Steam Curing of Portland Cement At Atmospheric Pressure

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Development of high early strength is desirable to the manufacturers of precast and prestressed concrete units, which often require expensive forms or stress beds. 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 a ages. The research described in this report was prompted by the need to establish realistic controls and specifications for the steam curing of such units manufactured in central plants.

The purpose of the laboratory investigation was to determine some of the relationships between development of concrete strength and various details of the steam curing procedure, such as (a) the interval between mixing of the concrete and beginning of steam curing, (b) the rate of temperature rise of the concrete during steam curing, (c) highest temperature attained by concrete, (d) length of steam curing period, and (e) rate of temperature decrease.

Conclusions incorporated in the standard specifications of the Iowa State Highway Commission include:

1. Initial temperature of the concrete shall not be raised above 100 F for a minimum of 2 hr after the units have been cast.
2. The rate of increase after the 2-hr period shall not exceed 25 F per hr and the maximum temperature attained shall not exceed 150 F.
3. The maximum temperature shall be held for a period sufficient to develop the required strength (4,500 psi for prestressed units.
4. Rate of decrease in temperature shall not exceed 20 F per hr.
5. In all cases units shall be kept covered for a minimum of 24 hr after casting.

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 (a) the time delay between the

mixing of the concrete and the beginning of steam curing, (b) the rate of temperature rise of the concrete during steam curing, (c) the highest temperature attained by the concrete during steam curing, and (d) 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, as follows:

Time (hr)	Temperature (°F)
18	100
42	125
66	150
	175
	200

Series II: Maximum Control

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; and
5. Maximum rate of temperature decrease.

In Series I the first two variables were investigated. 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.

Series III: Two Cements and Two Aggregates

This series was conducted to determine whether the steam curing procedures needed 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 increase water-cement ratio results in a decreased compressive strength. Series IV was to show what different effect, if any, an increase in mixing water would have on concrete subjected to conditions of steam curing.

Series V: Development of Strength in Steam-Cured Concrete

Series V was for the purpose of studying the effect of steam curing on concrete at several ages up to one year. Specimens were cured at three temperatures— 150, 175, and 200 F. They were tested at four ages—28, 90, 180, 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 that form the ends of the specimen. Test specimens made in these molds do not require capping.

Series VI was a laboratory investigation to compare the strength of concrete from test specimens made in the following four types of molds: (a) 4½- by 9-in. vertical, (b) 4½- by 9-in. horizontal, (c) 6- by 12-in. vertical, and (d) 6- by 12-in. 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 could be expected at this high temperature.

Series VIII: Field Studies

Series VIII was designed to study the steam curing procedures in use in two commercial plants, 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 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 2 hr may safely be as much as 50 F per hr. 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 1 day and at age 28 days.
3. Steam curing in the laboratory (see Figs. 1 through 4) 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 hr. The temperature of the atmosphere inside the steam chamber and of the center of the concrete specimens was determined by thermocouples and was automatically recorded every 6 min.
4. Unless otherwise specified, control specimens prepared in the laboratory were cured in a standard moist room maintained at 100 percent humidity and 73.4 ± 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 hr, except in Series I.

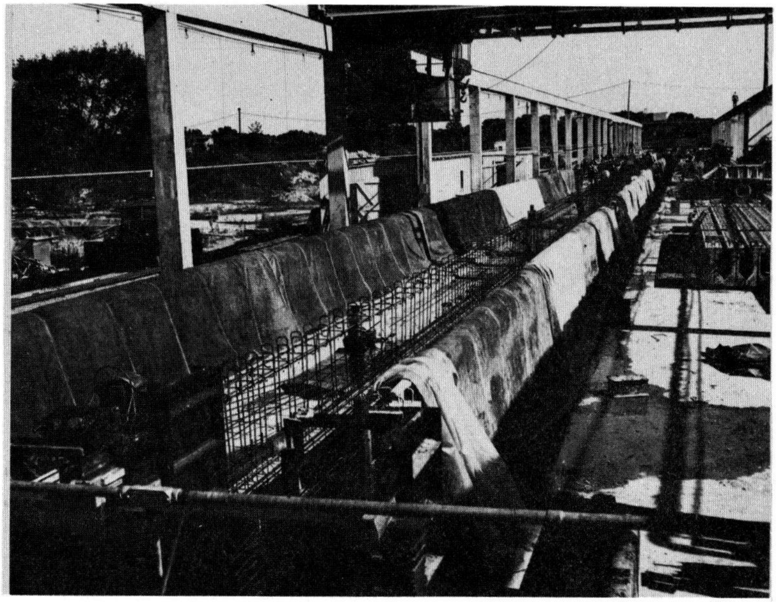


Figure 1. General view of prestressed concrete plant in Iowa.

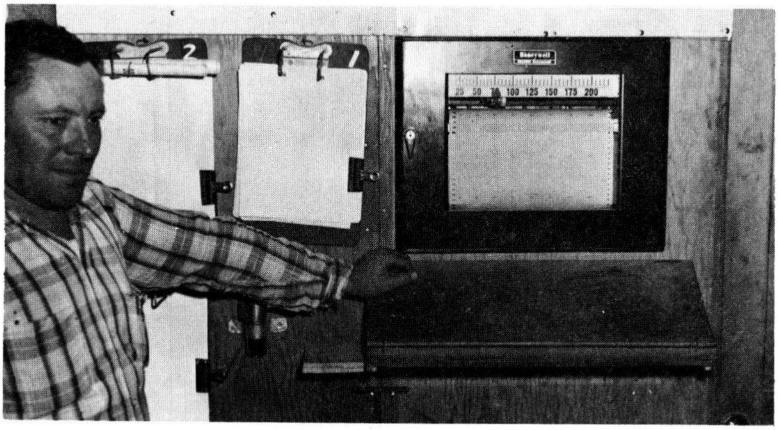


Figure 2. Instruction board where detailed instructions covering all anticipated steam curing situations are posted.

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 ⅝-in., rounded-nose, steel rod. After each lift has been rodded, hammer two sides of the mold 5 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-in., 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.

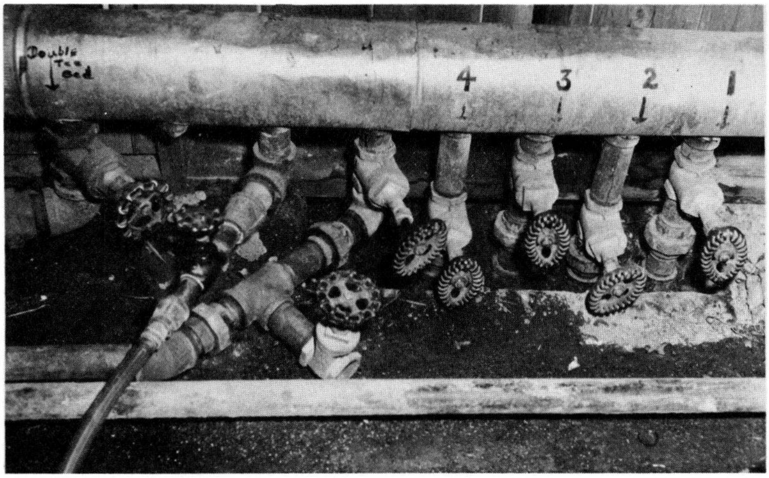


Figure 3. Point of distribution of steam to any part of plant.

