Materials Department
Iowa State Highway Commission
Ames, Iowa

STEAM CURING OF PORTLAND CEMENT CONCRETE AT ATMOSPHERIC PRESSURE

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INTRODUCTION

The primary reason for using steam in the curing of concrete is to produce a high early strength. This high early strength is very desirable to the manufacturers of precast and prestressed concrete units, which often require expensive forms or stress beds. They want to remove the forms and move the units to storage yards as soon as possible. The minimum time between casting and moving the units is usually governed by the strength of the concrete. Steam curing accelerates the gain in strength at early ages, but the uncontrolled use of steam may seriously affect the growth in strength at later ages.

The research described in this report was prompted by the need to establish realistic controls and specifications for the steam curing of pretensioned, prestressed concrete bridge beams and concrete culvert pipe manufactured in central plants. The complete project encompasses a series of laboratory and field investigations conducted over a period of approximately three years.

The purpose of the laboratory investigations was to determine some of the relationships between the development of concrete strength and various details of the steam curing procedure. The points of initial concern were:

1. The time delay between the mixing of the concrete and the beginning of steam curing.
2. The rate of temperature rise of the concrete during steam curing.

3. The highest temperature attained by the concrete during steam curing.

4. The length of time for which steam curing is continued.

The work of investigating these items was performed in seven laboratory series and one field series. The specific purpose of each series is as follows:

Series I - Minimum Control

The steam curing procedure used in Series I shows the effect of the minimum control situation. Three steam curing periods and five different steam curing temperatures were investigated. These were as follows:

Time	Temperature
18 hr.	100 F.
42 hr.	125 F.
66 hr.	150 F.
	175 F.
	200 F.

Series II - Maximum Control

In order to obtain maximum control over the steam curing procedure it is necessary to specify limits for the following variables.

1. Duration of steam curing
2. Maximum curing temperature
3. Time between mixing of the concrete and beginning of steam curing (delay time)
4. Maximum rate of temperature increase
5. Maximum rate of temperature decrease

In Series I the first two variables were investigated. Series II A is concerned with the effect of the rate of temperature decrease, and Series II B with the effect of delay time. In Series II C, the effect of the last four variables was investigated for one steam curing period.

Series III
Two Cements and Two Aggregates

This series was set up to determine whether or not the steam curing procedures might need to be changed if the brand of cement or aggregate used were changed. Two brands of cement and two types of coarse aggregate commonly used in Iowa were investigated.

Series IV - Water-Cement Ratio

It is generally accepted that an increased water-cement ratio results in a decreased compressive strength. This series was set up to determine what different effect, if any, an increase in mixing water might have upon concrete subjected to conditions of steam curing.

Series V
Development of Strength in Steam Cured Concrete

This series was set up to study the effect of steam curing upon concrete at several ages up to one year. Specimens were cured at three temperatures - 150 F, 175 F, and 200 F. They were tested at four ages - 28 days, 90 days, 180 days, and 365 days.

Series VI

Molds for Concrete Test Specimens

In order to overcome the capping problem, personnel in the Materials Department Laboratory developed a horizontal steel mold with machined end plates which form the ends of the specimen. Test specimens made in these molds do not require capping.

Series VI was a laboratory investigation made for the purpose of comparing the strength of concrete as determined from test specimens made in the following four types of molds:

4½ by 9 inch Vertical
4½ by 9 inch Horizontal
6 by 12 inch Vertical
6 by 12 inch Horizontal

Series VII
Temperature of Concrete When Tested

At a prestressed concrete plant the test specimens are cured with the beams, and they are not removed from the steam curing until immediately before they are to be tested. This means that the concrete specimens may have a temperature of almost 150 F when tested. This series was set up to determine what effect on strength might be expected at this high temperature.

Series VIII - Field Studies

Series VIII was set up to study the steam curing procedures in use in two commercial plants, and to determine the type and degree of control that would be feasible for field work, to determine the degree of uniformity of test results that might be expected, to study the inspection problems peculiar to steam cured, precast concrete construction, and to find solutions to these problems.

GENERAL CONCLUSIONS

Specific conclusions concerning particular details of steam curing procedure are to be found with the test data for each series. The general conclusions obtained from the project as a whole can best be summarized by the requirements for the steam curing of precast concrete units as stated in the 1960 Standard Specifications of the Iowa State Highway Commission. The pertinent part of this specification is as follows:

> "The initial temperature of the concrete shall not be raised above 100 F for a minimum of two hours after the units have been cast. After the two hour period, the temperature of the concrete may be raised to a maximum temperature of 150 F in increments not to exceed 25 F per hour. The maximum temperature shall be held for a period sufficient to develop the required strengths as specified in 2407.05 (Prestressed Units:4500 psi). The units shall be cooled in increments not to exceed 20 F per hour by reducing the amount of heat applied. In all cases, the units shall be kept covered for a minimum period of 24 hours after casting . . . After the units have been removed from the casting bed, they shall be protected as necessary to avoid cooling at a rate greater than 20 F per hour."

This specification contains a safety factor. Under controlled conditions in the laboratory it was found that a curing temperature of 175 F is not harmful to the concrete, and that the rate of temperature rise after two hours may safely be as much as 50 F per hour.

The specification takes into account the difficulty of obtaining the same accuracy of temperature control in the manufacturing plant as can be obtained in the laboratory. This does not imply a criticism of the methods or workmanship to be found in precast concrete plants.

GENERAL PROCEDURE

Each test series is reported separately in this report. Details concerning the materials and procedures are presented with the test data for each individual series. The following information relates to the entire project.

1. All of the materials used in this project complied with the Standard Specifications of the Iowa State Highway Commission.
2. The value of a particular steam curing procedure was judged principally on the basis of the compressive strength of concrete at age one day and at age 28 days.
3. Steam curing in the laboratory was done in a concrete block enclosure in which the temperature was automatically controlled to within 1 F. of the intended temperature. The rate of temperature rise was controlled within 4 F. per hour. The temperature of the atmosphere inside the steam chamber and of the concrete specimens was determined by thermocouples and was automatically recorded every 6 minutes.
4. Unless otherwise specified, control specimens prepared in the laboratory were cured in a standard moist room maintained at 100 per cent humidity and 73.4 F $\pm$ 3 F.

5. For this project the important variables were considered to be curing temperature, delay time, and the rate of temperature rise. In the laboratory tests, steam curing time did not exceed 18 hours, except in Series I.

6. During this project extra effort was made to cast uniform specimens. A standard was devised for casting the specimens and was as follows:
   Vertical Molds: Fill mold in three equal lifts, rod each lift 25 times with a 5/8 inch, rounded nose, steel rod. After each lift has been rodded, hammer two sides of the mold five blows each with a rubber mallet. Finish top with a minimum of troweling.
   Horizontal Molds: Fill mold in two equal lifts, rod each lift 25 times with a 1 inch, rounded nose, wooden rod. Hammer the ends and two sides of the mold 15 blows each with a rubber mallet. Finish top with a minimum of troweling.

7. In the laboratory series, where vertical molds were used, the one, two, and three day specimens were capped with sulphur. Specimens tested at later ages were capped with neat cement.

EQUIPMENT

The major items of equipment used in the laboratory and field experiments are described in the following:

Steam Chamber: This is a concrete block enclosure with a concrete slab roof and floor. The interior is approximately 3 ft. by 5 ft. in area, and 4 ft. high. It has a 3 ft. by 3 ft.

tight fitting door on one side. The inside is lined with a hard asphalt cement. Steam may be introduced through a coil of copper tubing with small holes drilled at regular spacing, and water is removed through a drain in the floor.

Steam Controls: The temperature of the chamber was controlled to within 1 F. by means of a temperature sensitive valve and thermostat. These controls are from the Johnson Service Company, Series 800. It is operated by air pressure from an outside source. With this valve, the temperature of the steam chamber could be controlled to any desired temperature from 100 F. to 240 F.

The rate of temperature rise was controlled by a pressure regulator from the Fisher Governor Company. This regulator is just ahead of the temperature sensitive valve. The rate of temperature rise could be controlled by varying the outlet pressure to within 4 F/hr. of the rate desired. The pressure used depended on the rate of temperature rise desired and the load in the steam chamber.

Steam Generator: Steam was generated in an automatic boiler fitted with a pressure regulator. This boiler was manufactured by the Lattner Company and rated at 3HP. Normally the boiler was operated with an internal pressure of approximately 8 psi.

Mixer: Laboratory specimens were prepared in a Type SKG Lancaster batch mixer with counter current mixing. This mixer has a capacity of a 300 lb. batch.

Temperature Recording Device: A 12 channel Brown potentiometer was used which recorded the temperature of each of 12 locations every 6 minutes on a strip chart.

Testing Machine: All the specimens cast in the laboratory series and part of the specimens cast in the field studies were tested on a 400,000 lb. compression testing machine. The remaining specimens were tested in the field on a semi-portable 200,000 lb. compression testing machine.

Molds: All the specimens made in the laboratory, except Series VI, were cast in vertical 6 by 12 inch molds. These molds were made from seamless steel tube, and were mounted on machined, cast iron base plates. All specimens made in the field were cast in horizontal 6 by 12 inch molds. These molds were made from seamless steel tube, and were fitted with a machined, cast iron plate on each end.

