THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
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Final Report

ACCELERATED CONCRETE STRENGTH TESTING IN HIGHWAY DEPARTMENT OPERATIONS

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INTRODUCTION

Ensuring use of concrete of adequate strength is important to every highway agency. Strengths must be such that traffic loads not overstress the concrete causing damage to the huge investment in pavements and structures. The fact that the strength of concrete varies with its age and that a substantial range of ultimate strengths may be attained depending upon mix proportions, ingredient characteristics, and treatment at the job site provides a bewildering number of variables with which to cope.

One of the most troublesome aspects of cement and concrete strength testing and one which is entirely out of tune with the rapidity of present-day construction is the classical dependence upon 28-day strengths for design and acceptance purposes.

At least two distinctly different remedies for the intolerable 28-day time lag exist:

1. Base design and acceptance upon strengths at ages earlier than 28 days.
2. Develop techniques to predict 28-day strengths at earlier ages.

Very slow progress has been made with respect to item 1; however, in 1942 ASTM did specify that laboratory acceptance testing of portland cement itself was to be based upon strengths at 3 and 7 days unless otherwise prescribed by the purchaser. However, 28-day requirements are carried by ASTM to this day if the purchaser wishes to invoke them.

Structural designers have shown little enthusiasm for basing designs on other than "ultimate" strengths, usually considered synonymous with 28-day strengths. This is understandable since the long-term life of the construction is of major consequence, and short-term strengths, i.e. during the first few hours or days, are more of a detail of fabrication convenience involving reuse of forms, construction safety, etc. Also, the designer is aware that the strength-gain pathway by which the concrete reaches its ultimate strength can be substantially altered to suit job circumstances by use of integral accelerating admixtures, retarders, modified curing techniques, etc.

The present investigation explores in behalf of the Department item 2 above, i.e. prediction of 28-day potential strength from measurements of only a few hours duration. It should be emphasized that the present program does not attempt assessment of in-place strength of job concrete; attention is confined only to such strength that the concrete is capable of attaining under standard conditions. Others are attacking the problem of in-place strength of job concrete, and it appears probable that further extensive research in this regard may be funded soon by AASHO for an NCHRP research program.

BACKGROUND OF ACCELERATED CONCRETE STRENGTH TESTING

Effort at predicting the 28-day strength of concrete from early tests was recorded as early as 1927 (1). Reference (2) includes a bibliography of some 89 entries recording developments up to very recently. Only a brief summary of this extensive effort will be here attempted; adequate coverage demands consideration of early chemical and physico-chemical reactions of the cement with the mixing water, temperature effects, heat release, etc.

1. All investigators recognize that a satisfactory test procedure must employ special techniques which accelerate reactions to acquire substantial early strengths; ideally these should approach strengths obtained at 28 days under "standard" curing conditions (73°F and 100% relative humidity). The closer the measured strength at an early age approaches the actual 28-day strength, the greater the assurance that early temporary retardation or acceleration effects are being eliminated. One investigator has even labeled the ratio of accelerated strength to 28-day strength as the "efficiency" of the procedure (3); the closer this ratio is to 1.00 the better.

2. Acceleration of strength gain of test specimens has been achieved by different investigators employing a variety of curing temperatures ranging from just above room temperature, namely, 95°F up to immersion in boiling water at 212°F and even autoclaving in saturated steam at 80 to 100 psi (324° to 338°F).

3. Curing periods of accelerated speicmens have variously been as brief as 5 hr and as long as 48 hr.

4. Most methods tried have involved a brief "delay" period prior to placing the specimens in high temperature environment. Some delay periods have been preset at arbitrary values and others have been adjusted so that the concrete achieves a designated degree of set prior to commencing heating.

5. One novel method does not supply additional heat to the specimens to accelerate strength gain but simply conserves the heat generated by the chemical reaction between the hydrating cement and the mixing water. This is achieved by storing the specimens immediately after casting in well insulated containers and is the so-called "autogenous" method which is the one used in the present investigation.

6. Recognizing the need for earlier prediction of concrete strength, ASTM established a special subcommittee in 1964 (Subcommittee II-i of Committee C-9 on Concrete and Concrete Aggregates) to explore acelerated strength testing. This work over the years included an extensive interlaboratory testing program and has culminated in a tentative test method just adopted by Committee C-9 (Ballot of April 12, 1971). Full society adoption is expected. This method is entitled, "Tentative Method of Making and Accelerated Curing of Concrete Compression Specimens." The complete text of this method is included as Appendix A hereto. It will be noted that the method includes three alternative procedures:

A - Warm water (95°F, 24 hr)
B - Boiling water (212°F, 28 1/2 hr)
C - Autogenous (__°, 49 hr)

TESTING PROGRAM

Appendix C records the minutes of a meeting held in Ann Arbor October 1, 1970, with MDSH and University of Michigan project staff. At this planning meeting it was decided to concentrate effort on the autogenous method of accelerated curing as probably most appropriate for the Department's immediate needs. The other two procedures have the following disadvantages:

1. The warm water method A demands use of a thermostatically controlled water bath at the job site since the test specimens are to be placed in the curing water immediately after casting. This does not seem feasible for the often widely dispersed projects of the Highway Department and would be more appropriate for a products manufacturer at a central location.

2. The boiling water method also requires the use of a fairly expensive curing tank ($300 for one of a capacity of only 4 test cylinders) with sufficient heating capacity to maintain the water close to the boiling point. Also, the question of personnel safety arises in handling many specimens in and out of boiling water. Again, the required apparatus seems more appropriate for central or district laboratory use or for permanent installation at a products manufacturer's plant.

The autogenous method employs apparatus normally used in compression testing of standard 6 x 12 in. concrete test cylinders with the exception of use of special insulated containers for storing the specimens during the 48-hour curing period. At the present stage of development of this method, these containers, when commercially procured, are undoubtedly more expensive than will prevail if the method receives wider usage. Single cylinder containers cost $59.50 each for the present investigation. These particular containers are ruggedly constructed and appear capable of long service; the polyurethane rigid foam insulation is thoroughly protected by a steel 20-gal drum with removable gasketed head and sturdy clamp to hold the assembly during transportation of the specimen to the laboratory. One other deviation from usual cylinder testing is the required use of disposable, sheet metal molds in which to cast the cylinders. These metal molds cost 48¢ each in the present program as against 29¢ each for the ordinary waxed cardboard molds. Figure 1 is a photograph of insulated container and metal cylinder mold. The temperatures generated inside the insulation during the curing process (as high as 130°F) discourages the use of waxed cardboard.

Briefly, in the autogenous method, test cylinders are cast in the usual manner in disposable metal molds, covered with tight fitting cap, and immediately placed individually in insulated containers and stored undisturbed at the job site for at least 12 hr. After the undisturbed storage period at the job, the container with enclosed test specimen is moved to the testing location and the cylinder removed from the container and demolded 48 hr from time of casting. At 48 1/2 hr, the cylinder is capped with quick-hardening sulfur mixture and tested in compression at the age of 49 hr. It is acknowledged that test specimens made from concrete cast on Thursdays or Fridays require handling during the weekend.

