

SCOPE

The scope was limited to the number of variables necessary to conform essentially to the requirements of Subcommittee II-i's cooperative testing programs.

VARIABLES

The variables included in various parts of this study were as follows:

(1) Cement Types: II and III

(2) Cement Contents: 450, 550, and 650 lb/cy

(3) Admixtures: Air entraining and water reducing retarder (ASTM Type D)

(4) Mixture Temperature: 50°F, 60°F, 70°F, 80°F and 90°F

(5) Curing Procedures:

(a) 95°F water bath immediately for 24 hours (Procedure A)*

(b) 212°F water bath after 23 hours for 3½ hours (Procedure B)*

(c) 212°F water bath after initial set (approximately 4 - 6 hours) for ≈ 15 hours (Procedure C)*

(d) Autogenous curing immediately in special containers (Procedure D)*

*In this report reference is made to the procedures as A, B, C, and D, which were the designations established for the cooperative testing program. Subsequently, Procedures A, B, and D were proposed for standardization. Thus the autogenous procedure (designated D in this report) became Procedure C in the ASTM proposed standard.

(6) Autogenous Curing Containers: One type designed for use in the Virginia study and a second type used in Canadian studies.

(7) Length of Curing and Storage Periods: 23 vs. 24 hours for Procedure B and 47 vs. 48 hours for Procedure D; indoor vs. outdoor storage.

Many of the variables were investigated in a limited way, and the results may be considered only as indicative of behavior under other conditions. The variables were evaluated in several distinct phases of the main studies, which were conducted over a period of three and one-half years. While materials (cement, aggregates, and admixtures) were from the same sources for all of the phases, they were from different lots. The agreement of results from the several phases indicates that these differences in materials did not significantly influence the results.

The important aspects of the various phases are summarized in Table I.

TABLE I

VARIABLES EVALUATED DURING THE STUDY

Phase	Number of Batches	Procedures Studied	Cement Types	Cement Contents, lb/cy	Admixtures	Nominal Mixture Temperature, Deg. F	Autogenous Containers	Storage Conditions	Dates of Mixing
A	72	A, B, C	II, III	450, 550, 650	AE, WR	70	----------	Constant	6/67 - 6/68
B	24	D	II, III	450, 550, 650	AE, WR	70	Virginia	Constant	6/69 - 8/69
C	16	D	II, III	550, 650	AE	50, 70, 90	Va. & Can.	Constant	4/70 - 6/70
D	12	B, D	II, III	650	AE	60, 80	Virginia	Variable	7/70 - 9/70

Phases A and B comprised the Research Council's participation in the ASTM Cooperative Testing Program while Phase C and D were supplemental, limited scope studies.

All concrete contained a granite-gneiss coarse aggregate, and a natural siliceous fine aggregate. The nominal characteristics of the mixtures are given in Table II.

The fineness modulus of the fine aggregate was 2.64. The specific gravities of the fine and coarse aggregates were 2.61 and 2.80, respectively.

TABLE II

NOMINAL MIXTURE CHARACTERISTICS

Cement Content, lb/cy	450	550	650
Cem./F.A./C.A., by wt.	1:3.1:4.0	1:2.4:3.3	1:1.9:2.8
W/C, by wt.	variable	variable	variable
Maximum Aggregate Size, in.*	1"	1"	1"
Slump, in.	$2\frac{1}{2} \pm \frac{1}{2}$	$2\frac{1}{2} \pm \frac{1}{2}$	$2\frac{1}{2} \pm \frac{1}{2}$
Air Content, Percentage	5.0 ± .5	5.0 ± .5	5.0 ± .5

*The coarse aggregate was artificially graded and recombined in a quantity sufficient for a single batch as follows:

Screen Sizes	Amount Retained, %
$-1 + \frac{3}{4}$	20
$+\frac{3}{4} + \frac{1}{2}$	27
$-\frac{1}{2} + \frac{3}{8}$	33
$-\frac{1}{4}$ + #10	10

RESULTS

The average slumps and air contents of the concretes for the several phases are shown in Table III along with the corresponding standard deviations, σ.

TABLE III

SLUMPS AND AIR CONTENTS OF LABORATORY BATCHES

Phase	Number of Batches	Slump, inches		Air Content, percent	
		Average	σ	Average	σ
A	72	2.5	0.26	5.4	0.34
B	24	2.4	0.30	5.5	0.35
C	16	2.6	1.60	6.2	1.23
D	12	2.4	0.38	5.5	0.40
Total	124				

ASTM Cooperative Testing Program (Phases A and B)

Strength Ratios

The strength ratios at various ages are shown in Table IV.

In all cases Procedure A gave the lowest strength ratios. Usually Procedure D gave the highest. Based upon the ratios of the accelerated strength to the 1 year results for the type II cement, there was little difference between the ratios from Procedures C and D. Procedure B gave ratios intermediate between these procedures and Procedure A. For the type III cement, Procedures B and C were usually close together while Procedure D gave slightly higher ratios.

It appears from these data that the ratios for Procedure C were affected by the presence of the retarding admixture more than by the change of cement. The higher strength ratios for the retarded concrete are at first glance unusual; however, they probably reflect the beneficial effect with Procedure C of delaying the accelerated curing until the beginning of setting. This has been discussed in detail by McGhee (1970). The ratios from the other methods are comparatively insensitive to the presence of the retarding admixture but increase significantly with mixture characteristics which increase heat liberation. This is also consistent with the dependence of accelerated curing methods upon internal heat generation.

In Procedure A, the temperature of the surrounding water is low so that the differences in heat liberated by the two concretes with different heat liberating characteristics are significant. In Procedure B the accelerated set during the normal curing period is a large part of the total acceleration. The importance of the increased heat liberation is obvious for Procedure D.

TABLE IV

STRENGTH RATIOS FROM PROCEDURES A, B, C, AND D

Cement Type and Admixture	Procedure	Accelerated Strength, a, psi	Cement Content 450 lb./cy.				Cement Content 550 lb./cy.					Cement Content 650 lb./cy.				
			a/28	a/91	a/364	28/364	a, psi	a/28	a/91	a/364	28/364	a, psi	a/28	a/91	a/364	28/364
Type II	A	790	.21	--	.18	.82	1260	.27	--	.22	.81	1930	.34	--	.28	.81
Plus AEA	B	1240	.31	--	.26	.84	1670	.35	--	.33	.93	2200	.41	--	.33	.82
	C	1800	.49	--	.41	.85	2480	.54	--	.45	.82	3240	.61	--	.50	.81
	D	1496	.47	.45	.43	.90	2460	.61	.56	.52	.85	3425	.70	.61	.57	.82
Type II	A	1060	.24	--	.20	.84	1740	.30	--	.25	.82	2380	.39	--	.34	.89
Plus AEA	B	1540	.34	--	.29	.85	2190	.38	--	.31	.83	2960	.48	--	.40	.84
Plus WR-R	C	2300	.55	--	.52	.85	3220	.63	--	.57	.82	4510	.69	--	.60	.76
	D	1810	.52	.48	.47	.89	3150	.64	.56	.54	.84	4235	.71	.62	.60	.84
Type III	A	2240	.45	--	.44	.97	3070	.51	--	.48	.94	4130	.60	--	.53	.89
Plus AEA	B	2470	.52	--	.48	.91	3540	.56	--	.51	.91	4250	.65	--	.57	.88
	C	2570	.51	--	.43	.95	3860	.60	--	.49	.89	4720	73	--	.56	.87
	D	2445	.69	.66	.67	.97	3560	.72	.69	.64	.89	4180	.73	.67	.63	.86
Type III	A	2460	.44	--	.43	.97	3450	.49	--	.48	.97	4420	.58	--	.49	.84
Plus AEA	B	2940	.55	--	.51	.93	3930	.59	--	.53	.90	5140	.66	--	.62	.94
Plus WR-R	C	3170	.58	--	.54	.94	4190	.64	--	.57	.83	5530	.76	--	.65	.86
	D	3245	.71	.67	.67	.94	3955	.73	.68	.68	.93	5260	.75	.68	.67	.90