Fig. 1

Inside of Steam Chamber

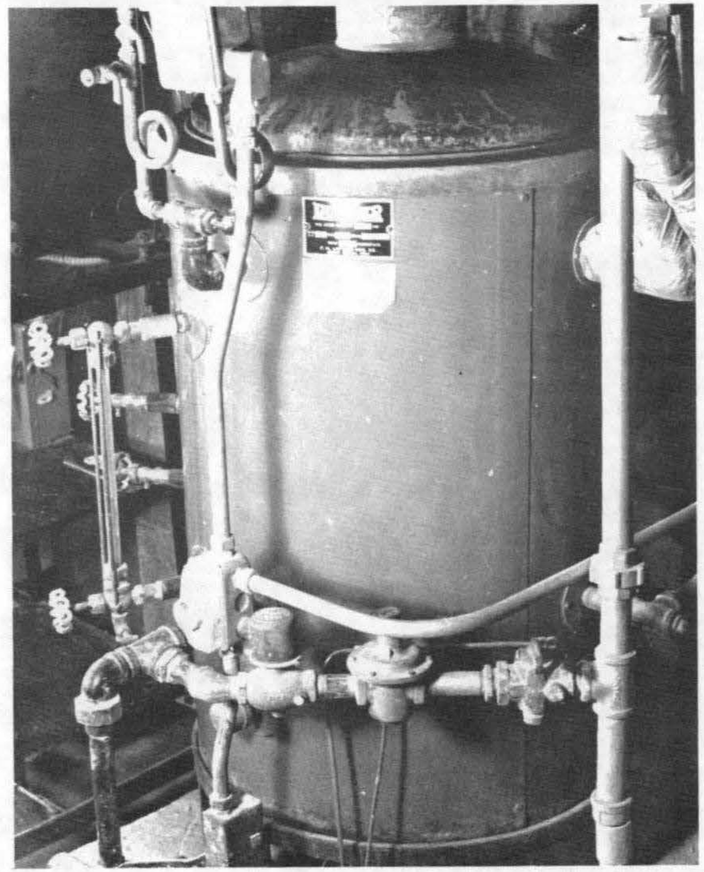


Fig. 2

Boiler and Boiler Controls

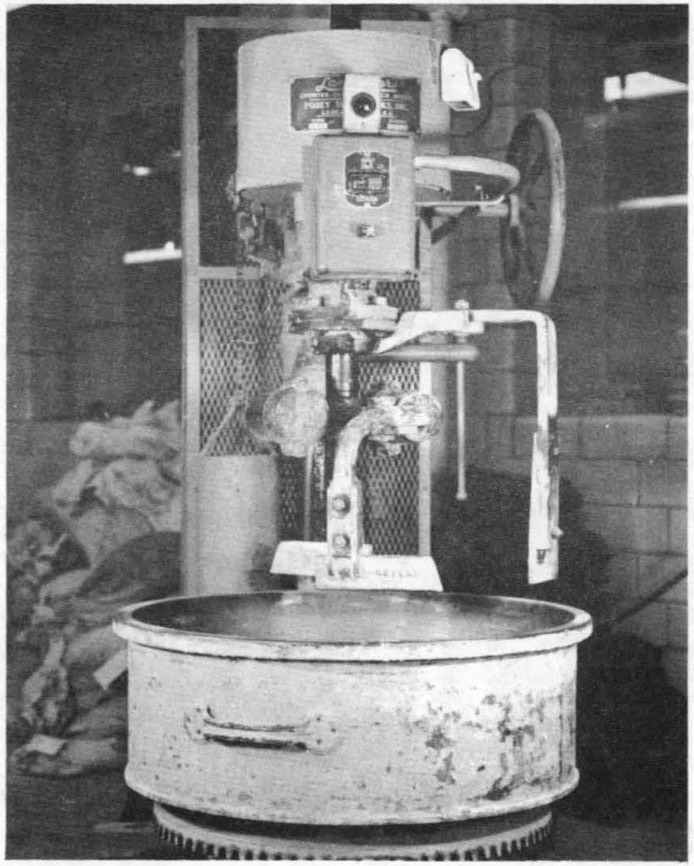


Fig. 3

Laboratory Mixer

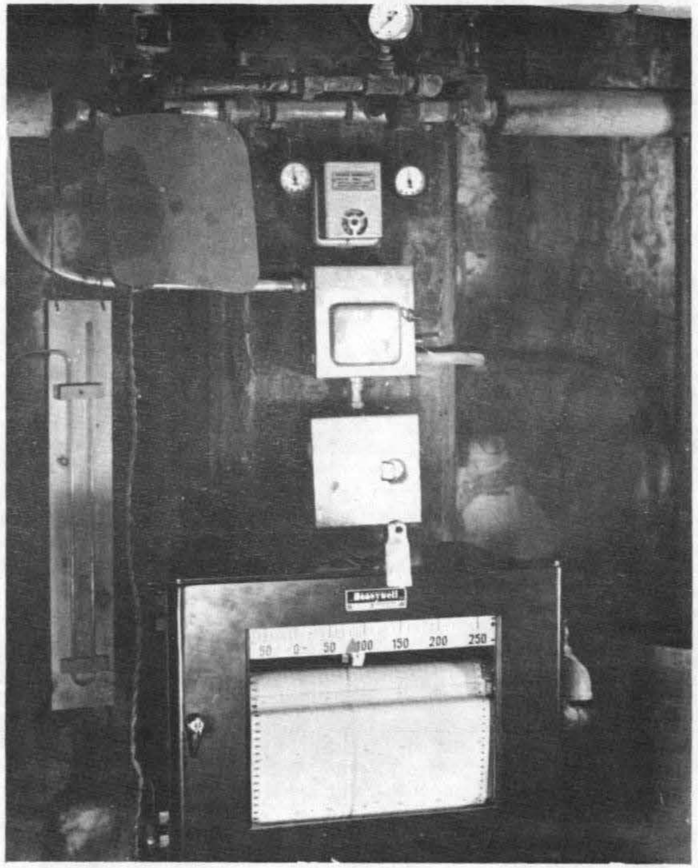


Fig. 4

Potentiometer and Steaming Controls

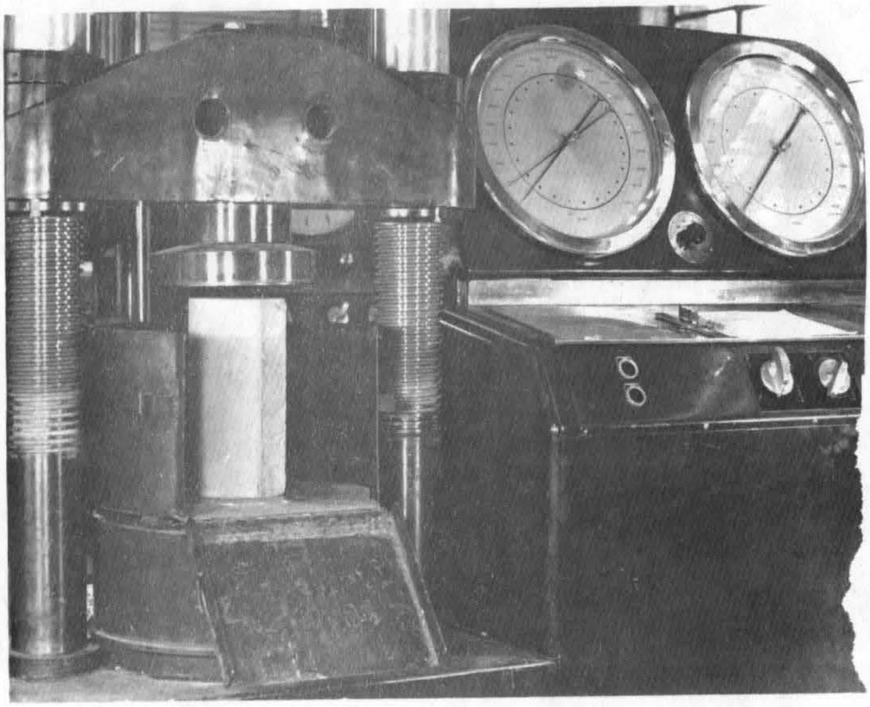
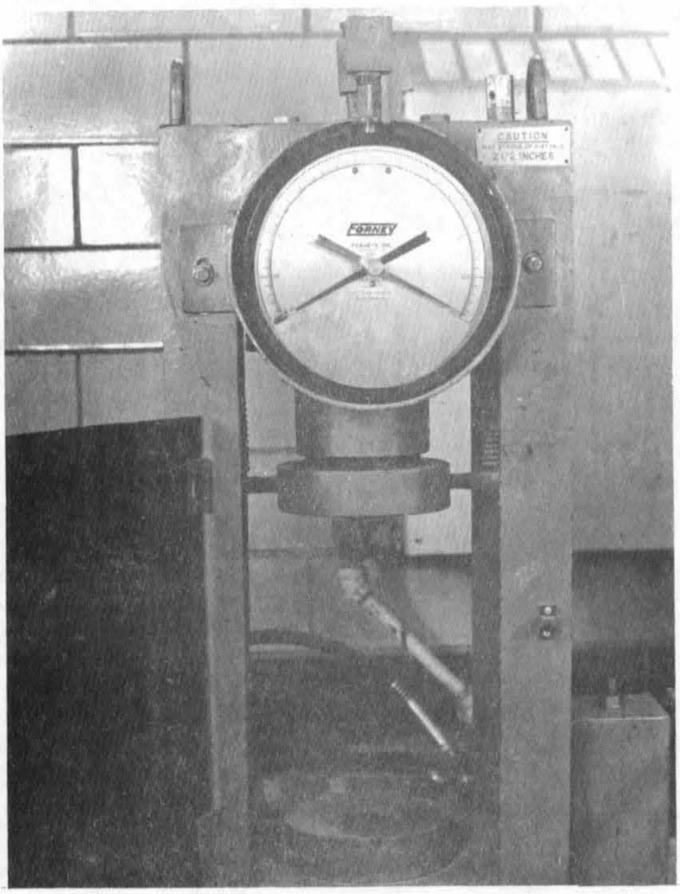


Fig. 5

Laboratory Testing Machine - 400,000 lb. Riehle



Portable Field
Testing Machine

200,000 lb. Forney

Fig. 6

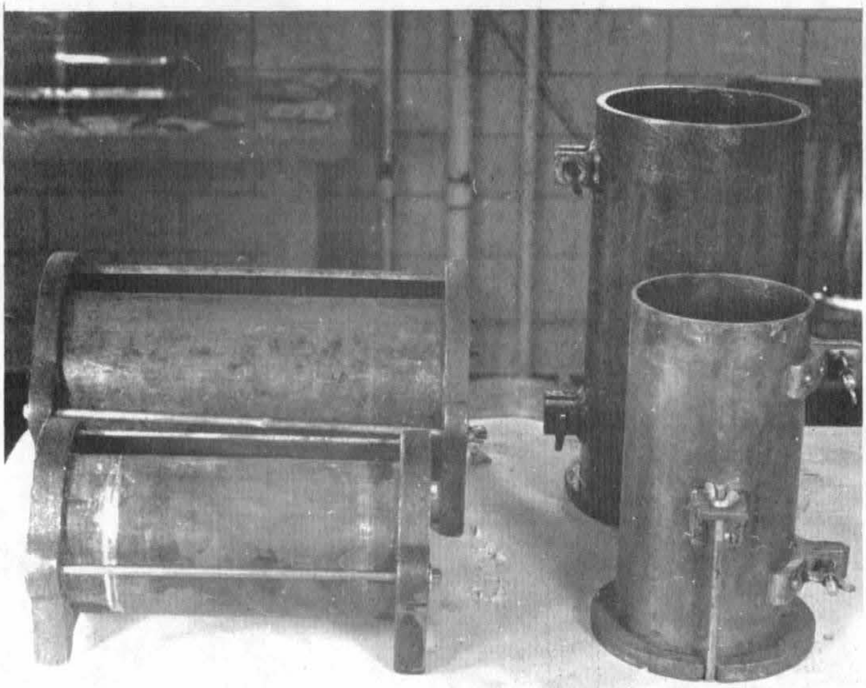


Fig. 7

Four types of molds used

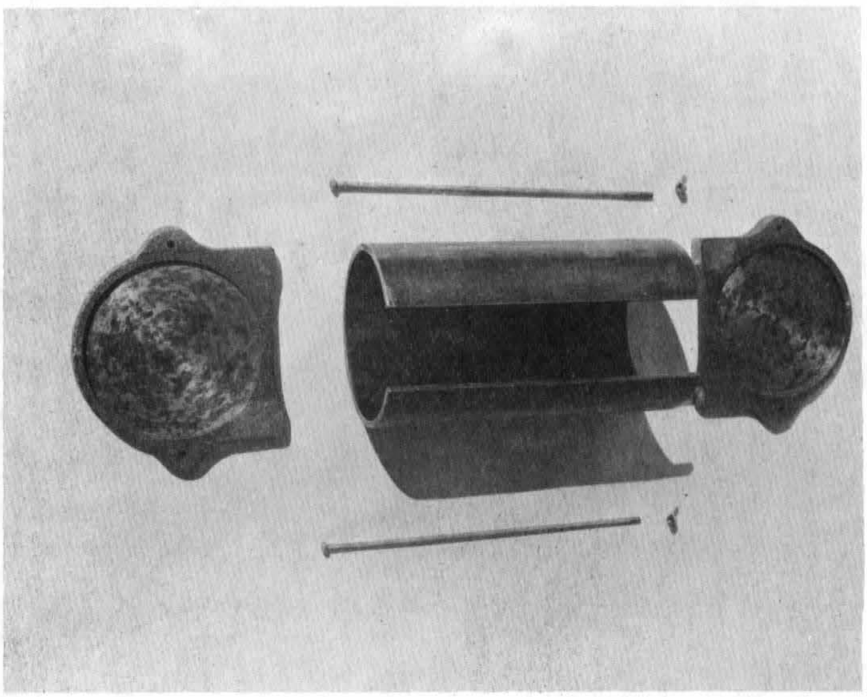


Fig. 8

Disassembled horizontal mold

Series I

MINIMUM CONTROL

The steam curing procedure used in Series I represents the minimum control situation. Three steam curing periods and five different curing temperatures were investigated. These are as follows:

Time	Temperature
18 hours	100 F.
42 hours	125 F.
66 hours	150 F.
	175 F.
	200 F.

Materials and Procedures

Cement

Type. I
Blaine Specific Surface . . 3555
Cube Strength . . . . 3 day 2035 psi
7 day 3122 psi

Aggregate

Sieve No.	Percent Passing Sand	Gravel
$1\frac{1}{2}$		100
1		85
3/4		54
1/2		25
3/8		11
4	100	0.6
8	89	
16	59	
30	22	
50	7.6	
100	2.2	
200	1.4	

Specific Gravity . . . . Cement 3.14
Sand 2.68
Gravel 2.68

Proportions	1:2.16:2.21
Water-Cement Ratio. . .	0.41
Maximum Slump	$2\frac{1}{2}$ inches
Mixing.	In counter-current batch mixer Dry mix - 1 minute Wet mix - 3 minutes
Molds	6 by 12 inch vertical molds
Capping of Test Specimens .	1-2-3 day tests with sulphur 7-14-28 day tests with neat cement
Curing	Steam - in steam chamber for period indicated, then in moist room until tested. Control - in moist room until tested

Discussion of Tests

At each different combination of temperature and length of steaming, approximately 24 specimens were made. Eight specimens were tested at age one day, two days, or three days, depending on the length of steaming. Eight were tested at age seven days, and eight were tested at age twenty eight days. In all cases as soon as steaming was complete the specimens were removed from the steam chamber and stored in the moist room until they were tested. An equal number of control specimens was made and placed immediately in the moist room. These were given the standard moist cure and were tested at the same ages as the steam cured specimens.

During this series no effort was made to control the rate of temperature rise of the concrete, and no delay time between mixing and beginning of steaming was given. It was noticed, however, that in all cases the specimens cast from the first batch each day, had higher compressive strengths than specimens from the second batch. This may be explained by the fact that specimens from the first batch actually had approximately 30 minutes delay time between mixing and beginning of steaming and the second batch had no delay at all. It was also noticed that at steaming temperatures of 150 F, 175 F, and 200 F, on days when the rate of temperature rise was lower, the compressive strengths tended to be slightly higher.

Discussion of Results

Even with the minimum of control used, the concrete gained strength at an accelerated rate during the first few hours of steaming. At all temperatures the concrete gained strength at a diminishing rate between 18 and 66 hours of steaming. At temperatures of 175 F and 200 F the concrete lost strength by additional steaming past 42 hours. By the end of 18 hours of steaming, the rate of gain in strength of concrete steam cured at any temperature is less than the rate of gain in strength of concrete which is moist cured.

The best early strengths were obtained after 18 hours of steaming at temperatures of 125 F and 150 F. At these temperatures the 28 day strengths with any length of steaming were about 75 percent of the 28 day control strength.

At 175 F and 200 F the specimens showed severe swelling. It is believed that this was caused by the expansion of the entrapped air during the time the concrete was still in the plastic state.