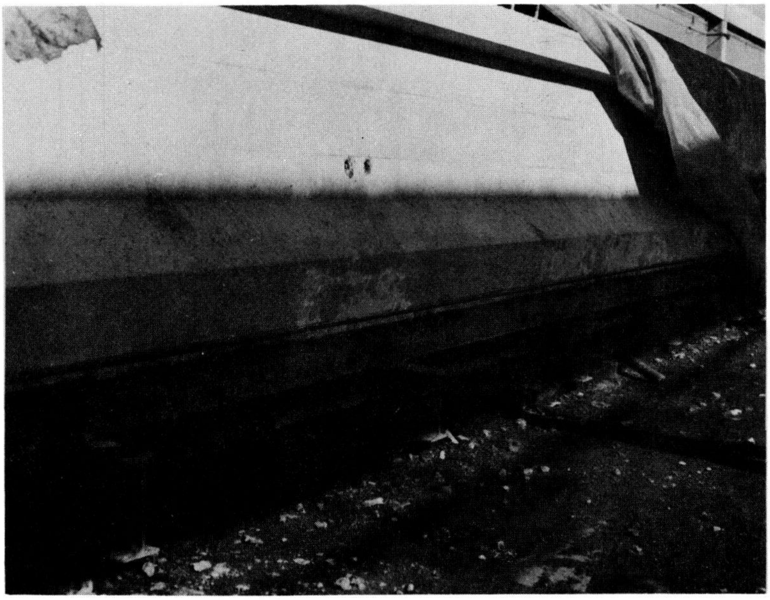


Figure 4. Line center showing beam on casting bed, steam line, and valves to direct steam either way from center.

7. In the laboratory series, where vertical molds were used, the 1-, 2-, and 3-day specimens were capped with sulfur. 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:

1. Steam Chamber (Fig. 5).—This is a concrete block enclosure with a concrete slab roof and floor. The interior is approximately 3 by 5 ft in area and 4 ft high. It

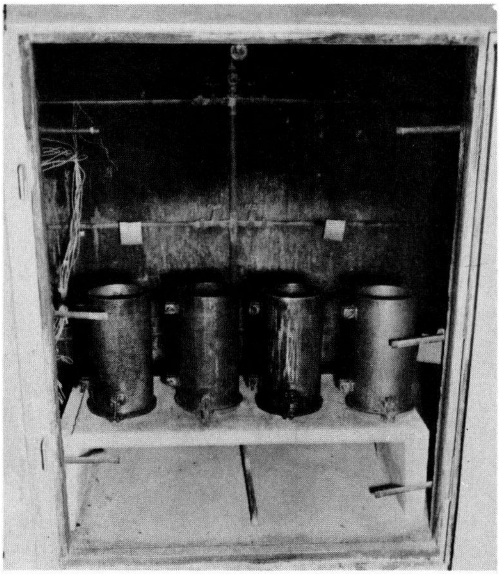


Figure 5. Inside of steam chamber.

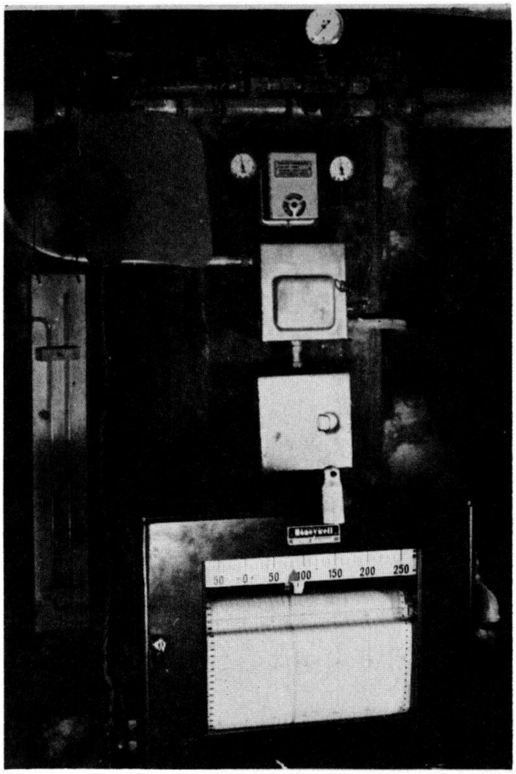


Figure 6. Potentiometer and steaming controls.

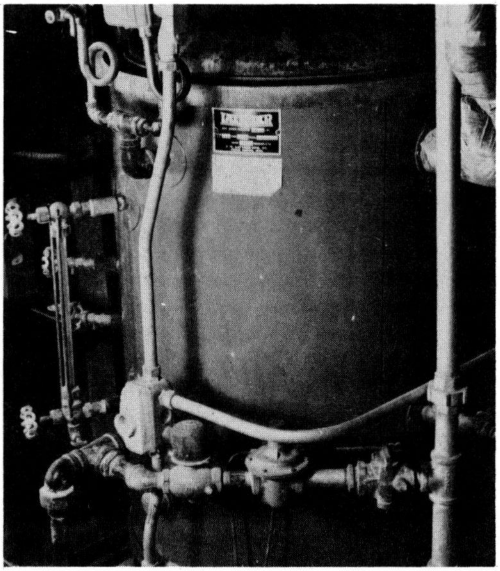


Figure 7. Boiler and boiler controls.

has a 3- 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.

2. Steam Controls (Fig. 6).—The temperature of the chamber was controlled to within 1 F by means of a temperature sensitive valve and thermostat. These controls are operated by air pressure. With this valve, the temperature of the steam chamber could be controlled to any desired temperature from 100 to 240 F.

The rate of temperature rise was controlled by a pressure regulator placed just ahead of the temperature sensitive valve. The rate of temperature rise could be controlled to within 4 F per hr by varying the outlet pressure. The pressure used depended on the rate of temperature rise desired and the load in the steam chamber.

3. Steam Generator (Fig. 7).—Steam was generated in an automatic boiler fitted with a pressure regulator. Normally, the boiler was operated with an internal pressure of approximately 8 psi.

4. Mixer (Fig. 8).—Laboratory specimens were prepared in a batch mixer with counter current mixing. This mixer has a capacity of a 300-lb batch.

5. Temperature Recording Device.— A 12-channel potentiometer was used which recorded the temperature of each of 12 locations every 6 min on a strip chart.

6. 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.

7. Molds (Figs. 9 and 10).—All the specimens made in the laboratory except in Series VI, were cast in vertical 6- by 12-in. 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-in. molds. These molds were made from seamless steel tube and fitted with a machined, cast-iron plate on each end.

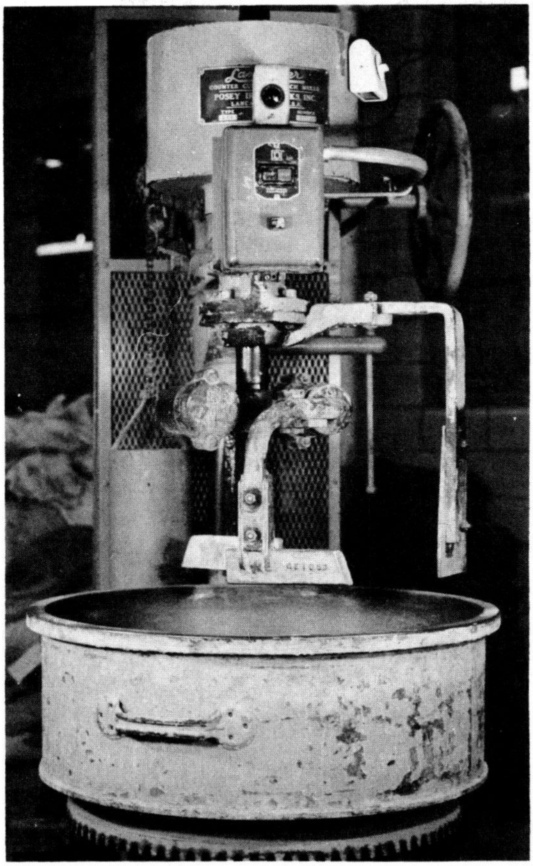


Figure 8. Laboratory mixer.

SERIES I: MINIMUM CONTROL

The steam curing procedure used in Series I represents the minimum control situation (see Fig. 11). As given previously, three steam curing periods and five different curing temperatures were investigated (Table 1).