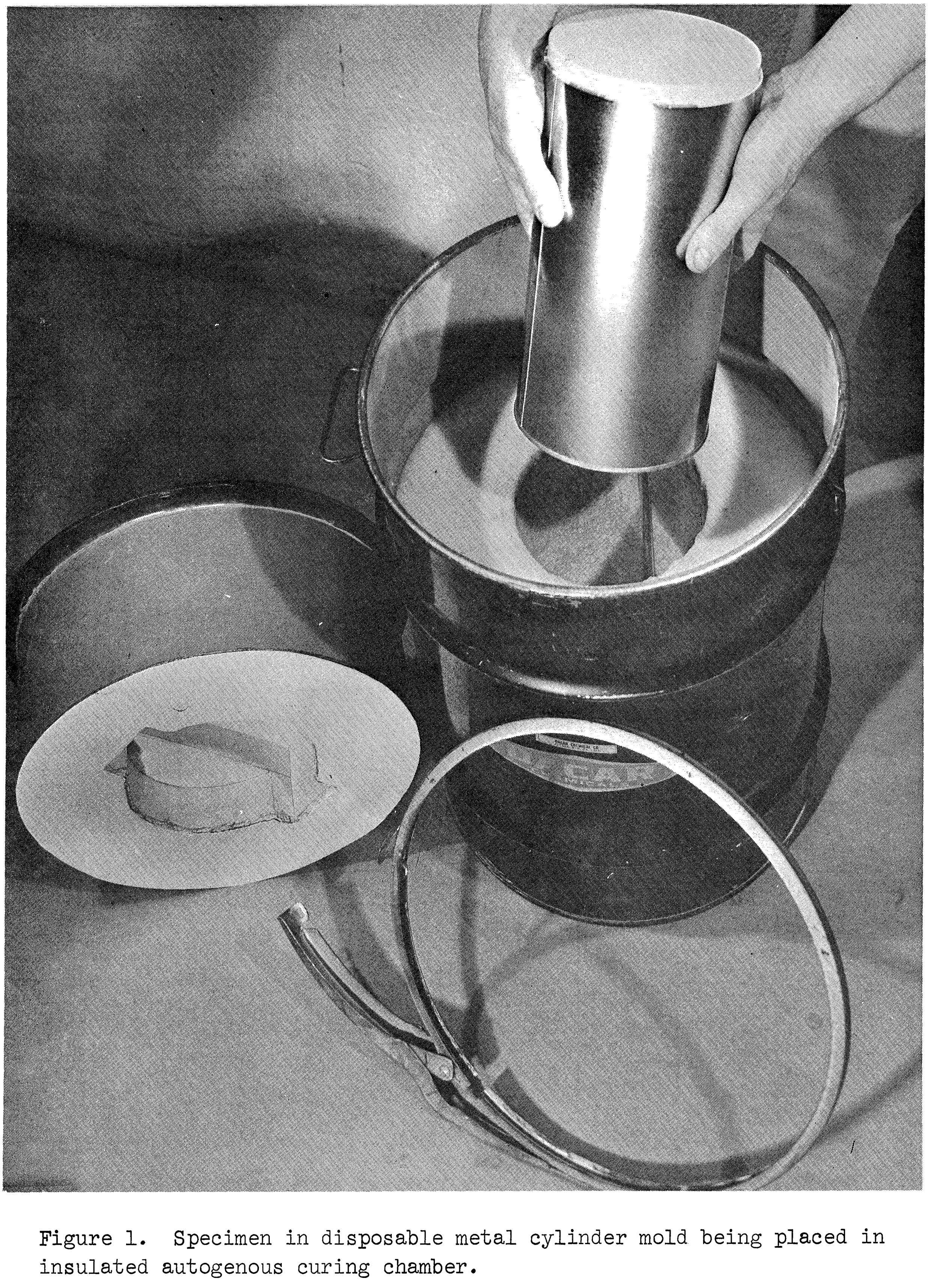

Figure 1. Specimen in disposable metal cylinder mold being placed in insulated autogenous curing chamber.

SELECTION OF MIXES

After settling on the autogenous method as a promising one to explore the decision was made to select a range of concretes typically used by the Michigan Department both as to mix proportions and aggregates. Table I lists the mixes selected. Four basic mixes were employed ranging in cement content from 5.5 to 7.0 sacks of cement per cu yd of concrete, each with three typical coarse aggregates, i.e. gravel, crushed limestone, and crushed blast furnace slag, all of 6A gradation. All concrete was made air-entrained by use of neutralized vinsol resin admixture. Appendix D gives the normal tests of the coarse and fine aggregates used in this program. Also included are acceptance tests of the Type I regular portland cement used throughout the program. No unusual properties of any of the ingredients were revealed by the routine tests.

TABLE I

CONCRETE MIXES SELECTED FOR USE IN THIS PROGRAM

MDSH Class of Concrete	Cement Content (sk/cyd)	Air Content (%)	Gravel	Crushed Stone	Slag
Base Course (BC)	5.5	5-8	X	X	X
Pavement Structures (A or P)	6.0	5-8	X	X	X
Structures (AA)	6.5	5-8	X	X	X
Pavement High Early (P-HE)	7.0	5-8	X	X	X

FABRICATION OF TEST SPECIMENS

The four concrete grades when combined with three coarse aggregates provide 12 combinations which were tested in this program. A complete round thus required 12 batches of concrete and with three replications made a total of 36 batches. The sequence of making the batches within each round was randomized by using a table of random numbers. Three autogenous cylinders for testing at 49 hr and three conventional cylinders for testing at 28 days were made from each batch, making a total of 6 x 36 = 216 cylinders for the entire program. Nine autogenous insulated containers were available so that only three batches of concrete per day could be made. Each day of making tied up the containers for two days, and this combined with minimum weekend work extended the entire program. The first batches were made January 12, 1971, and the last 28-day cylinders from the program were tested March 18, 1971.

The concrete batches of nominal 1.75 cu ft size were mixed in a Lancaster, revolving tub, revolving blade mixer with a 3-min initial mixing, followed by a 2-min wait period with the blades stopped and a final 1-min remixing period. Slight additions of water were made during the latter period if the slump seemed too low.

Air content of the crushed stone and gravel mixes were conducted with an Acme pressure meter and of the slag mixes with a volumetric Roll-a-Meter. Yield of each batch was determined from a weight per cu ft measurement of the fresh concrete using a 1/2 cu ft container. The aggregates were moist as they came from the storage bins, and the free mixing water compensated for and water-cement ratio calculated from absorption and surface water determinations.

Batch quantities were altered slightly in succeeding replications to acheive average values close to the desired air content, slump, and yield.

Temperatures of each batch of freshly mixed concrete were measured and averaged 60°F with an individual maximum of 66°F and a minimum of 54°F.

TEST RESULTS

A detailed tabulation of the test results is shown in Appendix E. Table II provides average results of the four classes of concrete.

The average water-cement ratio, mixing water requirements, and slump values do not reveal unusual results. For a given coarse aggregate, there is a tendency for increased strength accompanying diminished water-cement ratio, but air content is importantly influencing the strengths obtained.

AUTOGENOUS COMPRESSIVE STRENGTH

For a given class of concrete, there is marked similarity between the 49-hr autogenous strengths for all three coarse aggregates. This contrasts with the conventional 28-day strengths where the blast furnace slag mixes consistently provided higher strengths.

Relatively minor variations of the autogenous strengths within a given class of concrete do occur and question can be raised as to whether the average strengths are genuinely different or whether the differences are simply inadvertances of measurement. Statistical analysis of variance techniques indicate that at the 5% level of significance only in the case of the 7.0 sack high-early strength concrete do the aggregates appear to really cause different compressive strengths at 49 hr. Appendix F gives details of this analysis. Study of the data does not reveal why the 7-sack concrete should depart from this interesting trend exhibited by the concretes of lesser cement content. Our interpretation of this similarity of autogenous cured strengths is that

TABLE II

SUMMARY OF RESULTS OF LABORATORY CONCRETE

Class of Concrete		Cement Content (sk/cyd)	w/c by wt.	Mixing Water (lb/cyd)	Slump (in.)	Air Content (%)	Compressive Strength, psi*	
							Autogenous	28-day
Base Course (BC)	gravel	5.50	0.43	220	2.4	6.4	2980	4230
	stone	5.49	0.49	255	2.8	6.5	3050	4290
	slag	5.44	0.39	201	2.8	7.6	2780	4810
Structures Pavement (A or P)	gravel	6.03	0.41	231	2.5	5.4	3400	4740
	stone	5.99	0.46	260	2.5	6.1	3440	4520
	slag	6.03	0.37	211	2.7	6.6	3320	5350
Structures (AA)	gravel	6.62	0.37	232	2.2	5.0	3700	5080
	stone	6.49	0.46	282	2.9	5.4	3630	4910
	slag	6.52	0.36	224	2.8	6.0	3620	5610
Pavement High Early (P-HE)	gravel	7.04	0.36	233	2.3	5.0	3640	4910
	stone	7.00	0.40	241	2.3	5.2	3750	5150
	slag	7.00	0.33	217	2.5	5.7	3910	6210

*Each value represents 9 cylinders, three each from three batches only the most active ingredient of the concrete, i.e. the cement-water paste, has opportunity at such an early age to significantly influence the observed strength. This can variously be viewed as an advantage or detriment to the autogenous method (or any accelerated method, probably) and will be discussed more fully later.

28-DAY COMPRESSIVE STRENGTH

The 28-day compressive strengths in Table II are typical values for air entrained concrete, i.e. predominantly below 5000 psi when using conventional materials. This is not true for the mixes containing slag coarse aggregate where strengths greater than 5000 psi were consistently achieved for all concrete having cement contents of 6.0 sacks per cu yd or greater.

The gravel and crushed stone concretes at a given cement content provided strikingly similar average 28-day strengths, and analysis of variance techniques again confirmed that the means were not different at the 5% significance level for all concrete except the 7 sack mixes where it was still true at the 1% level (details in Appendix F).

These observations are significant, as will be pointed out later, since the possibility exists that prediction of 28-day strengths may be valid whether the aggregate is gravel or crushed stone. These aggregates constitute the bulk of aggregates used by the Department. The slag concretes are obviously in a separate category.

It is interesting to speculate as to why the slag concretes show an unexpected increment of strength at 28-days; it is postulated that grinding action in the mixer generates fines having pozzolanic properties which develop strength during the moist storage interval between 49 hr and 28 days. Fly ash and other finely ground pozzolanic silicious materials are often added to concrete to augment later strength as observed here for the slag concrete.

PREDICTION OF 28-DAY STRENGTH FROM AUTOGENOUS CURED SPECIMENS

Major interest centers in this investigation on how successfully the 28-day strengths can be predicted from the 49-hr autogenous values. Figures 2, 3, and 4 display plots of the gravel, crushed stone, and slag concrete strengths, respectively, at 28 days of normal, moist room curing vs. 49-hr autogenous cured specimens. Each point on the graphs represents the average of three autogenous cylinders and three companion 28-day cylinders made simultaneously from the same batch of concrete.