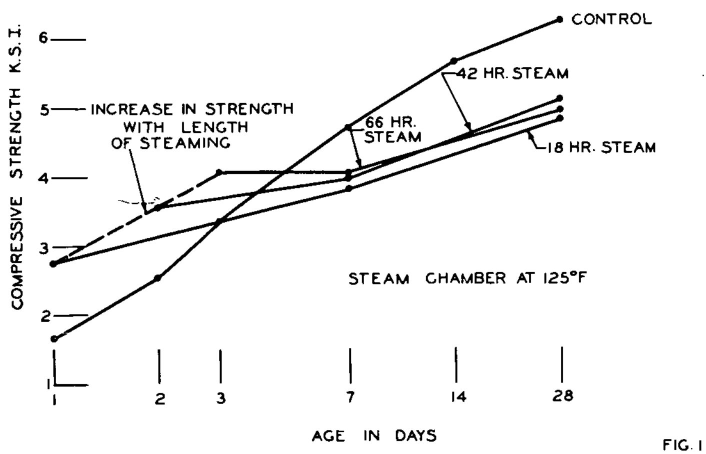


FIG. 1

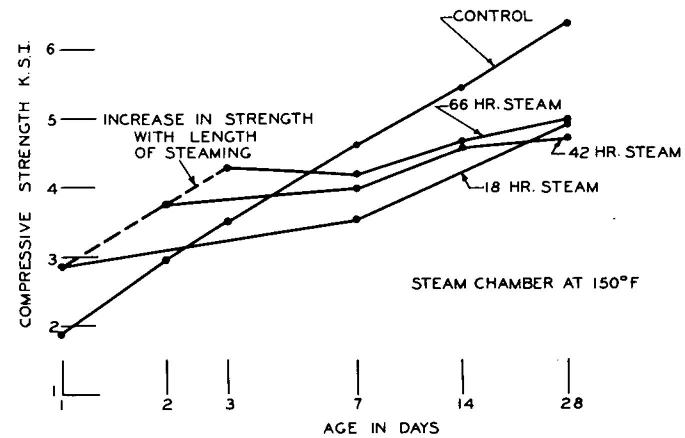


FIG. 2

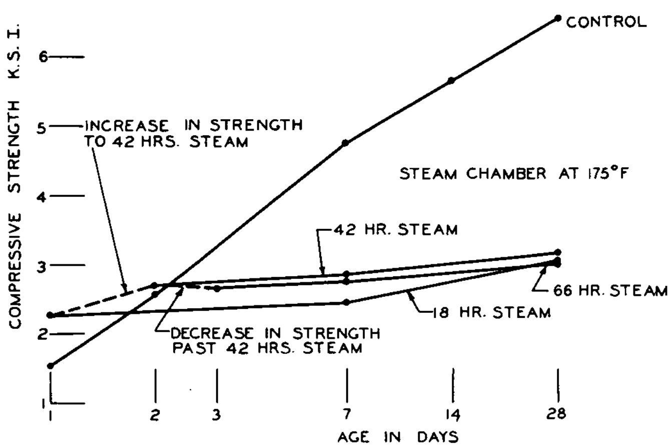


FIG. 3

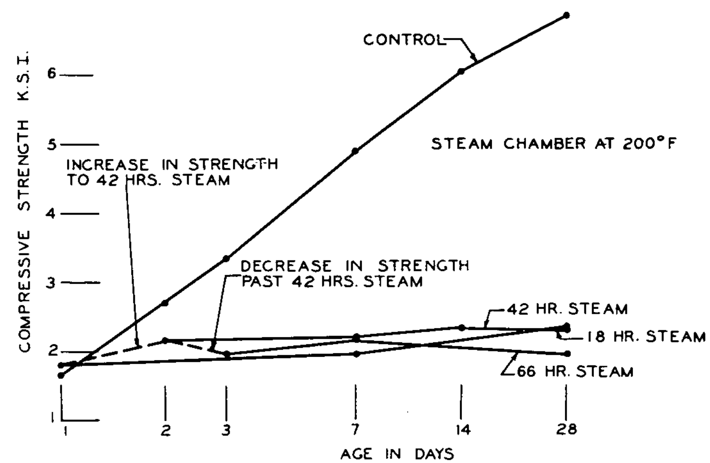


FIG. 4

SERIES I
MINIMUM CONTROL OF STEAM CURING

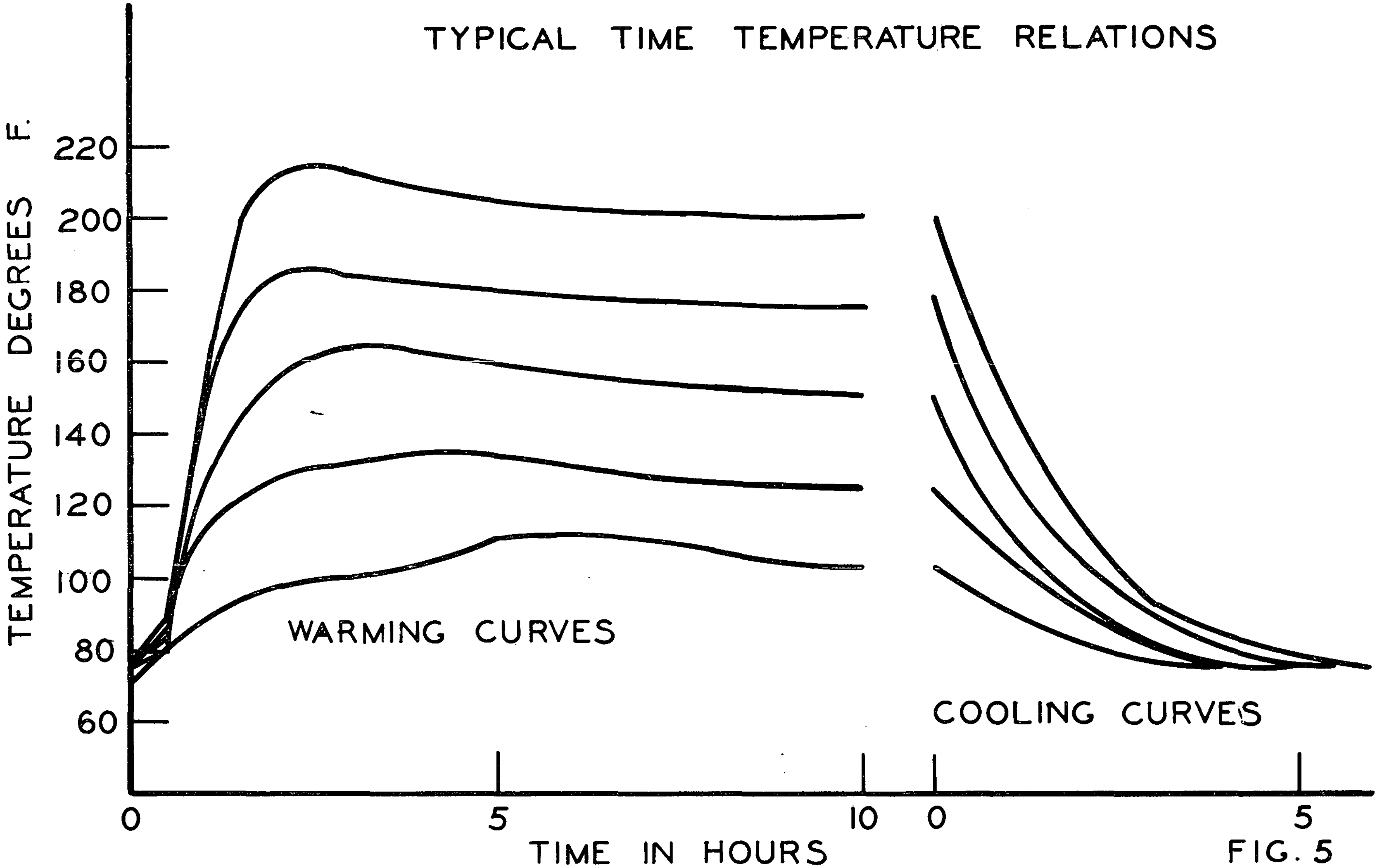


FIG. 5

SERIES I
MINIMUM CONTROL OF STEAM CURING

TABLE 1 - SERIES I

0 - ½ HOURS DELAY TIME

Nominal Curing Temperature (F.)	100	100	100	125	125	125	150	150	150	175	175	175	200	200	200
Warming Rate (F/hr.)	12	12	12	32	32	32	55	55	55	85	85	85	110	110	110
Steaming Time (hr.)	18	42	66	18	42	66	18	42	66	18	42	66	18	42	66
1-2-3 Day* Strength (psi)															
Steam Cured	2082	3058	3595	2704	3566	4036	2848	3741	4276	2229	2700	2623	1721	2154	1924
No. of Tests	6	6	6	8	12	8	8	10	8	10	10	8	10	10	8
Control	1587	2705	3397	1672	2538	3368	1874	2954	3461	1502	2540	3201	1628	2707	3355
No. of Tests	6	6	6	8	12	8	7	8	8	10	10	8	10	10	8
1-2-3 Day* Steam Cured as a Percent of Control	131	113	106	162	140	120	152	127	123	148	106	82	106	80	57
7-Day Strength (psi)															
Steam Cured	3897	3645	3872	3793	3944	4058	3534	3986	4175	2470	2832	2740	1939	2203	2132
No. of Tests	6	6	6	6	8	8	8	10	8	10	10	8	9	10	8
Control	4898	4737	4877	4692	4590	4820	4561	4607	4665	4772	4800	4713	4909	4941	4943
No. of Tests	6	6	6	6	8	8	8	9	8	10	10	8	9	10	8
7-Day Steam Cured as a Percent of Control	80	77	79	81	86	84	77	86	89	56	59	58	39	45	43
28-Day Strength (psi)															
Steam Cured	4923	4675	4870	4821	4960	4953	4893	4704	4960	3021	3194	3041	2351	2309	1979
No. of Tests	6	6	6	8	12	8	8	10	8	10	10	8	10	10	8
Control	6630	6870	6378	6087	6444	6406	6154	6483	6401	6605	6640	6467	6840	6713	7150
No. of Tests	6	6	6	8	12	8	8	9	8	10	10	8	10	10	8
28-Day Steam Cured as a Percent of Control	74	68	76	79	77	77	79	73	78	46	48	47	34	34	28

* 18 hours steam cured tested at age 1 day
42 hours steam cured tested at age 2 days
66 hours steam cured tested at age 3 days

Series II

MAXIMUM CONTROL

In order to obtain maximum control over the steam curing procedure, it is necessary to specify limits for the following variables.

1. Duration of steam curing
2. Maximum curing temperature
3. Time between mixing of the concrete and beginning of steam curing (delay time)
4. Maximum rate of temperature increase
5. Maximum rate of temperature decrease

In Series I, the first two variables were examined. Series IIA is concerned with the effect of the rate of temperature decrease, and Series IIB with the effect of delay time. In Series IIC the effect of the last four variables was investigated for one steam curing period.

Materials and Procedures

Cement

Type	I
Blaine Specific Surface. .	3485
Cube Strength.	3 day - 2250 psi
	7 day - 3250 psi

Aggregate

Sieve No.	Percent Passing Sand	Percent Passing Gravel
1½		100
1		100
3/4		64
1/2		29
3/8		13
4	100	0.7
8	89	
16	58	
30	22	
50	7.7	
100	2.2	
200	1.4	

Specific Gravity	Cement - 3.14 Sand - 2.68 Gravel - 2.68
Proportions	1:2.16:2.21
Water-Cement Ratio . . .	0.41
Maximum Slump	2½ inches
Mixing	In counter-current batch mixer Dry mix - 1 minute Wet mix - 2 minutes Batch undisturbed for 5 minutes Second wet mix 2 minutes
Molds	6 by 12 inch vertical steel cylinders
Capping of test specimens:	1 day tests with sulphur 28 day tests with neat cement
Curing	Steam - in steam chamber 18 hours, then in moist room until tested Control - in moist room until tested

Series IIA

EFFECT OF RATE OF COOLING

Discussion of Tests

At prestressed concrete plants in Iowa, the casting beds are not protected from the weather. Steam curing is accomplished by covering the beams with a single or double layer of tarpaulins. Winter temperatures are frequently below freezing, and concrete beams cool quite rapidly after the steam is shut off and the tarpaulins removed. Series IIA was set up to determine the effect of rapid cooling on the development of strength of the concrete after the initial steam cure period.

This study was divided into two parts. The major differences between these two parts were the differences in rate of cooling and the difference in lowest temperature attained.

In the first part, twelve specimens were cast on each of three days. Eight specimens were placed in the steam chamber and steamed 18 hours at 150 F. The remaining four specimens were placed in the moist room immediately after being cast. These were the control specimens. After the steaming was complete, four of the specimens were placed in the moist room, and four were placed in a freezer maintained at minus 20 F. The cooling time to reach freezing was 2.5 hours. The cooling time to minus 20 F. was 11 hours. The maximum rate of temperature drop, which occurred during the first hour in the freezer, was 72 F. per hour. After 48 hours in the freezer the specimens were moved to the moist room. The warming time to 32 F. was two hours. The maximum rate of temperature rise, which occurred during the first hour in the moist room, was 38 F. per hour. The specimens that were moved directly from the steam chamber to the moist room cooled to 74 F. in about 4 hours. The maximum rate of cooling of these specimens was 38 F. per hour.

The specimens that were steamed only, and the control specimens, were tested at ages 7 days and 28 days. It was assumed that hydration was stopped at temperatures below freezing. Therefore, the specimens that had been frozen were broken at ages 9 days and 30 days.

In the second part of this series, twelve specimens were cast on each of three days. Eight were placed in the steam chamber and steamed 18 hours at 150 F. The remaining four specimens were placed immediately after casting, in the moist room as control specimens. After the steaming was complete, four of the specimens were placed in the moist room, and four were placed in the freezer maintained at plus 25 F. The cooling time to freezing was 6 hours. The maximum rate of cooling was 43 F. per hour. After 24 hours in the freezer, the specimens were moved to the moist room. The warming time to constant temperature was about 4 hours. The maximum rate of temperature rise was 30 F. per hour. The specimens that were moved directly from the steam chamber to the moist room cooled to 75 F. in about 4 hours.

The specimens that were steamed only, and the control specimens were tested at ages 7 days and 28 days. The specimens that had been frozen were tested at ages 8 days and 29 days.

Discussion of Results

It may be noted that the average 7 day compressive strength of the specimens frozen for 24 hours at plus 25 F. is slightly higher than the average 7 day compressive strength of the specimens steamed only. This is probably due to a combination of two factors. One factor being that the specimens frozen at 25 F. were actually frozen only about 19 hours instead of the 24 hours assumed, thereby allowing an additional 5 hours for the cement to hydrate. The other factor being that hydration does not completely stop at the freezing point. The 7 day and 28 day strengths of the concrete which was steamed only was approximately 68 percent of the control strength. The strength of the concrete frozen in either part of the test does not appreciably differ from the strength of the concrete steamed only. Therefore, it is concluded that the very rapid cooling rate has little effect on the strength of the concrete.

TABLE 1 SERIES II A

	Control	Frozen 24 hrs. at + 25 F.	Frozen 48 hrs. at - 20 F.	Steamed only
Hours Steamed (hr.)		18	18	18
Temperature Steamed (F.)		150	150	150
Delay Time (hr.)		0	0	0
Warming Rate (F/hr.)		60	60	60
7 Day Strength (psi)	5158	3713	3327	3566
No. of Tests	12	6	6	12
7 Day Steam Cured as Percent of Control	100	72	65	69
28 Day Strength (psi)	6935	4490	4568	4614
No. of Tests	12	6	6	12
28 Day Steam Cured as Percent of Control	100	65	66	67

SERIES II B

EFFECT OF DELAY PERIOD

Discussion of Tests

The main factor considered in this part of Series II was the delay time before steaming was started. Four steaming temperatures were used - 125 F, 150 F, 175 F, and 200 F. All specimens subjected to steaming were steamed a total of 18 hours. The delay times used were one hour, three hours, and six hours. Test results from Series I provided additional information on delay times of 0.0 hours and 0.5 hours.

