FINAL REPORT

RADIANT HEAT CURING OF CONCRETE

by

Michael M. Sprinkel
Research Scientist

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

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SUMMARY

Comparisons were made of the properties of concrete mixtures cured with radiant heat and mixtures cured with low pressure steam and of the curing conditions. The concretes were prepared and cured at two plants which produce precast, prestressed concrete products and in the Research Council laboratory. The results indicate that radiant heat curing used in combination with a membrane curing compound can produce an acceptable concrete. Compressive strength, freeze-thaw performance, and permeability to chloride ions were not significantly different for concretes cured with the two curing methods.

The curing achieved at the plant with radiant heat was found to be much less uniform than that with low pressure steam but was adequate when proper precautions were exercised. Therefore, it is recommended that beds should be suitably enclosed and that heat pipes be properly positioned to minimize temperature differentials throughout the member. Also, cylinders should be cured at the same temperature used in curing the least mature part of the member.

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INTRODUCTION

Accelerated curing of concrete is being achieved with radiant heat rather than steam for an increasing number of precast products because the former is more economical and more energy efficient and results in a drier and thus a cleaner and safer production facility.(1)

With radiant heat curing the heat source is typically located near the bottom of the concrete member, and the heat comes from hot oil, hot water, or steam that circulates through pipes or cavities in the form and radiates through the concrete member. A membrane curing compound, or wet burlap and water spray, is used to prevent the loss of moisture from the exposed concrete surfaces. Since the temperature within a concrete member is governed by the proximity of the concrete to the heat source, the member is subjected to a temperature differential from top to bottom.

With steam curing, there is little temperature differential since live steam surrounds the member and thus provides a reasonably uniform environment. Cylinders can be cured at most any location along the bed and satisfy the requirements of Section 405.09(g) of the Road and Bridge Specifications, which state that "concrete test cylinders shall be subjected to the same curing conditions as the members."(2) On the other hand, when radiant heat curing is used, the proper location of the test cylinders is not so obvious. When a representative location cannot be found, precasters may use a special mold to cure the test cylinders,(3) and the temperature of the cylinders is controlled by a thermocouple in the concrete member. The proper location for the thermocouple is a matter of debate. Some people believe it should be located where the concrete is least mature at the time the forms are stripped, so that the rest of the member will have a compressive strength thought to be equal to or greater than that of the cylinders. Others believe it should be located in concrete having a maturity representative of the average maturity of the concrete in the member at the time the forms are removed. Thus, the compressive strength might vary from one location to another, but proponents of this method of locating the thermocouple argue that as long as the average strength of the cross section of the member is equal to that of the test cylinders there is no problem.

ORIGINATION OF STUDY

Although the use of radiant heat in the curing of concrete became of widespread interest in the 1960s,(1) it was not until June 1982 that a prestressed concrete producer in Virginia requested to use the method in the production of prestressed box beams.(4) Approval was granted for Shockey Brothers, Inc. of Winchester to use the method in the production of 11 box beams 27 in deep by 36 in wide by 50 ft long for a one-span bridge on Rte. 612 over the Shoemaker River in Rockingham County.

Personnel from the Research Council were present during two of the three days beams were cast for the project (June 30, 1982, and July 6, 1982). Thermocouples were installed to monitor the temperature distribution through the cross section of the beams. Also, 4 in x 8 in cylinders and 3 in x 4 in x 16 in prisms were prepared and cured at three locations in the casting bed so that the permeability, strength, and freeze-thaw performance of the specimens could be evaluated as a function of the location and temperature at which the specimens were cured.

It was observed that during the curing process there was as much as a 2°F temperature difference per inch of depth, with the highest temperatures being near the bottom of the bed and the lowest at the top. It was also found that cylinders cured near the top had a lower strength at the time of detensioning but a higher 28-day strength than cylinders cured near the bottom. Additionally, it was found that the freeze-thaw performance was better and the permeability was lower for specimens cured near the top. As a result of this preliminary experience, a working plan was prepared for the collection of data that would allow an evaluation of radiant heat curing.