Materials and Procedures

Cement:

Type	I
Blaine specific surface	3,555
Cube strength (psi):	
3-day	2,035
7-day	3,122

Aggregate:

Sieve	Percent Passing	
	Sand	Gravel
1½-in.		100
1-in.		85
¾-in.		54
½-in.		25
⅜-in.		11
No. 4	100	0.6
No. 8	89	
No. 16	59	
No. 30	22	
No. 50	7.6	
No. 100	2.2	
No. 200	1.4	

Specific gravity:

Cement	3.14
Sand	2.68
Gravel	2.68

Proportions 1:2.16:2.21

Figure 9. Four types of molds used.

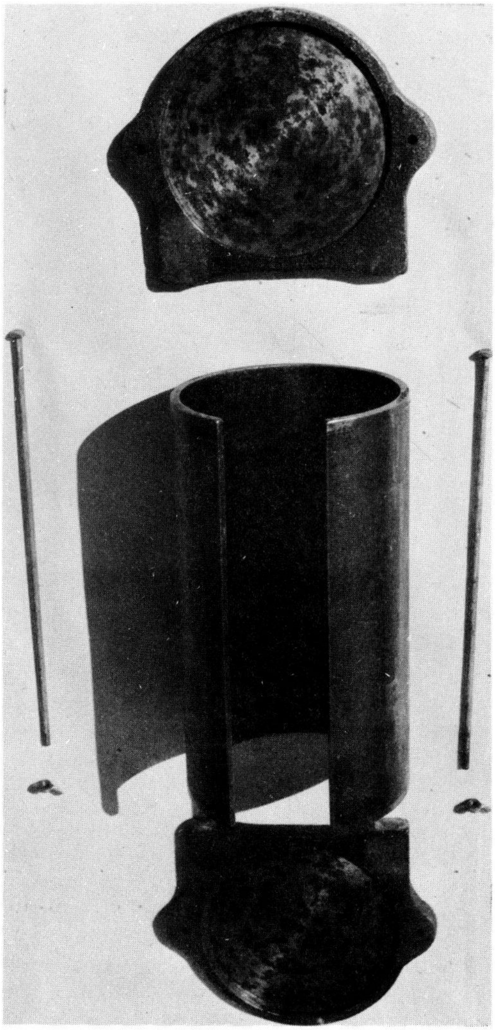


Figure 10. Disassembled horizontal mold.

Water-cement ratio	0.41
Maximum slump	$2\frac{1}{2}$-in.
Mixing	In counter-current batch mixer: Dry mix, 1 min; Wet mix, 3 min
Molds	6- by 12-in. vertical molds
Capping of test specimens	1-2-3 day tests with sulfur, 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

Tests

For each different combination of temperature and length of steaming, approximately 24 specimens were made. Eight specimens were tested at age 1, 2, or 3 days, depending on the length of steaming. Eight were tested at age 7 days, and 8 were tested at age 28 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 specified. However, 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 min delay time between mixing and beginning of steaming and the second batch had no delay at all. Also, the compressive strength of the 28-day specimens that were steam cured at 150 F and above was slightly higher when the rate of temperature rise was lower.

Results

Even with a minimum of control, 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 42 hr of steaming. At temperatures of 175 and 200 F the concrete lost strength by additional steaming past 42 hr. By the end of 18 hr 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 that is moist cured.

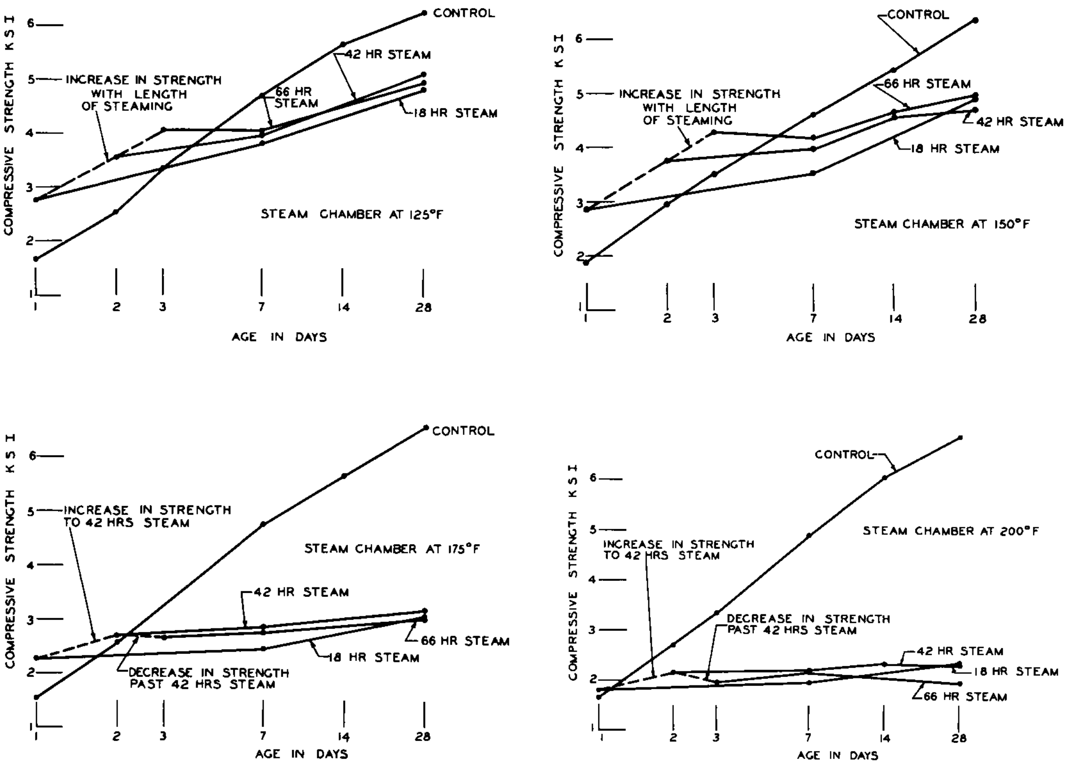


Figure 11. Minimum control of steam curing, Series I.

TABLE 1

ZERO TO ONE-HALF HOUR DELAY TIME

Nominal Curing Temp (°F)	Warming Rate (°F/hr)	Steaming Time (hr)	1-, 2-, 3-Day[1] Strength					7-Day Strength					28-Day Strength				
			Steam-Cured			Control		Steam-Cured			Control		Steam-Cured			Control	
			Psi	No of Tests	%[2]	Psi	No of Tests	Psi	No of Tests	%[2]	Psi	No of Tests	Psi	No of Tests	%[2]	Psi	No of Tests
100	12	18	2,082	6	131	1,587	6	3,897	6	80	4,898	6	4,923	6	74	6,630	6
		42	3,058	6	113	2,705	6	3,645	6	77	4,737	6	4,675	6	68	6,870	6
		66	3,595	6	106	3,397	6	3,872	6	79	4,877	6	4,870	6	76	6,378	6
125	32	18	2,704	8	162	1,672	8	3,793	6	81	4,692	6	4,821	8	79	6,087	8
		42	3,566	12	140	2,538	12	3,944	8	86	4,590	8	4,960	12	77	6,444	12
		66	4,036	8	120	3,368	8	4,058	8	84	4,820	8	4,953	8	77	6,406	8
150	55	18	2,848	8	152	1,874	7	3,534	8	77	4,561	8	4,893	8	79	6,154	8
		42	3,741	10	127	2,954	8	3,986	10	86	4,607	9	4,704	10	73	6,483	9
		66	4,276	8	123	3,461	8	4,175	8	89	4,665	8	4,960	8	78	6,401	8
175	85	18	2,229	10	148	1,502	10	2,470	10	56	4,772	10	3,021	10	46	6,605	10
		42	2,700	10	106	2,540	10	2,832	10	59	4,800	10	3,194	10	48	6,640	10
		66	2,623	8	82	3,201	8	2,740	8	58	4,713	8	3,041	8	47	6,467	8
200	110	18	1,721	10	106	1,628	10	1,939	9	39	4,909	9	2,351	10	34	6,840	10
		42	2,154	10	80	2,707	10	2,203	10	45	4,941	10	2,309	10	34	6,713	10
		66	1,924	8	57	3,355	8	2,132	8	43	4,943	8	1,979	8	28	7,150	8

[1]Age 1 day, 18 hr steaming time, age 2 days, 42 hr, age 3 days, 66 hr
[2]As percent of control strength

The highest strengths at age 1 day were obtained after 18 hr of steaming at temperatures of 125 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.