The derived equations and straight lines representing the data were drawn by the method of least squares. It is observed that the prediction of 28-day strength using the autogenous specimens would, in the worst case, be in error by 500 psi for the gravel concrete; however, no other point for the other two aggregates depart from their respective best fitting lines by more than 350 psi. Figure 5 presents a predictional equation for the limestone and gravel combined which yields only slightly larger errors. Based on these particular concrete materials and using a 500 psi safety factor, the following 49-hr strengths should ensure concrete of the indicated 28-day strength:

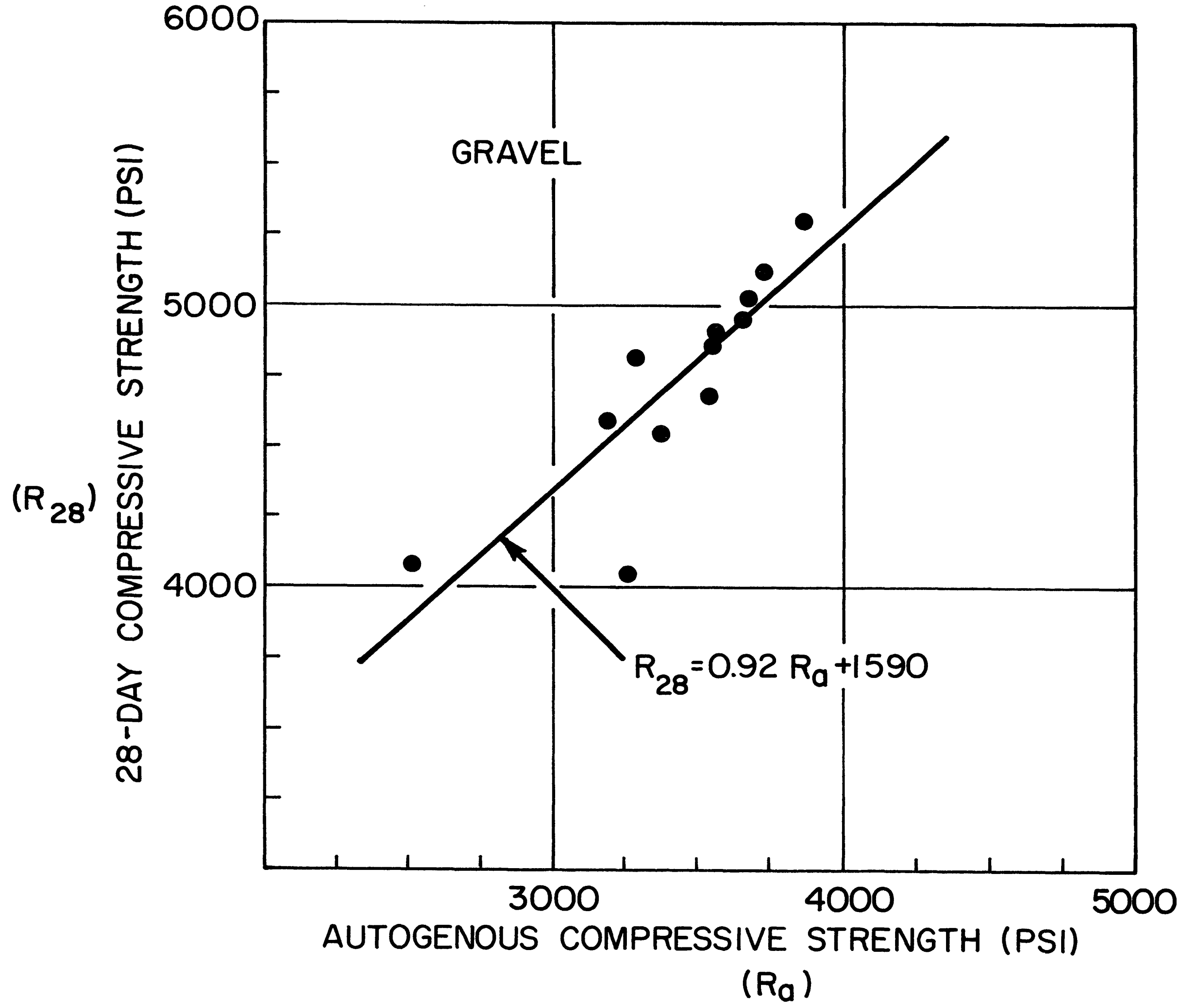

Figure 2. Forty-nine-hour strength vs. 28-day strength—gravel coarse aggregate.

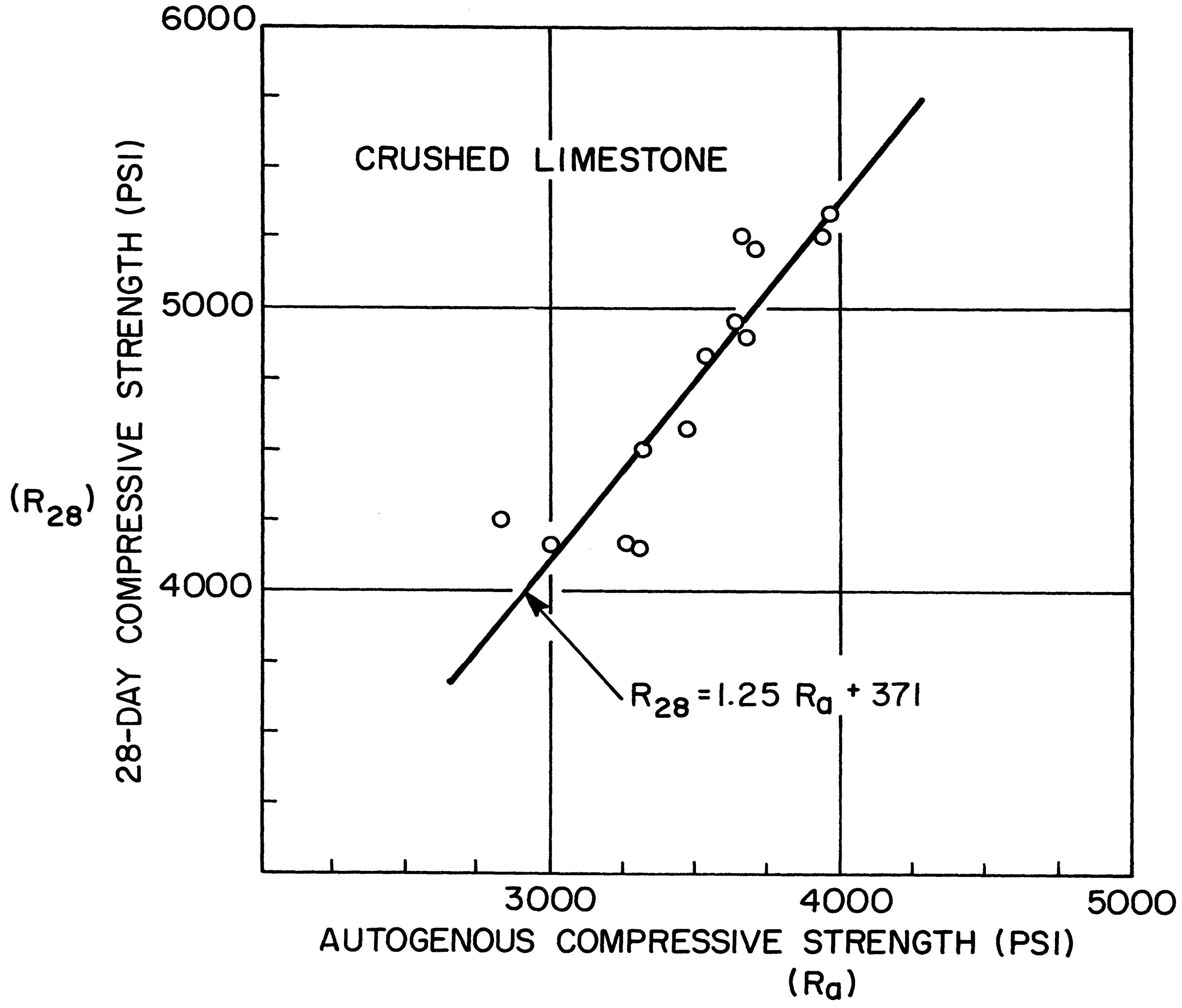

Figure 3. Forty-nine-hour strength vs. 28-day strength—crushed limestone coarse aggregate.