On each day three batches of six specimens each were mixed. The time of mixing of each batch was such that the desired delay time of all batches was reached at 2:30 P.M. Steaming was then started and continued until 8:30 A.M. the next morning. From each batch, four specimens were placed in the steam chamber and two were placed in the moist room. Two steam cured and one moist cured specimen from each batch were tested at age 24 hours and 28 days.

Discussion of Results

The results show that a delay period of a few hours prior to steam curing produces higher strengths at all ages than if the concrete were steamed immediately after being cast. The higher steam curing temperatures require longer delay periods to produce the maximum strength. At 125 F. about one hour delay, and at 150 F. and above about three hours delay appear to be optimum. At age one day the greatest strength was obtained by steaming at 175 F. after a three hour delay. At age 28 days the specimens which had a six hour delay period had slightly higher strengths than those which had only three hours delay. At age 28 days the highest strengths were produced with temperatures of 125 F. and 150 F. after a six hour delay prior to steaming. The results of these tests agree very closely with those obtained over similar work done by the U.S. Bureau of Reclamation. They conclude in their report titled "Early Strength of Concrete as Affected by Steam Curing Temperatures", "A delay of 2 to 6 hours prior to steam curing, depending upon the temperature, produced strengths 15 to 40 percent higher at age 24 hours than when steam curing was started immediately after the concrete was placed." In Series I the concrete was severely damaged during steaming at the higher temperatures and showed very little strength gain during subsequent moist room curing. In this part of Series II, at all temperatures, the specimens given the six hour delay prior to steaming had the best gain in strength between the one day test and the 28 day test.

MERRITT - JOHNSON

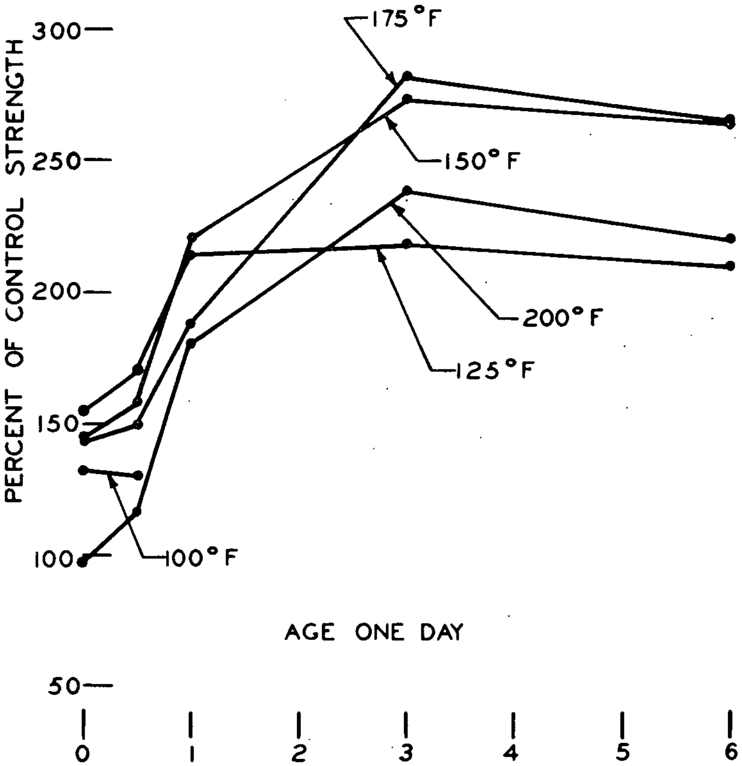


FIG. 6

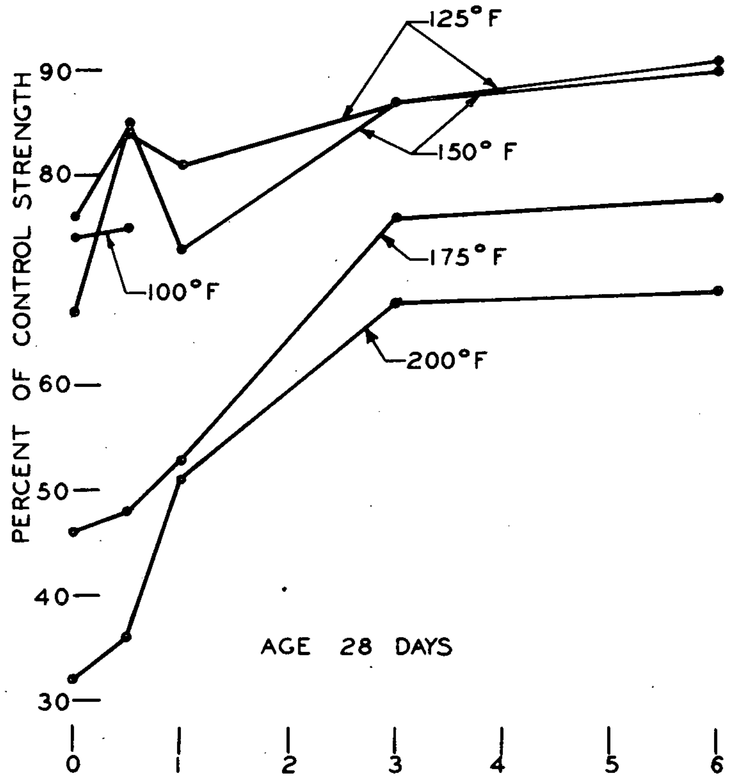


FIG. 7

SERIES II B

MAXIMUM CONTROL OF STEAM CURING

EFFECT OF DELAY TIME

MERRITT - JOHNSON

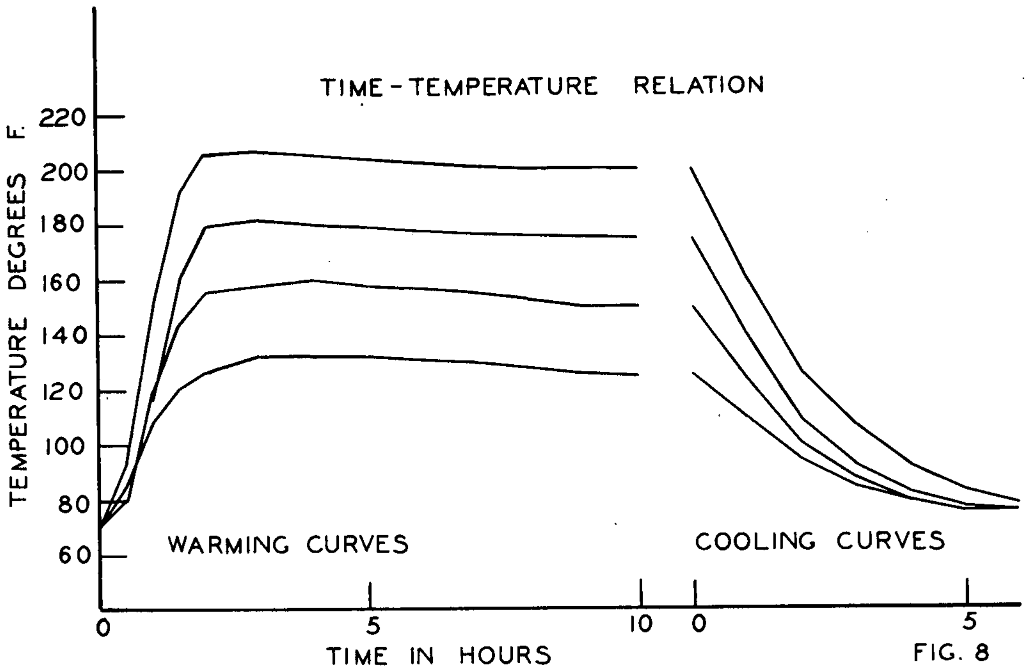


FIG. 8

SERIES II B
MAXIMUM CONTROL OF STEAM CURING
EFFECT OF DELAY TIME

SERIES II B TABLE I

Nominal Curing Temperature (F)	125	125	125	150	150	150	175	175	175	200	200	200
Warming Rate (F/hr)	34	34	34	50	50	50	50	50	50	80	80	80
Steaming Time (hr)	18	18	18	18	18	18	18	18	18	18	18	18
Delay Time (hr)	1.0	3.0	6.0	1.0	3.0	6.0	1.0	3.0	6.0	1.0	3.0	6.0
1 Day Strength (psi)												
Steam Cured	3003	3195	3321	2861	3506	3393	2150	3165	3228	2988	3868	3785
No. of Tests	8	8	8	8	8	8	10	10	10	8	8	8
Control	1380	1470	1585	1300	1292	1295	1146	1120	1220	1660	1630	1722
No. of Tests	4	4	4	4	4	4	5	5	5	4	4	4
1 Day Steam Cured as a percent of Control	217	217	210	220	271	262	188	283	265	180	237	220
28 Day Strength (psi)												
Steam Cured	5574	5753	6276	4805	5698	5969	3238	4623	4902	3559	4885	4996
No. of Tests	8	8	8	8	8	8	10	10	10	8	8	8
Control	6878	6590	6888	6584	6535	6710	6147	6098	6302	7072	7215	7235
No. of Tests	4	4	4	4	4	4	5	5	5	4	4	4
28 Day Steam Cured as a percent of Control	81	88	91	73	87	89	53	76	78	50	68	69

SERIES II B TABLE II

Information Secured from Series I

Nominal Curing Temperature (F)	100	100	125	125	150	150	175	175	200	200
Warming Rate (F/hr)	18	18	32	32	55	55	85	85	110	110
Steaming Time (hr)	18	18	18	18	18	18	18	18	18	18
Delay Time (hr)	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5
1 Day Strength (psi)										
Steam Cured	2030	2133	2670	2737	2715	2980	2152	2306	1538	1904
No. of Tests	3	3	4	4	4	4	5	5	5	5
Control	1533	1640	1757	1612	1875	1873	1460	1544	1604	1652
No. of Tests	3	3	4	4	4	4	3	5	5	5
1 Day Steam Cured as a percent of Control	132	130	152	169	145	159	147	149	96	115
28 Day Strength (psi)										
Steam Cured	4910	4940	4885	4977	4630	5155	3014	3028	2184	2518
No. of Tests	3	3	4	4	4	4	5	5	5	5
Control	6647	6613	6187	5967	6285	6022	6652	6558	6690	6990
No. of Tests	3	3	4	4	4	4	5	5	5	5
28 Day Steam Cured as a Percent of Control	74	75	79	83	74	86	45	46	33	36

SERIES II C

MAXIMUM CONTROL

Discussion of Tests

This part of Series II was set up to show the effect of maximum control of steam curing procedures. That is, the rate of temperature rise, the delay time, the length of steaming, and the rate of cooling were all controlled as closely as possible. The rate of temperature rise was varied to determine the optimum rate. Four steaming temperatures were used - 125 F, 150 F, 175 F, and 200 F. Three different delay periods were used. At 125 F and 150 F delays of 4.0 hours, 2.0 hours and 0.0 hours were used. At 175 F and 200 F delays of 6.0 hours 3.0 hours, and 0.0 hours were used. The maximum warming rates used were as shown in the following table:

Maximum Warming Rates

Degrees F per Hour

125 F	150 F	175 F	200 F
28°/hr	22°/hr	30°/hr	44°/hr
33°/hr	31°/hr	40°/hr	56°/hr
39°/hr	38°/hr	53°/hr	
	42°/hr		

On each day three batches of six specimens each were mixed. From each batch four specimens were placed in the steam chamber and two were placed in the moist room. The time at which each batch was mixed was such that the desired delay time had elapsed at 2:30 P.M. At this time a controlled quantity of steam was turned into the steam chamber. The total length of steaming was 18 hours. After steaming was complete, the specimens were cooled, at a specified rate. They were then stored in the moist room until tested. Two steam cured specimens and one moist cured specimen from each batch were tested at ages 24 hours and 28 days.

In all cases the maximum rate of cooling was held as near 20 F. per hour as possible.

Discussion of Results

If the primary consideration is to be one or two day strength, one particular set of steam curing procedures should be used. But if a maximum 28-day strength is desired along with high early strength, then another set of steam curing procedures should be used.

Consider first the case where it is desired to obtain the maximum early-age strength. The most important point of procedure is the delay time before steaming is started. At the higher temperatures a longer delay time should be used than at the lower temperatures. Up to 150 F. about two hours delay should be used. Above 150 F. three hours should be used. The optimum rate of temperature rise is also a variable. At the lower temperatures lower rates of temperature rise are optimum. Specifically, in this series at 125 F. a temperature rise of 28 F. per hour gave the best results. At 150 F, 31 F. per hour was best. At 175 F, 40 F. per hour gave the highest strengths of the series. And at 200 F, 44 F. per hour was best. These specific figures are not necessarily optimum. Too few warming rates were used to arrive at definite optimums. This work does indicate that the optimum rate of temperature rise in the concrete is dependent upon the steaming temperature used. In general, the higher the steaming temperature, the higher the optimum rate of temperature rise.

Now consider the case where it is desired to get the maximum possible 28-day strength along with a high early strength. Here again the most important point of procedure is the delay time before steaming is started. In this case, however, longer delay periods give better results. In this series the best results were obtained with a delay of four hours when the concrete was steamed at 125 F. and 150 F. and a delay of six hours when the concrete was steamed at 175 F. and 200 F. The rate of temperature rise appears to have little effect upon the 28-day strength if a delay of four hours or more is used. If only a short delay is used, then the trend seems to be that the lower the rate of temperature rise the higher the 28-day strengths. The best 28-day strengths were obtained by steaming at 150 F. after a four hour delay and at 175 F. after a six hour delay.

