FINAL REPORT

1221

AUTOGENOUS ACCELERATED CURING OF CONCRETE CYLINDERS

Part IV

Moisture Relationships

by

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

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

February 1971
VHRC 70-R28

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

Eighteen different concrete mixtures were proportioned to investigate the influence of cement types (II and III), water cement ratios (0.4, 0.5, and 0.6), and admixtures (accelerator, retarder, and air entraining agent) on the moisture changes during autogenous curing of concrete cylinders.

A total of 360 concrete cylinders were made comprising autogenously cured cylinders, 28 day, 91 day, and 1 year moist cured cylinders, and autogenously cured cylinders instrumented for moisture and temperature measurements.

In addition to measurements of moisture movement and temperature development routine tests for slump, unit weight, air content, and compressive strengths were made.

This report describes the influence of concrete mixture variables on the movement of moisture, the rate of water fixation, and the total quantity of water fixed during autogenous accelerated curing; and the relationships among the moisture parameters resulting from the measurements. The relationships between the moisture and temperature parameters are also presented.

The report lists nine observations and conclusions.

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INTRODUCTION

In recent years many accelerated curing methods have been investigated, (1, 2) most of which used heated or boiling water as a curing medium. Heated water provides both uniform moist curing conditions and high temperature, which accelerate the hydration of the cement.

It has been shown that curing a concrete cylinder autogenously (by a self-generated increase in curing temperature) inside a container sufficiently insulated to prevent heat and moisture losses will provide accelerated strengths comparable to those obtained by applying external heat. (1)

In the case of autogenous curing the moisture content assumes a larger role in the strength development than for conventional curing, because external water is not present to provide uniform moist curing conditions. It is conceivable that for very low water-cement ratios the process of self-desiccation would reduce the humidity below the 80 percent stated by Powers(3) as necessary for continued hydration. The movement of moisture and its relation to temperature are of considerable importance in autogenous curing.

McGhee(4) has studied the temperature relationships of accelerated methods employing water as a curing medium, using water temperatures ranging from 95°F to 212°F. Because of the added factor of possible variations in moisture during autogenous curing, the relationships between the strength developed and the changes in moisture and temperature accompanying this type of curing are especially important, (5) and refinement of the method would be benefited by a detailed study similar to that reported by McGhee.

OBJECTIVES

The objectives of this investigation were as follows:

1. To supplement the current understanding of the thermal and moisture behavior of concrete subjected to the high temperatures developed during autogenous curing. (5, 6, 7)

2. To examine the influence that variables such as cement type, cement factor, water-cement ratio, and admixtures have on moisture and temperature relationships.

The scope was restricted to the autogenous accelerated curing method(1) and included literature studies concerning accelerated strength development, and the thermal and moisture properties of freshly mixed concrete.

CURING OF CONCRETE

Curing is defined as the environment, during a relatively short period of time immediately after the cement and water are combined, which is beneficial to the setting and ultimate hardening of concrete.

The most desirable conditions for curing are ample moisture around the concrete or prevention of moisture loss of the already available water in the concrete mixture, protection against premature stressing or disturbance of the concrete, and a satisfactory temperature, which governs the rate of chemical reaction during the setting and subsequent hardening of concrete.

Moisture Environment

The purpose of curing is to maintain the concrete in a saturated, or nearly saturated, condition until the originally water filled space in the fresh cement paste has been replaced to the desired extent by the products of cement hydration.

Water retention is necessary because hydration of cement takes place only in the water filled capillaries, and the cement gel can form only when sufficient water is available for both the chemical reactions and the filling of the gel pores being formed.

The amount of water required to hydrate cement is closely related to the mechanism of curing.(2) The amount of water needed to meet the chemical requirements for complete cement hydration is equal to approximately 25 percent of the unhydrated weight of the cement. However, reaction products occupy approximately twice the volume of the original cement so that, at any time during hydration, the amount of water present in the concrete must be greater than twice the amount of water already combined at that time, or the hydration process will stop. Full hydration in a sealed specimen, then, is possible only when the mixing water (either by volume or weight) is at least twice what is required chemically for hydration, which is a water-cement ratio of approximately 0.50 by weight.

Therefore, a water loss by evaporation from the capillaries must be prevented. Water can also be lost internally by self-desiccation and must be replaced by water from the outside. Since full hydration requires a water-cement ratio of 0.50, self-desiccation of a sealed specimen is significant only in mixes having a water-cement ratio below 0.50.(3) It should be remembered, however, that even if the total water available is less than the water required for cement hydration, only half of the total water available in the paste will be used for chemical combination. Powers(3) found that hydration takes place only when the vapor pressure in the capillaries is sufficiently high — approximately 0.80 of the saturation pressure (p_s), as shown in Figure 1. Of course, the maximum rate of hydration can occur only under saturated conditions.

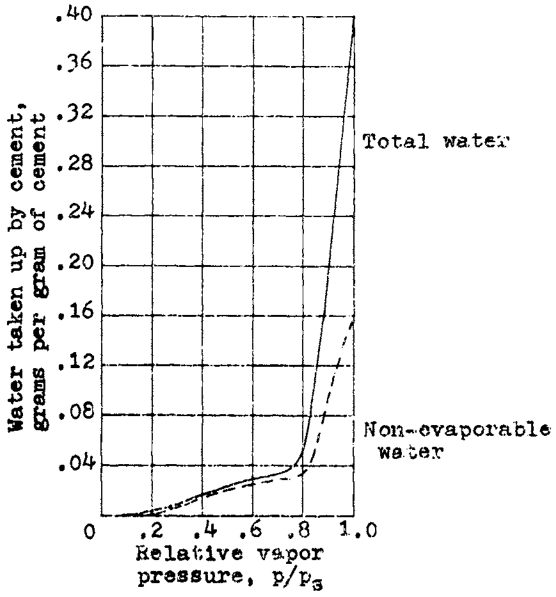

Figure 1. Water taken up by dry cement exposed to different vapor pressures over 6-month period. (From reference 3.)

Powers(3) shows the results of tests conducted on fresh cement paste in which the paste was placed in bottles and the bottles sealed and the vapor pressure inside the bottles periodically measured. The results of these tests are shown in Figure 2. It should be noted that the rate of pressure drop shown in Figure 2 becomes very small after the first week, except for one case, which had the highest water-cement ratio of 0.32 for a type II cement. In this case, the vapor pressure did not begin to drop until after the fifteenth day. Powers postulated(3) that the first 2 weeks were required to absorb the water accumulated on top of the sample because of bleeding while the other specimens were too stiff to bleed appreciably. Therefore, the results of Powers' study, along with other observations, indicate that in a sealed vessel the hydration of the cement will not cause the vapor pressure to drop much below $0.75p_s$ or $0.80\ p_s$. It should also be noted that these values of minimum pressure drop were for water-cement ratios ranging from 0.17 to 0.27. The pressure drop for a water-cement ratio of 0.32 after 28 days was to about $0.97\ p_s$. The values of minimum pressure drop shown in Figure 2 are either equal to or greater than the relative vapor pressure of $p/p_s = 0.80$ (Figure 1), below which practically all hydration stops.

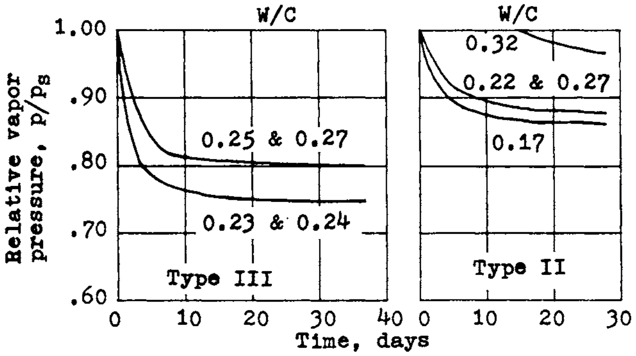

Figure 2. Effect of cement hydration on vapor pressure in sealed bottles. (From reference 3.)

It is not necessary for all the cement to hydrate in order to develop satisfactory strength;(8) in fact, complete hydration is seldom achieved in practice. Powers(8) showed that concrete strength is directly related to the gel-space ratio, which is defined as the ratio of the volume of the hydrated cement paste to the sum of the volumes of the hydrated cement and the capillary pores. If the water filled space is greater than the volume that can be filled by the hydration products, then hydration will continue, and result in higher strength and lower permeability.

The evaporation of water from concrete depends on the relative humidity and temperature of the surrounding air and is also affected by differences between the temperatures of the concrete and surrounding air. The amount of water lost depends primarily on the surface-volume ratio of the specimen.

MOISTURE PROPERTIES AND BEHAVIOR OF FRESH HYDRAULIC CEMENT CONCRETE

Pore Structure in Concrete

The original pores formed in plastic concrete are filled with either water or gas. As the concrete hardens, the water filled pores begin to dry and the air filled pores become saturated with water; these events are dependent upon the mixture proportions, the external moisture and temperature conditions, and the physical dimensions of the concrete specimen.

The moisture conductivity of concrete depends on its degree of hydration. As maturity increases, the number of capillary pores decreases and the number of gel pores increases. Therefore, the moisture conductivity, as measured by permeability, decreases with time.

States of Water in Concrete

The water contained in hardened concrete occurs in several states, which are characterized by the fixation of the water to the solid components of the concrete-cement and aggregate. The states of water in concrete are as follows:(9)

1. Water which is chemically bound as water of hydration in the clinker constituents and in the aggregates -- Chemically bound water consists of the water fixed chemically during cement hydration and the water fixed by sorption of the hydration products.(5)

2. Water which is adsorptively bound in the cement gel or in the aggregates -- Gel water is the water adsorbed or physically bound (states 2 and 3) in the gel pores. Since the gel pores are small, the gel water is within the range of the surface forces of the solid phase. The gel-water vapor pressure depends on the degree of saturation of the gel at any given temperature.(5)

3. Water which is capillarily bound in the cement gel or in the aggregates.

4. Water which is contained in large voids in the cement paste, in the aggregates, or between the paste and the aggregates, without being physically or chemically bound to the solid components, and which is called "free-water" -- Capillary water (states 3 and 4) is the water that occupies the space in the cement paste which is not occupied by the solid phase or the gel pores and which lies outside the range of the surface forces of the solids; therefore, in a saturated paste, the capillary water is under no stress.(5)

At any time during the hydration process, the concrete will tend to approach equilibrium among the four states of water defined above. This equilibrium condition can be expressed in terms of the weights of water in each state per unit weight of cement and is dependent upon the various concrete components and proportions, together with the thermal and hygrometrical states surrounding the concrete during curing. As hydration continues, the equilibrium conditions of the water change from states 3 and 4 into states 1 and 2.

The water of hydration formed in the cement paste is not reversible under the influence of changing vapor pressure since it becomes a constituent of the solid material in the paste. This water of hydration (state 1), or non-evaporable water, is defined by Powers and Brownyard(8) as the water that has a vapor pressure of less than 6×10^{-4} millimeters of mercury at 73°F. The remaining water in states 2, 3, and 4 will be in equilibrium with the water in the surroundings of the concrete.(9) The so-called free-water will evaporate as soon as the vapor pressure surrounding the concrete drops below the saturation pressure, as discussed in the previous section entitled "Moisture Environment." The amount of free-water corresponds to the volume of the large pores and cavities which are accessible to free-water.

The water that is adsorptively and capillarily bound is called "evaporable water"(8) and it varies in amount with the vapor pressure surrounding the concrete in much the same way as it does in aqueous gels.(9)

However, experimentally it is very difficult to make a distinction between the various states of water in concrete. The water within the hydration products is bound to the cement grains in different ways, which results in different degrees of fixation. It is possible, therefore, to distinguish only between evaporable and non-evaporable water at a given temperature and relative humidity.(5) These terms are here defined:

Evaporable water:	The water lost from concrete under atmospheric pressure and at an air temperature of 221°F.
Non-evaporable water:	The water, made up of water bound chemically during cement hydration and of water bound by strong sorption, which will not evaporate when oven dried at 221°F but will gradually escape when heated from 221°F to 1,832°F.