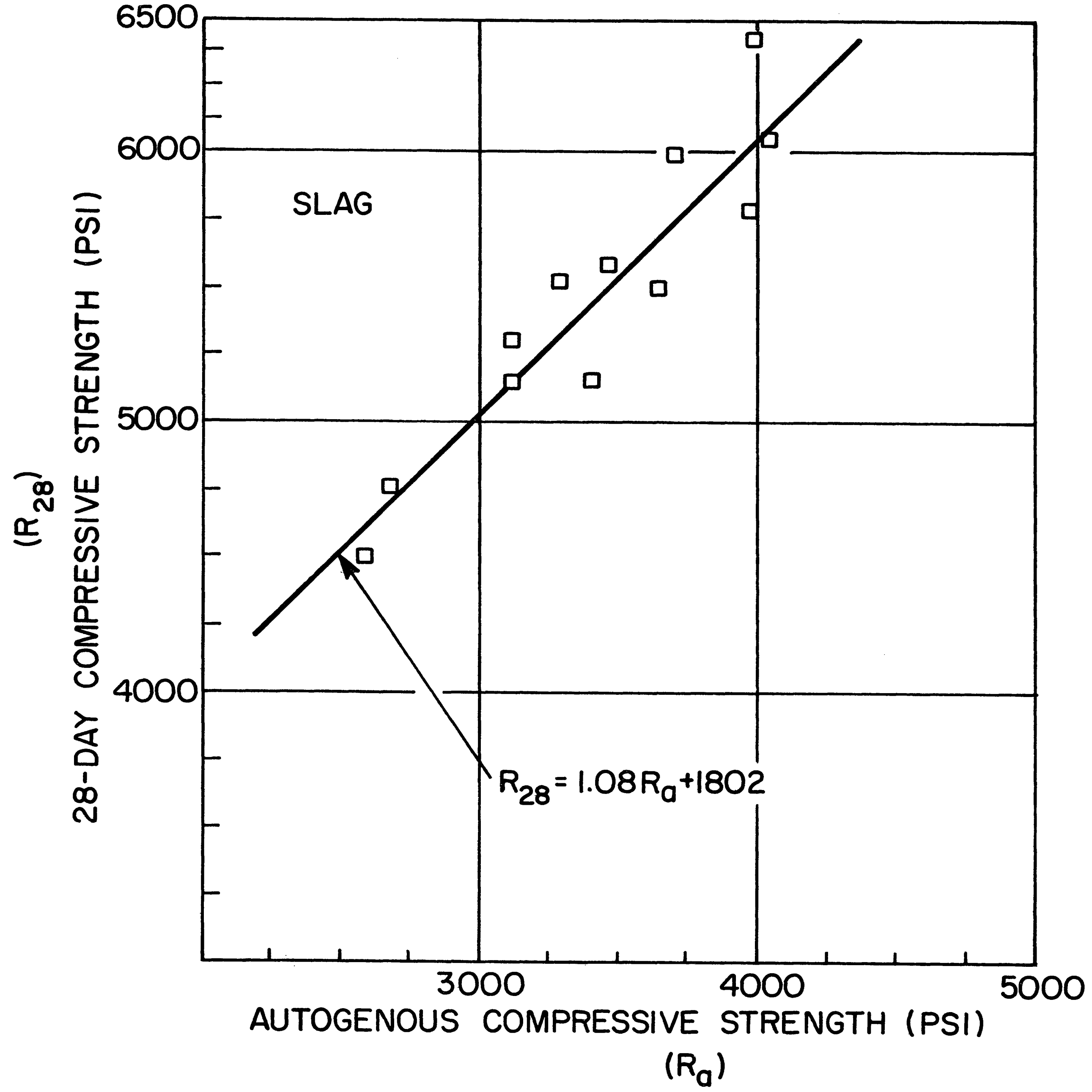

Figure 4. Forty-nine-hour strength vs. 28-day strength—slag coarse aggregate.

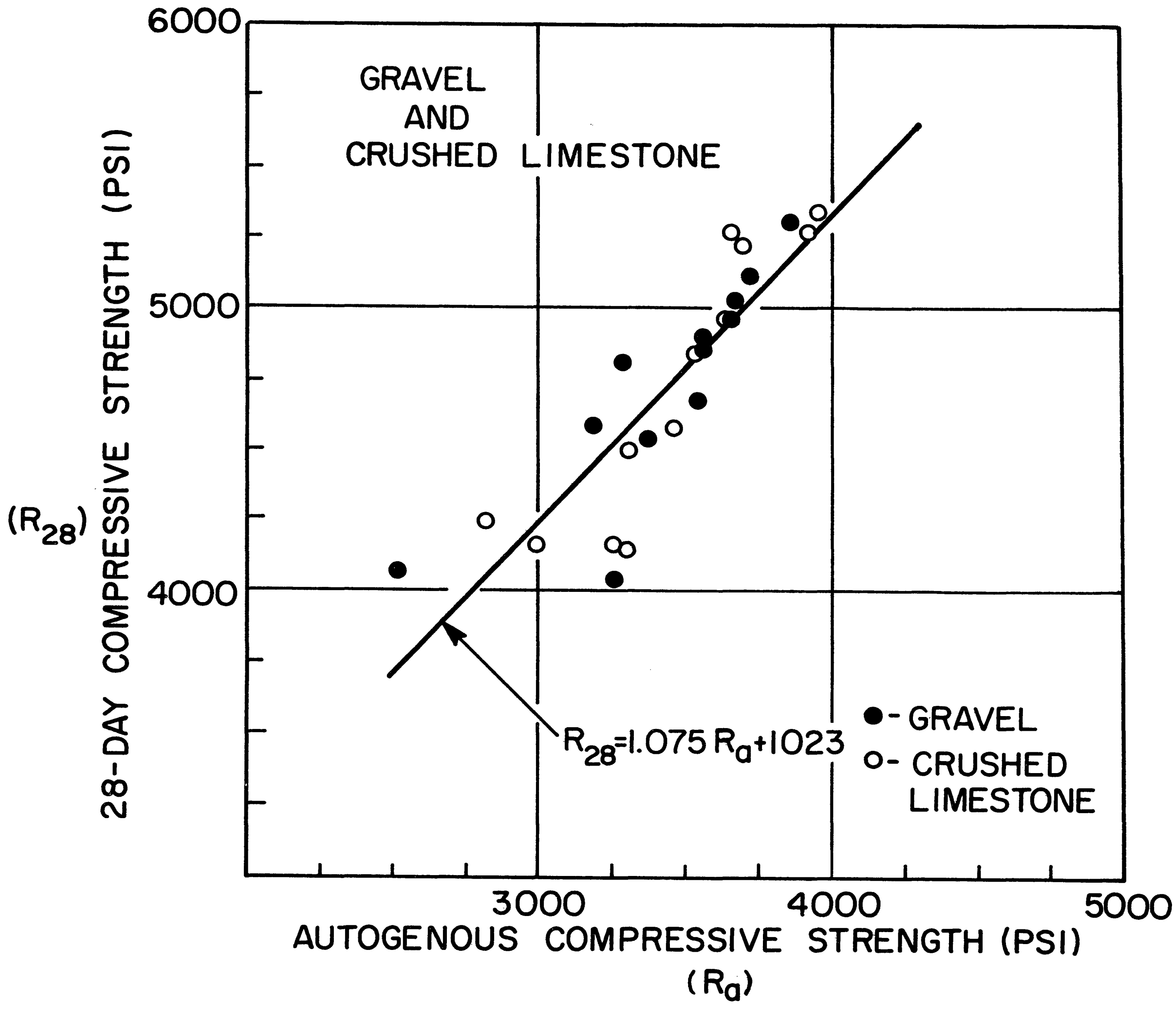

Figure 5. Forty-nine-hour strength vs. 28-day strength—gravel and crushed limestone coarse aggregate.

	28-Day Strength Classification, psi		
	3000	3500	4000
Required autogenous strength-gravel and crushed stone, psi	2500	2900	3300
Required autogenous strength, slag, psi	1600	2100	2500

For the gravel and crushed stone mixes, and within the range of usual strengths, the autogenous 49-hr specimens acquired from 65% to 76% of their 28-day strengths (i.e. "efficiency" as previously defined). The slag concretes' efficiency departed from this trend and had values ranging between 55% and 65%. The 49-hr strengths really do not differ greatly from what would be expected in seven days of normal curing.

NEEDED FURTHER INVESTIGATION

It is anticipated that the Department itself may wish to try this method, or encourage its trial by concrete suppliers, probably at first on one or two construction projects reasonably close to a location where sulfur capping and compression testing facilities are currently available. At least three questions arise, unanswered by the present investigation, regarding variables which would be suspected as influencing the prediction between 49-hr and 28-day strengths:

TYPE AND BRAND OF PORTLAND CEMENT

Michigan uses Type IA cement almost exclusively, but the differences in brand may influence behavior in the antogenous curing procedure and such differences will have to be determined by experience.

TEMPERATURE OF FRESH CONCRETE

Considerably higher temperatures of the fresh concrete will be encountered in midsummer construction than in the present investigation which will probably have effect on autogenous strengths. Fresh concrete temperatures in the present investigation averaged 60°F.

EFFECT OF WATER-REDUCING AND WATER-REDUCING RETARDING ADMIXTURES

Such admixtures often used in bridge deck construction and in prestressed beams will undoubtly affect autogenous strengths and should be investigated.

TESTING COSTS

Effort has been made to assess the overall costs of acceptance testing using the autogenous curing procedure as against conventional cylinder testing. In favor of the autogenous method is that maintaining operation of a temperature and humidity controlled room or water bath is not necessary, and labor cost benefits arise from completing the test in 49 hours rather than 28 days.

Against the autogenous method is the added initial cost of the insulated containers and the need to return them to the job site each time after use so as to be able to refill them. Also, the disposable sheet metal cylinder molds cost nearly twice that of a waxed cardboard mold ordinarily used. Also, there is need for overtime weekend work to handle testing of cylinders from job pours made on Thursday and Friday. The insulated containers are surprisingly bulky and take up considerable space during transport or storage. (A typical pickup truck load, if the containers are standing upright, is 18.)

All things considered, however, it is not believed that the testing and handling costs per cylinder would be too different for autogenous and conventionally cured specimens.