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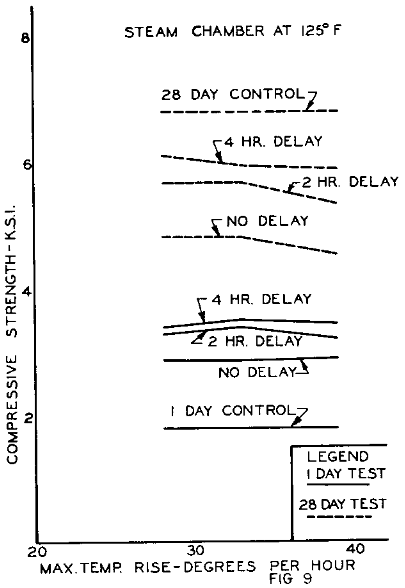

FIG 9

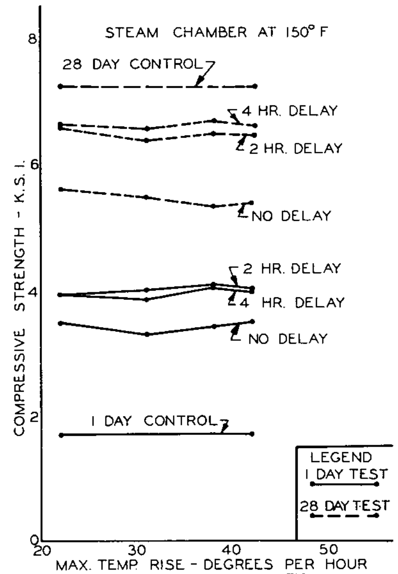

FIG 10

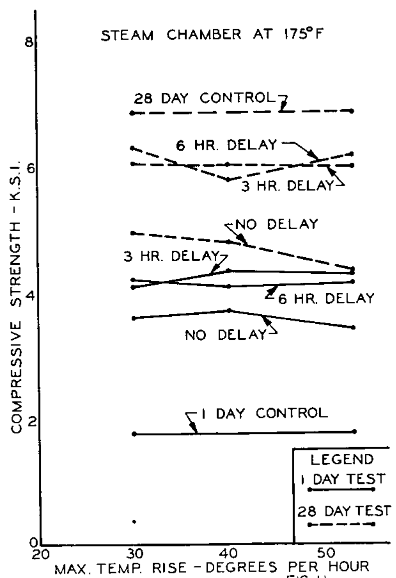

FIG 11

SERIES II C
MAXIMUM CONTROL

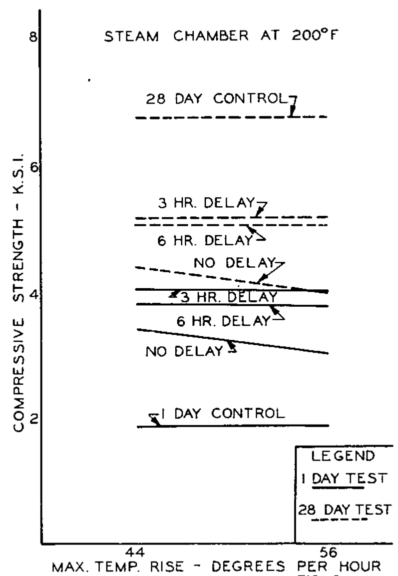

FIG 12

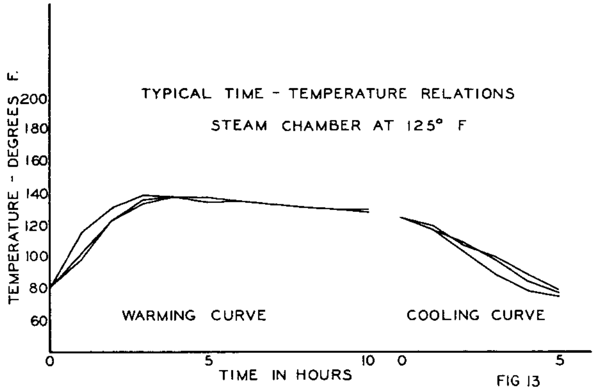

FIG 13

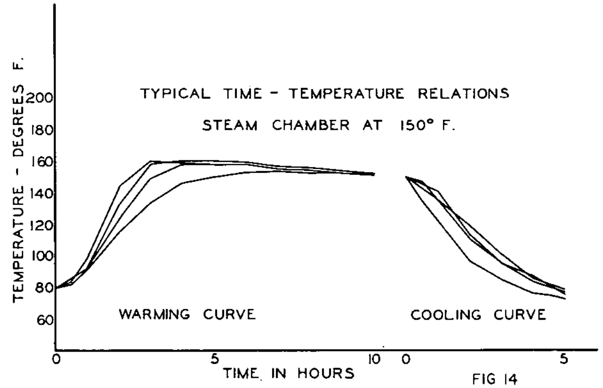

FIG 14

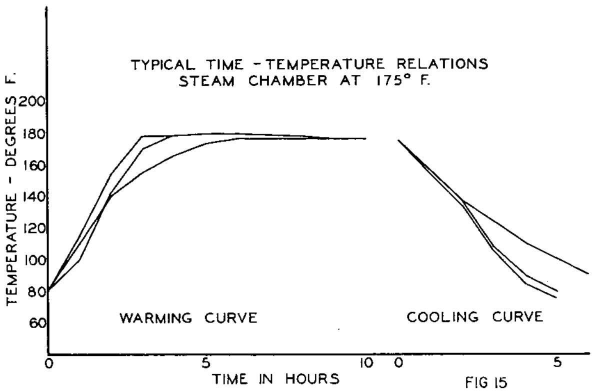

FIG 15

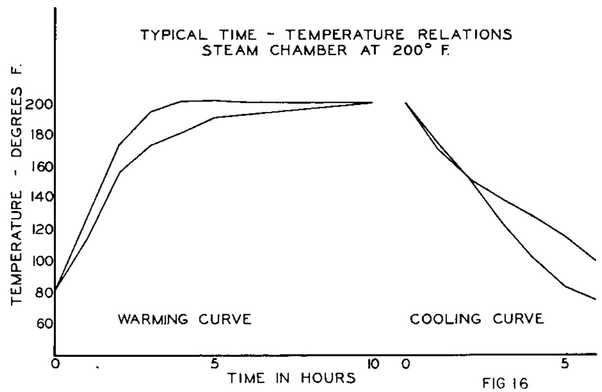

FIG 16

SERIES II C
MAXIMUM CONTROL

TABLE 1 - SERIES II C
125 F. for 18 HOURS

Warming Rate (F/hr)	28	28	28	C*	33	33	33	C*	39	39	39	C*
Dalay Time (hr)	0	2	4	–	0	2	4	–	0	2	4	–
1 - Day Strength (psi)	2864	3271	3400	1713	2883	3396	3506	1853	2920	3219	3459	1783
No. of Tests	8	8	8	12	8	8	8	11	8	8	8	12
1 - Day Steam Cured a Percent of Control	167	191	198	100	156	183	189	100	164	180	194	100
28 - Day Strength (psi)	4838	5640	6108	6965	4845	5660	5945	6628	4554	5363	5961	6764
No. of Tests	8	8	8	12	8	8	8	12	8	8	8	12
28 - Day Steam Cured as a Percent of Control	69	81	88	100	73	85	90	100	67	79	88	100

TABLE 2 - SERIES II C
150 F. for 18 HOURS

Warming Rate (F/hr)	22	22	22	C*	31	31	31	C*	42	42	42	C*
Delay Time (hr)	0	2	4	–	0	2	4	–	0	2	4	–
1 - Day Strength (psi)	3484	3924	3928	1697	3281	3995	3871	1624	3501	4011	3993	1823
No. of Tests	8	8	8	12	8	8	8	12	8	8	8	12
1-Day Steam Cured as a percent of Control	205	231	231	100	202	246	238	100	192	220	219	100
28 - Day Strength (psi)	5619	6584	6610	7176	5493	6380	6551	7099	5393	6460	6618	7228
No. of Tests	8	8	8	12	8	8	8	12	8	8	8	12
28 - Day Steam Cured as a Percent of Control	78	92	92	100	77	90	92	100	75	89	91	100

* C - Control

TABLE 3 - SERIES II C
175 F. for 18 HOURS

Warming Rate (F/hr)	30	30	30	C*	40	40	40	C*	53	53	53	C*
Delay Time (hr)	0	3	6	-	0	3	6	-	0	3	6	-
1 - Day Strength (psi)	3603	4129	4181	1841	3710	4360	4101	1777	3433	4320	4160	1724
No. of Tests	7	7	8	12	7	8	8	12	8	8	5	11
1 - Day Steam Cured as a Percent of Control	196	224	227	100	209	245	231	100	199	250	241	100
28 - Day Strength (psi)	4974	6056	6303	7122	4804	6029	5809	6943	4328	5990	6195	7172
No. of Tests	8	8	8	12	8	8	8	12	6	8	8	11
28 - Day Steam Cured as a Percent of Control	70	85	88	100	69	87	84	100	60	83	86	100

TABLE 4 - SERIES II C
200 F. for 18 HOURS

Warming Rate (F/hr)	44	44	44	C*	56	56	56	C*
Delay Time (hr)	0	3	6	-	0	3	6	-
1 - Day Strength (psi)	3419	4045	3823	1907	3054	4026	3770	1823
No. of Tests	8	8	6	11	8	8	8	12
1 - Day Steam Cured as a Percent of Control	179	212	200	100	167	221	207	100
28 - Day Strength (psi)	4416	5173	5082	6781	3986	5208	5075	6789
No. of Tests	8	8	6	11	7	8	8	12
28 - Day Steam Cured as a Percent of Control	65	76	75	100	59	77	75	100

* C - Control

SERIES III

TWO CEMENTS AND TWO AGGREGATES

This series was set up to study how the steam curing procedures might need to be changed for the various aggregates or brands of cement that might be used. Specifically two brands of cement were used and for the coarse aggregate a commonly used limestone and gravel were used.

Materials and Procedures

Cement (Brand A)

Type	I
Blaine Specific Surface . .	3485
Cube Strength	3 day - 2250 psi 7 day - 3200 psi

Cement (Brand B)

Type	I
Blaine Specific Surface . .	2820
Cube Strength	3 day - 2000 psi 7 day - 3090 psi

Aggregate

Sieve No.	Percent Passing Sand	Percent Passing Gravel	Percent Passing Limestone
1		100	100
3/4		64	67
1/2		29	35
3/8		13	17
4	100	0.7	1.7
8	92		
16	67		
30	32		
50	11		
100	1.7		
200	1.0		

Specific Gravity	Cement 3.14
	Sand 2.68
	Gravel 2.68
	Limestone 2.58
Proportions	1:2.16:2.21
Water Cement Ratio	0.41
Maximum Slump	2½ inches

Mixing: In counter-current batch mixer
Dry mix - one minute
Wet mix - two minutes
Batch undisturbed for five minutes
Second mix two minutes

Molds: 6 x 12 inch vertical steel cylinders
with machined base plates.

Capping of Test Specimens:
1-day tests with sulphur
28-day tests with neat cement

Curing: Steam - In steam chamber for 18 hours,
then in moist room until tested.
Control - In moist room until tested.

Discussion of Tests

In this series all specimens were steamed 18 hours at a temperature of 150 F. Delay times of 0.0 hours, 2.0 hours, and 4.0 hours were used. In all cases the maximum rate of temperature rise was held as near 30 F. per hour as possible. The maximum rate of cooling was held as near 20 F. per hour as possible.

On each day three batches of six specimens each were mixed. From each batch, four specimens were placed in the steam chamber and two specimens were placed in the moist room. The time at which each batch was mixed was such that the desired delay time had elapsed at 2:30 P.M. At this time a controlled quantity of steam was allowed to flow into the steam chamber. After steaming was complete, the specimens were stored in the moist room until tested. Two steam cured specimens and one moist cured specimen from each batch were tested at ages 24 hours and 28 days.

Discussion of Results

The varying factors studied in this series were delay time between casting and steaming and the four various materials - two brands of cement, limestone, and gravel.

In the mixes using cement "A" the highest strengths at age 24 hours were attained after a two hour delay. With cement "B" at age 24 hours, the highest strengths were attained after a four hour delay. This difference may be due, at least in part, to the fact that cement "A" is more finely ground than cement "B". At age 28 days, in all cases except one, the highest strengths were attained after the four hour delay. The exception was the combination of cement"B" and limestone aggregate where the highest 28-day strength was attained after a two hour delay.

Using gravel, the highest 24-hour strength was obtained by using cement "A" and a two hour delay. The highest 28-day strength was obtained by using cement "A" and a four hour delay.

Using limestone, the highest 24-hour strength and 28-day strength was obtained by using cement "B" and a four hour delay.

Using cement "A", the highest 24-hour strength was obtained by using gravel and a two hour delay. The highest 28-day strength was obtained by using limestone and a two hour delay.

Using cement "B", the highest 24-hour strength and 28-day strength was obtained by using limestone and a four hour delay.

From this it is seen that the optimum steam curing procedures are also dependent upon the materials being used.