Specimens cured at 175 and 200 F showed severe swelling. This was believed caused by the expansion of the entrapped air during the time the concrete was still in the plastic state.

SERIES II: MAXIMUM CONTROL

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; and
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	3,485
Cube strength (psi):	
3-day	2,250
7-day	3,250

Aggregate:

Sieve	Percent Passing	
	Sand	Gravel
$1\frac{1}{2}$-in.		100
1-in.		100
$\frac{3}{4}$-in.		64
$\frac{1}{2}$-in.		29
$\frac{3}{8}$-in.		13
No. 4	100	0.7
No. 8	89	
No. 16	58	
No. 30	22	
No. 50	7.7	
No. 100	2.2	
No. 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	$2\frac{1}{2}$-in.
Mixing	In counter-current batch mixer Dry mix, 1 min Wet mix, 2 min Batch undisturbed for 5 min

Mixing (continued)	Second wet mix, 2 min
Molds	6- by 12-in. vertical steel cylinders
Capping of test specimens	1-day tests with sulfur 28-day tests with neat cement
Curing:	
Steam	In steam chamber 18 hr, then in moist room until tested
Control	In moist room until tested

SERIES IIA: EFFECT OF RATE OF COOLING

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 to determine the effect of rapid cooling on the development of strength of the concrete after the initial steam cure period (see Table 2).

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

In the first part, 12 specimens were cast on each of three days. Eight specimens were placed in the steam chamber and steamed 18 hr at 150 F. The remaining 4 specimens were placed in the moist room immediately after being cast. These were the control specimens. After the steaming was complete, 4 of the steam-cured specimens were placed in the moist room, and 4 were placed in a freezer maintained at -20 F. The cooling time to reach freezing was 2.5 hr. The cooling time to -20 F was 11 hr. The maximum rate of temperature drop, which occurred during the first hour in the freezer, was 72 F per hr. After 48 hr in the freezer the specimens were moved to the moist room. The warming time to 32 F was 2 hr. The maximum rate of temperature rise, which occurred during the first hour in the moist room, was 38 F per hr. The specimens that were moved directly from the steam chamber to the moist room cooled to 74 F in about 4 hr. The maximum rate of cooling of these specimens was 38 F per hr.

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

In the second part of this series, 12 specimens were cast on each of three days. Eight were placed in the steam chamber and steamed 18 hr at 150 F. The remaining 4 specimens were placed immediately after casting, in the moist room as control specimens. After the steaming was complete, 4 of the steam-cured specimens were placed in the moist room, and 4 were placed in the freezer maintained at 25 F. The cooling time to freezing was 6 hr. The maximum rate of cooling was 43 F per hr. After 24 hr in the freezer, the specimens were moved to the moist room. The warming time to constant temperature was about 4 hr. The maximum rate of temperature rise was 30 F per hr. The specimens that were moved directly from the steam chamber to the moist room cooled to 75 F in about 4 hr.

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

TABLE 2

EFFECT OF RAPID COOLING ON DEVELOPMENT OF STRENGTH

Condition	Hours Steamed	Temp Steamed (°F)	Delay Time (hr)	Warming Rate (°F/hr)	7-Day Strength			28-Day Strength		
					Psi	No of Tests	Steam-Cured[1] (%)	Psi	No of Tests	Steam-Cured (%)
Control					5,158	12	100	6,935	12	100
Frozen 24 hr at +25 F	18	150	0	60	3,713	6	72	4,490	6	65
Frozen 48 hr at -20 F	18	150	0	60	3,327	6	65	4,568	6	66
Steamed only	18	150	0	60	3,566	12	69	4,614	12	67

[1]As percent of control strength

Results

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.

SERIES IIB: EFFECT OF DELAY PERIOD

Tests

The main factor in Series IIB was the delay time before steaming was started (Table 3). Four steaming temperatures were used: 125, 150, 175, and 200 F. All specimens subjected to steaming were steamed a total of 18 hr. The delay times were 1, 3, and 6 hr. Test results from Series I provided additional information on delay times of 0.0 and 0.5 hr (Table 4).

TABLE 3

TEST RESULTS, SERIES IIB

Nominal Curing Temp (°F)	Warming Rate (°F/hr)	Steaming Time (hr)	Delay Time (hr)	1-Day Strength					28-Day Strength				
				Steam-Cured			Control		Steam-Cured			Control	
				Psi	No of Tests	%[1]	Psi	No of Tests	Psi	No of Tests	%[1]	Psi	No of Tests
125	34	18	1 0	3,003	8	217	1,380	4	5,574	8	81	6,878	4
			3 0	3,195	8	217	1,470	4	5,753	8	88	6,590	4
			6 0	3,321	8	210	1,585	4	6,276	8	91	6,888	4
150	50	18	1 0	2,861	8	220	1,300	4	4,805	8	73	6,584	4
			3 0	3 506	8	271	1,292	4	5,698	8	87	6,535	4
			6 0	3,393	8	262	1,295	4	5,969	8	89	6,710	4
175	50	18	1 0	2,150	10	188	1,146	5	3,238	10	53	6,147	5
			3 0	3,165	10	283	1,120	5	4,623	10	76	6,098	5
			6 0	3,228	10	265	1,220	5	4,902	10	78	6,302	5
200	80	18	1 0	2,988	8	180	1,660	4	3,559	8	50	7,072	4
			3 0	3,868	8	237	1,630	4	4,885	8	68	7,215	4
			6 0	3,785	8	220	1,722	4	4,996	8	69	7,235	4

[1]As percent of control strength

TABLE 4

INFORMATION FROM SERIES I ON DELAY TIMES

Nominal Curing Temp[1] (°F)	Warming Rate (°F/hr)	Delay Time (hr)	1-Day Strength					28-Day Strength				
			Steam-Cured			Control		Steam-Cured			Control	
			Psi	No of Tests	%[2]	Psi	No of Tests	Psi	No of Tests	%[2]	Psi	No of Tests
100	18	0 0	2,030	3	132	1,533	3	4,910	3	74	6,647	3
		0 5	2,133	3	130	1,640	3	4,940	3	75	6,613	3
125	32	0 0	2,670	4	152	1,757	4	4,885	4	79	6,187	4
		0 5	2,737	4	169	1,612	4	4,977	4	83	5,967	4
150	55	0 0	2,715	4	145	1,875	4	4,630	4	74	6,285	4
		0 5	2,980	4	159	1,873	4	5,155	4	86	6,022	4
175	85	0 0	2,152	5	147	1,460	3	3,014	5	45	6,652	5
		0 5	2,306	5	149	1,544	5	3,028	5	46	6,558	5
200	110	0 0	1,538	5	96	1,604	5	2,184	5	33	6,690	5
		0 5	1,904	5	115	1,652	5	2,518	5	36	6,990	5

[1]For 18 hr steaming time
[2]As percent of control strength

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 PM. Steaming was then started and continued until 8:30 AM 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 ages 24 and 28 days.

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 (see Fig. 12). The higher steam curing temperatures require longer delay periods to produce the maximum strength. At 125 F about 1-hr delay, and at 150 F and above about 3-hr delay appear to be optimum. At age 1 day the highest strength was obtained by steaming at 175 F after a 3-hr delay. At age 28 days the specimens that had a 6-hr delay period had slightly higher strengths than those that had only a 3-hr delay. At age 28 days the highest strengths were produced with temperatures of 125 and 150 F after a 6-hr delay before steaming. The results of these tests agree very closely with those obtained from similar work done by the U.S. Bureau of Reclamation. It concludes in its report, "Early Strength of Concrete as Affected by Steam Curing Temperatures," that "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."