Drying of Concrete

The drying process is controlled by the moisture content (relative vapor pressure) of the drying concrete and is based on the following mechanisms:(5)

1. Evaporation from outer surface of concrete
2. Water movement in pore structure
3. Chemical reaction of water with solids during hydration

By consolidating the first two mechanisms, the drying process can be divided into categories: evaporation drying and fixation drying. Evaporation drying is the evaporation of the water from the surface of the concrete into the air. The liquid water moves to the surface under the influence of gravity, external pressure, capillary forces, and sorption forces. Fixation drying is the decrease in evaporable water content because of hydration of the cement, which results in an increase in the non-evaporable water as hydration continues.

In autogenous accelerated curing there is very little, if any, moisture loss by evaporation. Therefore, no moisture gradients are developed, except for variations in moisture movements within the concrete cylinder itself, the determination of which was one of the objectives of this investigation.

Temperature Effects on Moisture

In general, an increase in temperature increases the mobility of the water, thereby decreasing the equilibrium moisture content and the amount of non-evaporable water, while accelerating the diffusion process. Conclusive experimental data on the effect of temperature on the water content of concrete are very incomplete. At present, all the data available on sorption isotherms are for temperatures below 95°F.

Estimating the Drying of Concrete Theoretically

The water content of concrete depends on many parameters, is very difficult to predict, and is subject to uncertainties even if all the major parameters are known and controlled.

For a constant or a linearly varying moisture conductivity, Hilsdorf(10) has shown that the diffusion theory does not sufficiently describe the drying of concrete. Empirical modifications of the diffusion theory have not advanced beyond the stage of curve fitting. Therefore, if accurate knowledge of the moisture movement in concrete is necessary, it appears justifiable to abandon the diffusion theory for the present and to base the prediction of concrete drying on empirical relationships best suited to the parameters involved for a specific drying condition.

EXPERIMENTAL TEST MATERIALS AND PROCEDURES

Materials

A discussion of the materials used in this experiment is presented in Appendix A. This moisture measurement study was undertaken with the concrete mixtures in Phase II (Appendix B) of the three phases of this project.

Variables

Table I lists the concrete mixture variables investigated in Phase II of this study to determine their influence on moisture of the autogenous cylinders. The air content was held constant at 5.5 ± 0.5 percent for all mixtures.

TABLE I

CONCRETE VARIABLES INVESTIGATED

Cement types	II and III
Water cement ratios	0.4, 0.5, 0.6
Admixtures	accelerator and retarder

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Mixture and Specimen Preparation Schedules

Phase II of the experiment was designed such that the main variables were water cement ratios and admixtures.

The constants were:

Initial mixture temperature = $73^{\circ} \pm 3^{\circ}$F
Cement factor = 550 lb/cu yd
Air content = 5 to 6 percent

The mixture schedule for Phase II is given in Table II.

TABLE II

MIXTURE SCHEDULE FOR PHASE II

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

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

Phase II comprised the following:

Total number of mixtures = 18
Total number of batches = 54
Total cylinders per mixture = 20
Total number of cylinders = 360

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

TABLE III

SPECIMEN PREPARATION SCHEDULE FOR PHASE II

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

*"Autogenous moisture" denotes cylinders instrumented for moisture measurement. Two moisture gages were embedded in each cylinder; there was a total of 72 moisture gages used in Phase II.

**"Autogenous temperature" denotes cylinders instrumented for temperature measurement. Results of the temperature study are presented in Part III of this report.(11)

A more detailed discussion of the mixture and specimen preparation schedules is presented in Appendices A and B of Part I of this report.(12)

Concrete Mixture Design

The recommended practice for selecting proportions for concrete (ACI 613-54)(13) was used for the design of all mixtures.

Mixing and Testing Procedures

Mixing and testing were in accordance with ASTM C 192.(14) Mixing was accomplished in a Lancaster pan mixer as follows:

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

When a retarding or accelerating admixture was used, part of the mixing water contained the retarder or accelerator and the remaining water contained the air-entraining admixture. Immediately after initial mixing, the temperature of the concrete was recorded, then tests for slump, air content, and density were conducted in accordance with ASTM C 143, C 231, and C 138, respectively.(14) If the results of these tests did not meet the requirements previously established for the project the batch was discarded. Provided the requirements were met, the concrete from the slump test was returned to the mixer and the concrete was remixed for 1 minute. Concrete used in the air test was always discarded.

All cylinders were made according to ASTM C 192 procedures. The two cylinders from each batch for autogenous curing were cast simultaneously so that fluctuations in temperature would be the same for both cylinders. The cylinders designated for moist curing were stored in a moist room meeting the requirements of ASTM C 511 and were cured according to ASTM C 192 procedures.

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

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

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

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

Moisture Sensing Method Used in Study

After investigation of approximately 20 different methods of measuring moisture, the resistance method was selected. The sensing element used was the Bouyoucos gypsum type moisture gage,(7, 15) shown in Figure 3.

A detailed discussion of the moisture gage selection and calibration is presented in reference 16 and in Part II of this report.(17)

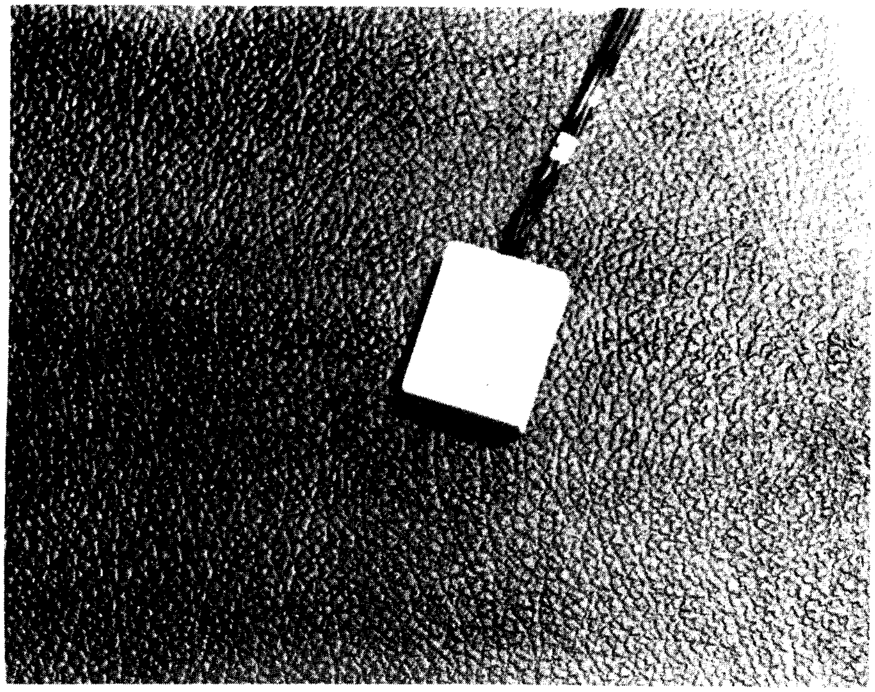

Figure 3. Bouyoucos gypsum type moisture gage.(15)

Moisture and Temperature Monitoring

A pilot study was undertaken to determine the number of thermocouples needed in each cylinder to describe accurately the autogenous adiabatic temperature rise.

As a result of this pilot study on temperature, one copper constantan thermocouple located in the center of the cylinder at a depth of 6 inches into the cylinder was used to record temperatures for the main investigation. Temperature readings were also taken at 1/2 hour intervals since they were recorded automatically. A detailed discussion on the temperature pilot study is presented in Part III of this report.(11)

One cylinder in the pilot study was also instrumented with moisture gages in order to determine the location of moisture gage and the proper time interval between moisture (resistance) readings. This interval was established as 1 hour but was reduced to 1/2 hour, since the readings were recorded automatically.

In the main experiment, two moisture gages were used in each moisture cylinder. These gages were located in the center of the cylinder, 2 inches from both the top and bottom of the cylinder, and were positioned at these locations as shown in Figure 6 in Part II of this report.(17)

Development of Moisture Data

The mechanics involved in correcting an original resistance-time curve for the influence of salt ions and temperature were reported in Part II of this report.(17) The general procedures discussed in Part II for applying correction factors to the moisture calibration curves were also applied to the 104 resistance-time curves resulting from the main experiment.

Procedure for Analyzing Moisture Data

The dry weights of each of the five cylinders used for the calibration, described in Part II, are shown in Table IV, together with the conversion from percent moisture content to pounds of water. Figure 4 presents the relationship between the moisture content in percent by total weight of concrete and pounds of water used for conversions throughout the investigation. Throughout this report the terms "water lost" and "water loss" refer to the removal of water from the moisture gage as a result of fixation drying by the hydrating cement. From the point of view of the cement hydration, the water is "gained" and becomes fixed by the hydration products.

TABLE IV

DATA FROM CALIBRATION CYLINDERS USED TO ESTABLISH PERCENT MOISTURE/POUNDS WATER RELATIONSHIP SHOWN IN FIGURE 4

Gage group	1	2	3	4	5	Average
Dry weight*	27.80	27.60	27.80	27.65	27.30	27.63
Percent moisture	Weight of water in pounds					
6.0	1.67	1.66	1.67	1.66	1.64	1.66
5.0	1.39	1.38	1.39	1.38	1.37	1.38
4.0	1.11	1.10	1.11	1.11	1.09	1.11
3.0	0.83	0.83	0.83	0.83	0.82	0.83
2.0	0.56	0.55	0.56	0.55	0.55	0.55

*Dry weight of calibration cylinders in pounds.

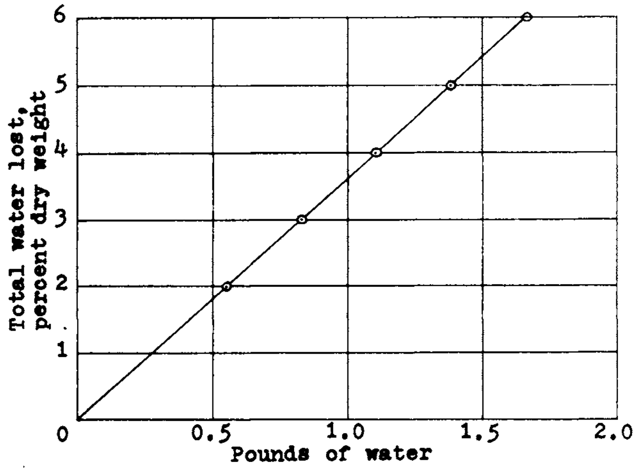

Figure 4. Relationship between percent moisture and pounds of water in concrete cylinders based on oven-dry weights.

During autogenous curing, the average initial percent moisture for 104 gages at a lapsed time of 1 hour was 5.38 percent, with a range from 5.10 to 6.00 percent. The average final percent moisture at a lapsed time of 47 hours was 3.04 percent; with a range from 2.40 to 5.05 percent. The range of percent moisture at 47 hours utilizes almost the entire range of the calibration curves. Typical percent moisture-time curves ranging from the slowest to the fastest rate of measured moisture loss are shown in Figure 5.