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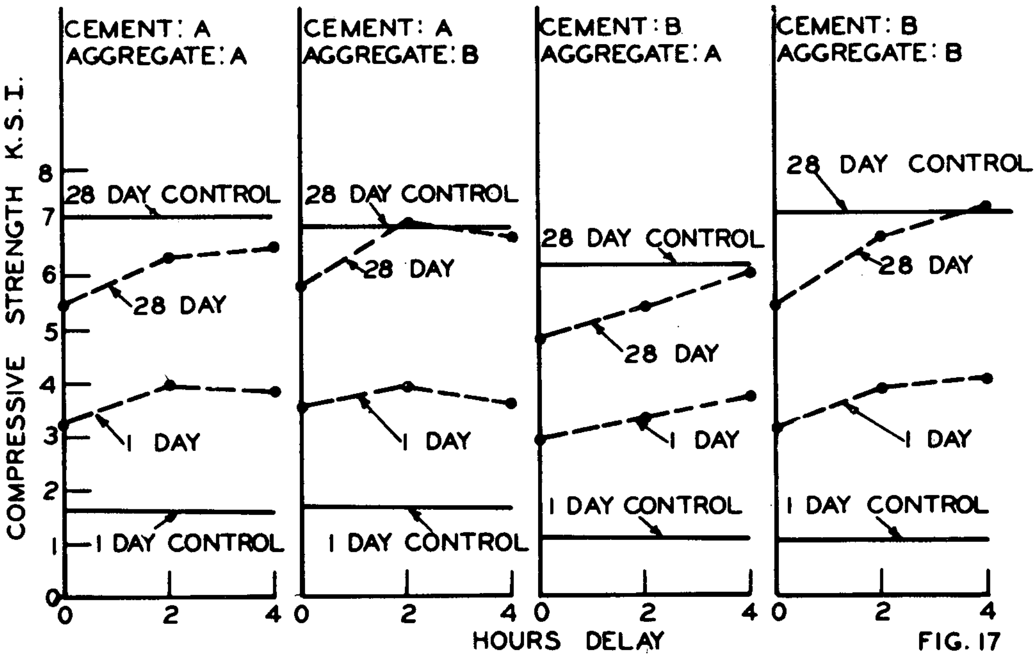

FIG. 17

SERIES III

TWO CEMENTS AND TWO AGGREGATES

MERRITT - JOHNSON

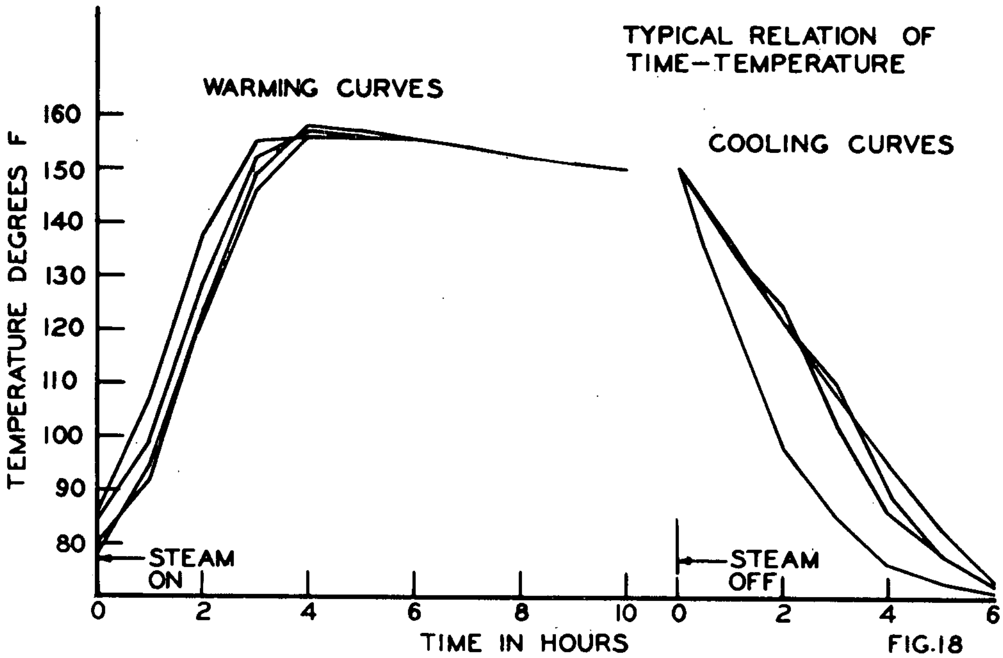

FIG.18

SERIES III

TWO CEMENTS AND TWO AGGREGATES

TABLE 1 - SERIES III
COMPARISONS OF TWO CEMENTS AND TWO AGGREGATES
150 F. FOR 18 HOURS

Cement	A	A	A	A	A	A	B	B	B	B	B	B
Coarse Aggregage	G	G	G	LS	LS	LS	G	G	G	LS	LS	LS
Delay Time (hr)	0	2	4	0	2	4	0	2	4	0	2	4
1 - Day Strength (psi)												
Steam Cured	3281	3995	3871	3548	3960	3633	2923	3324	3728	3169	3890	4069
No. of Tests	8	8	8	6	6	8	8	8	8	8	4	8
Control	All Delays		1624	All Delays		1659	All Delays		1091	All Delays		1057
No. of Tests	-	-	12	-	-	10	-	-	12	-	-	10
1 - Day Steam Cured as a Percent of Control	202	246	238	214	239	219	268	305	342	300	368	385
28-Day Strength (psi)												
Steam Cured	5493	6380	6551	5828	7000	6736	4819	5429	6064	5434	6703	7240
No. of Tests	8	8	8	6	6	8	8	7	8	8	4	8
Control	All Delays		7099	All Delays		6908	All Delays		6206	All Delays		7147
No. of Tests	-	-	12	-	-	10	-	-	12	-	-	10
28-Day Steam Cured as a Percent of Control	77	90	92	84	101	97	78	87	98	76	94	101

SERIES IV

WATER - CEMENT RATIO

It is generally accepted that concrete will have decreased strength with an increase in mixing water. This series was set up to determine what different effect, if any, an increase in mixing water might have upon concrete subjected to conditions of steam curing.

Materials and Procedures

Cement

Type	I
Blaine Specific Surface. . .	2820
Cube Strength	3 day - 2000 psi
	7 day - 3090 psi

Aggregate

Sieve No.	Percent Passing Sand	Percent Passing Limestone
1		100
3/4		67
1/2		35
3/8		17
4	100	1.7
8	92	
16	67	
30	32	
50	11	
100	1.7	
200	1.0	

Specific Gravity.	Cement 3.14
	Sand 2.68
	Limestone 2.58
Proportions	1:2.16:2.21
Water-Cement Ratio . .	0.416
	0.456
Maximum Slump	2½ inches (w/c - 0.416)
	5½ inches (w/c - 0.456)

Mixing: In counter-current batch mixer
Dry mix 1 minute
Wet mix 2 minutes
Batch undistrubed for 5 minutes
Second mix 2 minutes

Molds: 6 x 12 inch vertical steel cylinders with machined base plates

Capping of Test Specimens:
1-day tests with sulphur
28-day tests with neat cement

Curing: Steam - In steam chamber for 18 hours then in moist room until tested
Control - In moist room until tested

Discussion of Tests

Three temperatures were used - 150 F, 175 F, and 200 F. Delay times between casting and steaming of two hours, four hours, and six hours were used at each temperature. At each combination of steam curing procedures concrete was mixed at a two inch slump and a five inch slump. The only difference between the two mixes was the quantity of mixing water.

All specimens were steamed 18 hours. The maximum rate of temperature rise of the concrete was held as near 30 F. per hour as possible for a steaming temperature of 150 F, 35 F. per hour for 175 F, and 40 F. per hour for 200 F. From previous work these rates of temperature rise seem to be about optimum. The maximum rate of cooling was held to 20 F. per hour or less. The 24 hour test specimens with a six hour delay were tested immediately at the end of steaming. Other work, reported later in this paper, shows that all things being equal except the temperature at the time of testing, the cooler concrete has a slightly higher compressive strength than the warmer concrete. No attempt was made in this series to consider this difference. All other specimens had two hours or more cooling time.

On each day three batches of six specimens each were mixed. From each batch four specimens were placed in the steam chamber and two were placed in the moist room. The time at which each batch was mixed was such that the desired delay time had elapsed at 2:30 P.M. At this time a controlled quantity of steam was allowed to flow into the steam chamber. After steaming was complete, the specimens were stored in the moist room until tested. Two steam cured specimens and one moist cured specimen from each batch were tested at ages 24 hours and 28 days.

Discussion of Results

The results were very nearly as expected. That is, the concrete with the greater slump had lower strength. At age one day the higher slump concrete showed less reduction in strength when steamed at 175 F. than when steamed at either 150 F. or 200 F. In most cases the higher slump concrete showed a greater reduction in strength at age 28 days than at age one day.

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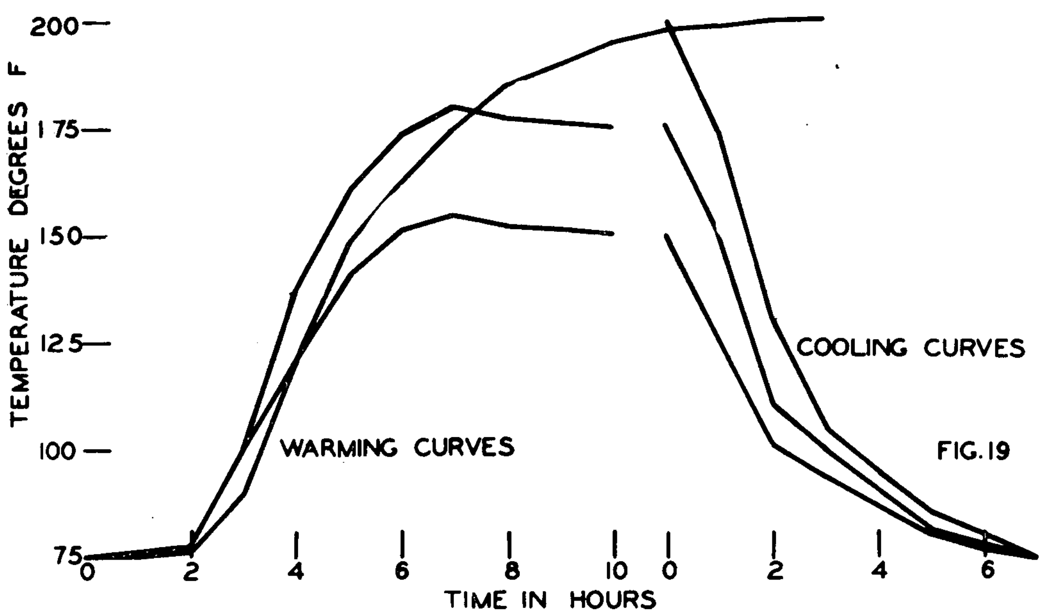
TYPICAL TIME - TEMPERATURE RELATION



SERIES IV
EFFECT OF WATER-CEMENT RATIO

TABLE 1 - SERIES IV
EFFECT OF WATER - CEMENT RATIO
18 HOURS STEAM CURING

Curing Temperature (F)	150	150	150	C*	175	175	175	C*	200	200	200	C*
Warming Rate (F/hr)	35	35	35	-	40	40	40	-	38	38	38	-
Delay Time (hr)	2	4	6	-	2	4	6	-	2	4	6	-
<u>W/C = 0.416</u>												
1 - Day Strength (psi)	3860	4200	-	1076	3861	4218	4170	1131	4000	4350	3949	1106
No. of Tests	8	8	-	10	6	8	8	11	8	6	8	11
1 - Day Steam Cured as a Percent of Control	359	391	-	100	341	372	368	100	361	393	357	100
28-Day Strength (psi)	6725	7166	7298	7401	5382	6473	6580	7222	5140	5500	5549	7396
No. of Tests	8	8	6	10	6	8	8	11	8	8	8	12
28 - Day Steam Cured as a Percent of Control	91	97	99	100	74.5	90	91	100	69.5	74	75	100
<u>W/C = 0.456</u>												
1 - Day Strength (psi)	3205	3268	3146	838	3690	3813	3598	849	3474	3502	3433	795
No. of Tests	6	8	8	10	6	6	4	8	8	6	8	11
1 - Day Steam Cured as a Percent of Control	383	390	376	100	435	450	424	100	437	441	432	100
28 - Day Strength (psi)	5800	6078	5900	6146	5435	5628	5667	6267	4826	5025	4874	6507
No. of Tests	9	8	10	12	6	6	6	9	8	8	8	12
28 - Day Steam Cured as a Percent of Control	94	99	96	100	87	90	90.5	100	74	77	75	100

* C - Control

SERIES V

DEVELOPMENT OF STRENGTH IN STEAM CURED CONCRETE

This series was set up to study the effects of steam curing upon concrete at several ages up to one year. Specimens were cured at three temperatures - 150 F, 175 F, and 200 F. They were tested at four ages - 28 days, 90 days, 180 days, and 365 days.

In this series all specimens were stored out of doors after the first 28 hours.

The steam cured specimens were stored outside because this treatment approximates that given to precast steam cured units at commercial plants. The control specimens were stored outside rather than in the moist room so that any difference between the two sets of specimens could be attributed to the steam curing.

Materials and Procedures

Cement

Type	I
Blaine Specific Surface. .	3485
Cube Strength.	3 day 2250
	7 day 3200

Aggregate

Sieve No.	Percent Passing Sand	Gravel
1		100
3/4		64
1/2		29
3/8		13
4	100	0.7
8	89	
16	59	
30	22	
50	7.7	
100	2.2	
200	1.4	

Specific Gravity . . . Cement 3.14
Sand 2.68
Gravel 2.68

Proportions. 1:2.16:2.21

Water-Cement Ratio . . 0.41

Maximum Slump. . . . . $2\frac{1}{2}$ inches

Mixing: In counter-current batch mixer
Dry mix 1 minute
Wet mix 2 minutes
Batch undisturbed for 5 minutes
Second mix 2 minutes

Molds: 6 by 12 vertical steel cylinders
with machined base plates

Capping of Test Specimens:
All tests with neat cement

Curing: Steam - In steam chamber 18 hours, then out
of doors until 7 days before testing.
Control-In laboratory air for 28 hours, then
out of doors until 7 days before testing;
in moist room 7 days before testing.

Discussion of Tests

On each day two batches of eight specimens each were cast. The first batch was completed three hours before steaming was started and the second batch was completed two hours before steaming was started. From each batch four specimens were steam cured and four were air cured.

The steam cure was as follows: The specimens were placed in the steam chamber and after the desired delay time a controlled quanitity of steam was allowed to flow into the steam chamber. The maximum rate of temperature rise was held as near as possible to 25 F per hour for a steaming temperature of 150 F, 30 F per hour for 175 F and 35 F per hour for 200 F. Total steaming time was 18 hours. The cooling of the specimens was held as near 20 F per hour as possible. At age about 28 hours the steam cured specimens were stored upright on the ground out of doors.

The cure of control specimens consisted of standing in laboratory air, covered with plastic, for about 28 hours, after which the specimens were stored in the same manner as the steam cured.

Seven days before testing the specimens were moved to the moist room to bring them to a uniform temperature and moisture condition. One steam cured and one control specimen from each batch were tested at each of the four ages.

Discussion of Results

It was observed that in the first four series the steam cured specimens did not develop 28-day strengths equal to the strength of the control specimens. This difference varied from 10 percent to 30 percent, with the greatest difference noted when the curing was done at 175 F and 200 F and with a zero delay time.

In this series the specimens steam cured at 150 F and 175 F had strengths equal to or greater than the control specimens at all ages. The specimens steam cured at 200 F had strengths slightly lower than the control specimens at all ages.