For all methods the ratios increased with increasing cement content in a fairly consistent pattern.

The strength ratios of the cylinders moist cured for 28 days to those similarly cured for 1 year are reasonably consistent for a given combination of variables. This consistency is encouraging, since the procedures were evaluated over a two year period as was indicated previously in Table I. Of some interest is the fact that these ratios were generally highest for the lowest cement content (i.e., the highest water-cement ratio). This means that the lowest cement content (highest water-cement ratio) hydrated at a higher rate than did the highest cement content (lowest water-cement ratio). This is consistent with the basic concepts of cement hydration in that the ratio of the surface area of cement grains to water would be higher in leaner mixtures so that early hydration reactions would be promoted. The 1 year strengths of the richer (i.e., lower water-cement ratio) mixtures were significantly higher than those of the leaner mixtures.

Correlations

Smith and Tiede (1967) and others have questioned the necessity for and the wisdom of correlating the results from accelerated tests with those from specimens conventionally cured until later ages. Nevertheless, numerous correlations have been presented in the technical literature, and it is of value to compare the ability of the accelerated methods to predict the strengths at later ages and their variabilities when compared with the similar predictive ability of conventionally cured specimens.

The least-squares equations for predicting 28-day compressive strength from the results obtained with the four accelerated procedures are shown in Table V. The equation of the form

$$Y = B_0 + B_1 x$$

was used, where

Y = later age strength, psi, and

x = accelerated strength, psi.

Also shown are the correlation coefficients (r) and standard errors of estimate (s_e). The correlation coefficients are all high, and the standard errors acceptable. Although the errors in predicting one-year strengths are somewhat higher than for predictions of 28-day strength, all of the procedures appear to be acceptable predictions of the 28-day and 1-year strengths. Procedures C and D appear to be somewhat better predictors than Procedures A and B.

TABLE V

PREDICTION OF 28-DAY AND 1-YEAR STRENGTHS

(a) Prediction by Accelerated Tests of 28-Day Strengths

Simple Linear Regression

Cement	B_0	B_1	r	s_e	Slope Significance Test
Procedure A					
II	2770	1.515	0.955	285	same
III	2750	1.095	0.925	400	same
Procedure B					
II	2580	1.290	0.965	225	same
III	2025	1.145	0.955	315	same
Procedure C					
II	2375	0.900	0.970	220	same
III	2680	0.870	0.970	225	same
Procedure D					
II	1660	1.000	0.990	140	different
III	550	1.230	1.000	60	different

(b) Prediction by Accelerated Tests of 1-Year Strengths

Cement	B_0	B_1	r	s_e	Slope Significance Test
Procedure A					
II	3940	1.345	0.830	625	same
III	1910	1.510	0.935	510	same
Procedure B					
II	2720	1.685	0.915	455	different
III	2340	1.220	0.950	380	different
Procedure C					
II	2200	1.330	0.980	260	same
III	1925	1.240	0.985	235	same
Procedure D					
II	1406	1.350	0.987	225	same
III	445	1.383	0.975	298	same

The correlation coefficients, r, and standard errors, s_e, judge the degree of fit and dispersion of the data about the straight line which best fits the data. A question of practical significance is whether or not the slopes of the regression equations developed from tests by the same procedure on mixtures made with different materials are the same. This was tested statistically using a slope significance test described by Dixon and Massey (1951). As shown in Table V, curves for predicting 28-day strengths from accelerated results from Procedure D and from Procedure B for predicting 1-year strengths were significantly different at the 95% level for the two cements. In other cases the slopes were not significantly different at the 95% level.

Of some interest is a comparison of the ability of the accelerated and 28-day strengths to predict the strengths at one year. The significant statistical measures are shown in Table VI.

TABLE VI

COMPARISON OF 1-YEAR COMPRESSIVE STRENGTH PREDICTIONS BY 28-DAY AND ACCELERATED METHODS

Cement Type	Prediction	Simple Linear Regression			
		B_0	B_1	r	s_e
II	Procedure A	3740	1.545	0.830	625
	28-day	580	1.085	0.925	425
	Procedure B	2720	1.685	0.915	455
	28-day	-690	1.315	0.955	325
	Procedure C	2200	1.330	0.980	260
	28-day	-945	1.420	0.950	410
	Procedure D	1406	1.350	0.987	225
	28-day	-604	1.311	0.992	177
III	Procedure A	1910	1.510	0.935	510
	28-day	-900	1.230	0.895	640
	Procedure B	2340	1.220	0.950	380
	28-day	385	1.040	0.900	520
	Procedure C	1925	1.240	0.985	235
	28-day	-1700	1.395	0.990	195
	Procedure D	445	1.382	0.975	298
	28-day	-577	1.213	0.988	221

The same data are shown graphically in Figures 1a and 1b. From the data in Table VI and Figure 1, it is evident that the ability of the accelerated methods to predict the 1-year strengths is no less reliable than is currently tolerated for testing after 28 days of conventional curing. Similar results were obtained in an analysis of all data from the ASTM II-i Cooperative Testing Program by Miller and Chamberlin (1970).