CONCLUSIONS

The 49-hr autogenous method of accelerated testing of compressive strength of concrete offers promise of satisfactorily predicting the 28-day strength. In this method, the heat generated by the chemical reaction between the cement and mixing water is conserved by storing the standard 6 x 12-in. cylinder individually in a well-insulated container. The insulated container regeneratively heats the specimen so as to hasten strength gain to about 60% to 80% of that attained at 28 days of usual laboratory curing. At 48-hr after casting, the cylinder is removed from the container, its disposable sheet metal mold taken off and the specimen allowed to cool for 30 min at which time the cylinder is capped with melted sulfur mortar. At 49-hr the cylinder is tested in the compression machine.

In this investigation, one type and brand of portland cement was incorporated in air-entrained concrete having cement contents in the range used by the Department and with three typical coarse aggregates, i.e. natural gravel, crushed limestone, and blast furnace slag. Sufficient companion specimens and repeat batches of concrete were made to ensure being able to draw statistically valid conclusions.

1. At each one of the cement contents of 5.5, 6.0, and 6.5 sacks per cu yd, respectively, the 49-hr autogenous cured strengths were essentially the same regardless of whether gravel, crushed limestone, or slag coarse aggregate was employed.

2. In rich concrete having a cement content of 7.0 sacks per cu yd, the

49-hr autogenous strength of the slag concrete was sufficiently different from that made with gravel or crushed limestone as to demand separate classification.

3. At each cement content of 5.5, 6.0, 6.5 and 7.0 sacks per cu yd, the 28-day strengths of the standard cured concretes containing gravel or crushed limestone—but not slag—were essentially similar.

4. The 28-day strength of the standard cured slag concrete departed substantially from that of gravel and crushed stone concrete at all cement contents.

5. Prediction of the 28-day strength of the concrete made in this study could be satisfactorily made using a graph or by use of the following equations:

For gravel or crushed stone coarse aggregate,

$$R_{28} = 1.08R_a + 1023 \text{ psi}$$

and for slag coarse aggregate,

$$R_{28} = 1.08R_a + 1802 \text{ psi}$$

where: R_{28} = Compressive strength of standard cured 6 x 12-in. specimens at 28-days, psi, and

R_a = Compressive strength of 49-hr autogenous cured specimens, psi

In this study, no prediction of 28-day strength, when based on an average of 3 autogenous cured cylinders would be in error by more than 500 psi using these equations.

6. Based on an average strength from three autogenous specimens, the following minimum 49-hr strengths should ensure concrete of the indicated 28-day strength classification:

	28-Day Strength Class, psi		
	3000	3500	4000
Required minimum 49-hr autogenous cured strength, gravel or crushed stone, psi	2500	2900	3300
Required minimum 49-hr autogenous cured strength, slag, psi	1600	2100	2500

7. It is recommended that the Department undertake a limited program to validate the autogenous procedure on actual construction projects where data outlined in the previous section entitled, "Needed Further Investigation" can be gathered. This includes effect of cement brand, use of admixtures, and temperatures of fresh concrete on the 28-day strength prediction; all are variables more expeditiously studied in the field than in the laboratory.

At the conclusion of this program, and if the added variables do not seriously jeopardize the ability to predict 28-day strength, the Department will be in an excellent position to effect a transition in its concrete quality assurance program, a need long felt but heretofore not attainable.

Much of the inspection burden of selecting proportions for the concrete, verifying batch quantities, checking scales, slump, etc., now undertaken by the Department can then be shifted to the contractor's responsibility because deficiencies in the concrete strength can be discovered by the Department in the much more reasonable period of 49 hours rather than 28 days.

ACKNOWLEDGMENTS

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The opinions and conclusions expressed or implied in this report are those of the author and are not necessarily those of the Michigan Department of State Highways or of the Office of Research Administration, The University of Michigan.

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APPENDIX A

TEXT OF ASTM TEST METHODS FOR ACCELERATED CURING OF CONCRETE

TENTATIVE METHOD OF MAKING AND ACCELERATED CURING OF CONCRETE COMPRESSION TEST SPECIMENS

1. SCOPE

1.1 This method covers three procedures for making, curing, and testing specimens of concrete stored under conditions intended to accelerate the development of strength. The choice of which procedure to use should be made by the user on the basis of his experience and local condition. The three procedures are: Procedure A—Warm Water Method; Procedure B—Boiling Water Method; and Procedure C—Autogenous Curing Method.

Note 1. All material in this method not designated as belonging specifically to one of the three procedures applies to all procedures.

2. APPLICABLE DOCUMENTS

ASTM C 470, C 31, C 172, C 33, C 39, and 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 hr depending upon the procedure selected. Procedures A and B utilize storage of specimens in heated water at elevated curing temperatures without moisture loss. The primary function of the moderately heated water used in Procedure A is to serve as insulation to conserve the heat generated by hydration. The temperature level employed in Procedure B provides thermal acceleration. Procedure C 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).

3.2 Important characteristics of the procedures are given in Table A.1.

TABLE A.1

BRIEF DESCRIPTION OF ACCELERATED CURING PROCEDURES

Procedure	Molds	Accelerated Curing Medium	Accelerated Curing Temperature	Age Accelerated Curing Begins	Duration of Accelerated Curing	Age at Testing
A. Warm water	reusable or single-use	water	95°F (35°C)	immediately after casting of cylinder	23 1/2 hr ± 30 min	24 hr ± 15 min
B. Boiling water	reusable or single-use	water	212°F (100°C)	23 hr after casting	3 1/2 hr ± 5 min	28 1/2 hr ± 15 min
C. Autogenous	single-use	heat of hydration	initial concrete temperature augmented by heat of hydration	immediately after casting	48 hr ± 15 min	49 hr ± 15 min

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 depend 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. PROCEDURE A. WARM WATER

5.1 Apparatus

5.1.1 General

Equipment and small tools for fabricating specimens, measuring slump and determining air content shall conform, if necessary, to the applicable requirements of Method C 31—Making and Curing Concrete Compressive and Flexural Test Specimens in the Field.

5.1.2 Molds

5.1.2.1 Molds for specimens shall conform to the requirements for cylinder molds in Method C 31, except that cardboard molds shall not be used.

5.1.2.2 Single-use light gage molds with lids shall conform to the requirements of Specification C 470—Single-Use Molds For Forming 6 x 12 in. Concrete Compression Test Cylinders.

5.1.2.3 When test specimens are to be tested without capping, reusable molds having machined plates which can be securely connected to the molds and which will provide bearing surfaces plane within 0.002 in. (0.050 mm) shall be provided for both top and bottom. The mold assembly shall be sufficiently tight to permit the filled mold to be turned from the vertical filling position to a horizontal curing position without loss of water or damage to the test specimen.

5.1.3 Accelerated Curing Tank

5.1.3.1 The tank may be of any configuration suitable for the number of cylinders to be tested and the cylinders may be arranged in a line or in rectangular configuration provided a clearance of 2 in. (50 mm) between the side of the cylinder and the surface of the tank and 4 in. (100 mm) between adjacent cylinders is maintained.

Note 2. A number of different tanks have been used successfully. Guidelines are shown in the Appendix.

5.1.3.2 The tank shall be capable of providing the specified water temperature. The temperature, at any point in the water shall be maintained within ±5°F (2.8°C) of that specified. Depending upon the design features of the tank (and whether it is to be capable of use for Procedure B—boiling water, as well as for Procedure A—warm water) insulation, mechanical agitation or both might be necessary to meet the specified temperature requirements. Electrical immersion heater(s) controlled by a thermostat are the most suitable form of heating elements. Thermometers or other temperature recording devices shall be used, independent of the thermostat, to check the temperature of the water.

Note 3. For a particular procedure, size of heating element required will depend upon the size of the tank and the number of cylinders to be tested at one time. For controlling the temperature, some household thermostats may be satisfactory, but generally they are not sufficiently sensitive.

5.1.3.3 The plate supporting the cylinders shall have sufficient open perforations so as not to interfere with the circulation of the water.

5.1.3.4 A close fitting, but not pressure tight, lid shall be provided where the tank is to be capable of use for Procedure B as well as Procedure A. The water level shall be checked periodically and maintained at 4 in. (102 mm) above the top of the cylinders (Note 4).

Note 4. Provision for an overflow pipe is a convenience in controlling the maximum depth of water.

5.2 Procedure

5.2.1 Preparation of Test Specimens

5.2.1.1 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.

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

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

5.2.2 Curing

5.2.2.1 Cover the top of the specimen with a rigid plate to prevent loss of mortar to the water bath (Note 5).

5.2.2.2 Place the specimen into the curing tank (Note 5). The water at the time of immersion and throughout the curing period shall be 95°F ± 5°F (35°C ± 3°C). The temperature of the curing water after immersion of the cylinders shall not drop more than 5°F (2.8°C) and shall return to 95°F ± 5°F (35°C ± 3°C) within 15 min.

5.2.2.3 The temperature of the curing water should be continuously recorded or periodically measured throughout the curing period.

5.2.2.4 After curing for 23 1/2 hr ± 30 min, remove the cylinder from the tank and demold the cylinder.

Note 5. When the cylinders are cast in molds with plates on both ends to conform with the provisions of 5.1.2.3, the plates shall prevent the loss of mortar. If the cylinders are cast in molds meeting the requirements of 5.1.2.3 they may be stored horizontally, otherwise they are to be stored in the curing tank with the long axis vertical.

5.2.3 Capping and Testing

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

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

5.2.3.3 Specimens shall not be tested sooner than 30 min after capping.

5.2.3.4 The cylinder shall be tested for strength in accordance with the requirements of ASTM Method C 39 at an age of 24 hr ± 15 min.