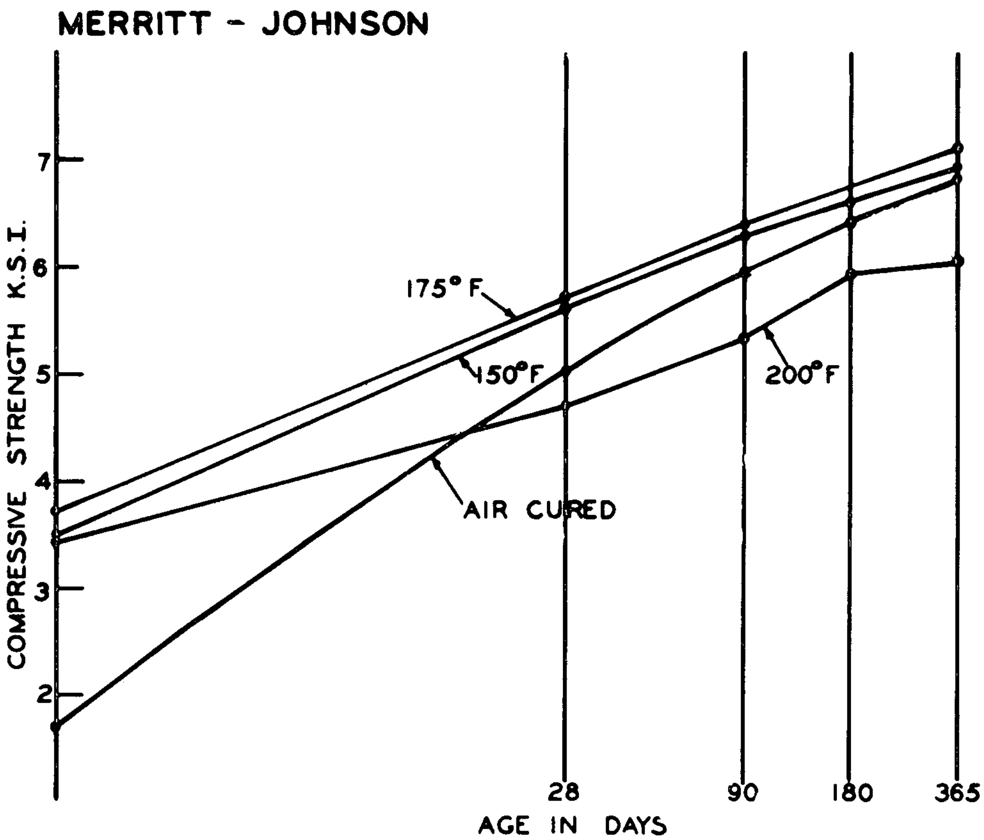


FIG. 20

SERIES V

DEVELOPMENT OF STRENGTH IN STEAM CURED CONCRETE

MERRITT - JOHNSON

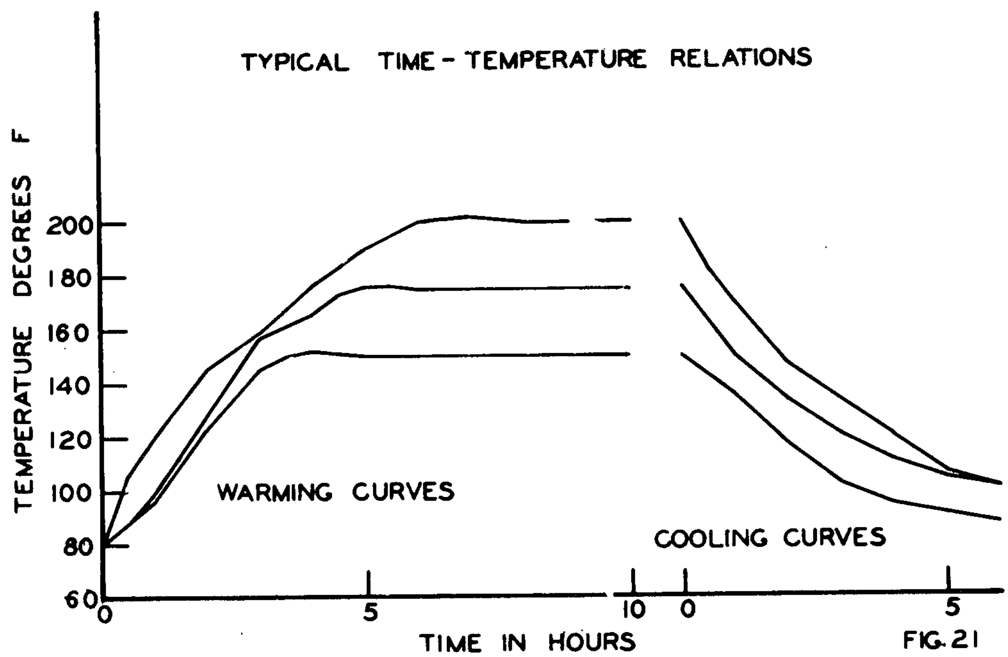


FIG. 21

SERIES V

DEVELOPMENT OF STRENGTH IN STEAM CURED CONCRETE

TABLE I - SERIES V

STRENGTH AT AGES 28 TO 365 DAYS

STEAM CURED 18 HOURS

Curing Temperature (F)	150	150	150	150	175	175	175	175	200	200	200	200
Warming Rate (F/hr)	25	25	25	25	29	29	29	29	36	36	36	36
Delay Time (hr)	2	2	2	2	2	2	2	2	2	2	2	2
Test Age (days)	28	90	180	365	28	90	180	365	28	90	180	365
Steam Cured Str. (psi)	5606	6443	6588	6955	5710	6330	6483	7117	4733	5366	5981	6070
No. of Tests	8	8	8	8	7	7	7	7	8	8	8	8
Control Str. (psi)	4956	5969	6183	6713	4933	5857	6467	6883	5284	6079	6605	7073
No. of Tests	8	8	8	8	7	7	7	7	8	8	8	8
Steam Cured as a Percent of Control	113	108	107	104	116	108	100	103	90	88	91	86

SERIES VI

MOLDS FOR CONCRETE TEST SPECIMENS

At prestressed concrete plants in Iowa it is customary for the plant superintendent to notify the inspector when he plans to transfer the stress to the concrete. The inspector then tests a number of 6 by 12 inch concrete specimens, which have been curing with the beams. This he does on a semi-portable compression test machine at the plant. If the strength of the concrete specimens is at least 4500 psi, the stress transfer is permitted. The important point in this procedure is that the test specimens should remain with the beams for as long as possible before testing.

Vertical steel cylinder molds were first used for the 6 by 12 inch specimens, and it was necessary to cap the top of each specimen. The caps were made from neat cement, and the plane surface was obtained with glass plates. This was done shortly after the cylinders were molded, and they were then placed with the beams for steam curing. Good technique and considerable care was required by this method, and the results were sometimes unsatisfactory.

In order to overcome the capping problem, personnel in the Materials Department laboratory developed a horizontal steel mold with machined end plates which form the ends of the cylinder. Test specimens made in these molds do not require capping.

Series VI consisted of a laboratory investigation made for the purpose of comparing the strength of concrete as determined from test specimens made in the following four types of molds:

4½ by 9 inch Vertical
4½ by 9 inch Horizontal
6 by 12 inch Vertical
6 by 12 inch Horizontal

Two groups of tests were made. The first using 8000 psi concrete; the second using 3000 psi concrete.

The specimens made in the 6 by 12 inch vertical molds were prepared according to ASTM specifications and the strength of these specimens should be considered the standard against which the strength of specimens prepared in the other molds may be compared. Concrete test specimens prepared in 6 by 12 inch horizontal molds will have an indicated strength which is 93 to 97 percent of the strength of specimens containing concrete from the same batches, but prepared in vertical molds.

TABLE I - SERIES VI

MOLDS FOR CONCRETE TEST SPECIMENS

Group	Type of Mold	28 - Day Strength (psi)	No. of Tests	Coefficient of Variation (%)	Percent of Standard
A	4½ by 9 Vertical	8541	30	2.3	108
	4½ by 9 Horizontal	8128	30	2.6	103
	6 by 12 Vertical	7894	30	2.6	100
	6 by 12 Horizontal	7658	30	3.7	97
B	4½ by 9 Vertical	3290	30	7.6	103
	4½ by 9 Horizontal	3089	30	5.4	97
	6 by 12 Vertical	3201	30	7.8	100
	6 by 12 Horizontal	2964	30	5.9	93

SERIES VII

TEMPERATURE OF CONCRETE WHEN TESTED

At a prestressed concrete plant the test specimens are cured with the beams, and they are not removed from the steam curing until immediately before they are to be tested. This means that the concrete specimens may have a temperature of almost 150 F when tested. This series was set up to determine what effect on strength might be expected at this high temperature.

Discussion of Tests

In order to evaluate the effect of temperature at the time of the test on the apparent strength of test specimens, two limited experiments were performed.

In the first experiment, the test specimens were steam cured for 18 hours at 150 F. Half of these specimens were tested immediately after being taken from the steam chamber and half were cooled to 80 F before being tested. Two different systems were used to cool the specimens. With one system they were cooled to 80 F in one hour, and with the other system they were cooled to 80 F in three hours.

In the second experiment, two batches of six specimens each were cast each day. These specimens were also steam cured at 150 F for 18 hours. At the end of steaming eight specimens were removed from the steam chamber. Four of these were tested immediately and four were placed in a water bath and cooled to 80 F in one hour. After this hour they were removed from the water bath and tested immediately. The four specimens left in the steam chamber were steamed during this additional hour. They were then removed from the steam chamber and tested immediately.

Discussion of Results

From the results it appears that the temperature of the concrete at the time of testing does have a slight effect on the compressive strength. Under the particular conditions of these experiments the difference averages about 5 percent or about 175 psi - the cooler specimens having the higher strengths.

TABLE 1 - SERIES VII

Group No.	1	1	1	2	2	2
Temperature at Test (F)	150	80	80	150	80	150
Age at Test (hr)	20	21	23	20	21	21
Cooling Time (hr)	0	1	3	0	1	0
Average Strength (psi)	3481	3625	3936	3214	3447	3276
Number of Tests	20	12	8	16	16	16
Strength at 150 F. as a Percent of 80 F. Strength	96.0, 88.5			93.2		95.0

SERIES VIII

FIELD STUDIES

Series VIII was set up to study the steam curing procedures in use in commercial plants, and to determine the type and degree of control that would be feasible for field work. It was also desired to determine the degree of uniformity of test results that might be expected at a commercial plant and to study the inspection problems peculiar to steam cured, precast concrete construction and to find solutions to these problems.

Field studies were made at two prestressed concrete plants. In this paper they will be referred to as Plant A and Plant B.

Materials and Procedures

Plant A

Cement

Type.	1
Blaine Specific Surface .	3450
Cube Strength	3 day 2750 psi
	7 day 3560 psi

Aggregate

Sieve	Percent Passing Sand	Percent Passing Gravel
1		100
3/4		82
3/8	100	33
4	97	2
8	78	0
16	60	
30	35	
50	10	
100	1.2	
200	0.4	

Specific Gravity. . Cement 3.14
Sand 2.66
Gravel 2.68

Proportions 1:1.93:2.35

Water-Cement Ratio. 0.35

Maximum Slump . . . 3 inches

Pozzolith Type 3. . ¼ lb. per sack cement

Mixing. . . . . In transit-mix trucks

Molds . . . . 6 by 12 inch horizontal steel cylinders with machined end plates

Curing. . . . . Steam - Cured with bridge beams until tested
Control - Covered with plastic membrane 2 days then in moist room until tested

PLANT B

Cement

Type 1
Blaine Specific Surface. . 3400
Cube Strength. . . . . 3 day 2400 psi
7 day 3500 psi

Aggregate

Sieve	Percent Passing Sand	Percent Passing Gravel
1		100
3/4	100	93
3/8	94	37
4	90	5
8	72	2
30	27	

Specific Gravity . .Cement 3.14
Sand 2.69
Gravel 2.63

Proportions. 1:2.18:2.41

Water-Cement Ratio.	0.26
Maximum Slump . . .	3 inches
Pozzolith Type 8. .	¼ pound per sack cement
Mixing.	In transit-mix trucks
Molds	6 by 12 inch horizontal steel cylinders with machined end plates
Curing.	Steam - Cured with bridge beams until tested Control-Covered with plastic membrane 2 days then stored under water until tested

Discussion of Tests

Plant A

On each day five batches of concrete were used to cast a line of beams. Four specimens were made from each of the five batches. Three of the four specimens were placed along the line where concrete from the same batch was placed. The fourth specimen was moist cured.

On each of four days a thermocouple was placed in the center of one steam cured specimen from each batch. On the same four days a thermocouple was placed about three inches deep in the top of the beam at each of five stations along the length of the line. See Figure 1 A. A set of typical results is summarized in Table 3.

On each of three other days a thermocouple was placed in the center of one steam cured specimen from each batch. The specimens were distributed along the line in the same five positions as before. On these three days, five thermocouples were distributed through the cross-section of the beam as shown in Figure 1 B. Typical results are summarized in Table 4.

At the end of the steaming cycle, which was age about 45 hours, one or two specimens from each of the five stations were tested. All other steam cured specimens and all moist cured specimens were tested at age 28 days.

Plant B

The discussion of tests at plant B is identical to that of plant A with one exception. At plant B temperatures were recorded and specimens cured at only four stations along the length of the line instead of five stations. Typical results of the steam curing temperatures are summarized in Table 5 and Table 6.

Discussion of Results

Plant A

After the beams were cast a period of two hours was allowed to elapse before the steam was turned onto the line. The increase in temperature during the first two hours was due only to the heat of hydration. In only one case the temperature reached 100 F before age two hours. The maximum rate of temperature rise of the concrete varied from 12 F per hour to 39 F per hour. The maximum temperatures attained during the several cycles recorded varied from 151 F to 173 F.

After about 15 hours of steaming the canvas covers were removed and the forms were stripped off the beams. The maximum temperature drop during stripping varied from 16 F to 40 F. The time required for stripping was about 2.5 hours. To reduce this temperature drop it was suggested that only half of the line be uncovered at a time and that steam be supplied to the other half. This procedure is now being used. After stripping, steaming was continued for about 12 hours. The canvas covers were left in place for about 12 hours after the steam was shut off to control the cooling rate. The cooling rate varied from 3 F per hour to 11 F per hour.