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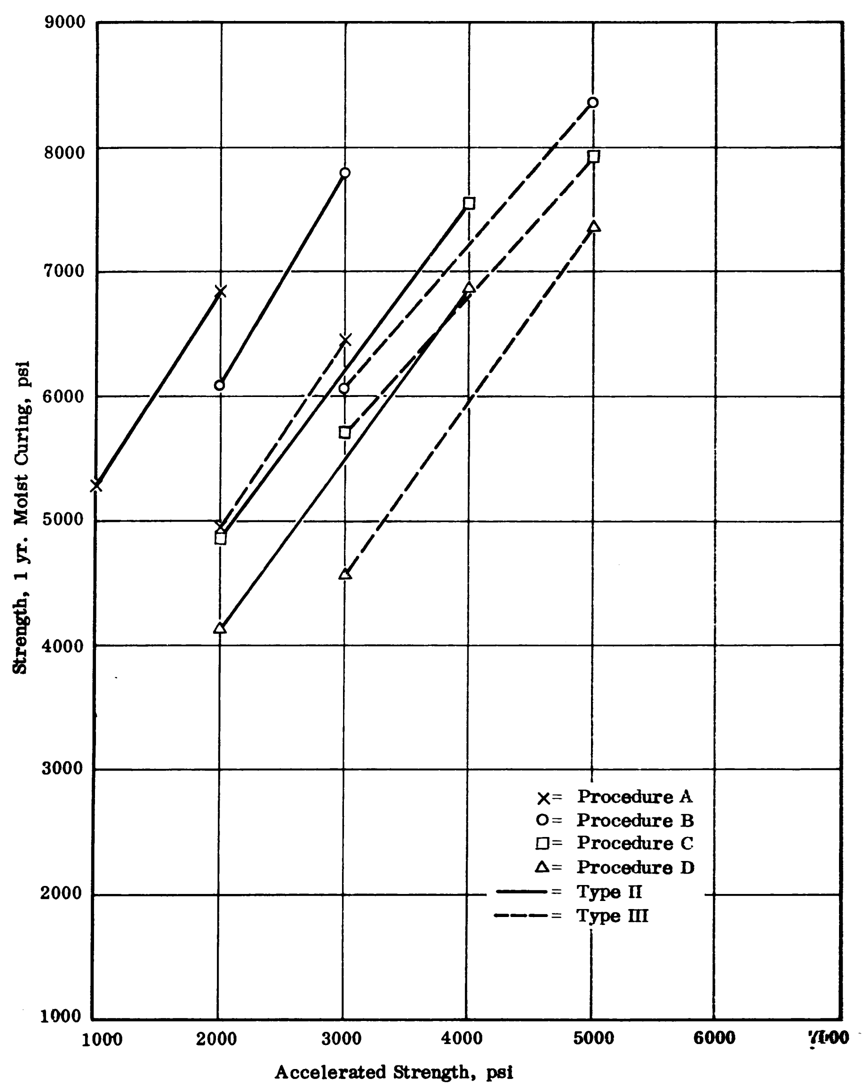

Figure 1a. Calculated correlating equations for predicting 1 yr.-strengths from accelerated results.

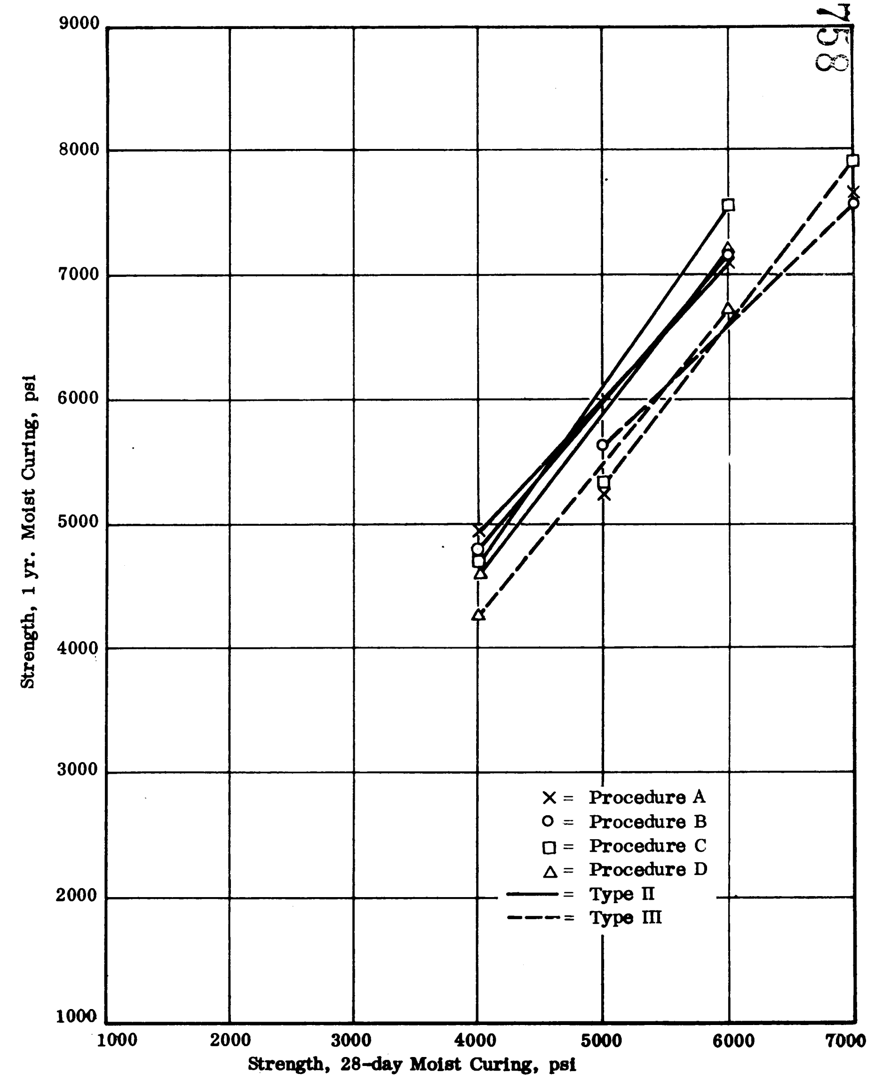

Figure 1b. Calculated correlating equations for predicting 28-day strengths from accelerated results.

Effect of Container and Mixture Temperature (Phase C)

During the study of the autogenous acceleration of compressive strength specimens reported in Parts I - IV of this report (Cook -- 1970, 1971), it was observed that the ratios of strengths of specimens autogenously cured for 48 hours to those after 28 days of standard moist curing varied considerably with initial mixture temperature, particularly when the cement composition or mixture proportions were such as to provide reduced evolution of heat.

Differences also were observed between the heat retention characteristics of the containers used in the Virginia studies and values published for similar containers used in Canadian studies. It was speculated that differences among containers might have sufficient influence to explain the wide range of strength ratios variously reported so as to indicate the need for controls in any recommended test procedure for autogenous curing.

One important relationship discussed in detail by Cook (1971) is shown in Figure 2. As would be expected, the strength ratios increased with factors which caused increased heat evolution. For mixtures with low or moderate heat cements, an initial mixture temperature of 50°F resulted in significantly lower ratios than those for the other conditions for which the differences are probably not significant. The differences between the initial mixture temperature and the maximum temperatures reached in the container (shown as Δ T in Figure 2) are consistent among the various combinations and show maximum values at 73°F (Figure 2) in cases where the differences appear to be significant.

To evaluate the effect on strength of containers with different heat retention characteristics, containers were exchanged by the Virginia Highway Research Council and the Ontario Department of Highways. These containers are shown in Figure 3. Both containers met most of the requirements of a proposed ASTM test method. The important difference between the two containers was the heat retention capability shown in Figure 4 compared with the proposed specification values. The differences in temperatures between water initially at 180°F after storage in the two containers were respectively 22°F and 24° at 24 and 48 hours. A limited series of tests (phase C) was initiated to study the influences of the differences in the strength results obtained. A supplementary objective of this series of tests was to study further the influence of initial mixture temperature on the autogenous procedure (D) when compared with the boiling water procedure (B).