Radiant heat curing was used for 10 beams 21 in deep x 36 in wide fabricated on November 9, 11, and 12, 1982, for a bridge on Rte. 612 over Long Run in Rockingham County,(5) and for 57 beams 27 in deep x 36 in wide x 42 ft long fabricated in February and March 1983 for a bridge on Rte. 340 over Elk Run in Rockingham County.(6) Data were collected during the castings on March 2 and 9, 1983. Additional data were collected on March 25, 1983, during the fabrication of type III beams for the Maryland Department of Transportation. For comparison, data for low pressure steam curing were collected during the production of type III beams and voided slabs on April 27, 1983, at the Lone Star Plant in Chesapeake.

Radiant heat curing was approved on a project-by-project basis for the production of beams for the Virginia Department of Highways & Transportation on April 18-22, 1983, December 16, 1983, through March 1, 1984, and February 29 through March 26, 1984.(7) When cylinders failed to attain the 5,000 lbf/in^2 strength required to permit shipment of some of the beams produced for the last two projects, cores were taken from the diaphragms of the box beams expected to have low strength to verify the strength.(7) On the average, the cores exhibited a higher strength than the cylinders, which provided additional evidence that an evaluation of radiant heat curing was needed. As of this report, additional requests to use radiant heat curing have not been made but are anticipated.

OBJECTIVE AND SCOPE

The objective of this research was to determine if radiant heat curing is acceptable for use in the production of precast, prestressed products for the Virginia Department of Highways and Transportation and, if it is found to be acceptable, to establish specification requirements for the use of the process.

For the study, specimens were given conventional moist curing, conventional steam curing, and experimental curing with radiant heat. They were tested for strength, (ASTM C39), permeability to chloride ions,(8) and freeze-thaw performance (ASTM C666 Procedure A modified). Specimens were prepared and cured at two precast plants in Virginia and in the laboratory of the Research Council. During the curing at the plants, the temperature gradients within the precast members and the temperature of the specimens were measured.

EVALUATIONS

Mixture Proportions

The mixture proportions for the concretes are shown in Table 1, and the properties of the cement and aggregates in Table 2. Type III cement was used in all mixtures, but the properties of the cement used in the plant specimens were not available for inclusion in the report.

Table 1

Mixture Proportions

Mix	8 bag - lab	7-1/4 bag - lab	6-3/4 bag - lab
Cement, lb/yd³	752	682	635
Water, lb/yd³	315	313	311
C.A. lb/yd³	1,778	1,778	1,778
F.A. lb/yd³	1,017	1,080	1,125
W/C	0.42	0.46	0.49
Admixtures	MBVR	MBVR	MBVR

Mix	8 bag, HRWR, lab	7-1/4 bag, HRWR, lab	6-3/4 bag, HRWR, lab
Cement	752	682	635
Water	256	266	266
C.A.	1,778	1,778	1,778
F.A.	1,170	1,202	1,242
W/C	0.34	0.39	0.42
Admixtures	MBVR, WRDA19	MBVR, WRDA19	MBVR, WRDA19

Mix	8 bag, plant rad.heat, box	7.6 bag, plant rad.heat, Type III beam	7.5 bag, plant steam
Cement	752	715	705
Water	308	250	250
C.A.	1,778	1,755	1,820
F.A.	1,037	1,277	1,216
W/C	0.41	0.35	0.35
Admixtures	Darex AEA, Daratard 17	Darvair, WRDA19, WRDA Hycol	MBVR, Pozzolith 400-N, Pozzolith 300-N

Table 2

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Properties of Cement and Aggregates

Lab Cement[a]	
Type	III
S_1O_2	20.2%
Al_2O_3	5.3%
Fe_2O_3	2.2%
CaO	62.9%
MgO	3.8%
SO_3	3.4%
Total alkalies	0.76%
Insoluble residue	0.18%
Ignition loss	0.86%
C_3S	53.9%
C_3A	10.3%
Fineness - Blaine	5,316

[a] Based on test report from Lone Star Cement, Inc., Roanoke, Virginia, June 27, 1983.