6. PROCEDURE B. BOILING WATER

6.1 Apparatus

6.1.1 The requirements for small tools and molds are the as those stated in 5.1.

6.1.2 The tank shall conform to the requirements specified in 5.1.3.

Caution 1. The use of boiling water imposes the need for safety measures to prevent scalding or eye burns resulting from sudden escape of steam upon opening and immersion or dropping the cylinders into the boiling water. Lifting tongs are suggested.

6.2 Procedure

6.2.1 Preparation of Test Specimens

Specimens shall be prepared in accordance with 5.2.1.

6.2.2 Initial Curing

Cover the cylinder to prevent loss of moisture and store so that they will not be disturbed or subjected to vibration or jarring. In the storage area the temperature adjacent to the cylinders shall be maintained at 70°F ± 10°F (21°C ± 5°C). Protection and storage shall conform to the requirements of ASTM Method C 31.

Note 6. Strict attention to the protection and storage of the cylinder during this initial period is necessary for meaningful results because of the short total curing period.

6.2.3 Accelerated Curing

6.2.3.1 Place the covered cylinder molds in the water tank at 23 hr ± 15 min after molding. The temperature of the water at the time of immersion and throughout the curing period shall be at boiling 212°F (100°C) at sea level (Notes 5 and 7). The temperature of the water shall not drop more than 5°F (2.8°C) after the cylinders are placed and shall return to boiling within 15 min.

Note 7. In confined places the temperature of the water may be kept just below the boiling point to avoid excessive evaporation. The temperature at which water boils varies because of differences in elevation above sea level. Differences in strengths caused by the differences in temperatures are not believed to be significant, but comparison of results among areas so affected should be supported by appropriate correlations and interpreted with the knowledge of the temperature variations.

6.2.3.2 The temperature of the curing water should be continuously recorded or measured at regular intervals throughout the curing period.

6.2.3.3 After curing for 3 1/2 hr ± 5 min, remove the cylinder from the boiling water, remove the mold and allow the cylinder to cool for 1 hr at room temperature.

6.2.4 Capping and Testing

The cylinders shall be capped and tested in accordance with 5.2.3 except that the age at time of test shall be 28 1/2 hr ± 15 min.

7. PROCEDURE C. AUTOGENOUS CURING

7.1 Apparatus

7.1.1 General

7.1.1.1 The container shall consist of thermal insulation meeting heat retention requirements of 7.1.2.1 and closely surrounding the concrete test cylinder.

7.1.1.2 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.

7.1.1.3 The container may be provided with a maximum or minimum recording thermometer which shall not be insulated from the test cylinder (Note 9).

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

7.1.1.5 The container shall be capable of holding either one or two cylinders. A satisfactory container is shown in Appendix Figure B-2 (Note 8).

Note 8. 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 7.1.

7.1.2 Proving Tests Requirements

7.1.2.1 Heat retention. A watertight container with internal dimensions of 12 in. x 6 in. diam (30 x 15 cm) shall be placed in the curing container and then filled to within 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 ± 2°F (21°C ± 1°C), the water temperature shall be:

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

7.1.2.2 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 min.

7.1.2.3 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 hr, nor softening or distortion when maintained at an ambient temperature of 140°F (60°C) for 72 hr. The gasket type heat seal shall immediately fully recover its original thickness after 50% compression under the temperature conditions specified above.

7.2 Procedure

7.2.1 Preparation of Test Specimens

Specimens shall be prepared in accordance with 5.2.1.

7.2.2 Curing

7.2.2.1 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.

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

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

7.2.2.4 For at least 12 hr after molding the container shall not be moved, disturbed, or subjected to vibration or jarring and shall be stored out of the sun, preferably at a temperature between 60°F and 80°F.

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

7.2.2.6 Record the maximum and minimum temperatures in the container indicated on the thermometer (Note 9).

Note 9. 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.

7.2.3 Capping and Testing

The cylinders shall be capped and tested in accordance with 5.2.3 except that the age at the time of test shall be 49 hr ± 15 min (Note 10).

Note 10. Capping and testing may be performed at ages different from that specified in 7.2.3. Agencies using the procedure have for convenience established relationships between test results at 24, 72, and 96 hr with those obtained by standard moist curing. However, at 24 hr, the relationship is less satisfactory than those obtained by accelerated autogenous curing for 48, 72, or 96 hr. Where the curing period is other than that specified in 7.2.3, the age at testing shall be the curing period plus 1 hr. The tolerance of ± 15 min shall still apply.

8. INTERPRETATION OF TEST RESULTS

8.1 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 10, Precision, the variability of the method is the same or less than that from traditional methods. Thus, results can be used in rapid assessment of variability for process control and signaling 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.

9. REPORT

9.1 The Report Shall Include the Following:

9.1.1 Identification number

9.1.2 Diameter (and length, if not standard) in in.

9.1.3 Cross-sectional area, in sq in.

9.1.4 Maximum load, in lb

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

9.1.6 Type of fracture, if other than the usual cone

9.1.7 Defects in either specimen or caps

9.1.8 Age of specimens

9.1.9 Accelerated curing method used

9.1.10 Initial mix temperature to the nearest °F (°C)

9.1.11 Maximum and minimum temperature to the nearest °F (°C), if Method C was used

9.1.12 Method of transportation used for shipping specimens to the laboratory

9.1.13 Ambient temperature of specimen or container during storage for Methods B and C

10. PRECISION

10.1 The single-laboratory coefficient of variation has been determined as 3.6% 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% of their average.

10.2 The single-laboratory, multi-day coefficient of variation has been determined as 8.7% 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% of their average.

APPENDIX B (APPENDIX TO ASTM TEST METHODS)

B.1 ACCELERATED CURING TANK

B.1.1 Curing tanks similar to that shown in Figure B.1 have been used successfully (Notes B.1, B.2, and B.3).

Note B.1. Properly designed cabinets will ensure an almost uniform temperature throughout the tank without the need for a mechanical stirrer. The immersion heater(s) should be located centrally in plan, as near to the bottom of the tank as possible. The water above the heater will then be kept in circulation by convection currents.

Note B.2. For a tank containing two or three cylinders, two coupled elements (1,500 and 5,000 watts) have been found suitable for use with Procedure B. While the smaller elements will maintain the specified curing, the larger element is required as a booster to reestablish boiling within the specified time after the cylinders have been immersed. Where the tank is to be used solely for Procedure A, while the above heaters are also suitable, a single element (3,000 watts) has also been found suitable. With the latter heater the tank, when used for Procedure A, may be of larger dimensions to hold more than two or three cylinders.

Note B.3. Overflow pipe, closely fitting lid and exterior insulation are not essential for curing tanks used only for Procedure A.

B.2 AUTOGENOUS CURING CONTAINER

B.2.1 A satisfactory container is shown in Figure B.2.

Note B.4. Space for maximum-minimum thermometer (if required) and means of opening the container, securing when closed and lifting not shown.

Note B.5. 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 polyurethan foam (2 lb/cu ft, 32.0 kgm^3) maintained when closed at 50% compression.

Note B.6. 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/°F/in. (28.8 k cal/hr/m^2/°C) 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.

Note B.7. The maximum-minimum thermometer (if used) should cover a range from 20°F to 150°F (-7°C to 66°C) in 1° increments.