Sixteen mixtures were prepared using two cements (types II and III) at cement contents of 550 lb/cy at each of three initial mixture temperatures (50, 70, and 90°F). The type II cement was used at 70°F at cement contents of 550 lb/cy and 650 lb/cy.

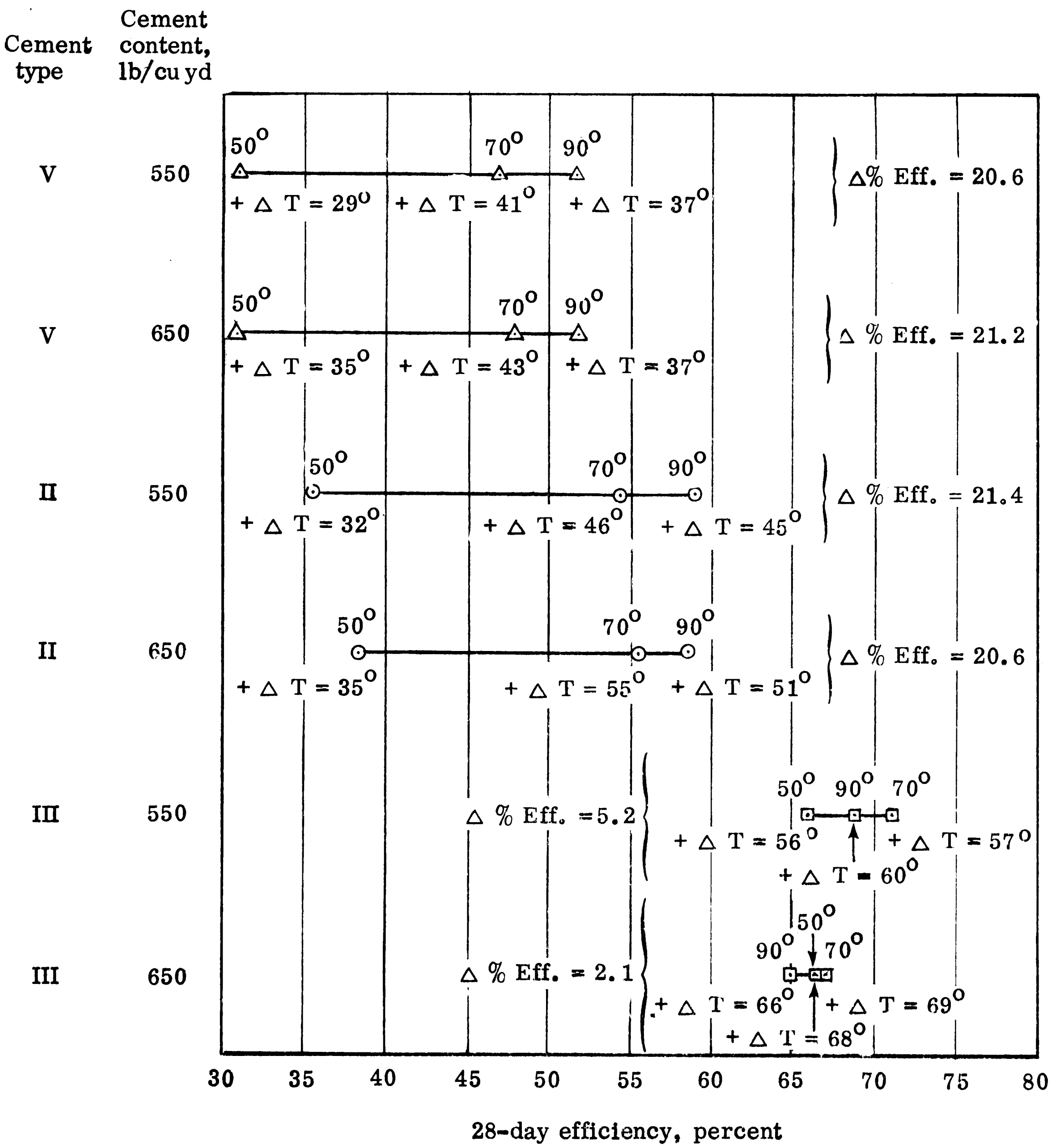

Figure 2. Relationship of autogenous temperature increase (+ △T), 28-day efficiency, and initial mix temperature to three cement types used in Phase III of Cook's Study reported in Parts I - IV of this Report. (Also Figure 13 in Part I.)

Figure 3. Autogenous containers — Canadian container (left) and Virginia container (right).

Generally, the mixtures and procedures were like those required in the II-i Cooperative Testing Program (phases A and B); however, considerable deviations from slump and air content requirements were tolerated as seen earlier in Table III. The materials were from subsequent lots from the same sources as were used in phases A and B. Each of the eight combinations was repeated in two batches. The properties of the mixtures are summarized in Table VII.

From each batch, two 6" x 12" cylinders were cured by each of four procedures:

(1) Autogenously, using the Virginia containers (V),

(2) Autogenously, using the Canadian containers (C),

(3) Using the boiling water procedure (B), and

(4) Moist for 28 days (M).