	Plant Radiant Heat, Fine Aggregate	Plant Steam, Fine Aggregate
Type	Limestone	Siliceous sand
Specific gravity	2.72	2.62
Fineness modulus	2.80	2.80
Absorption, %	0.7	0.6

	Plant Radiant Heat, Coarse Aggregate	Plant Steam, Coarse Aggregate
Type	Limestone	Gravel
Specific gravity	2.75	2.68
Dry rodded unit weight, lb/ft^3	98.3	104
Size no.	57	57

Lab, Fine Aggregate	
Type	Siliceous sand
Specific gravity	2.59
Fineness modulus	2.90
Absorption, %	0.8%

Lab, Coarse Aggregate	
Type	Crushed granite gneiss
Specific gravity	2.78
Dry rodded unit weight	103.1 lb/ft^3
Nominal maximum size	1 in

Lab Tests

The effects of curing temperature on 22-hr and 28-day compressive strengths, permeability at 3 weeks and 38 weeks, and freeze-thaw performance at 3 weeks were evaluated by testing specimens prepared in the laboratory. The lab work included the preparation and curing of 12 triplicate batches and 4 duplicate batches of concrete as shown in Table 3.

For 6 of the triplicate batches (group L1), specimens were cured with radiant heat at 130°, 150°, 170°, and 200°F. Control specimens were cured at the 73°F ambient temperature of the lab and at 150°F using low pressure steam. The concrete had an air content of 6.5% ± 1.5% as specified by Section 219.07 of the Department's specification for class A-5 concrete used in bridge decks. Since this air content is higher than the 4.0% ± 2.0% specified for other class A-5 concrete, 2 other triplicate batches (group L1L) were prepared at an air content of 4.0 ± 2.0% and cured with radiant heat at 150° and 200°F.

For the first 8 sets of triplicate batches (groups L1 and L1L) the cement content was 8 bags/yd^3, the amount used at the plant using radiant heat curing.

In addition, in anticipation of requests to use radiant heat curing and lower cement contents or a high range water reducer (HRWR), 4 duplicate and 4 triplicate batches were prepared to assess the effect of these variables. For the 4 duplicate batches (group L2) the cement contents were 7-1/4 and 6-3/4 bags/yd^3, the curing temperatures were 150° and 200°F, and the air content was 6.5% ± 1.5%. For the 4 triplicate batches (group L3H), an HRWR, a 42% solids naphthalene sulfonate polymer condensate WRDA19, was added after the initial mixing, and the cement contents were 8, 7-1/4, and 6-3/4 bags/yd^3, the curing temperatures were 100° and 150°F, and the air content was 6.5 ± 1.5% for 3 triplicate batches and 4.0 ± 2% for one triplicate batch. Since it was not possible to make batches to represent every possible combination of curing temperature, dosage of HRWR, and cement content, batches were prepared so as to provide some indication of acceptable and unacceptable combinations.

Plant Tests

Specimens were prepared and data were collected at the two precast plants on four occasions during the production of 5 prestressed concrete members, 2 box beams (groups P1 and P2), and a type III I-beam cured by radiant heat (group P3) and a voided slab and a type III I-beam cured with low pressure steam (group P4).

Table 3

Properties of Plastic Concrete

Group	Batch No.	Cure Temp. °F	Cement, bags/yd³	Slump, in	Air, %	Unit Wt., lb/ft³	Mix Temp. °F
L1	2,10,15	73	8	1.9	6.4	43.8	82
	6,13,28	130	8	2.3	7.2	43.4	79
	4,9,26	150	8	1.7	6.2	43.8	82
	7,14,29	170	8	2.4	6.9	43.5	79
	3,11,30	200	8	2.4	6.7	43.6	80
	8,16,27	150(S)	8	2.4	7.0	43.7	80
L1L	1,17,32	150	8	1.7	3.7	44.8	80
	5,12,31	200	8	1.7	3.5	45.0	81
L2	18,24	150	7-1/4	2.6	7.4	43.2	80
	20,22	200	7-1/4	2.4	7.0	43.3	80
	19,25	150	6-3/4	3.1	8.0	42.8	78
	21,23	200	6-3/4	3.0	7.5	43.1	79
L3H	47,50,53	100	8	3.5	6.9	43.9	80
	46,48,54	100	7-1/4	3.3	6.2	44.0	80
	45,49,55	150	6-3/4	3.9	6.9	43.7	80
	51,52,56	150	6-3/4	2.6	3.7	45.2	78
P1	Box 3/2/1983	≦196	8	3.0	5.1	--	--
P2	Box 3/9/1983	≦180	8	4.0	6.8	--	--
P3	Type III 3/25/1983	≦170	7.6	5.5	6.5	--	--
P4	Voided Slab 4/27/1983	≦167(S)	7.5	7.5	2.0	--	--
P4	Type III 4/27/1983	≦176(S)	7.5	7.5	2.0	--	--