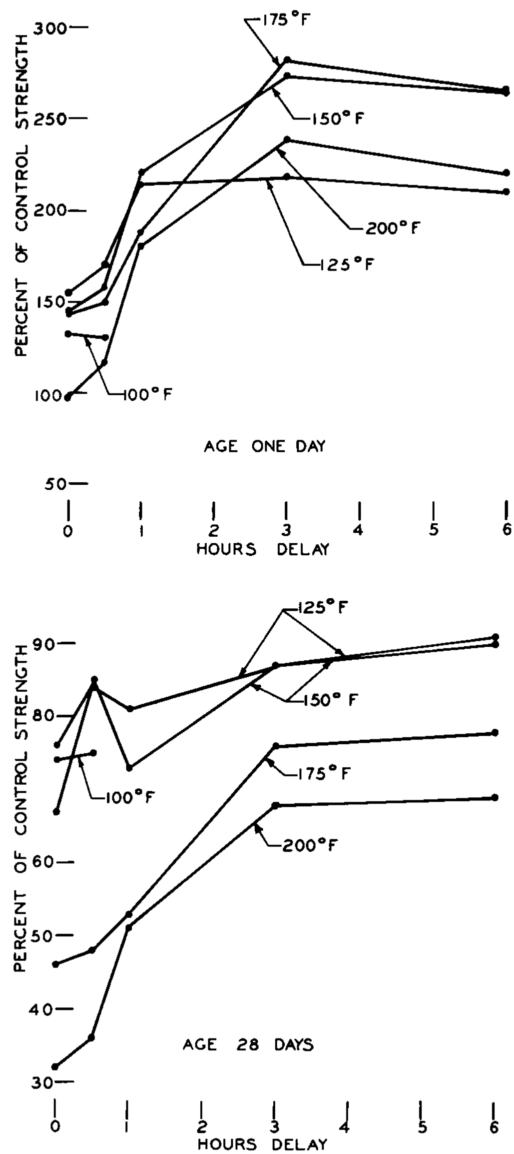


Figure 12. Maximum control of steam curing, effect of delay time, Series IIB.

There was only one difference between the curing procedure used in Series I and that used in Series IIB— the delay time. There is, however, a very significant difference in the compressive strengths of the concrete. The concrete with the delay period has the higher strength. The magnitude of this difference is dependent on the length of the delay period and the temperature at which the concrete was cured.

SERIES IIC· MAXIMUM CONTROL

Tests

This part of Series II was set up to show the effect of maximum control of steam curing procedures (see Fig. 13 and Table 5). That is, the rate of temperature rise, the delay time, the length of steaming, and the rate of cooling were all controlled as

TABLE 5

EFFECT OF MAXIMUM CONTROL OF STEAM CURING PROCEDURES

Curing Temp.[1] (°F)	Warming Rate (°F/hr)	Delay Time (hr)	1-Day Strength			28-Day Strength		
			Psi	No. of Tests	Steam-Cured (%)[2]	Psi	No. of Tests	Steam-Cured (%)[2]
125	28	0	2,864	8	167	4,838	8	69
		2	3,271	8	191	5,640	8	81
		4	3,400	8	198	6,108	8	88
	Control	—	1,713	12	100	6,965	12	100
	33	0	2,883	8	156	4,845	8	73
		2	3,396	8	183	5,660	8	85
		4	3,506	8	189	5,945	8	90
	Control	—	1,853	11	100	6,628	12	100
	39	0	2,920	8	164	4,554	8	67
		2	3,219	8	180	5,363	8	79
		4	3,459	8	194	5,961	8	88
	Control	—	1,783	12	100	6,764	12	100
150	22	0	3,484	8	205	5,619	8	78
		2	3,924	8	231	6,584	8	92
		4	3,928	8	231	6,610	8	92
	Control	—	1,697	12	100	7,176	12	100
	31	0	3,281	8	202	5,493	8	77
		2	3,995	8	246	6,380	8	90
		4	3,871	8	238	6,551	8	92
	Control	—	1,624	12	100	7,099	12	100
	42	0	3,501	8	192	5,393	8	75
		2	4,011	8	220	6,460	8	89
		4	3,993	8	219	6,618	8	91
	Control	—	1,823	12	100	7,228	12	100
175	30	0	3,603	7	196	4,974	8	70
		3	4,129	7	224	6,056	8	85
		6	4,181	8	227	6,303	8	88
	Control	—	1,841	12	100	7,122	12	100
	40	0	3,710	7	209	4,804	8	69
		3	4,360	8	245	6,029	8	87
		6	4,101	8	231	5,809	8	84
	Control	—	1,777	12	100	6,943	12	100
	53	0	3,433	8	199	4,328	6	60
		3	4,320	8	250	5,990	8	83
		6	4,160	5	241	6,195	8	86
	Control	—	1,724	11	100	7,172	11	100
200	44	0	3,419	8	179	4,416	8	65
		3	4,045	8	212	5,173	8	76
		6	3,823	6	200	5,082	6	75
	Control	—	1,907	11	100	6,781	11	100
	56	0	3,054	8	167	3,986	7	59
		3	4,026	8	221	5,208	8	77
		6	3,770	8	207	5,075	8	75
	Control	—	1,823	12	100	6,789	12	100

[1]For 18 hr steaming time.
[2]As percent of control strength.

closely as possible. Four steaming temperatures were used—125, 150, 175, and 200 F. Three different delay periods were used—at 125 and 150 F, 4.0-, 2.0-, and 0.0-hr delays; at 175 and 200 F, 6.0-, 3.0-, and 0.0-hr delays. The rate of temperature rise was varied to determine the optimum rate. The maximum warming rates used are given in Table 6.

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 PM. At this time a controlled quantity of steam was turned into the