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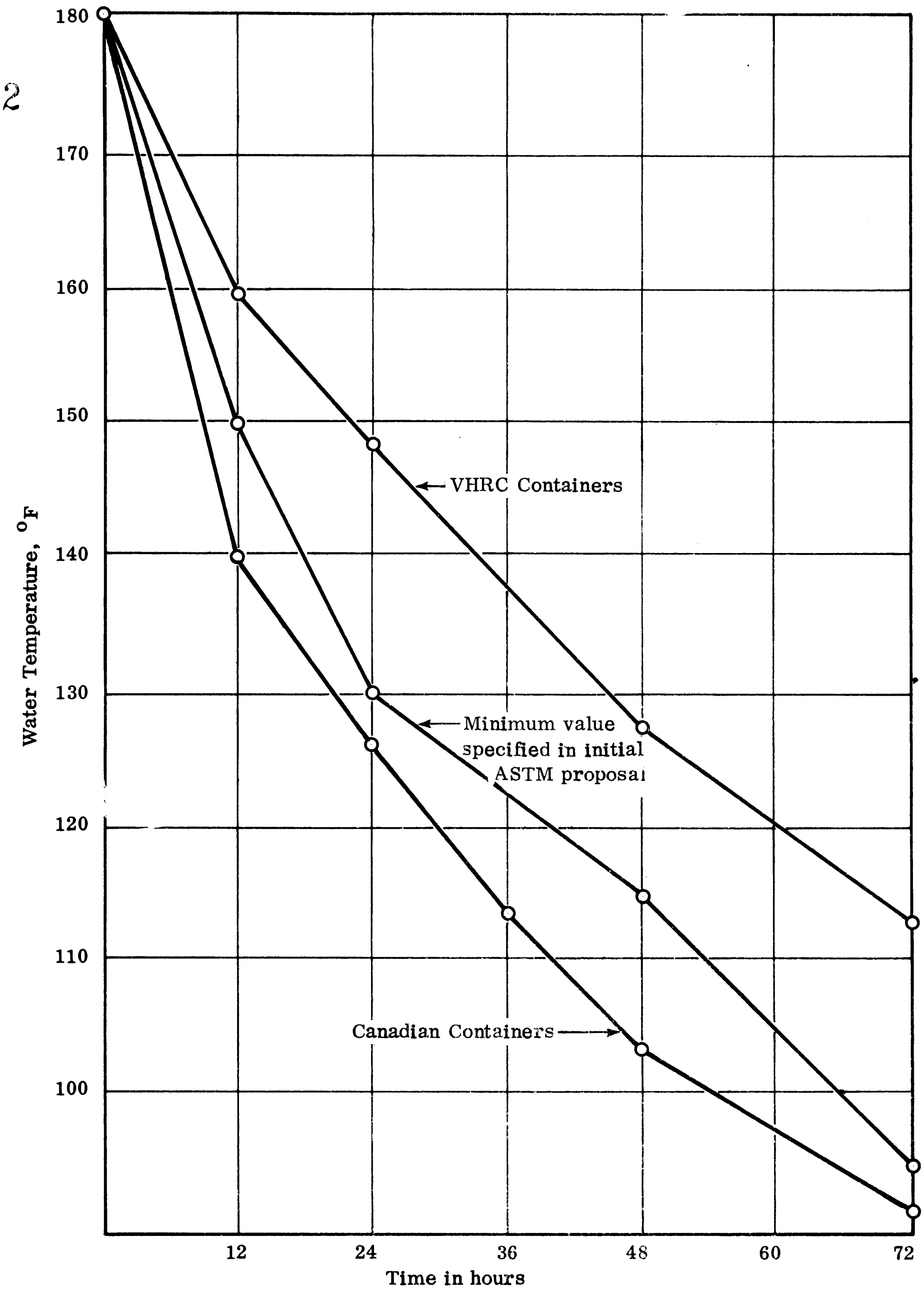

Figure 4. Water temperature vs. time for heat retention tests of Virginia and Canadian containers.

TABLE VII

CHARACTERISTICS OF LABORATORY BATCHES OF CONCRETE (PHASE C)

Batch	Cement Type	Cement Content,	W/C (by wt.)	Initial Mixture Temperature, Deg. F	Slump, in.	Air Content, percent
1a	II	550	.51	51	2.6	7.0
1b	II	550	.51	53	2.8	6.9
2a	II	550	.51	71	1.9	6.3
2b	II	550	.51	72	1.2	5.6
3a	II	550	.51	92	2.3	6.2
3b	II	550	.51	92	0.4	4.0
4a	II	650	.50	71	3.6	7.2
4b	II	650	.50	72	3.6	6.8
5a	III	550	.51	52	0.8	4.9
5b	III	550	.51	51	6.7	9.5
6a	III	550	.51	72	2.2	6.5
6b	III	550	.51	74	1.6	5.8
7a	III	550	.51	89	2.0	5.0
7b	III	550	.51	91	1.7	4.9
8a	III	650	.50	72	6.0	6.8
8b	III	650	.50	71	2.8	6.0

After storage of the specimens in the various autogenous containers, the containers were stored at 70°F regardless of the initial mixture temperature. The results are given in Table VIII, in which the strengths from the various procedures are presented as ratios based on those obtained using the Virginia containers. The same data are presented as conventional strength ratios for comparative purposes in Table IX. Also shown in parentheses in Table IX are the ratios obtained in the II-i Cooperative Testing Program (phases A and B) conducted on similar materials during the year preceding phase C. These were discussed earlier.

TABLE VIII

INFLUENCE OF CONTAINER AND INITIAL MIXTURE TEMPERATURE ON STRENGTH RATIOS (BASED UPON VIRGINIA CONTAINERS) — PHASE C

Batch	Cement Type	Cement Content, lb/cy	Mixture Temperature, Deg. F	Autogenous Strength at 48 hours, Virginia Containers	Strength Ratio Based upon Va. Containers V	C	B	M
1a	II	550	50	2580	1.00	0.96	0.71	1.87
1b	II	550	50	2570	1.00	0.97	0.79	2.04
2a	II	550	70	2430	1.00	1.01	0.67	1.67
2b	II	550	70	3070	1.00	0.95	0.68	1.65
3a	II	550	90	2410	1.00	0.92	0.60	1.65
3b	II	550	90	3355	1.00	0.94	0.70	1.64
4a	II	650	70	2575	1.00	0.98	0.68	1.67
4b	II	650	70	2735	1.00	0.98	0.77	1.68
5a	III	550	50	4210	1.00	1.00	0.83	1.54
5b	III	550	50	2610	1.00	0.98	0.75	1.59
6a	III	550	70	3360	1.00	0.97	0.82	1.40
6b	III	550	70	3500	1.00	0.93	0.78	1.50
7a	III	550	90	3270	1.00	0.99	0.93	1.53
7b	III	550	90	3515	1.00	1.00	0.86	1.53
8a	III	650	70	3020	1.00	1.01	0.83	1.52
8b	III	650	70	3720	1.00	0.98	0.82	1.36

From the limited investigation (data in Table VIII) the following observations appear valid:

(1) The autogenous containers with the lower heat retention mixtures showed a slightly lower strength in 12 of the 16 cases. The largest difference between the two container types was 7 percent but differences of 2 - 3 percent were most common.

(2) Limits in the heat retention test at least as wide as those defined in Figure 4 by the Canadian and Virginia containers would be satisfactory. it is likely that the upper limit is less critical than the lower.

TABLE IX

INFLUENCE OF CONTAINER AND INITIAL MIXTURE TEMPERATURE ON STRENGTH RATIOS (BASED UPON 28-DAY MOIST CURED VALUES) — PHASE C

Batch	Cement Type	Cement Content, lb/cy	Mixture Temperatures, Deg. F	Ratio of Accelerated Strength to that after 28-days of moist curing		
				V	C	B
1a	II	550	50	.535	.512	.379
1b	II	550	50	.488	.474	.385
Avg.				.512	.493	.382
2a	II	550	70	.597	.605	.403
2b	II	550	70	.604	.576	.413
Avg.				.600 (.605)	.590	.408 (.354)
3a	II	550	90	.607	.558	.366
3b	II	550	90	.610	.571	.429
Avg.				.608	.564	.398
4a	II	650	70	.597	.583	.408
4b	II	650	70	.597	.587	.458
Avg.				.597 (.699)	.585	.433 (.409)
5a	III	550	50	.648	.646	.541
5b	III	550	50	.630	.618	.473
Avg.				.639	.632	.507
6a	III	550	70	.715	.694	.583
6b	III	550	70	.661	.642	.604
Avg.				.688 (.719)	.668	.594 (.562)
7a	III	550	90	.653	.647	.607
7b	III	550	90	.653	.651	.565
Avg.				.653	.649	.586
8a	III	650	70	.660	.665	.549
8b	III	650	70	.736	.719	.602
Avg.				.698 (.732)	.692	.576 (.645)

Note: Values in parentheses are ratios obtained for equivalent mixtures in II-i Cooperative Tests reported earlier.