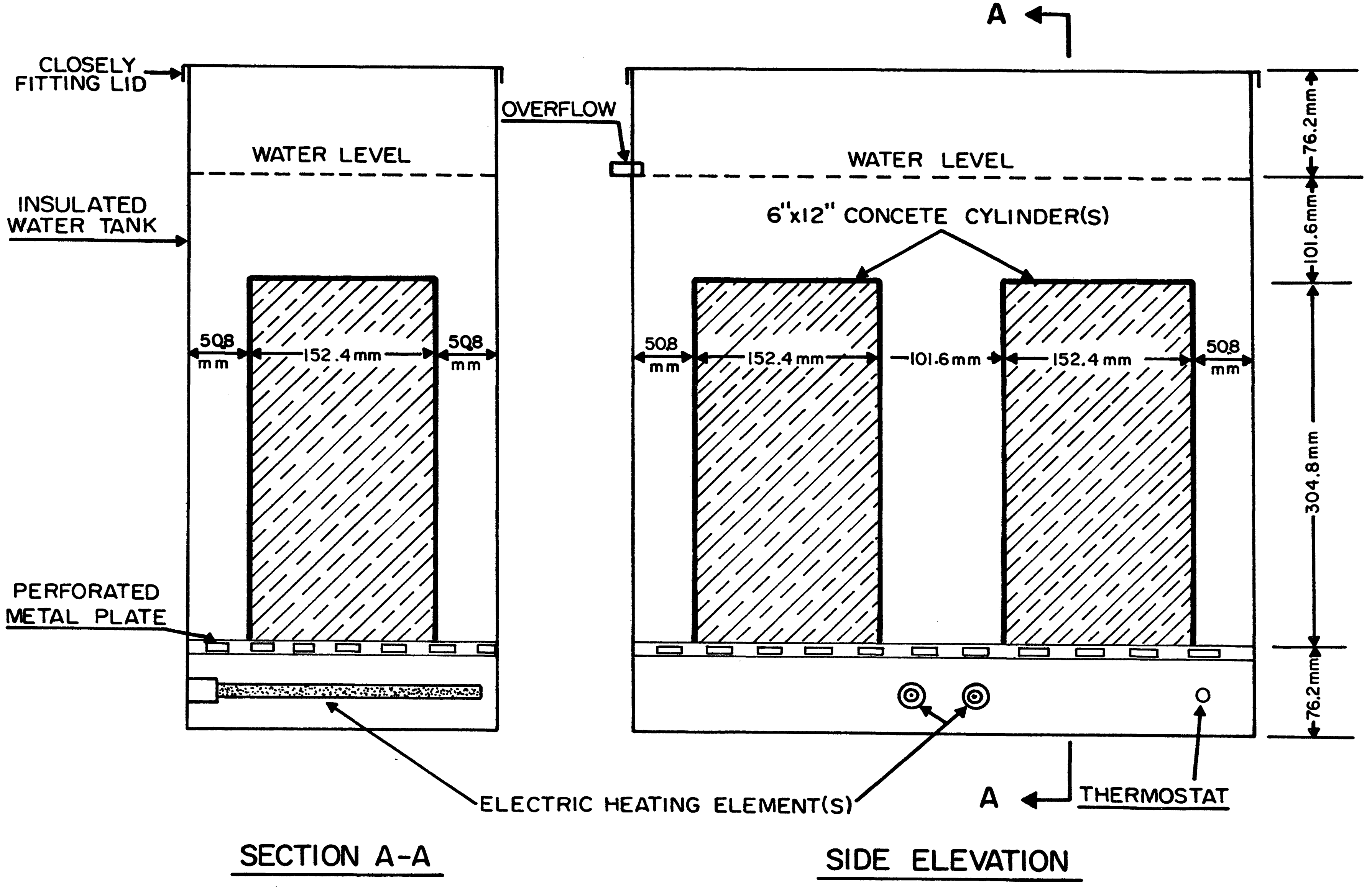

Figure B-1. Accelerated curing water tank.

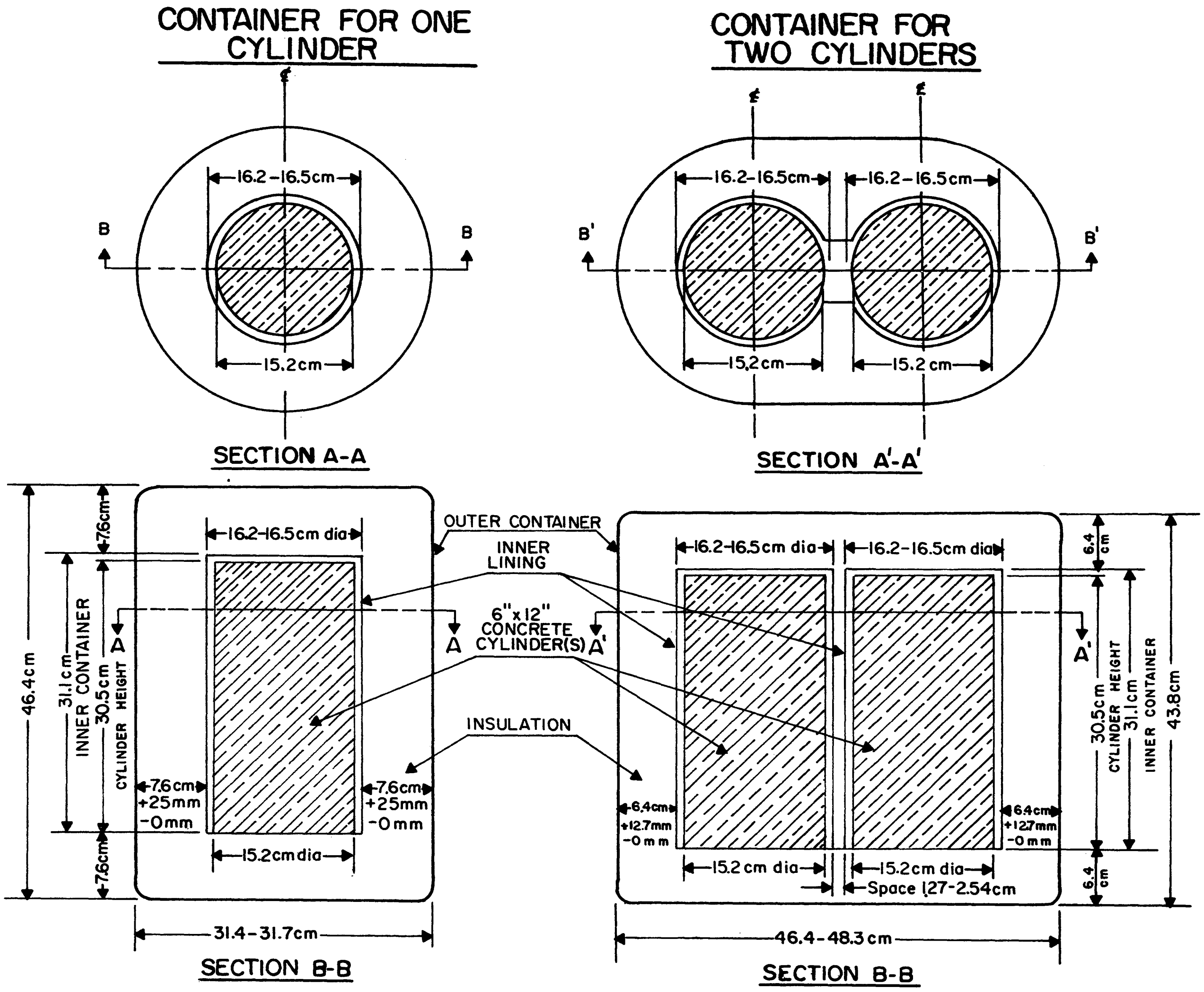

Figure B-2. Autogenous curing container for one or two cylinders (basic requirements).

APPENDIX C

MINUTES OF MEETING WHICH PLANNED THIS INVESTIGATION—OCTOBER 21, 1970

Minutes

Meeting of October 21, 1970
Ann Arbor, Michigan

ACCELERATED CONCRETE STRENGTH TESTING IN HIGHWAY DEPARTMENT OPERATIONS

Contract No. 70-0582

(U. of M. Project No. 335150)

Personnel Present:	MDSH	U. of M.
	R. L. Greenman	F. E. Legg, Jr.
	D. Wickham	D. L. Dailey
	C. Curnow	
	H. Barnes	

The topics discussed included:

1. Comparison of the three most widely used accelerated curing methods: (1) Autogenous Method; (2) Hot Water Method; and (3) Modified Boiling Method.

2. Possible applicability of accelerated curing to determining when an intersection may be opened to traffic. Investigations of accelerated curing to date have emphasized estimating <u>potential</u> ultimate strength of concrete, but early prediction of 28-day strength, when coupled with job day-to-day temperature records, might facilitate decision.

3. The validity of the temperature table on page 555 (Assumed Daily Percentage Increase in Compressive Strength of Concrete Cured at Various Temperatures) of "Standard Specifications for Highway Construction for the Michigan Department of State Highways—1970" was questioned, and it was suggested that the present values be verified. It was pointed out that companion beams made and cured alongside the pavement almost always exceed the strength predictions of the table. The latter can reflect either improper percentage gain values in the table or that the strength level of the actual concrete as cast far exceeded the 28-day "design" strength, as a consequence of which measured strengths at early ages would be expected to exceed those based on percentages of the "design" strength.

4. Decision was made to test several MDSH typical concrete mixes using the Autogenous Curing Method. The Hot Water and Modified Boiling Methods were temporarily discarded, for economic reasons, as probably not applicable to Highway Department operations.

In the course of discussion, several other items came up:

(a) In the Autogenous Method, why are metal molds used instead of the cheaper waxed cardboard molds?

(b) Why is the Autogenous Method being reduced from 49 hr to 48 hr?

(c) Does P. Smith of Ontario Highways design own mix proportions or does contractor make the selection?

Following the meeting, it was suggested by telephone that the project include the possibility that accelerated curing techniques be adapted to acceptance testing of reinforced concrete pipe and prestressed beams. Presumably, prediction in 48 hr of satisfactory 28-day strengths, when coupled with verification of proper steam curing, might be a basis for early acceptance of the precast units.