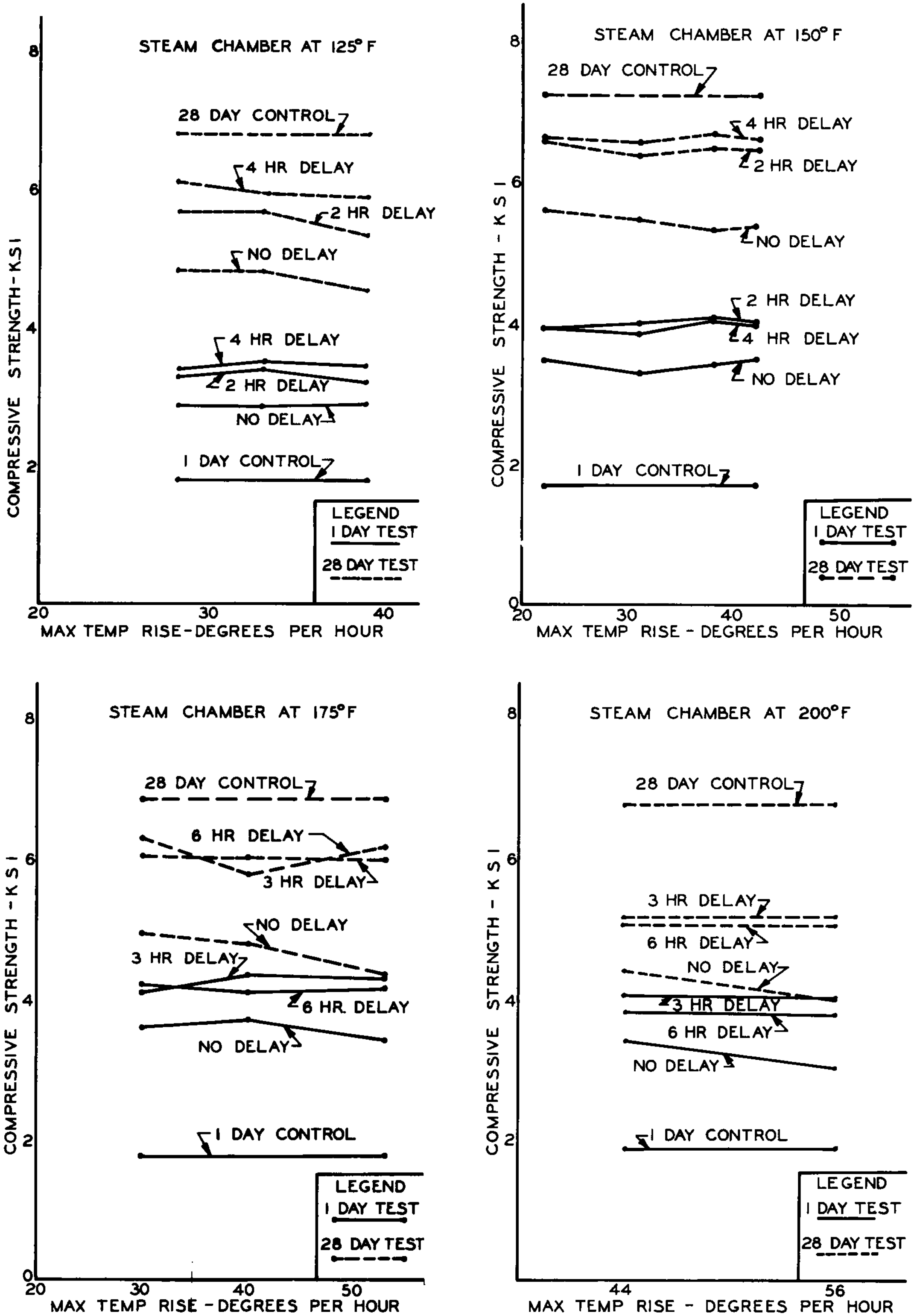


Figure 13. Maximum control, Series IIC.

TABLE 6

MAXIMUM WARMING RATES

Degrees per Hour for			
125 F	150 F	175 F	200 F
28	22	30	44
33	31	40	56
	38	53	
	42		

steam chamber. The total length of steaming was 18 hr. After steaming was complete, the specimens were cooled at 20 F per hr. 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 hr and 28 days.

Results

If the primary consideration is to be 1- or 2-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.

In considering the case where maximum early-age strength is desired, 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 2-hr delay should be used. Above 150 F, 3 hr 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 hr gave the best results. At 150 F, 31 F per hr was best. At 175 F, 40 F per hr gave the highest strengths of the series. And at 200 F, 44 F per hr 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 on the steaming temperature used. In general, the higher the steaming temperature, the higher the optimum rate of temperature rise.

In considering the case where the maximum 28-day strength along with a high early strength is desired, 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 4 hr when the concrete was steamed at 125 and 150 F and a delay of 6 hr when the concrete was steamed at 175 and 200 F.

The rate of temperature rise appears to have little effect on the 28-day strength if a delay of 4 hr 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 4-hr delay and at 175 F after a 6-hr delay.

SERIES III: TWO CEMENTS AND TWO AGGREGATES

This series was conducted 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 employed (see Fig. 14 and Table 7).

Materials and Procedures

Cement:

	Brand A	Brand B
Type	I	I
Blaine specific surface	3,485	2,820
Cube strength (psi):		
3-day	2,250	2,000
7-day	3,200	3,090

Aggregate:

Sieve	Percent Passing		
	Sand	Gravel	Limestone
1-in.		100	100
¾-in.		64	67
½-in.		29	35
⅜-in.		13	17
No. 4	100	0.7	1.7
No. 8	92		
No. 16	67		
No. 30	32		
No. 50	11		
No. 100	1.7		
No. 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 in.
Mixing	In counter-current batch mixer Dry mix, 1 min Wet mix, 2 min Batch undisturbed for 5 min Second mix, 2 min
Molds	6- by 12-in. vertical steel cylinders with machined base plates
Capping of test specimens	1-day tests with sulfur 28-day tests with neat cement
Curing:	
Steam	In steam chamber 18 hr, then in moist room until tested
Control	In moist room until tested

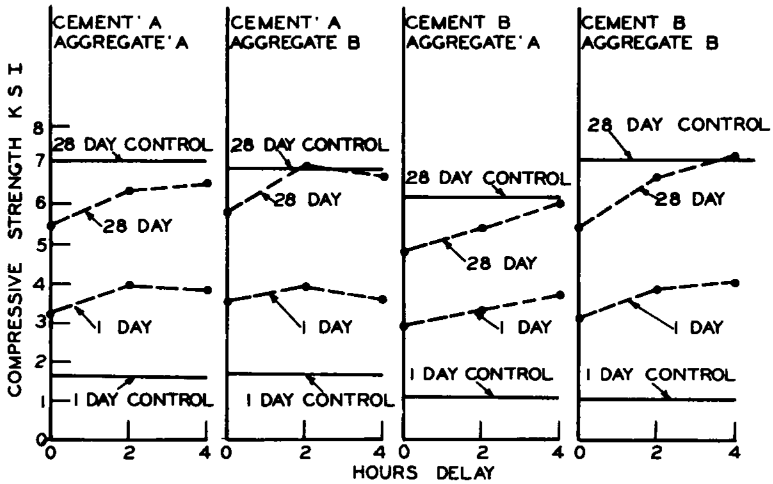


Figure 14. Two cements and two aggregates, Series III.

Tests

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

TABLE 7

COMPARISON OF TWO CEMENTS AND TWO AGGREGATES, 150 F FOR 18 HOURS

Cement	Coarse Aggregate	Delay Time (hr)	1-Day Strength					28-Day Strength				
			Steam-Cured			Control		Steam-Cured			Control	
			Psi	No. of Tests	%[1]	Psi	No of Tests	Psi	No. of Tests	%[1]	Psi	No of Tests
A	G	0	3,281	8	202	—[2]	—	5,493	8	77	—[2]	—
		2	3,995	8	246	—[2]	—	6,380	8	90	—[2]	—
		4	3,871	8	238	1,624	12	6,551	8	92	7,099	12
	LS	0	3,548	6	214	—[2]	—	5,828	6	84	—[2]	—
		2	3,960	6	239	—[2]	—	7,000	6	101	—[2]	—
		4	3,633	8	219	1,659	10	6,736	8	97	6,908	10
B	G	0	2,923	8	268	—[2]	—	4,819	8	78	—[2]	—
		2	3,324	8	305	—[2]	—	5,429	7	87	—[2]	—
		4	3,728	8	342	1,091	12	6,064	8	98	6,206	12
	LS	0	3,169	8	300	—[2]	—	5,434	8	76	—[2]	—
		2	3,890	4	368	—[2]	—	6,703	4	94	—[2]	—
		4	4,069	8	385	1,057	10	7,240	8	101	7,147	10

[1]As percent of control strength.
[2]All delays

moist room. The time at which each batch was mixed was such that the desired delay time had elapsed at 2:30 PM. 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 hr and 28 days.

Results

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

The length of the delay period, as long as it is in the range of about 2 to 6 hr is of only small importance. The optimum delay is dependent on the curing temperature and the materials in the concrete.

The changes in the steam curing procedure necessary to produce maximum strength when the materials are changes are only minor.

SERIES IV: WATER-CEMENT RATIO

It is generally accepted that an increased water-cement ratio results in a decreased compressive strength. Series IV was to show what different effect, if any, an increased water-cement ratio might have on concrete subjected to conditions of steam curing (see Table 8).