(3) The effect of initial mixture temperature appears significant only for mixtures with low heat cements at low temperatures. Results from the boiling water procedure were not consistently related to initial mixture temperature.

(4) The difference in the heat retention capabilities of the containers tested might become more significant when the ambient temperature conditions surrounding the autogenous containers is considerably lower (10^{o}F to 20^{o}F) than the initial mixture temperature. During this study of containers, the ambient curing temperature was 73^{o}F for all mixtures.

(5) Agreement among results for similar mixtures and materials tested at different times during the project is encouraging.

Influence of Length of Storage and Storage Conditions (Phase D)

During the consideration of proposed testing methods within ASTM Committee C-9, questions were raised as to the influence of comparatively small changes in the storage times and conditions for Procedures B and D, the methods in which variations in such characteristics would be most evident. As an extension of the work described previously, a limited series of tests was undertaken to evaluate these effects.

Mixtures were made which were similar to those used in the other phases of the study. Types II and III cements were used in mixtures with a cement content of 550 lb/cy. All mixtures had a water-cement ratio of 0.50 (by weight) and were prepared with initial temperatures of 60^{o} and 80^{o}F. From each of three replicate batches single cylinders were exposed as follows:

(a) Procedure B with initial storage out-of-doors (variable) and in the laboratory moist room (73^{o}F ± 3^{o}F and 100% R. H.) both followed by $3\frac{1}{2}$ hours of boiling, and

(b) Procedure D, with both laboratory and out-of-door storage of the autogenous containers.

In both cases, storage periods of 23 and 24 hours were used.

The characteristics of the mixtures are given in Table X.

The storage conditions and temperatures, along with the average strengths of the three cylinders, $\bar{X}$, and standard deviations, σ, are given in Table XI. The cylinders stored out-of-doors were exposed to a temperature range greater than the 60-80^{o}F required in ASTM C 31 and the proposed accelerated test methods.

TABLE X

MIXTURE CHARACTERISTICS (PHASE D)

ch	Cement Type	Initial Mixture Temperature, Deg. F	Slump, In.	Air Content, percent
1	II	63	3.1	6.0
2	II	60	2.2	5.0
3	II	62	2.6	6.0
4	III	64	2.5	5.4
5	III	62	2.2	5.3
6	III	63	1.8	5.0
7	II	78	2.2	5.2
8	II	78	2.5	5.9
9	II	79	2.9	5.9
10	III	79	2.9	5.2
11	III	83	1.9	4.9
12	III	79	2.5	5.3

TABLE XI

CONCRETE PROPERTIES AND STORAGE CONDITIONS (PHASE D)

ment ype	Initial Mixture Temperature, Deg. F	Storage Length, Hours*	Storage Location	Air Temperature during Storage, Deg. F Max.	Min.	Compressive Strength, psi Procedure D Average $\bar{X}$, psi	Procedure D Standard Deviation, σ psi	Procedure B Average $\bar{X}$, psi	Procedure B Standard Deviation, σ psi
II	60	23/46	Lab.	74	72	2146	102	2213	121
		23/46	outdoor	95	63	2134	97	1901	79
		24/48	Lab.	74	72	2270	149	2243	106
		24/48	outdoor	95	63	2243	109	1898	87
II	60	23/46	Lab.	74	72	3749	113	3110	271
		23/46	outdoor	86	63	3747	128	3036	80
		24/48	Lab.	74	72	3673	135	3272	420
		24/48	outdoor	86	63	3643	18	3083	178
II	80	23/46	Lab.	74	72	2290	219	2049	186
		23/46	outdoor	92	66	2252	259	1904	124
		24/48	Lab.	74	72	2305	212	2152	306
		24/48	outdoor	92	66	2269	107	1954	145
	80	23/46	Lab.	74	72	3119	135	2712	187
		23/46	outdoor	93	59	3092	119	2797	124
		24/48	Lab.	74	72	3195	151	2661	252
		24/48	outdoor	93	59	3174	176	2800	96

*The cylinders tested by Procedure D were stored twice as long as those cured by Procedure B.

For Procedure D, there was no significant difference in the results for any of the conditions. The cylinders tested after two hours additional curing showed a slightly but insignificantly higher strength. These results are consistent with the results presented in Part III of this report, in which Cook showed that maximum temperature was achieved before 39 hours and that only insignificant strength increases would be expected beyond that point.

Results from Procedure B were influenced by the storage location. In three of the four combinations of mixture temperature and cement type, the specimens stored out-of-doors gave lower strengths than those stored in the laboratory moist room. The greatest difference was for the low mixture temperature with the type II cement. This mixture had the lowest potential for heat evolution, and the difference was about 15 percent. The situation reversed for the type III cement at the higher initial mixture temperature; i.e., the specimens stored outdoors gave slightly higher strengths. The other two conditions showed intermediate differences.

One unexplained result is that in 5 of 8 cases for Procedure D and in all 8 cases for Procedure B standard deviations for the specimens stored out-of-doors were smaller than those for specimens stored in the laboratory.

Since this fact was not evident until all of the data had been analyzed, no special observations were made which might explain the results.

The results from Procedure D can probably be explained in terms of random variation since about one-half of the cases fall each way. Why all of the samples given initial curing in the laboratory moist room were consistently more variable than samples given initial curing out-of-doors and then treated exactly the same thereafter is not consistent with what would be expected. No explanation can be offered at this time.

Potential Use of Procedures

From the data presented in this report and that from similar studies reported in the published technical literature, there are no technical reasons why any of the accelerated procedures could not be used for quality control at the present time. It also appears that the methods can be used for quality assurance with about the same degree of assurance as is currently being achieved with conventional curing. Each of the procedures has certain advantages and disadvantages and the selection of the one to be used is primarily a matter of convenience, economy, and suitability for the specific application.

For a large job or for testing at a given plant, the water bath methods offer the advantage of providing results in one rather than two days.

Procedure C has generally been shown to be the least variable, but in the Council's work Procedure D also showed a low variability. The primary advantage of Procedure A is the absence of safety hazards associated with the use of boiling water. A disadvantage of Procedures A and C is the need for a water tank near the testing machine. This is partially overcome by Procedure B, and is absent in the case of Procedure D. The primary deterrent to the use of Procedure C is the need to determine time-of-set; which is a cumbersome and expensive procedure.

Considering the characteristics and dispersion of the jobs in a highway department, it would appear that Procedure D, which is sufficiently reliable, is the most practical of the methods evaluated.

CONCLUSIONS

From the results discussed in this report, the conclusions listed below appear justified. It is recognized that the limited scope of this investigation in which aggregates from a single source and only two cements were used would restrict the general applicability of the results. However, comparison with other work suggests that differences would be in degree rather than in kind.

(1) Each of the four accelerated procedures is capable of predicting strengths at later ages with accuracy equivalent to that currently achieved with moist curing.