APPENDIX D

TESTS OF AGGREGATES AND CEMENT USED IN THIS INVESTIGATION

TABLE D.1

AGGREGATES USED IN MAKING LABORATORY CONCRETE

	Sand	Gravel	Crushed Limestone	Slag
Passing, percent by weight				
1 1/2 in.		100		
1 in.		97	100	100
3/4 in.		74	91	80
1/2 in.		45	55	30
3/8 in.		23	27	8
No. 4	100	2.9	4.7	2.0
No. 8	86			
No. 16	63			
No. 30	41			
No. 50	20			
No. 100	5.1			
Loss by washing, percent	1.6	0.2	1.3	0.4
1. soft particles, percent		0.7	0.1	
2. chert particles, percent		5.1	0.0	
3. hard abs. particles, percent		0.5	0.3	
Sum of 1, 2, and 3		6.3	0.4	
Organic matter, plate No.	1			
Specific gravity (dry)	2.60	2.68	2.65	2.20
Absorption, percent	1.40	1.05	0.97	5.39
Dry unit weight, loose, lb/cu ft		103.7	91.9	71.6
Dry unit weight, rodded, lb/cu ft		108.7	98.9	78.0

TABLE D.2

TESTS OF PORTLAND CEMENT

PHYSICAL TESTS

Normal consistency, percent	26.0
Time of set, Gillmore	
initial, hr min	2:45
final, hr min	4:30
Air in mortar, percent	12.5
Specific surface, air permeability, sq cm/g	3986
Autoclave expansion, percent	0.06
Compressive strength, mortar, psi	
3-days	2520
7-days	3280
28-days	4700
False set, mortar	OK

CHEMICAL COMPOSITION (percent by weight)

Silicon dioxide,	SiO_2	20.9
Aluminum oxide,	Al_2O_3	6.0
Ferric oxide,	Fe_2O_3	2.7
Calcium oxide,	CaO	62.8
Magnesium oxide,	MgO	2.5
Sulfur trioxide,	SO_3	2.4
Loss on ignition		1.5
Sodium oxide,	Na_2O	0.28
Potassium oxide,	K_2O	0.77
Total alkali as	Na_2O	0.79
Insoluble residue		0.1
Calculated compounds		
tricalcium silicate,	C_3S	46.2
dicalcium silicate,	C_2S	25.0
tricalcium aluminate,	C_3A	11.3
tetracalcium aluminoferrite,	C_4AF	8.2

APPENDIX E

DETAILED TEST RESULTS OF LABORATORY CONCRETE MADE IN THIS INVESTIGATION

DETAILED TEST RESULTS

CLASS OF CONCRETE	COARSE AGGREGATE																					
		GRAVEL							CRUSHED STONE							SLAG						
	BATCH NUMBER	CEMENT CONTENT (sk/cyd)	WATER-CEMENT RATIO (by wt)	MIXING WATER (lb/cyd)	SLUMP (in)	AIR CONTENT (per-cent)	COMPRESSIVE STRENGTH (psi)		CEMENT CONTENT (sk/cyd)	WATER-CEMENT RATIO (by wt)	MIXING WATER (lb/cyd)	SLUMP (in)	AIR CONTENT (per-cent)	COMPRESSIVE STRENGTH (psi)		CEMENT CONTENT (sk/cyd)	WATER-CEMENT RATIO (by wt)	MIXING WATER (lb/cyd)	SLUMP (in)	AIR CONTENT (per-cent)	COMPRESSIVE STRENGTH (psi)	
							AUTO-GENOUS	28-DAY						AUTO-GENOUS	28-DAY						AUTO-GENOUS	28-DAY
BASE COURSE (BC)	1	5.76	0.37	200	1.5	5.0	3250 3330 3180	4150 3960 4010	5.56	0.45	240	3.5	7.0	2900 2830 2760	4120 4490 4150	5.66	0.34	183	2.0	6.4	3290 3020 3010	5120 5140 5230
						Av	3250	4040						2830	4250						3110	5160
	2	5.26	0.47	233	3.25	7.7	2480 2510 2550	4240 3860 4120	5.63	0.48	254	2.0	5.3	3300 3360 3300	4590 4280 4510	5.32	0.42	211	2.0	8.2	2650 2670 2690	4850 4740 4700
						Av	2510	4070						3320	4460						2670	4760
	3	5.47	0.44	226	2.5	6.4	3220 3140 3180	4780 4420 4560	5.29	0.54	271	3.0	7.3	2970 3000 3000	4160 4100 4240	5.35	0.42	209	4.5	8.3	2560 2580 2580	4360 4590 4560
						Av	3180	4590						2990	4170						2570	4500
	Av	5.50	0.43	220	2.4	6.4	2980	4230	5.49	0.49	255	2.8	6.5	3050	4290	5.44	0.39	201	2.8	7.6	2780	4810
STRUCTURES, PAVEMENT (P or A)	1	6.20	0.39	230	3.0	5.4	3270 3270 3310	4930 4660 4840	6.16	0.41	242	2.5	5.6	3290 3270 3360	4360 4150 3890	6.13	0.37	215	3.0	5.7	3470 3330 3380	5160 5160 5160
						Av	3280	4810						3310	4130						3390	5160
	2	6.09	0.40	230	1.0	4.6	3600 3430 3620	4750 4880 4930	5.90	0.49	272	2.5	6.1	3500 3390 3500	4580 4810 4360	6.06	0.37	213	2.5	7.4	3100 3130 3120	5410 5140 5370
						Av	3550	4850						3460	4580						3120	5310
	3	5.79	0.43	234	3.5	6.2	3370 3370 3370	4510 4460 4670	5.92	0.48	265	2.5	6.6	3500 3520 3610	4950 4810 4780	5.92	0.37	206	2.5	6.6	3410 3480 3470	5750 5550 5480
						Av	3370	4550						3540	4850						3450	5590
	Av	6.03	0.41	231	2.5	5.4	3400	4740	5.99	0.46	260	2.5	6.1	3440	4520	6.03	0.37	211	2.7	6.6	3320	5350
STRUCTURES (AA)	1	6.89	0.36	231	1.5	4.2	3710 3890 4000	5160 5510 5300	6.50	0.46	270	4.3	6.2	3240 3300 3250	4260 4060 4170	6.73	0.34	217	2.0	5.5	4050 3930 3890	5690 5740 5940
						Av	3870	5320						3260	4160						3960	5790
	2	6.54	0.37	230	2.0	5.2	3590 3610 3500	5000 4730 4980	6.55	0.48	298	2.0	4.4	3990 3890 3980	5320 5230 5410	6.42	0.37	226	2.5	5.7	3640 3640 3620	5580 5230 5710
						Av	3570	4900						3950	5320						3630	5510
	3	6.42	0.39	234	3.0	5.5	3710 3640 3670	4850 5020 5200	6.42	0.45	270	2.5	5.5	3640 3640 3710	5420 5410 4950	6.42	0.38	230	4.0	6.8	3520 3020 3290	5270 5660 5660
						Av	3670	5020						3660	5260						3280	5530
	Av	6.62	0.37	232	2.2	5.0	3700	5080	6.49	0.46	282	2.9	5.4	3630	4910	6.52	0.36	224	2.8	6.0	3620	5610
PAVEMENT-HIGH EARLY (P-HE)	1	7.18	0.34	227	3.0	5.2	3540 3540 3540	4730 4580 4730	7.10	0.35	236	2.0	5.2	3640 3640 3640	4770 5230 4880	7.07	0.33	217	2.5	5.5	3640 3800 3630	6040 6040 5920
						Av	3540	4680						3640	4960						3690	6000
	2	6.91	0.38	247	2.0	5.1	3540 3640 3710	4810 4890 5160	6.91	0.42	205	2.0	5.0	3960 3890 3920	5440 5260 5070	7.03	0.31	205	2.0	6.1	3980 4070 4000	6400 6470 6470
						Av	3630	4950						3920	5260						3990	6450
	3	7.03	0.37	245	2.0	4.6	3640 3690 3890	5220 4920 5130	6.99	0.43	283	3.0	5.5	3750 3710 3640	5160 5340 5160	6.91	0.35	228	3.0	5.5	4170 3890 4060	6010 6230 6260
						Av	3720	5090						3700	5220						4040	6170
	Av	7.04	0.36	233	2.3	5.0	3640	4910	7.00	0.40	241	2.3	5.2	3750	5150	7.00	0.33	217	2.5	5.7	3910	6210

APPENDIX F

ANALYSIS OF VARIANCE OF MEANS OF 49-HR AND 28-DAY CONCRETE COMPRESSIVE STRENGTH

TABLE F.1

ANALYSIS OF VARIANCE—COMPARISON OF AVERAGE STRENGTHS FOR THREE COARSE AGGREGATES

(49-hr Autogenous Test)

Class of Concrete		Sum of Squares	Mean Square	F-Ratio	$F_{.95}(2,24)$
Base Course (5.5 sk)	category means	339,163	169,582	2.1	3.40
	within	1,937,756	80,740		
Pavement Structures (A or P) (6.0 sk)	category means	64,067	32,033	1.72	3.40
	within	447,134	18,631		
Structures (AA) (6.0 sk)	category means	36,385	18,193	0.25	3.40
	within	1,756,112	73,171		
Pavement High Early (7.0 sk)	category means	352,824	176,412	7.8*	3.40
	within	544,446	22,685		

*Exceeds critical value

TABLE F.2

ANALYSIS OF VARIANCE—COMPARISON OF AVERAGE 28-DAY STRENGTHS FOR CONCRETE MADE WITH GRAVEL AND CRUSHED STONE COARSE AGGREGATE

Class of Concrete		Sum of Squares	Mean Square	F-Ratio	$F_{.95}(1,16)$
Base Course (5.5 sk)	category means	16,200	16,200	0.26	4.49
	within	1,006,600	62,913		
Pavement Structures (A or P) (6.0 sk)	category means	209,089	209,089	2.67	4.49
	within	1,253,689	78,355		
Structures (AA) (6.5 sk)	category means	128,356	128,356	0.65	4.49
	within	3,174,022	198,376		
Pavement High Early (7.0 sk)	category means	254,422	254,422	5.4	4.49
	within	753,579	47,099		$F_{.99}(1,16) = 8.53$