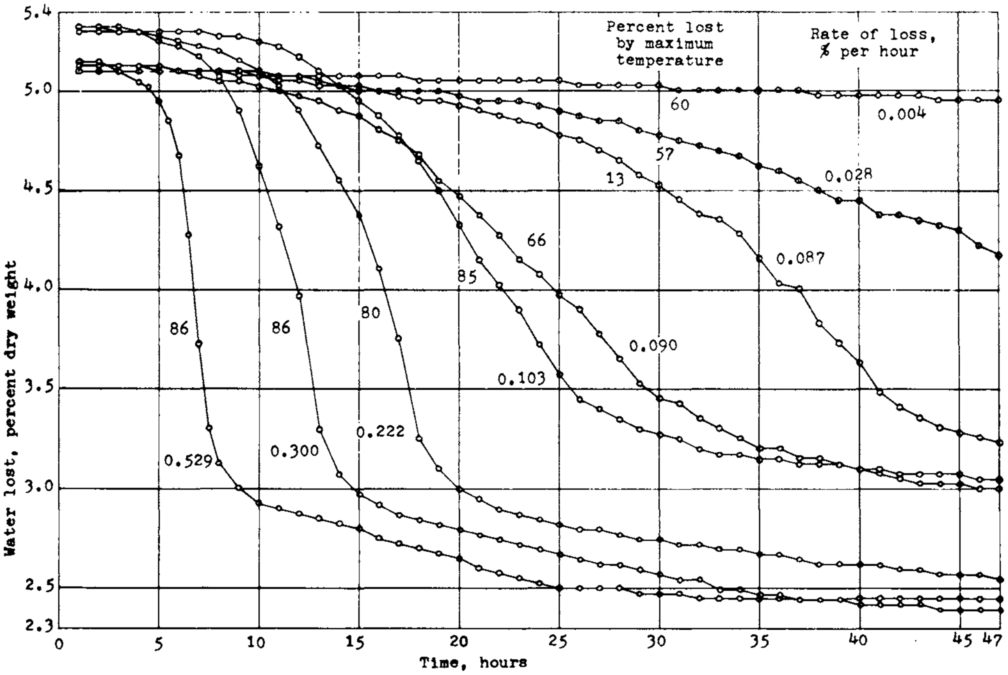

Figure 5. Typical percent moisture — time curves ranging from slowest to fastest rate of moisture loss.

A typical plot of percent moisture against time is shown in Figure 6. The following parameters designated in Figure 6 may be derived from all the moisture curves:

A = Total water lost, percent dry weight

B = Percent of total water lost by time of maximum autogenous temperature

C = Absolute maximum rate of water loss, percent per hour

D = Average time of absolute maximum rate of water loss, hours

E = Average maximum rate of water loss, percent per hour

F = Average time of average maximum rate of water loss, hours.

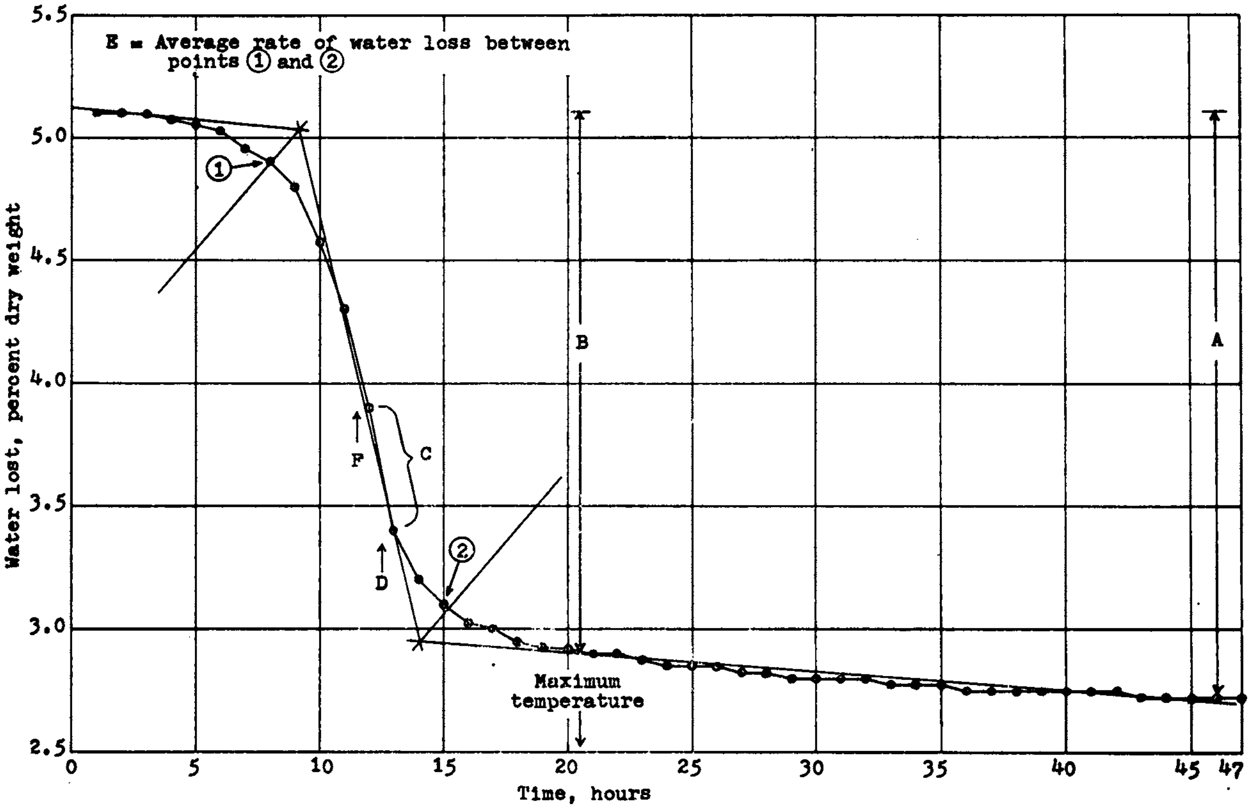

Figure 6. Typical curve of percent moisture plotted against time for autogenously cured concrete cylinder.

B is the water lost at the time of maximum temperature expressed as a percentage of A, the total water lost at 47 hours. E, the average maximum rate of water loss, occurs during the period of maximum rate of water loss, and was determined by taking the average rate between points ① and ② in Figure 6. These points were determined by constructing tangents to the curves and bisecting the resulting interior angles. The datum point of the moisture curve nearest to the bisector was taken as the end point. There is an error involved in estimating the tangent locations, but the average rate of water loss more nearly defines the actual drying process than does the absolute maximum rate of water loss. This is illustrated by data drawn from the autogenous curing experiment and is shown in Figures 7 and 8. These figures show the relationships between C and E, and D and F, respectively. The absolute rate is approximately twice the average rate, yet the average times of both rates of water loss are approximately the same. Consequently, the average maximum rate of water loss gives a more realistic picture of what is actually taking place.

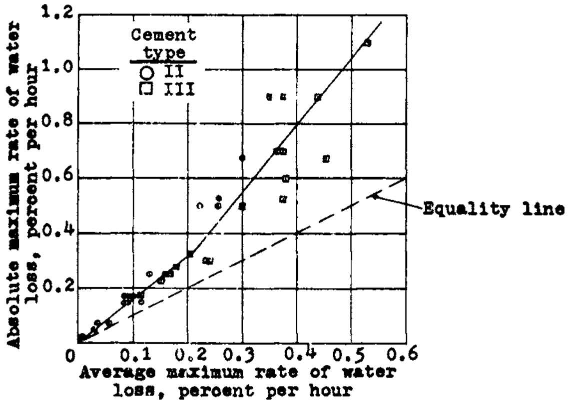

Figure 7. Relationship between absolute maximum rate of water loss and average maximum rate of water loss for several concretes with an initial mixture temperature of 70°F.

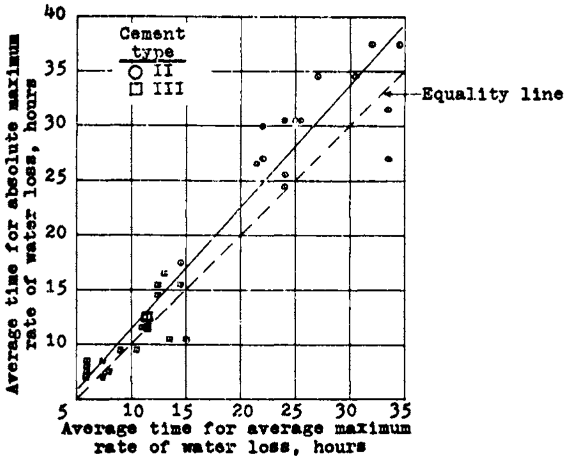

Figure 8. Relationship between average time of absolute maximum rate of water loss and average time of average maximum rate of water loss for several concretes with an initial mixture temperature of 70°F.

Table V lists the moisture, temperature, and strength parameters discussed in the remainder of this report. The moisture parameters were also plotted against all the temperature, maturity, and strength parameters listed in Part III of this report.(11)

TABLE V

MOISTURE, TEMPERATURE, AND STRENGTH PARAMETERS

Moisture Parameters

Total water lost, percent dry weight of concrete

Percent of total water lost by time of maximum autogenous temperature

Average maximum rate of water loss, percent per hour

Average time for average maximum rate of water loss, hours

Absolute maximum rate of water loss, percent per hour

Average time for average maximum rate of water loss, hours

Starting time for average maximum rate of water loss, hours

Temperature Parameters*

Maximum autogenous temperature (T), ^{o}F

Time to maximum autogenous temperature, hours

Autogenous temperature increase (+ΔT), ^{o}F

Initial rate of temperature rise, ^{o}F per hour

Total heat generated, ^{o}F x hr

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*These temperature parameters are presented in detail in Part III of this report.(11)

Strength Parameter

Autogenous cylinder strength, psi

Some combinations had no bearing on the nature of autogenous curing and therefore were not investigated. More than 300 relationships involving the moisture parameters were investigated, and only those relationships showing a high degree of correlation or having a noticeable influence on the moisture, temperature, and strength of autogenously cured concrete are discussed in the remainder of this report. Because many of the variables are interrelated, the discussion of results includes an evaluation of strength development as influenced by autogenous curing parameters. A full discussion of strength relationships is presented in Part I.(12)

RESULTS

Since many of the variables are interrelated, which makes it difficult to isolate completely one variable for discussion, the discussion of results has been divided into four categories. A more detailed discussion of the influence of moisture, temperature, and concrete mixture variables on the performance of the autogenous accelerated curing method is presented in reference 16.

Influence of Mixture Variables on Moisture Parameters

The curves shown in presenting the influence of mixture variables on moisture parameters represent the average values for each parameter. In Figures 9 through 13, each datum point represents an average value from 12 moisture gages for all admixtures and water-cement ratios.

Figure 9 shows the influence of the concrete mixture variables (cement type, water-cement ratio, and admixtures) on the total water lost during autogenous accelerated curing. The mixture variables showed marked effects on the total water lost. Of the two types of cements used, the total water lost for type III was affected the least by the admixtures and water-cement ratio. The effect of the water-cement ratio on total water lost was three times as great for type II cement as it was for type III, and the effect of admixtures was twice as great for type II as for type III.

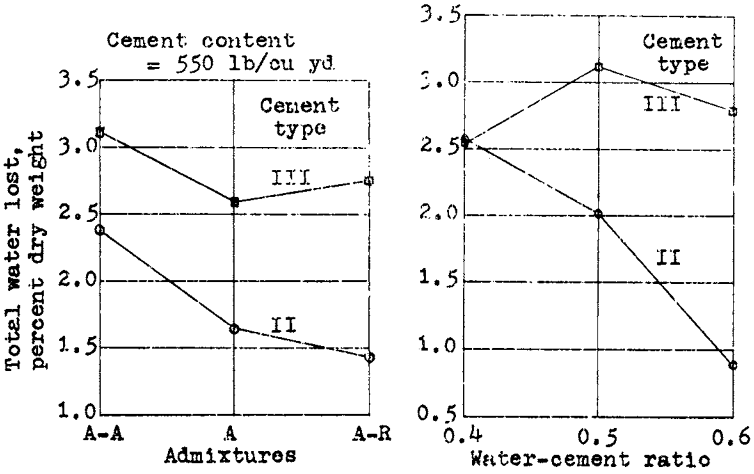

Figure 9. Influence of mixture variables on total water lost.