(2) Procedure A gives the lowest strength ratios (i.e., accelerated strength to that at later ages) while Procedures C and D give the highest ratios. Procedure B is intermediate.

(3) The variability of test results from accelerated tests is of the same order as that from conventional procedures.

(4) The four procedures are comparatively insensitive to the presence of retarding admixtures at normal dosages. Procedure C appeared to be affected by the presence of the admixture more than by changes in cement type.

(5) Differences in results among the procedures and the influence of other factors such as initial mixture temperatures are greatest for mixtures at lower initial temperatures and with a low potential for heat evolution.

(6) Variations of initial mixture temperatures above 60^{o}F do not significantly influence results. Temperatures below 60^{o}F may give slightly lower strength ratios than do higher temperature mixtures.

(7) For the Autogenous Procedure, D, a fairly wide range of heat retention characteristics between container types ($\approx 25^{\circ}$ F at 48 hours) had no significant influence on strength ratios. It is postulated that a minimum heat retention value is necessary but that limits on maximum values are not necessary.

(8) Minor variations in storage conditions and/or lengths of curing do not significantly affect results for either procedure B or D although Procedure B is slightly more influenced than Procedure D.

RECOMMENDATIONS

(1) It is recommended that Procedure D (autogenous curing) be given field trials within the Virginia Department of Highways. A proposed tentative test method is included as Appendix A.

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APPENDIX

PROPOSED VIRGINIA TEST METHOD
FOR
MAKING AND ACCELERATED CURING OF
CONCRETE COMPRESSION TEST SPECIMENS

1. Scope

   1.1 This method covers a procedure for making, curing, and testing specimens of concrete stored under conditions intended to accelerate the development of strength.

2. Applicable Documents

   ASTM C 470, C 31, C 172, C 33, C 39, C 617

3. Summary of Method

   3.1 Concrete specimens are exposed to elevated temperatures and to moisture conditions adequate to develop a significant portion of their ultimate strength within 24 to 48 hours. The procedure involves storage of specimens in insulated curing containers in which the elevated curing temperature is obtained from heat of hydration of the cement. The sealed containers also prevent moisture loss. Sampling and testing procedures are the same as for normally cured specimens (Methods C 172 and C 39 respectively).

4. Significance

   4.1 The accelerated curing procedures provide, for a particular combination of materials at the earliest practical time, an indication of the ultimate strength to be expected. They also provide information on the variability of the production process for use in process control.

   4.2 The correlation between the accelerated and later strengths depends upon the materials comprising the concrete and the specific procedure employed. Prediction should be limited only to concretes using the same materials as those used for establishing the correlations.

   4.3 The ratio of accelerated to ultimate strength increases with the cement content and initial mixture temperature.

5. Apparatus

5.1 General

5.1.1 The container shall consist of thermal insulation meeting the heat retention requirements specified in 5.2.1 and closely surrounding the concrete test cylinder.

5.1.2 The container shall be capable of being opened to permit insertion and/or withdrawal of the cylinder and where required shall have an outer casing and inner liner to protect the insulation from mechanical damage.

5.1.3 The container may be provided with a maximum and minimum recording thermometer which shall not be insulated from the test cylinder (See Note 2).

5.1.4 Provision shall be made to keep the container securely closed during the specified curing period.

5.1.5 The container shall be capable of holding either one or two cylinders. A satisfactory container is shown in Appendix Figure A-1 (Note 1).

Note 1 — Drawings and guidelines for construction of suitable containers are included in the Appendix. Any configuration is acceptable so long as it meets the performance requirements of 5.2 and Notes A-3 through A-6.

5.2 Proving tests requirements.

5.2.1 Heat Retention. A watertight container with internal dimensions of 12 in. by 6 in. diameter (30 by 15 cm) shall be placed in the curing container and then filled to within $\frac{1}{4}$ in. (6 mm) of the brim with water at a temperature of 180°F (82°C). A thermocouple shall be inserted in the water and the initial temperature of the water measured with an electrical potentiometer. The water container shall then be sealed with a cap or plastic bag. The autogenous container shall then be closed. When the autogenous curing container is stored in still air at 70°F (21°C) ± 2°F (1°C), the water temperature shall be:

After 12 hrs.	152° ± 5°F (67 ± 3 C)
24 hrs.	136° ± 6°F (58 ± 3 C)
48 hrs.	114° ± 7°F (45 ± 4 C)
72 hrs.	100° ± 8°F (38 ± 4 C)

5.2.2 Tightness Test for gasket heat seal. When the autogenous curing container is immersed in water to a depth of 6 in. above the joint between the separable parts, no air shall escape through the heat seal within a period of 5 minutes.

5.2.3 Stability of the Container. The container or any part thereof shall not display embrittlement, fracturing or distortion when maintained in an ambient temperature of -20°F (-29°C) for 72 hours, nor softening or distortion when maintained at an ambient temperature of 140°F (60°C) for 72 hours. The gasket type heat seal shall immediately fully recover its original thickness after 50 percent compression under the temperature conditions specified above.

6. Procedure

6.1 Preparation of Test Specimens

6.1.1 Samples of concrete for test specimens shall be taken in accordance with ASTM Method C 172 Sampling Fresh Concrete. The place of depositing in the structure of the sampled batch shall be noted in the job records.

6.1.2 The slump and air content shall be measured and the specimens molded as required in ASTM Method C 31.

6.1.3 The test specimens shall conform to the requirements for 6 by 12 in. (15 by 30 cm) cylinders contained in ASTM Method C 31.

6.2 Curing

6.2.1 Immediately after molding, cover the mold with a metal plate or a tightly fitted cap and place in a heavy duty plastic bag from which as much of the entrapped air as possible is expelled prior to tying the neck. (Alternatively, a moisture-tight plastic cap may be used.) The plastic bag should be of sufficient weight and strength to resist punctures and serve as a lifting grip for removal of the cylinder from the autogenous container.

6.2.2 Reset the maximum-minimum thermometer (if used) and secure the container lid.

6.2.3 Record the time of molding to the nearest 15 minutes and the temperature of the fresh concrete clearly on the outside of the container.

6.2.4 For at least 12 hours after molding, the container should not be moved, disturbed or subjected to vibrating or jarring and should be stored out of the sun, preferably at a temperature between 60 and 80°F.

6.2.5 At an age of 48 hours ± 15 minutes after the time at which the cylinder was molded, remove the cylinder from the container and demold. Allow to stand for 30 minutes at room temperature.

6.2.6 Record the maximum and minimum temperatures in the container indicated on the thermometer (Note 2).

Note 2 — Comparison of the maximum and minimum with the recorded temperature of the fresh concrete will provide an indication of abnormal or interrupted curing which may cause high or low strength results.

6.3 Capping and Testing

6.3.1 The ends of specimens that are not plane within 0.002 in. (0.050 mm) shall be capped as specified in ASTM Method C 617.

6.3.2 When tested in accordance with provisions of ASTM Method C 617, the capping material shall develop at an age of 30 minutes a strength equal to or greater than the strength of the cylinders to be tested.