Materials and Procedures

Cement:
- Type — I
- Blaine specific surface — 2,820
- Cube strength (psi):
  - 3-day — 2,000
  - 7-day — 3,090

Aggregate:

Sieve	Percent Passing	
	Sand	Limestone
1-in.		100
$\frac{3}{4}$-in.		67
$\frac{1}{2}$-in.		35
$\frac{3}{8}$-in.		17
No. 4	100	1.7
No. 8	92	
No. 16	67	
No. 30	32	
No. 50	11	
No. 100	1.7	
No. 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: $2\frac{1}{2}$ in. (W/C = 0.416); $5\frac{1}{2}$ in. (W/C = 0.456)

Mixing: In counter-current batch mixer
- Dry mix, 1 min
- Wet mix, 2 min

Batch undisturbed for 5 min
Second mix, 2 min

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

Capping of test specimens: 1-day tests with sulfur; 28-day tests with neat cement

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

Tests

The concrete was steam cured at temperatures of 150, 175, and 200 F. Delay times between casting and steaming of 2, 4, and 6 hr were used at each temperature. At each combination of steam curing procedures, concrete was mixed at a 2- and a 5-in. slump. The only difference between the two mixes was the quantity of mixing water.

All specimens were steamed 18 hr. The maximum rate of temperature rise of the concrete was held as near 30 F per hr as possible for a steaming temperature of 150 F,

TABLE 8

EFFECT OF WATER-CEMENT RATIO

Curing Temp[1] (°F)	Warming Rate (°F/hr)	Delay Time (hr)	Water-Cement Ratio = 0 416: 1-Day Strength Psi	No of Tests	Steam-Cured[2] (%)	28-Day Strength Psi	No. of Tests	Steam-Cured[2] (%)	Water-Cement Ratio = 0 456: 1-Day Strength Psi	No of Tests	Steam-Cured[2] (%)	28-Day Strength Psi	No of Tests	Steam-Cured[2] (%)
150	35	2	3,860	8	359	6,725	8	91	3,205	6	383	5,800	9	94
		4	4,200	8	391	7,166	8	97	3,268	8	390	6,078	8	99
		6	—	—	—	7,298	6	99	3,146	8	376	5,900	10	96
Control	—	—	1,076	10	100	7,401	10	100	836	10	100	6,146	12	100
175	40	2	3,861	6	341	5,382	6	74 5	3,690	6	435	5,435	6	87
		4	4,218	8	372	6,472	8	90	3,813	6	450	5,628	6	90
		6	4,170	8	368	6,580	8	91	3,598	4	424	5,667	6	90.5
Control	—	—	1,131	11	100	7,222	11	100	849	8	100	6,267	9	100
200	38	2	4,000	8	361	5,140	8	69 5	3,474	8	437	4,826	8	74
		4	4,350	6	393	5,500	8	74	3,502	6	441	5,025	8	77
		6	3,949	8	357	5,549	8	75	3,433	8	432	4,874	8	75
Control	—	—	1,106	11	100	7,396	12	100	795	11	100	6,507	12	100

[1]For 18 hr steaming time
[2]As percent of control strength

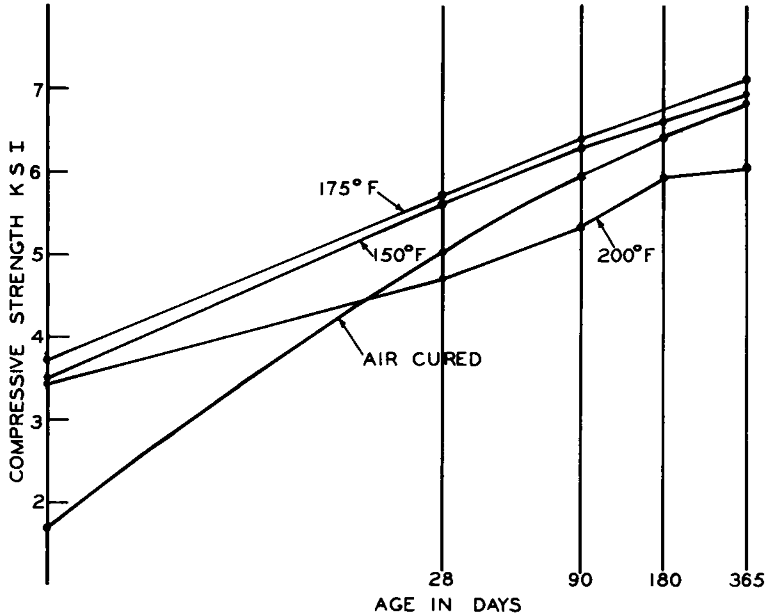


Figure 15. Development of strength in steam-cured concrete, Series V.

35 F per hr for 175 F, and 40 F per hr 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 hr or less.

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 PM. 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 hr and 28 days.

Results

The results were very nearly as expected; that is, the concrete with the higher W/C had lower strength. At age 1 day the higher W/C concrete showed less reduction in strength when steamed at 175 F than when steamed at either 150 or 200 F. In most cases the higher W/C concrete showed a greater reduction in strength at age 28 days than at age 1 day.

TABLE 9

STRENGTH AT AGES 28 TO 365 DAYS

Curing Temp[1] (°F)	Warming Rate (°F/hr)	Delay Time (hr)	Test Age (days)	Steam-Cured Strength			Control Strength	
				Psi	No of Tests	%[2]	Psi	No of Tests
150	25	2	28	5,606	8	113	4,956	8
			90	6,443	8	108	5,969	8
			180	6,588	8	107	6,183	8
			365	6,955	8	104	6,713	8
175	29	2	28	5,710	7	116	4,933	7
			90	6,330	7	108	5,857	7
			180	6,483	7	100	6,467	7
			365	7,117	7	103	6,883	7
200	36	2	28	4,733	8	90	5,284	8
			90	5,366	8	88	6,079	8
			180	5,981	8	91	6,605	8
			365	6,070	8	86	7,073	8

[1]For 18 hr steaming time
[2]As percent of control strength

SERIES V: DEVELOPMENT OF STRENGTH IN STEAM-CURED CONCRETE

Series V was for the purpose of studying the effects of steam curing on concrete at several ages up to one year (see Fig. 15). Specimens were cured at three temperatures—150, 175, and 200 F—and tested at four ages—28, 90, 180, and 365 days (Table 9).

In this series all specimens were stored outdoors after the first 28 hr. 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: 3,485
- Cube strength (psi):
  - 3-day: 2,250
  - 7-day: 3,200

Aggregate:

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

Mixing: In counter-current batch mixer
- Dry mix, 1 min
- Wet mix, 2 min

Batch undisturbed for 5 min

Second mix, 2 min

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

Capping of test specimens: All tests with neat cement

Curing:
- Steam: In steam chamber 18 hr, then outdoors until 7 days before testing.
- Control: In laboratory air 28 hr, then outdoors until 7 days before testing; in moist room 7 days before testing.

Tests

On each day two batches of eight specimens each were cast. They were completed 2 hr 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 quantity 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 hr for a steaming temperature of 150 F, 30 F per hr for 175 F, and 35 F per hr for 200 F. Total steaming time was 18 hr. The cooling of the specimens was held as near 20 F per hr as possible. At age about 28 hr the steam-cured specimens were stored upright on the ground outdoors.

The cure of control specimens consisted of standing in laboratory air, covered with plastic, for about 28 hr, 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.

TABLE 10

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-in vert	8,541	30	2 3	108
	4½- by 9-in horiz	8,128	30	2 6	103
	6- by 12-in vert	7,894	30	2 6	100
	6- by 12-in horiz	7,658	30	3 7	97
B	4½- by 9-in vert	3,290	30	7 6	103
	4½- by 9-in horiz	3,089	30	5 4	97
	6- by 12-in vert	3,201	30	7 8	100
	6- by 12-in horiz	2,964	30	5 9	93

TABLE 11

EFFECT OF TEMPERATURE ON STRENGTH

Group	Temp at Test (°F)	Age at Test (hr)	Cooling Time (hr)	Avg Str (psi)	No of Tests	Str at 120 F As Percent of 80 F Str
1	150	20	0	3,481	20	96 0
						88 5
	80	21	1	3,625	12	
		23	3	3,936	8	
2	150	20	0	3,214	16	93 2
		21	0	3,276	16	95 0
	80	21	1	3,447	16	

Results

In this series the specimens steam cured at 150 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.