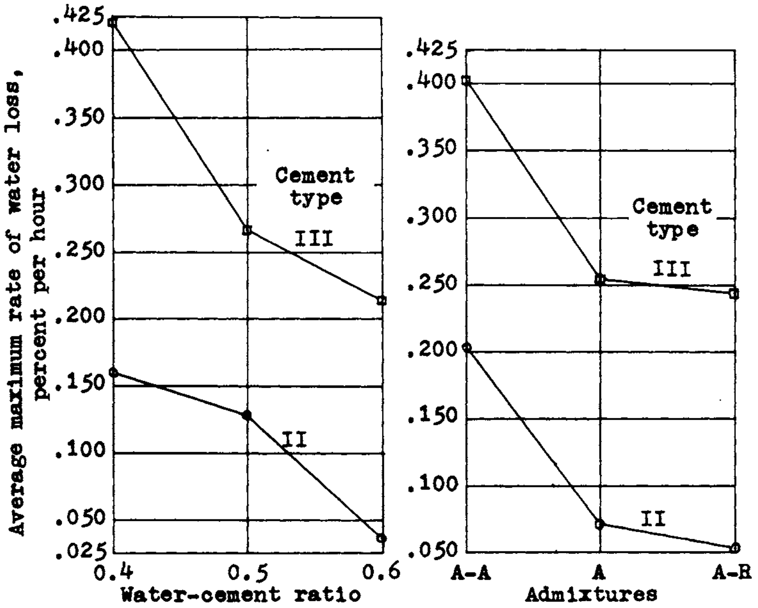

Figure 10. Influence of mixture variables on average maximum rate of water loss.

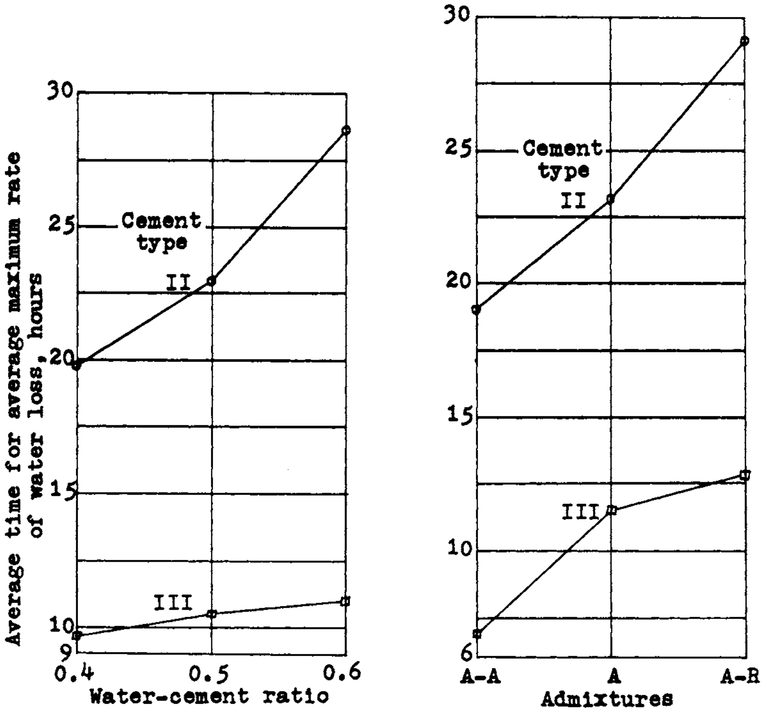

Figure 11. Influence of mixture variables on average time for average maximum rate of water loss.

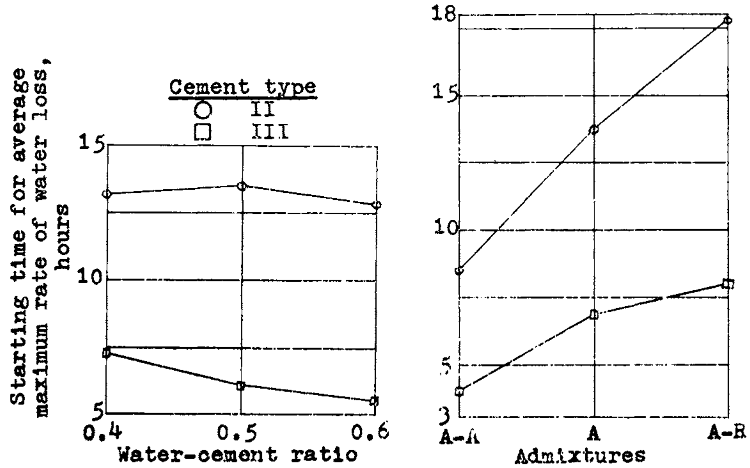

Figure 12. Influence of mixture variables on starting time for average maximum rate of water loss.

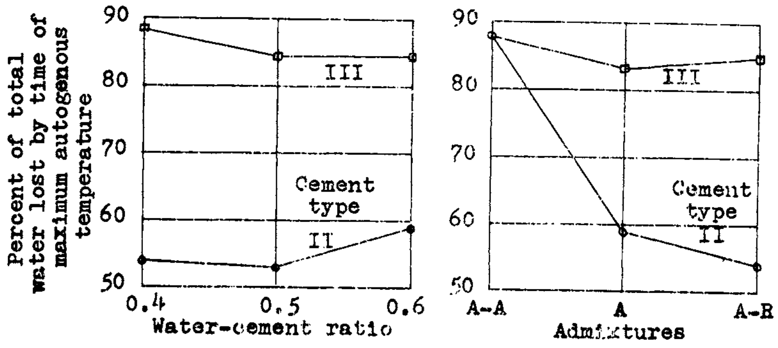

Figure 13. Influence of mixture variables on percent of total water lost by time of maximum autogenous temperature.

Figure 10 demonstrates the effect of mixture variables on the average maximum rate of water loss during autogenous accelerated curing. The cement type, water-cement ratio, and admixtures had greater effects on the rate of water loss (i.e., hydration) than on the total water lost. The effect of the water-cement ratio on the rate of water loss was twice as great for type III cement as for type II, and the effect of admixtures was the same for both cements.

As shown in Figures 9 and 10, the total water lost and the rate of water loss both decrease as the water-cement ratio increases. The total water lost and the rate of water loss both are measures of the process of cement hydration in that they represent the amount and rate of water fixation. The literature on the influence of water-cement ratio on the rate of cement hydration presents conflicting results as evidenced by the results presented by Kondo, Ueda, and others in the Proceedings of the Fifth International Symposium on the Chemistry of Cement.(18) Some researchers report that as the water-cement ratio increases the rate of hydration decreases, while others say the reverse is true.

Figure 11 shows the influence of the mixture variables on the average time for the average maximum rate of water loss. The water-cement ratio and admixtures have the same effects on the average time for the type II cement and include approximately the same range of time. For the type III cement, the water-cement ratio has very little effect on the average time, whereas the admixtures do show a sizeable effect on the average time which is consistent with their influence on setting time.

The influence of mixture variables on the starting time for the average maximum rate of water loss is presented in Figure 12. The water-cement ratio for either cement type has little effect on the starting time of the average rate of water loss. The effect of admixtures on the starting time is highly significant and is twice as great for the type II cement as for the type III. The starting times were delayed approximately 6 hours longer for the type II cement as compared with those for the type III cement.

Figure 13 shows the influence of mixture variables on the percent of total water lost by the time of maximum autogenous temperature. The water-cement ratio had little effect on the percent of total water lost; however, type II cement ranged between 50 and 60 percent total water lost, whereas type III cement ranged between 80 and 90 percent. Admixtures did show an appreciable effect on percent of total water lost for type II cement.

Movement of Moisture Within Cylinder

The loss of moisture by the moisture gage is a measure of the degree of fixation of water by the cement during the hydration process as discussed earlier.

There was very little, if any, movement of moisture between the top and bottom of the cylinders as measured by the gages. A total of 28 of the 52 (53 percent) cylinders instrumented showed a lower moisture content at the bottom of the cylinder than at the top at an age of 47 hours. Twenty-four cylinders (47 percent) had a lower moisture content at the top of the cylinders.

Any significance which could be attached to these percentages of 53 and 47 is minimized by the fact that 38 of the cylinders showed no differences in moisture between the top and bottom of each cylinder, based on the percent of moisture in each of the two moisture gages within a cylinder. These cylinders were rated for location of lower moisture content, dependent upon the resistance of the gages; if both gages showed a final moisture content of 2.40 percent (difference = 0) at 47 hours but the gages in the bottom and top had resistances of 150,000 ohms and 145,000 ohms, respectively, then the gage in the bottom was rated as being in a lower moisture state. (An example of a case such as this in which the resistances fell on the vertical portion of the calibration curve for the same percent water content is explained in Part II, of this report.(17)) The remaining 14 cylinders had the following distribution of moisture difference between the gages in the bottom and top of each cylinder:

Number of cylinders	Percent difference in moisture content
11	0.05% (0.014 pound water)
2	0.10% (0.028 pound water)
1	0.55% (0.150 pound water)

These 14 cylinders had an average difference in moisture content of 0.09 percent (0.025 pound water), which is also insignificant.

The largest number of actual differences in percent moisture content occurred at the time of maximum autogenous temperature: 26 cylinders showed a difference at this time, as compared with 14 cylinders at a lapsed time of 47 hours. The average percent difference was 0.11 percent (0.03 pound water), and again 53 percent of the cylinders had a lower moisture content in the bottom than in the top.

Subsequent to the determination of which moisture gage (top or bottom) for each cylinder had a lower moisture content after 47 hours of autogenous curing (the procedure just described), the state of moisture content for each cylinder was related to the concrete mixture variables. In relating mixture variables to the relative state of moisture within each cylinder, the degree of difference in moisture content between the gages in each cylinder was not considered. A cylinder either had a lower moisture in the bottom than in the top or vice versa. It was found that the cement type and admixture had very little effect on the trend in movement of moisture between the top and bottom of the autogenously cured cylinders and, as shown in Figure 14, the amount of moisture in the top of the cylinder, relative to that in the bottom, decreased as the water-cement ratio increased.

When considering the influence of the mixture variables on moisture movement, the reader should remember that the results showed no movement of moisture within the cylinders.

As discussed earlier, the moisture conductivity of concrete depends on its degree of hydration. As maturity increases, the number of capillary pores decreases and the number of gel pores increases. Therefore, the permeability and moisture conductivity decrease with time. The autogenous curing process accelerates maturity by approximately 70 percent of that obtained through normal 28-day moist curing.

In autogenous curing there is very little, if any, moisture loss by evaporation and, therefore, no moisture gradients except for variations in moisture movements within the concrete itself. The results of this investigation showed that moisture migration within the sealed cylinder did not occur. Since evaporation drying was not a factor in

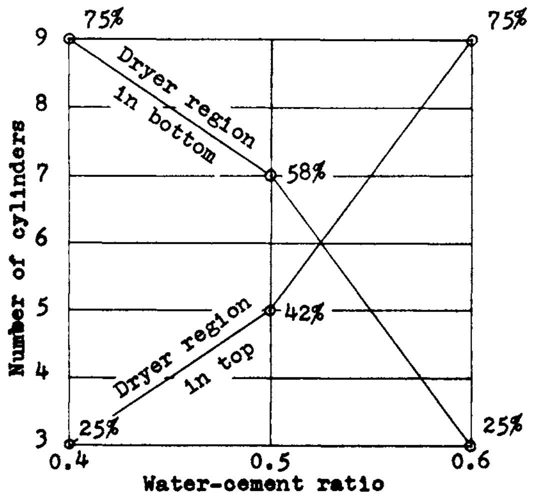

Figure 14. Frequency of dryer regions at 47 hours as influenced by water-cement ratio for an initial mixture temperature of 70°F.

autogenous curing, the only other mode of drying was that of fixation drying, which is the decrease in evaporable water content because of cement hydration, as discussed previously. In this investigation of autogenous curing the thermal gradients were minimal, which indicated a uniform hydration and/or subsequent water fixation.