6.3.3 The cylinder shall be tested for strength in accordance with the requirements of ASTM Method C 39 at an age of 49 hours ± 15 minutes (Note 3).

Note 3 — Capping and Testing may be performed at ages different from that specified in 6.3. Agencies using the procedure have for convenience established relationships between test results at 24, 72, and 96 hours with those obtained by standard moist curing. However, at 24 hours, the relationship is less satisfactory than those obtained by accelerated autogenous curing for 48, 72, or 96 hours. Where the curing period is other than that specified in 7.2.3, the age at testing shall be the curing period plus 1 hour. The tolerance of ± 15 minutes shall still apply.

7. Interpretation of Test Results

7.1 Because strength requirements in existing specifications and codes are not based upon accelerated curing, use of results from this method in the prediction of specification compliance of strengths at later ages must be applied with great caution. As stated in Section 9, Precision, the variability of the method is the same or less than that from traditional methods. Thus, results can be useful in rapid assessment of variability for process control and signalling the need for indicated adjustments. On the other hand, the magnitude of the strength values obtained is influenced by the specific combination of materials so that the use of the results from either conventional tests at any arbitrary age or those from this method must be supported by experience or correlations developed by the specific agency for the existing local conditions and materials. Factors influencing relationships between measured strengths and those of concrete in place are no different from those affecting conventional strength tests.

8. Report

8.1 The report shall include the following:

8.1.1 Identification number

8.1.2 Diameter (and length, if not standard), in inches

8.1.3 Cross-sectional area, in square inches

8.1.4 Maximum load, in pounds

8.1.5 Compressive strength calculated to the nearest 10 psi (0.7 Kgf./cm^2)

8.1.6 Type of fracture, if other than the usual cone

8.1.7 Defects in either specimen or caps

8.1.8 Age of specimens

8.1.9 Initial mix temperature to the nearest ^{o}F

8.1.10 Maximum and minimum temperature to the nearest ^{o}F

8.1.11 Method of transportation used for shipping specimens to the laboratory

8.1.12 Ambient temperature of specimen or container during storage.

9. Precision

9.1 The single-laboratory coefficient of variation 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 more than 10 percent of their average.

9.2 The single-laboratory, multi-day coefficient of variation 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 percent of their average.

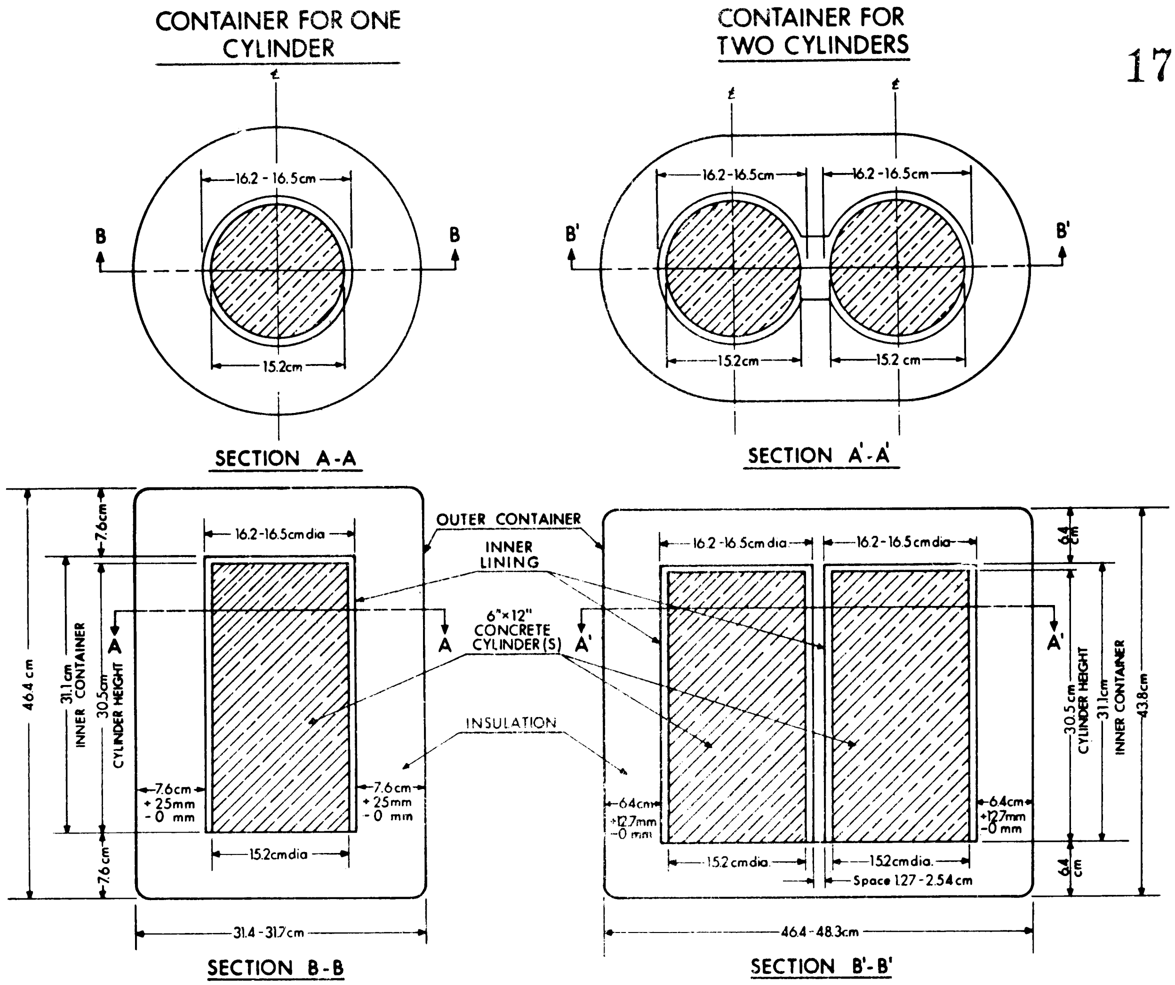

Figure A-1. Autogenous curing container for one, or two cylinders (basic requirements).

Note A.1 — Space for max-min thermometer (if required) and means of opening the container, securing when closed and lifting not shown.

A.2 — Heat seal required at the joint face between the separable parts of the container. May be labyrinth or gasket type provided requirements of Sections 7.1.2.1., 7.1.2.2. and 7.1.2.3. are met. A suitable gasket is flexible polyurethane foam (2 lb/cu ft, 32.0 kgm^3) maintained when closed at 50 percent compression.

A. 3 — Foamed in place closed cell polyurethane having a density of between 2 and 3 lb/cu ft (32.0 and 48.0 kgm^3) and thermal conductivity equal to or less than 0.15 BTU/hr/sq ft/^{o}F/in. (28.8 k cal/hr/m^2/^{o}C/m) by ASTM Method C 177 has been found to be a suitable insulating material at the thicknesses specified to meet the heat retention requirements of section 7.1.1.

A. 4 — The max-min thermometer (if used) should cover a range from 20^{o}F to 150^{o}F (-7^{o}C to 66^{o}C) in 1 degree increments.