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-in. concrete specimens that 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 4,500 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-in. 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.

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 comparing the strength of concrete as determined from test specimens made in four types of molds (Table 10).

Two groups of tests were made—the first using 8,000-psi concrete; the second using 3,000-psi concrete.

The specimens made in the 6- by 12-in. 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 can be compared. Concrete test specimens prepared in 6- by 12-in. horizontal molds will have an indicated strength that is slightly lower than the strength of specimens containing concrete from the same batches, but prepared in vertical molds.

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 (see Table 11).

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 hr 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 1 hr, and with the other system they were cooled to 80 F in 3 hr.

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 hr. 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 1 hr. 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.

Results

From the results it appears that the temperature of the concrete at the time of testing has 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.

SERIES VIII: FIELD STUDIES

Series VIII was designed 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, 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 are referred to as Plant A and Plant B (see Table 12).

Materials and Procedures

PLANT A

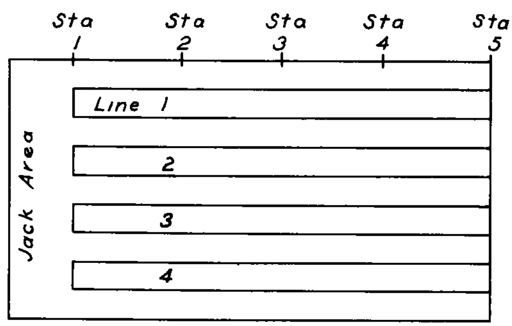
Cement:	
Type	I
Blaine specific surface	3,450
Cube strength (psi):	
3-day	2,750
7-day	3,560

TABLE 12

TEST RESULTS FROM TWO PRESTRESSED CONCRETE PLANTS

Station	2-Day Strength		28-Day Strength				
			Steam-Cured			Control	
	Psi	No of Tests	Psi	No of Tests	(%)[1]	Psi	No of Tests
Plant A							
1	5,185	15	6,239	19	86	7,268	13
2	5,265	16	6,206	17	87	7,146	13
3	5,090	17	6,073	17	89	6,858	13
4	5,176	15	6,041	17	87	6,973	12
5	4,958	18	5,964	14	87	6,853	12
Plant B							
1	4,231	12	5,168	12	82	6,274	6
2	4,748	25	5,748	24	90	6,375	12
3	4,509	27	5,593	26	91	6,144	13
4	4,570	26	5,670	27	89	6,355	13

[1]As percent of control strength



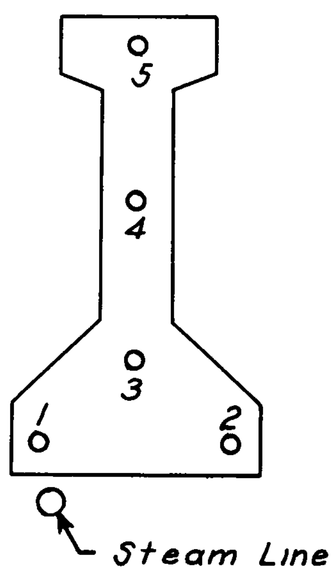


Figure 16. Distribution of thermocouples used in field study both along line and through cross-section.

TABLE 13

TYPICAL TIME-TEMPERATURE RELATIONS ALONG LENGTH OF LINE

Hours After Placement of Concrete	Temperature (°F)								
	Plant A					Plant B			
	Station 1	Station 2	Station 3	Station 4	Station 5	Station 1	Station 2	Station 3	Station 4
0	80	80	82	82	79	95	97	96	97
5	125	129	120	132	120	121	132	132	128
10	154	157	146	161	153	123	132	135	131
15	156	159	154	163	155	130	139	141	137
20	150	156	144	160	150	122	131	131	130
25	136	146	139	146	133	131	140	138	136
30	132	139	127	148	123	119	131	129	127
35	116	119	116	126	104	117	134	130	127
40	90	88	90	91	80	95	100	102	116

TABLE 14

TYPICAL TIME-TEMPERATURE RELATIONS THROUGH CROSS-SECTION OF BEAM, SERIES VIII

Hours After Placement of Concrete	Temperature (°F)									
	Plant A					Plant B				
	Station 1	Station 2	Station 3	Station 4	Station 5	Station 1	Station 2	Station 3	Station 4	Station 5
0	80	80	81	83	82	99	98	97	100	96
5	131	140	126	136	148	124	127	129	129	132
10	166	173	171	173	175	124	134	134	137	137
15	166	172	166	171	175	128	135	138	139	140
20	135	132	141	140	133	123	127	129	132	133
25	159	161	160	168	155	119	120	122	122	—
30	144	141	148	152	140	118	122	123	123	—
35	122	114	126	126	118	111	113	119	119	—
40	101	92	104	103	98	—	—	—	—	—

Aggregate:

Sieve	Percent Passing	
	Sand	Gravel
1-in.		100
¾-in.		82
⅜-in.	100	33
No. 4	97	2
No. 8	78	0
No. 16	60	
No. 30	35	
No. 50	10	
No. 100	1.2	
No. 200	0.4	

Specific gravity:
- Cement: 3.14
- Sand: 2.68

Specific gravity (continued):
- Gravel: 2.68

Proportions: 1:1.93:2.35

Water-cement ratio: 0.35

Maximum slump: 3 in.

Pozzolith type 3: ¼ lb per sack cement

Mixing: In transit-mix trucks

Molds: 6- by 12-in. 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: I
- Blaine specific surface: 3,400
- Cube strength (psi):
  - 3-day: 2,400
  - 7-day: 3,500

Aggregate:

Sieve	Percent Passing	
	Sand	Gravel
1-in.		100
3/4-in.	100	93
3/8-in.	94	37
No. 4	90	5
No. 8	72	2
No. 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 in.
Pozzolith type 8	1/4 lb per sack cement
Mixing	In transit-mix trucks
Molds	6- by 12-in. 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

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 cured with the bridge beams. 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 3 in. deep in the top of the beam at each of five stations along the length of the line (see Fig. 16 a). A set of typical temperatures is summarized in Table 13.

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 16 b. Typical results are summarized in Table 14.

At the end of the steaming cycle, which was age about 45 hr, 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 13 and Table 14.

Results

Plant A.—After the beams were cast a period of 2 hr was allowed to elapse before the steam was turned onto the line. The increase in temperature during the first 2 hr was due only to the heat of hydration. In only one case the temperature reached 100 F before age 2 hr. The maximum rate of temperature rise of the concrete varied from 12 to 39 F per hr. The maximum temperatures attained during the several cycles recorded varied from 151 to 173 F.

After about 15 hr of steaming, the canvas covers were removed and the forms were stripped off the beams. The maximum temperature drop during stripping varied from 16 to 40 F. The time required for stripping was about 2.5 hr. To reduce this temperature drop, it was suggested that only one-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 hr. The canvas covers were left in place for about 12 hr after the steam was shut off to control the cooling rate. The cooling rate varied from 3 to 11 F per hr.

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 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 3 in. 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 to 13 F per hr. The maximum temperature attained during the several cycles recorded varied from 129 to 165 F. The normal average temperature was about 130 F.

After about 15 hr of steaming, the canvas covers were removed and the forms were stripped off the beams. The maximum temperature drop during stripping varied from 8 to 12 F. The time required for stripping was about 3 hr. In most cycles the steam was turned off when any work was being done on an adjacent line. The total time of interruption of steaming was from 4 to 9 hr. 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 hr.

The control of distribution of steam along the line was good. The compressive strengths at station 1 show somewhat lower than at the other three stations. This is explained by the fact that the concrete at station 1 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 were 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.