The bleeding, or settlement of the solid components of concrete, results in a subsidence of the top surface of a concrete cylinder. The bleeding will continue until the paste has set sufficiently to stop the sedimentation process. As stated before, the maturity process was accelerated by approximately 70 percent; therefore, any bleeding tendencies were retarded at an early age. Powers(19) showed that the bleeding rate decreases rapidly above 81°F. In this study the maximum temperatures reached for the moisture cylinders ranged from 117°F to 137°F.

As a result of this study it was concluded, at least for the mixes investigated, that fixation drying was the cause of measurable moisture loss and that the fixation processes were uniform throughout the cylinder.

Moisture Parameter Relationships

This section pertains to the relationships between moisture parameters, without regard to mixture variables; only the cement types are identified in the figures.

Figure 15 demonstrates the relationship between the total water lost and the percent of total water lost by the time of maximum autogenous temperature. With respect to the percent of total water lost, the cylinders can be placed in two primary ranges, these being from 50 to 60 percent and from 80 to 90 percent. Out of a total of 52 cylinders, 26 were in the 80 to 89 percent range, 12 in the 50 to 59 percent range, 6 in the 90 to 99 percent range, 3 in the 70 to 79 percent range, 3 in the 60 to 69 percent range, and 2 in the 10 percent range.

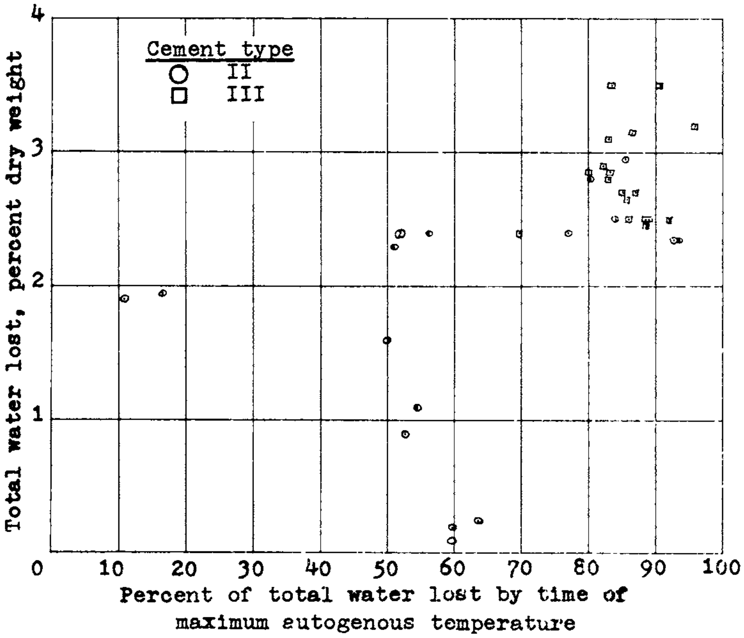

Figure 15. Relationship between total water lost and percent of total water lost by time of maximum autogenous temperature.

The range of total water lost for all cylinders was from 0.10 percent to 3.5 percent. In Figure 11, those points ranging from 50 to 60 percent were for type II cement and had a total water lost range from 0 to 2.4 percent, whereas the points in the 80 to 100 percent range were largely for type III cement and had a total water lost range from 2.4 to 3.5 percent. The reason that the percent of total water lost occurred in two primary groups (50 percent and 80 percent) is because of the interrelationship of the rate of water loss, the time at which maximum autogenous temperature occurred, and the total water lost. The total water lost and the rate of water loss determined the shape of the moisture-time curves, as was shown in Figure 5. The relationship between the curve shape and the time of maximum temperature causes the grouping of the data points in Figure 15. As the maximum autogenous temperature increased, the time required to reach maximum temperature decreased, and the rate of water loss and the average time at which the rate of water loss occurred combined in such a way that for lower maximum autogenous temperatures a larger percentage of the total water was lost before maximum temperature was reached, whereas, for higher maximum autogenous temperatures, the rate of water loss was slow, the maximum temperature was reached early, and the percentage of total water lost by the time of maximum temperature was low. The effect of temperature on the percent of total water lost is discussed in the next section.

The relationship between total water lost and the average maximum rate of water loss is shown in Figure 16. The total quantity of water lost, up to approximately 2.4 percent, had a small but directly proportional effect on the rate of water loss (0.031

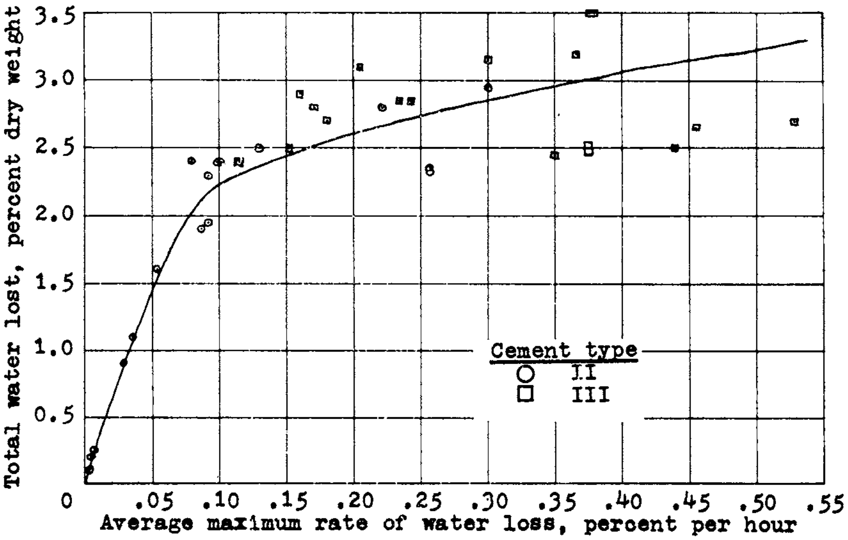

Figure 16. Relationship between total water lost and average maximum rate of water loss.

percent per hour per 1 percent increase in total water lost). Above 2.4 percent, small increases in total water lost drastically increased the rate of water loss (0.400 percent per hour per 1 percent increase in total water lost).

Figure 17 shows the relationship between the total water lost and the average time for average maximum rate of water loss. As the total water lost increases from 0.10 to 1.00 percent, the average time for the average rate of water loss increases rapidly. Between 1 and 2 percent total water lost, the average time is fairly constant; and for an increase in total water lost from 2.0 to 3.5 percent, the average time decreases rapidly. The reason for an average time having two total water lost values — for example, 0.15 percent and 2.4 percent for an average time of 24 hours — is that for these two total water lost values, the starting times for the average maximum rate of water loss are 1 hour and 15 hours, respectively, as shown in Figure 18. In Figure 18 the starting time increases up to a total water lost of 1.5 percent and then decreases as the total water lost increases to 3.5 percent.

Figure 19 displays the relationship between total water lost and autogenous strength. The effect of total water lost on strength was approximately 15 times as great for strengths between 3,000 and 5,500 psi than it was for strengths between 1,500 and 3,000 psi.

The relationship between the average maximum rate of water loss and the autogenous moisture cylinder strength is shown in Figure 20. The rate of water loss has less effect on strength than does the total water lost. Above 3,500 psi there is considerable difference in the slope of the curves in Figures 19 and 20. The moisture curves in

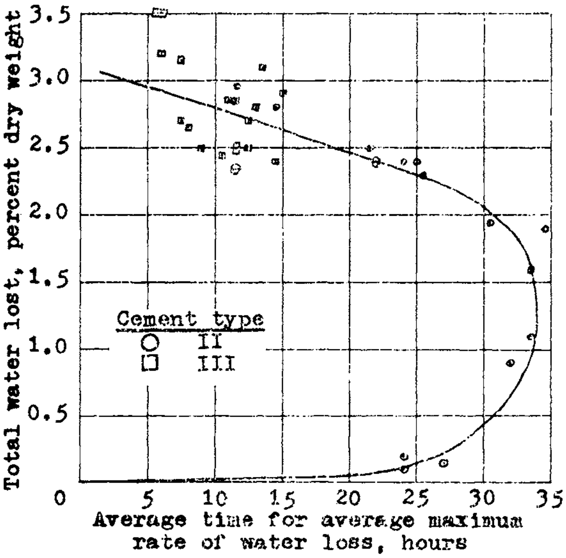

Figure 17. Relationship between total water lost and average time for average maximum rate of water loss.

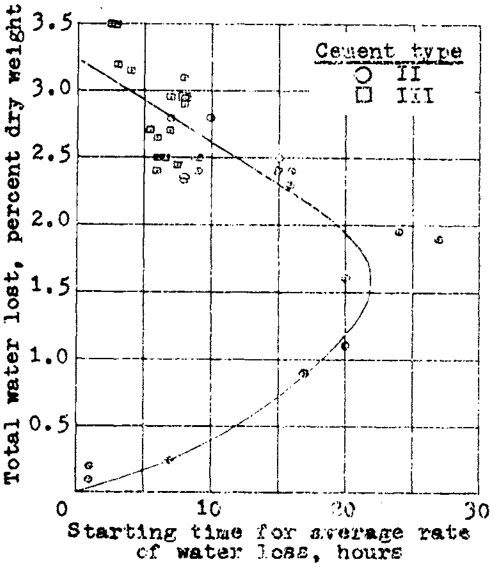

Figure. 18. Relationship between total water lost and starting time for average maximum rate of water loss.

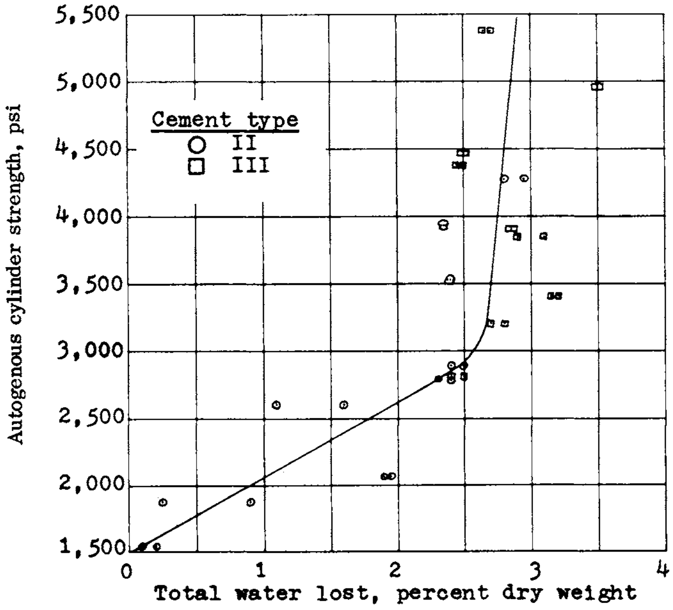

Figure 19. Relationship between total water lost and autogenous strength.

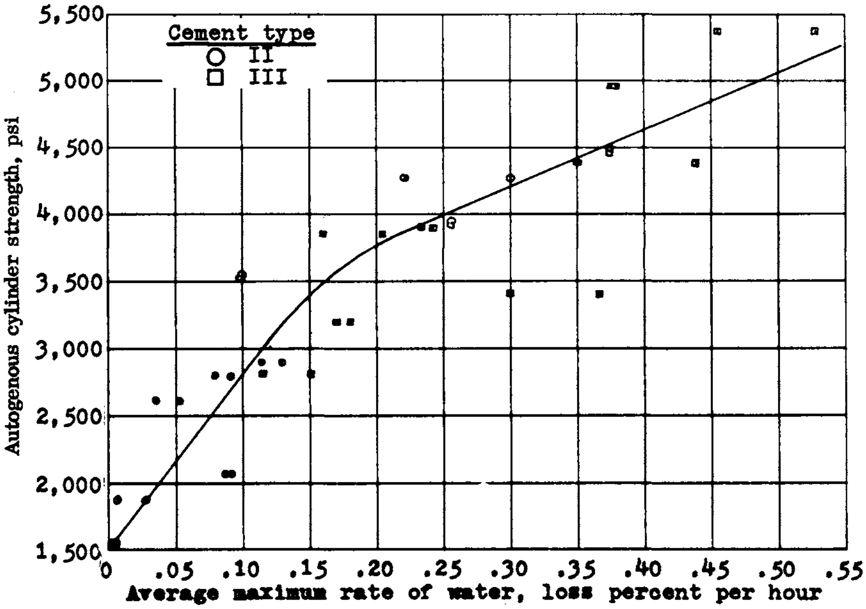

Figure 20. Relationship between average maximum rate of water loss and autogenous cylinder strengths.