The control of distribution of steam along the length of the line was very good. The maximum difference in temperature along the line varied from 3 F to 10 F. The conclusion that the degree of control here is good is borne out by the fact the difference in compressive strength along the line is very small.

The distribution of steam around the beams was good also. The difference in temperature through the cross-section averaged only 5 F. At this plant the deck plates of the casting bed are supported about three inches above the concrete floor slab. This allows steam to circulate all the way around the beams.

Plant B

Immediately after the casting of the beams was complete, the line was covered and the steam was turned on. The maximum rate of temperature rise of the concrete varied from 7 F per hour to 13 F per hour. The maximum temperature attained during the several cycles recorded varied from 129 F to 165 F. The normal average temperature was about 130 F.

After about 15 hours of steaming the canvas covers were removed and the forms were stripped off the beams. The maximum temperature drop during stripping varied from 8 F to 12 F. The time required for stripping was about three hours. In most cycles the steam was turned off while any work was being done on an adjacent line. The total time of interruption of steaming was from four hours to nine hours. After the steaming was completed, the canvas covers were left in place as long as possible to reduce the rate of cooling. The maximum rate of cooling was 5 F per hour.

The control of distribution of steam along the line was good. It should be noted that the compressive strengths at station one shows somewhat lower than at the other three stations. This is explained by the fact that the concrete at station one was the last to be placed and had no delay time at all.

The distribution of steam around the beam was not as good as at plant A. Here the forms set directly on the concrete floor slab. The only path open to the steam then is up and over the top of the beam and down. The temperature through the cross-section was fairly uniform except for the lower flange of the beam on the side opposite from the steam line.

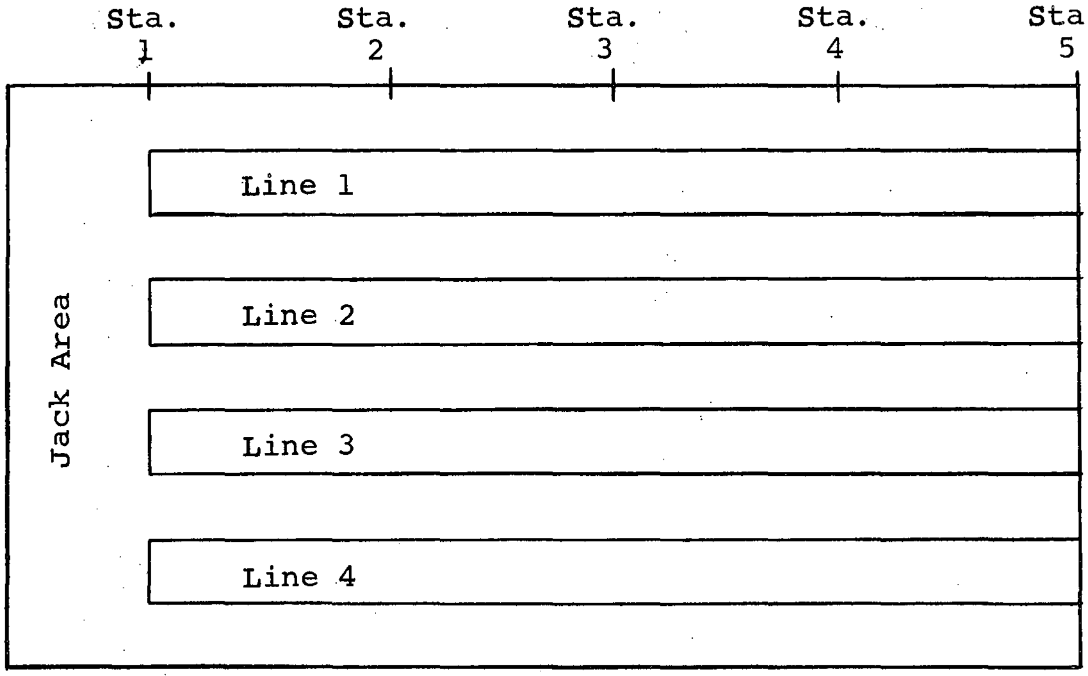


Figure 1A

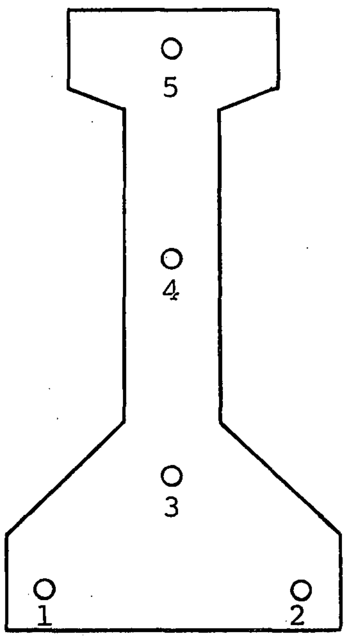


Figure 1B

These Figures show the distribution of thermocouples used in the field study both along the line and through the cross-section.

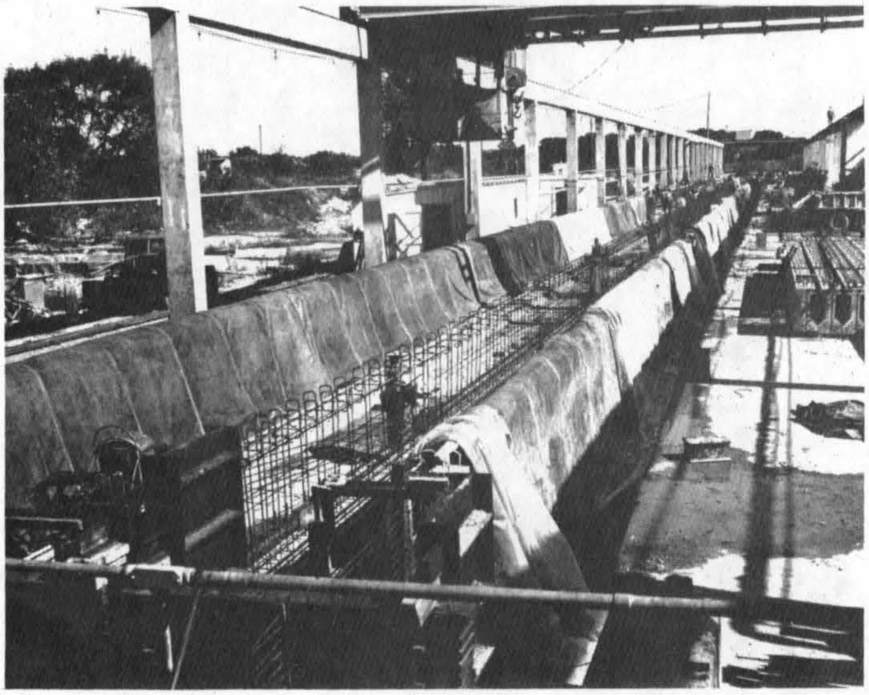


Fig. 2

General view of a Prestressed Concrete Plant in Iowa

Instruction Board Fig. 3

Detailed instructions covering all anticipated steam curing situations are posted here.

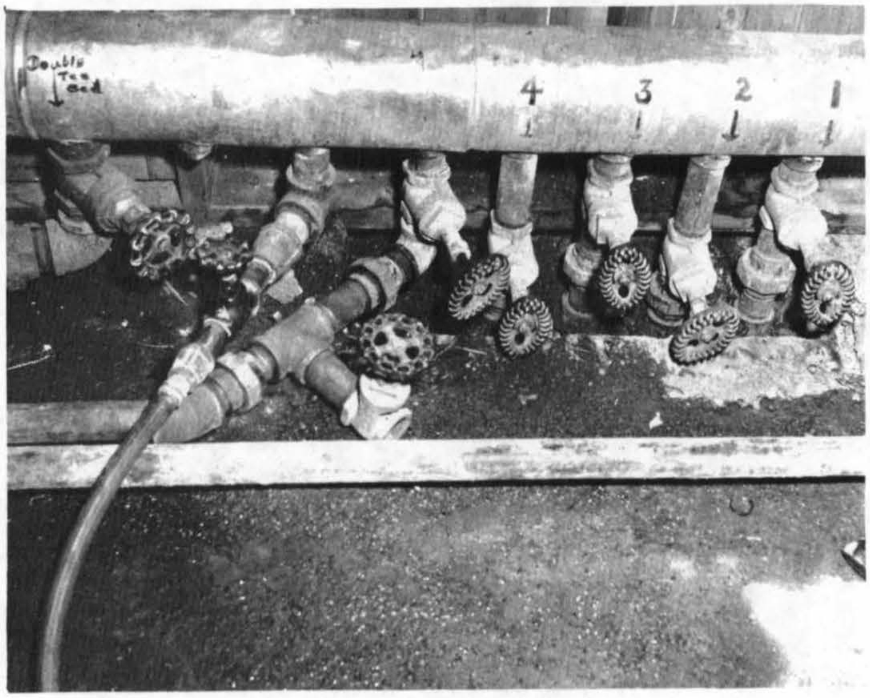


Fig. 4

Point of distribution of steam to any part of the plant.

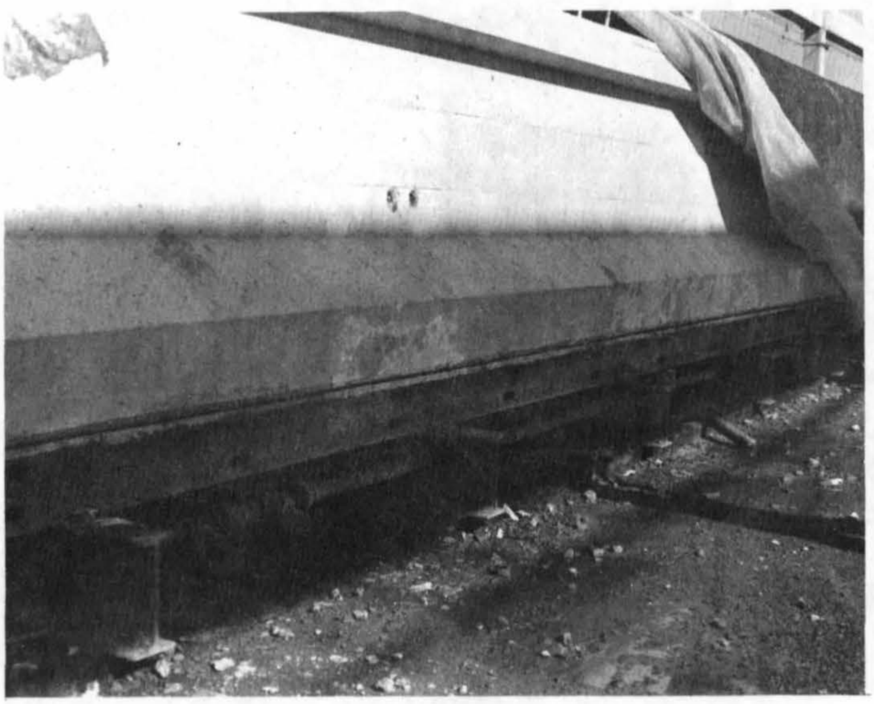


Fig. 5

View at the center of a line showing a beam on casting bed, steam line, and valves to direct steam either way from center.

TABLE I - SERIES VIII

PLANT A

	Station 1	Station 2	Station 3	Station 4	Station 5
2-Day Strength (psi)	5185	5265	5090	5176	4958
No. of Tests	15	16	17	15	18
28-Day Strength (psi)	6239	6206	6073	6041	5964
No. of Tests	19	17	17	17	14
28-Day Control (psi)	7268	7146	6858	6973	6853
No. of Tests	13	13	13	12	12
28-Day Steam Cured Strength as a Percent of Control	86	87	89	87	87

TABLE II - SERIES VIII

PLANT B

	Station 1	Station 2	Station 3	Station 4
2-Day Strength (psi)	4231	4748	4509	4570
No. of Tests	12	25	27	26
28-Day Strength (psi)	5168	5748	5593	5670
No. of Tests	12	24	26	27
28-Day Control (psi)	6274	6375	6144	6355
No. of Tests	6	12	13	13
28-Day Steam Cured Strength as a Percent of Control	82	90	91	89

TABLE III - SERIES VIII

PLANT A
Typical Time - Temperature Relations Along Length of Line

Time After Placement of Concrete (hr)	Station 1	Station 2	Station 3	Station 4	Station 5
0	80	80	82	82	79
5	125	129	120	132	120
10	154	157	146	161	153
15	156	159	154	163	155
20	150	156	144	160	150
25	136	146	139	146	133
30	132	139	127	148	123
35	116	119	116	126	104
40	90	88	90	91	80

TABLE IV - SERIES VIII

PLANT A
Typical Time-Temperature Relations Through Cross-Section of Beam

Time After Placement of Concrete (hr)	Station 1	Station 2	Station 3	Station 4	Station 5
0	80	80	81	83	82
5	131	140	126	136	148
10	166	173	171	173	175
15	166	172	166	171	175
20	135	132	141	140	133
25	159	161	160	168	155
30	144	141	148	152	140
35	122	114	126	126	118
40	101	92	104	103	98

TABLE V - SERIES VIII

PLANT B
Typical Time - Temperature Relations Along Length of Line

Time After Placement of Concrete (hr)	Station 1	Station 2	Station 3	Station 4
0	95	97	96	97
5	121	132	132	128
10	123	132	135	131
15	130	139	141	137
20	122	131	131	130
25	131	140	138	136
30	119	131	129	127
35	117	134	130	127
40	95	100	102	116

TABLE VI - SERIES VIII

PLANT B
Typical Time - Temperature Relations Through Cross-Section of Beam

Time After Placement of Concrete (hr)	Station 1	Station 2	Station 3	Station 4	Station 5
0	99	98	97	100	96
5	124	127	129	129	132
10	124	134	134	137	137
15	128	135	138	139	140
20	123	127	129	132	133
25	119	120	122	122	-
30	118	122	123	123	-
35	111	113	119	119	-