Figure 5 showed that at 47 hours of autogenous curing the water loss became negligible, which indicated that the water loss process was completed relative to being stopped midway through the average maximum rate of water loss. Figure 15 shows that for the majority of the cylinders, more than 80 percent of the total water lost had been lost by the time that the maximum autogenous temperature had been reached. Therefore, the rate of water loss is not as important in autogenous strength development as is the total water lost, which is a measure of the degree of hydration.

Figure 21 shows the relationship between the average time for average maximum rate of water loss and autogenous cylinder strengths. This curve shows that the strength increases as the average time decreases and that the effect is generally the same for the whole strength range. The average times also occurred early enough in the 47 hours to allow the accelerated process to reach a maximum degree of completion.

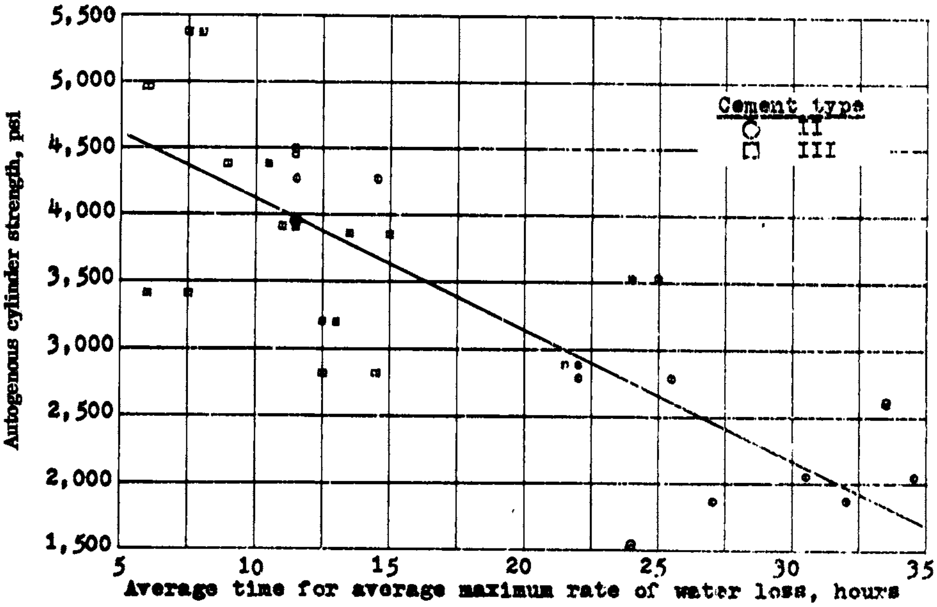

Figure 21. Relationship between average time for average maximum rate of water loss and autogenous cylinder strengths.

Figures 22 and 23 present the relationships between the average time of occurrence and the average and absolute maximum rates of water loss, respectively. When these two curves are compared, it can be seen that the scatter of data points about the curve of the average maximum rate of water loss (Figure 22) is less than for the absolute maximum rate curve (Figure 23). Therefore, the average maximum rate of water loss is a better representation of the actual fixation-drying process taking place. The time at which either maximum rate of water loss occurs has little effect on the rate in the time interval from 15 to 35 hours but has a pronounced effect on the rate for the interval between 5 and 15 hours. The average maximum rates ranged from 0.004 percent per hour to 0.550 percent per hour, whereas the absolute maximum rates ranged from 0.025 percent per hour to 1.100 percent per hour.

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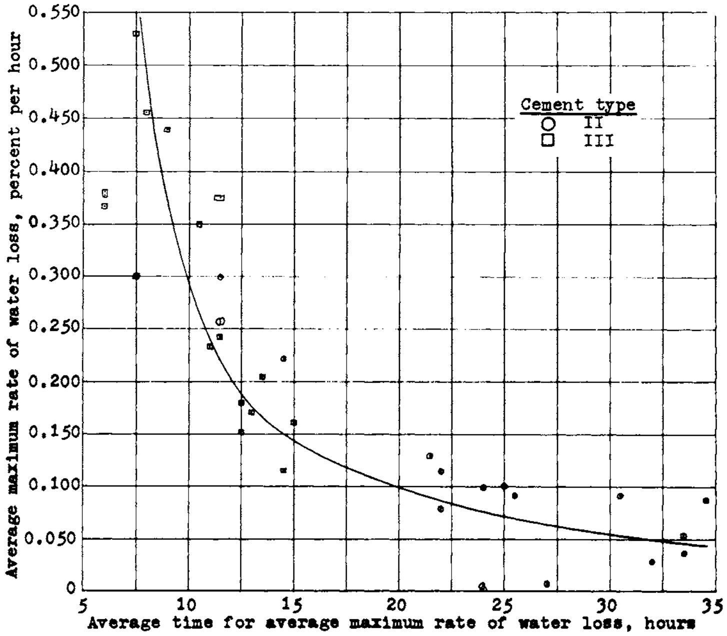

Figure 22. Relationship between average time for average maximum rate of water loss and average maximum rate of water loss.

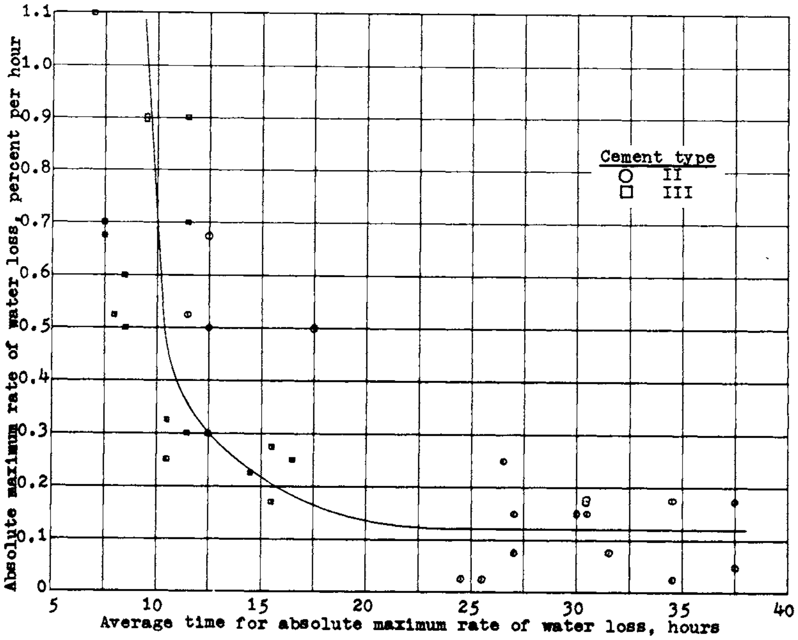

Figure 23. Relationship between average time for absolute maximum rate of water loss and absolute maximum rate of water loss.

Moisture-Temperature Relationships

This section deals with the relationships between temperature parameters and moisture parameters. Each datum point in Figures 24 through 34 represents the average of two values.

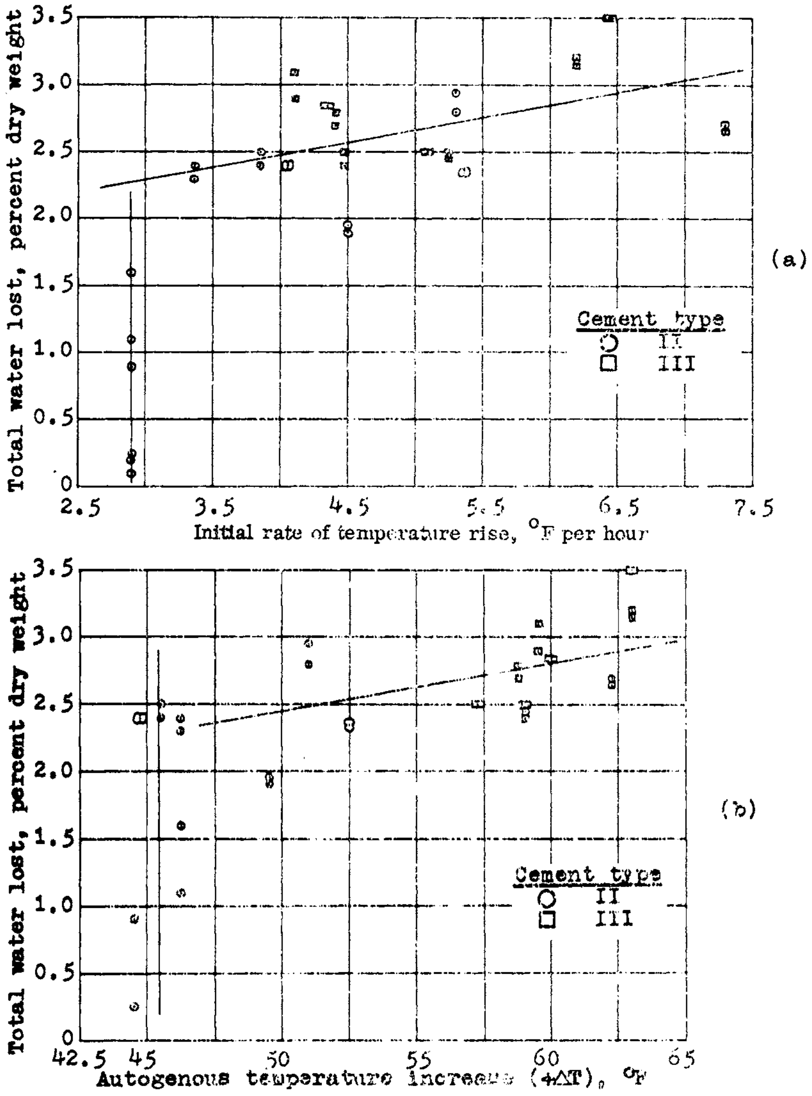

Figure 24. Total water lost plotted against initial rate of temperature rise and autogenous temperature increase for an initial mixture temperature of 70°F.

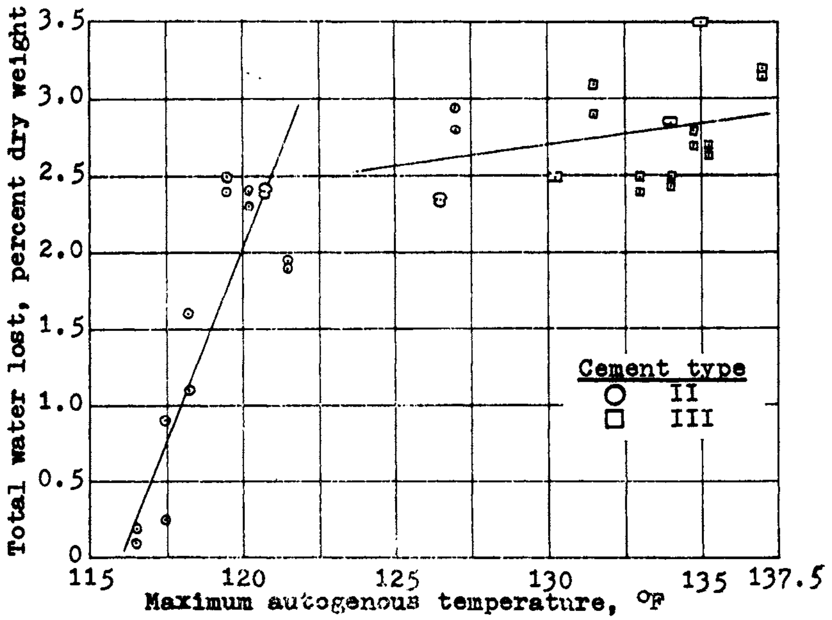

Figure 25. Total water lost plotted against maximum autogenous temperature for an initial mixture temperature of 70°F.

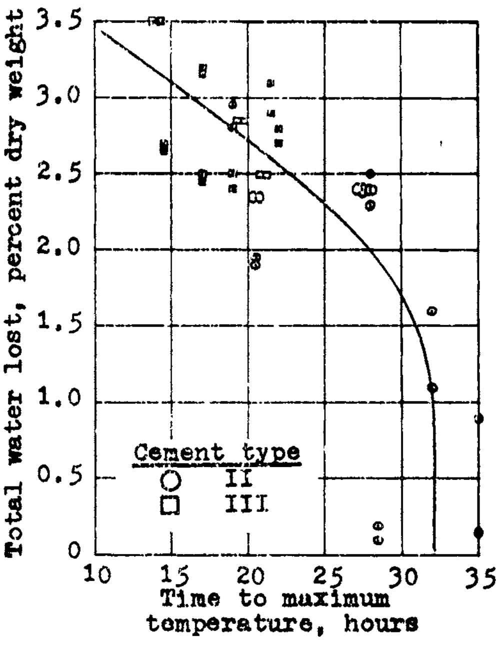

Figure 26. Relationship between total water lost and time to maximum temperature for an initial mixture temperature of 70°F.

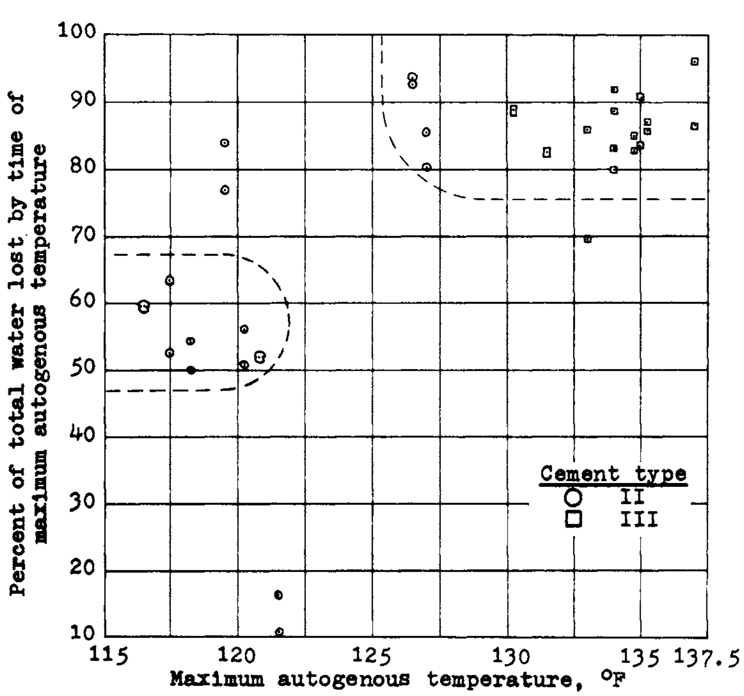

Figure 27. Relationship between percent of total water lost by time of maximum autogenous temperature and maximum autogenous temperature for an initial mixture temperature of 70°F.

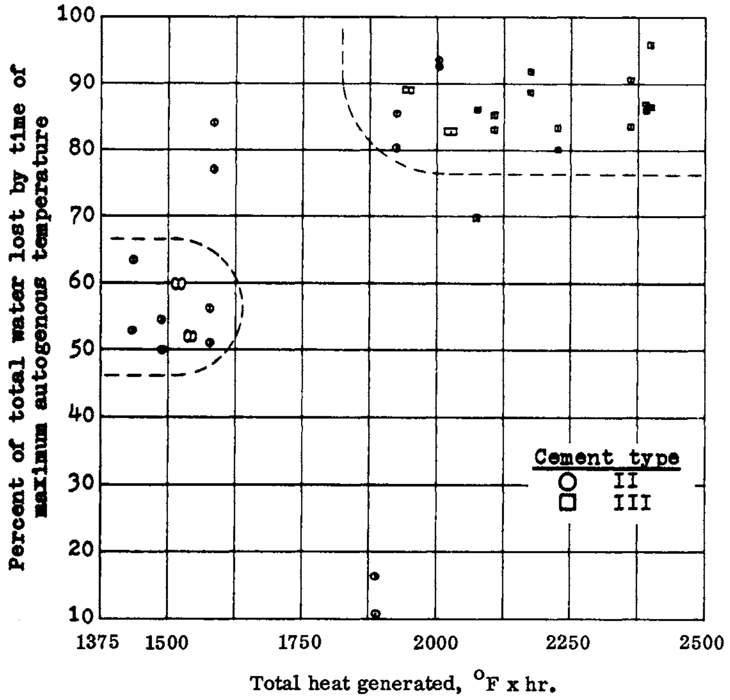

Figure 28. Relationship between percent of total water lost by time of maximum autogenous temperature and total heat generated for an initial mixture temperature of 70°F.

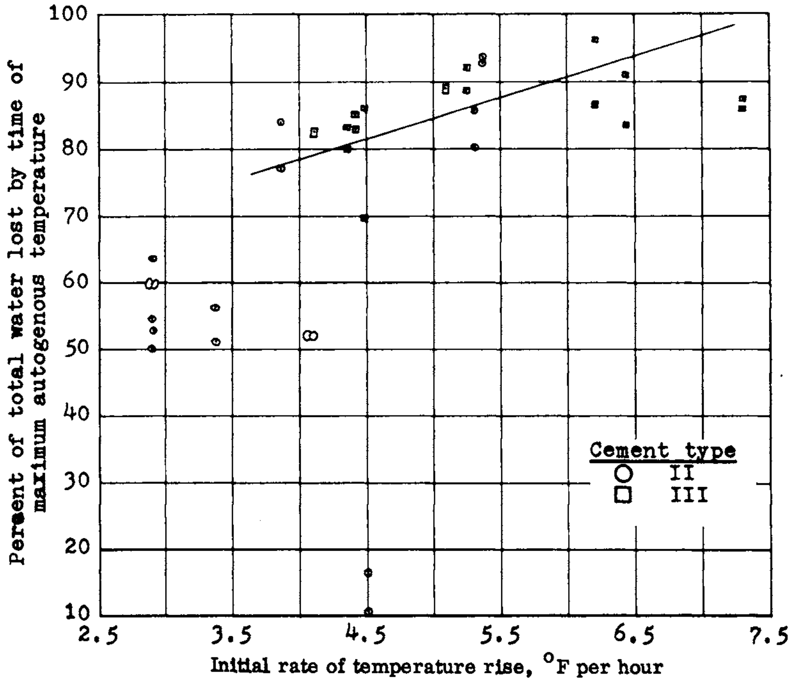

Figure 29. Relationship between percent of total water lost by time of maximum autogenous temperature and initial rate of temperature rise for an initial mixture temperature of 70°F.

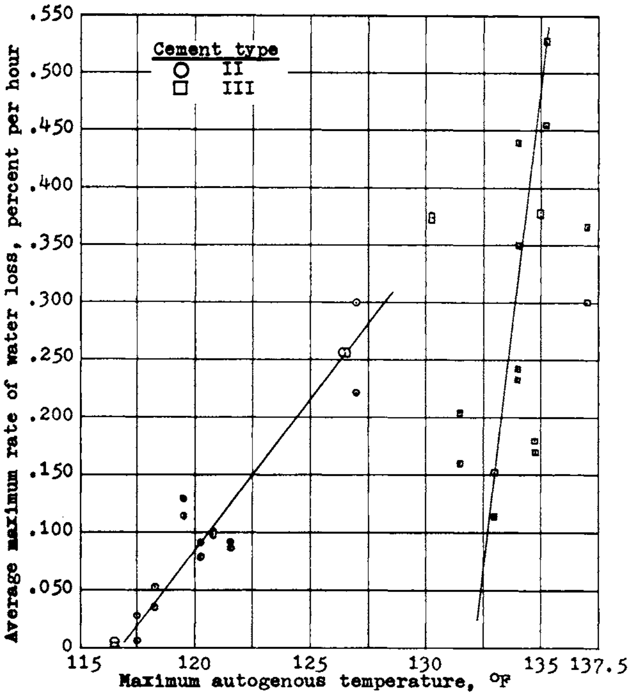

Figure 30. Relationship between average maximum rate of water loss and maximum autogenous temperature for an initial mixture temperature of 70°F.

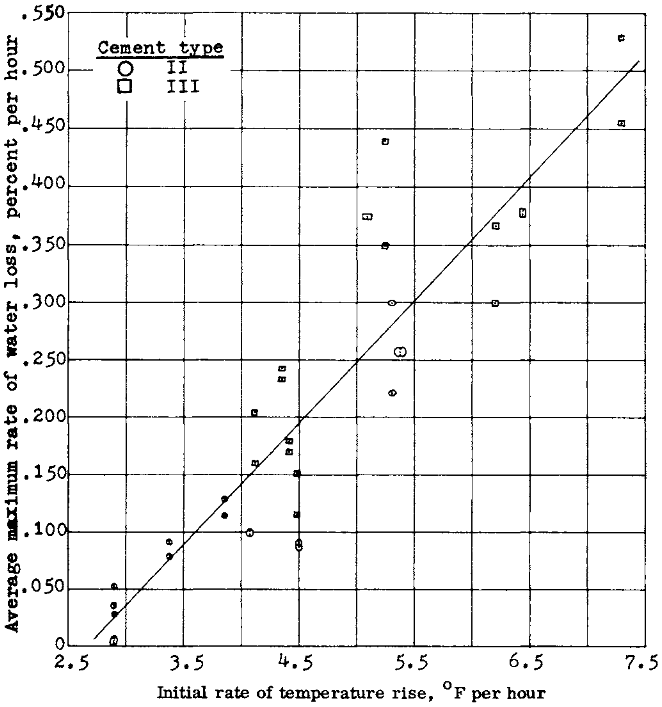

Figure 31. Relationship between average maximum rate of water loss and initial rate of temperature rise for an initial mixture temperature of 70°F.

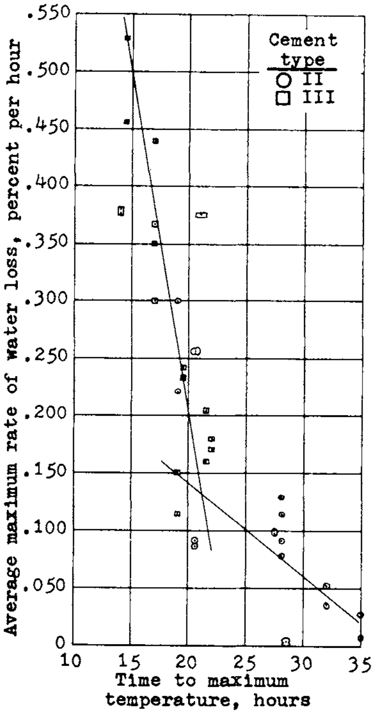

Figure 32. Relationship between average maximum rate of water loss and time to maximum temperature for an initial mixture temperature of 70°F.

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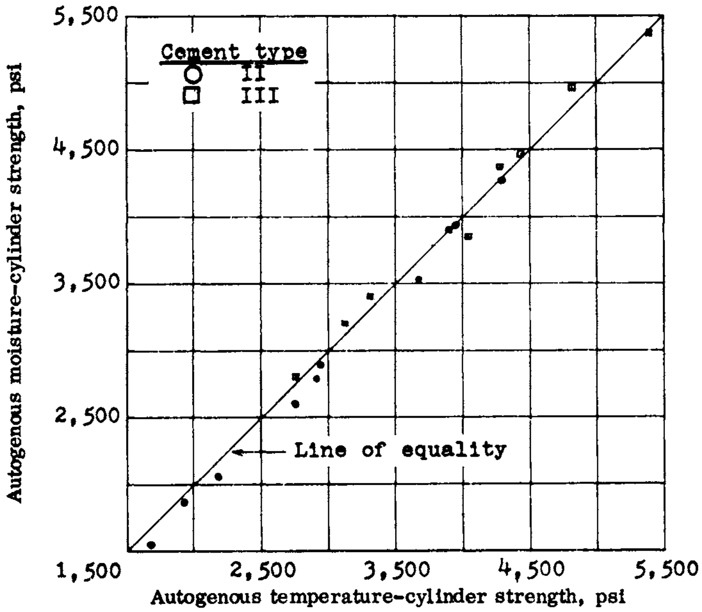

Figure 33. Relationship between autogenous moisture-cylinder strength and autogenous temperature-cylinder strength for an initial mixture temperature of 70°F.

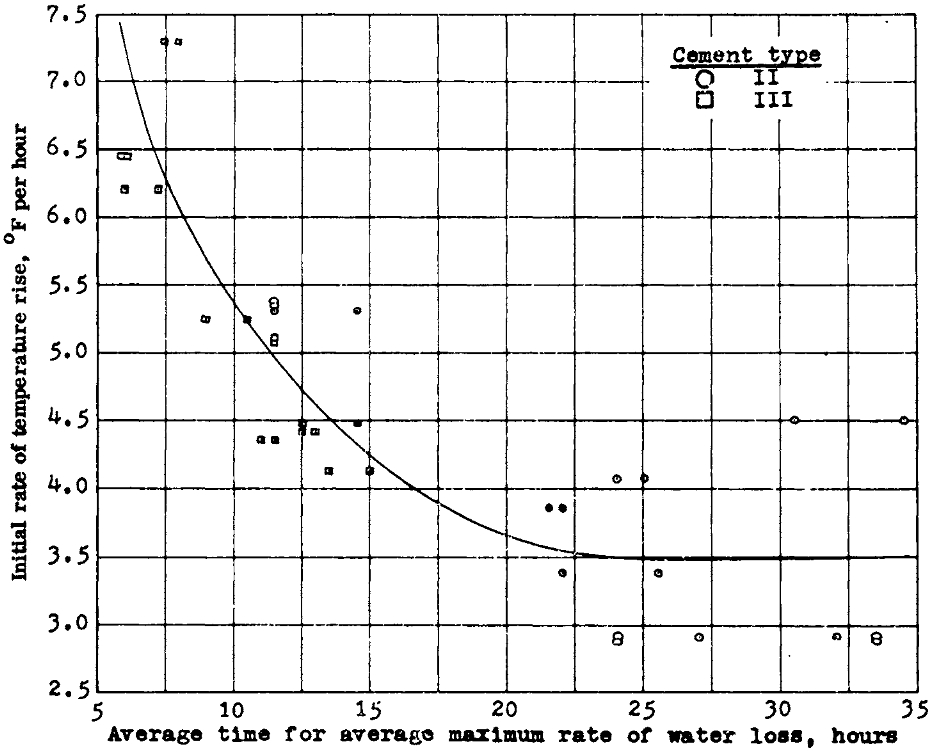

Figure 34. Relationship between average time for average maximum rate of water loss and initial rate of temperature rise for an initial mixture temperature of 70°F.

Figures 24 through 26 display the relationships between the total water lost and the temperature parameters. The relationships between the total water lost and the initial rate of temperature rise (Figure 24(a)) and the autogenous temperature increase (Figure 24(b)) are almost identical. As the total water lost decreases from 3.5 to approximately 2.3 percent, the initial rate of temperature rise and the autogenous temperature increase both decrease. Below this point, however, the relationship between total water lost and the two temperature variables is less certain. It appears that the initial rate of temperature rise and the autogenous temperature increase both decrease much more rapidly as total water lost decreases from 2.3 percent to zero.

A similar relationship exists between the total water lost and the maximum autogenous temperature (Figure 25) as was developed in Figure 24. In Figure 25 as the total water lost decreases from 3.5 to approximately 2.3 percent, the maximum autogenous temperature decreases. Below this point, however, it appears that the maximum autogenous temperature decreases much more rapidly as total water lost decreases from 2.3 percent to zero. The relationship between the total water lost and autogenous temperature increase was very similar to that shown in Figure 25.

The vertical portions of the curves in Figures 24 and 25 were expected since a certain quantity of water must be lost regardless of the rate of temperature rise. In Figure 24(a), for instance, the four data points on the low end of the vertical line are for a water-cement ratio of 0.6. The upper two points are for a water-cement ratio of 0.5. The lower two points represent cylinders that were air entrained only, whereas the upper four points represent cylinders that were also retarded. The combined effects of admixtures and water-cement ratio on the rate of temperature rise is shown in Figure 24(a) by the data points for a rate of temperature rise of 3.5°F per hour and those at a total water lost of 1.90 and 1.95 percent having a water-cement ratio of 0.5 and 0.6, respectively, and admixtures of air only and air plus accelerator, respectively.

Figure 26 displays the relationship between the total water lost and the time to maximum temperature. The type III cement has a short time to maximum temperature and a high percent of total water lost resulting from the rapid hydration reactions.

Figures 27 through 29 show the relationships between the percent of total water lost by the time of maximum autogenous temperature and the temperature parameters. In Figures 27 and 28, the influence of maximum temperature and total heat generated on the percent of total water lost by the time of maximum temperature is generally the same. The influence of the autogenous temperature increase ($+\Delta T$) on the percent of total water lost by the time of maximum temperature was the same as shown in Figure 27. High maximum temperatures (Figure 27) and large temperature increases (not shown) were partially responsible for the groupings of the data points in the 80 to 100 percent range of total water lost by the time of maximum temperature. The other factors influencing the grouping of the data were the rate of water loss and the time at which water loss occurred. Since the majority of the total water lost was lost by the time of maximum temperature, the effect of the total heat generated (Figure 28) resulted in the same tight grouping of data points as in Figure 27, even though the total heat generated included hydration reactions that occurred after the maximum autogenous temperature was reached.

The relationship between the percent of total water lost by the time of maximum temperature and the initial rate of temperature rise is shown in Figure 29. The initial rate of temperature rise had little influence on the percent of total water lost in the 50 to 60 percent range but did have an influence in the 80 to 100 percent range.

Figures 30 through 32 show the relationships between the average maximum rate of water loss and the temperature parameters. The influence of the maximum autogenous temperature (Figure 30) and the autogenous temperature increase (not shown) on the rate of water loss is approximately the same. The influence of these two temperature parameters is dependent upon the cement type, with type III resulting in a greater influence on the rate of water loss than type II cement.

The influence of the initial rate of temperature rise on the rate of water loss was generally the same for both cement types, as shown in Figure 31. As the rate of temperature rise increased, the rate of water loss increased, and the slope of the curve appears to be constant over the entire range of initial temperature rise.

Figure 32 shows that as the time to maximum temperature decreased the average maximum rate of water loss increased. The influence of the time to maximum temperature on the rate of water loss for the type III cement was approximately four times as great as for the type II cement.

Since strength is influenced by so many variables and is an indicator of quality and control, the data in Figure 33 are shown to establish the absence of variability between the moisture and temperature instrumented concrete cylinders. (These cylinders were instrumented differently.) The correlation coefficient for the data presented is 0.996, the standard error is 94.8 psi.

The average time for the average maximum rate of water loss is independent of the initial rate of temperature rise (Figure 34) for times greater than approximately 20 hours, and for the same reasons that applied to the relationships in Figures 24, 25, and 26. For times between 5 hours and 15 hours the average time is related to the initial rate of temperature rise. This relationship is very similar to that shown in Figure 22.

OBSERVATIONS AND CONCLUSIONS

1. Use of the Bouyoucos moisture gage was a satisfactory method of measuring moisture in the concrete cylinders used in this investigation.

2. Of the 52 cylinders instrumented for moisture measurements, 38 showed no differences in moisture between the top and bottom, based on the percent of moisture in each of the two gages within a cylinder at 47 hours. The remaining 14 cylinders had the following distribution of moisture difference between the gages in the top and bottom

Number of cylinders	Percent difference in moisture content
11	0.05% (0.014 pound water)
2	0.10% (0.028 pound water)
1	0.55% (0.150 pound water)

3. There was no measureable movement of moisture between the top and bottom of the 6-inch diameter by 12-inch high autogenously cured concrete cylinders investigated.

4. The measured moisture loss during autogenous curing was due to water fixation, which is the decrease in the evaporable water content because of cement hydration.

5. Since there was no movement of moisture within the cylinder and since autogenous cylinder temperature gradients were minimal, it follows that the water fixation processes were uniform throughout the cylinder.

6. As the average maximum rate of water loss increases from zero to approximately 0.10, the total water lost increases rapidly. Beyond this point, however, the total water lost increases at a much slower rate as the average maximum rate of water loss increases.

7. As the total water lost increased, the average time for the average maximum rate of water loss increased to a value of 34 hours for a total water lost value of 1.5 percent; then the average time decreased for further increases in total water lost. This same phenomenon also occurred for the starting time for the average maximum rate of water loss.

8. As the total water lost increased, the autogenous strength increased. The increase was much more rapid for strengths above 3,000 psi than it was for those below 3,000 psi.

9. As the maximum autogenous temperature, autogenous temperature increase $(+\Delta T)$, and total heat generated increased, the percent of total water lost by the time of maximum autogenous temperature increased. In general, type II cements resulted in 50 to 60 percent of the total water lost being lost by the time of maximum autogenous temperature, and type III resulted in 80 to 100 percent being lost by the time of maximum autogenous temperature.

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APPENDIX A

EXPERIMENTAL TEST MATERIALS

Cements

In order to provide a range of heat liberation during curing, three types of portland cement were used in this experiment. One of the three cements met each of the specifications for types II, III, or V portland cement as set forth in ASTM C 150-68.(14)

Heat evolution tests were conducted by the Portland Cement Association on all three cements at temperatures of 50°F, 70°F, and 90°F using a conduction calorimeter,(20) and the results of these tests are presented in Part I of this report.(12)

Admixtures

The air-entraining agent was commercially marketed neutralized vinsol resin conforming to ASTM C 260.(14)

The retarding admixture was a water-reducing, retarding, non-air-entraining, metallic salt of hydroxylated carboxylic acid conforming to ASTM C 494, Type D.(14)

Calcium chloride ($CaCl_2$) flakes conforming to ASTM C 494, Type E and ASTM D98, Type 1, were used as the accelerator.

Water

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

Aggregates

A crushed granite gneiss having a maximum size of 1 inch was used as coarse aggregate. The same type of aggregate, graded artificially, was used throughout the experiment. The coarse aggregate gradation was in conformance with ASTM standard C 136-67.(14)

The fine aggregate was a washed, natural silica sand conforming to ASTM standard C 33-67.(14) The same type and gradation of fine aggregate was used for the entire project.

A more detailed discussion of the experimental test materials is presented in Part I of this report.(12)

APPENDIX B

CONCRETE MIXTURE SCHEDULES

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

The constants in Phase I were

Initial mixture temperature = 73°F

Slump = 2 to 3 inches

Air content = 5 to 6 percent

The mixture schedules for Phase I are given in Table A-I.

TABLE A-I

MIXTURE SCHEDULES FOR PHASE I

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

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

The constants in Phase II were:

Initial mixture temperature = 73°F

Cement factor = 550 lb/cu yd

Air content = 5 to 6 percent

The mixture schedules for Phase II are given in Table A-II.

TABLE A-II
MIXTURE SCHEDULES FOR PHASE II

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

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

The constants in Phase III were

Water-cement ratio = 0.5
Admixture = Air only
Air content = 5 to 6 percent

The mixture schedules for Phase III are given in Table A-III.

TABLE A-III

MIXTURE SCHEDULES FOR PHASE III

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

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

A more detailed discussion of the concrete mixture schedules is presented in Part I of this report.(12) Also presented in Part I is a discussion of the specimen preparation schedules for the three phases of the experiment.