(S) Steam Cure

During the production of each member the distribution of the curing temperature from top to bottom at the center of its cross section was recorded. Also, specimens were prepared and cured on top of the member, on the bottom of the form alongside the member, and at ambient temperature away from the member so that --

1. the effect of curing temperature on the compressive strength of 4 in x 8 in cylinders at the time the prestress strands were cut and at 28 days could be noted;

2. the effect of curing temperature on the permeability to chloride ions of specimens cut from 4 in x 8 in cylinders could be determined; and

3. the effect of curing temperature on the freeze-thaw performance of 3 in x 4 in x 16 in prisms could be noted.

Preparation and Curing of Specimens

The specimens were cured in accordance with the requirements of Section 405.09 of the Department's specifications,(2) except that when radiant heat curing was used, the heat source was radiant, the temperature of the concrete or the air in the curing chamber in the lab was monitored, and a liquid curing compound was used on exposed surfaces to prevent a loss of moisture. Of course, specimens cured at temperatures in excess of 165°F did not meet the specification.

Laboratory Specimens

The laboratory specimens were prepared from 1.5 ft^3 batches of concrete. For all batches except the ones containing an HRWR admixture, the ingredients were added to the mixer, mixed for 3 minutes, let set in the mixer for a 3-minute rest period, and mixed for another 2 minutes. For the mixes containing the HRWR admixture WRDA-19, the admixture was added at the beginning of the final 2 minutes of mixing.

The mixture was tested for slump (ASTM C143), air content (ASTM C231), temperature, and unit weight as the specimens were prepared. From each batch, 1 specimen was prepared for a determination of the time of set (ASTM C403), six 4 in x 8 in cylinders were prepared for 22-hr and 28-day compression tests (ASTM C39), two 4 in x 8 in cylinders were prepared for the rapid permeability test, and three 3 in x 4 in x 16 in prisms were prepared for the rapid freeze-thaw test (ASTM C666 Procedure A modified). In addition, three 4 in x 8 in cylinders were prepared from control batches 2, 10, and 15, so that the

7-day compressive strength could be determined. In all, 537 specimens were fabricated from 44 batches prepared in the laboratory.

The specimens were placed in an insulated curing chest, except for the control specimens cured at ambient temperature, which were left overnight on a table in the lab. When the sheen had disappeared from the surface of the specimens, they were coated with a white pigmented curing compound (Saunders Oil Company 1000-D), with the exception that the specimens cured with live steam were not coated or covered.

When measurements indicated that the initial set occurred at 3 hr, which was typical, the curing chamber was programmed to start the temperature rise for the accelerated cured specimens 3 hr after the mixing water was added. The temperature increased at a rate of 40°/hr until the curing temperature was reached, the maximum curing temperature was maintained until 22 hr after the addition of the mixing water, then the 22-hr compressive strength determinations were made. The other accelerated cured specimens were allowed to cool to room temperature over a 2-hr period and then were removed from the molds, numbered, and stored in the lab for testing at a later date. To simulate radiant heat curing, the curing chamber was set on dehumidify and the specimens were cured with hot, dry air. The steam cured specimens were accelerated cured with live steam. The control specimens from batches 2, 10, and 15 were moved to the moist room after the first 24 hours and those which were scheduled for permeability and freeze-thaw tests were moist cured for 2 weeks and those scheduled for 7- and 28-day compression tests were moist cured until they were tested.

Plant Specimens

At the precast, prestressed concrete plants, specimens were prepared from a wheelbarrow load of concrete obtained as the concrete was placed around the thermocouple wires in the member being evaluated. The slump and air content of the sample were determined and twenty-four 4 in x 8 in cylinders and nine 3 in x 4 in x 16 in prisms were prepared for each evaluation. One-third of the specimens were cured at each of three locations: on top of the member but underneath the tarp cover, on the bottom of the form alongside the member, and at ambient temperature away from the member. One 4 in x 8 in cylinder was prepared for each of the three locations so that the temperature of the specimens could be monitored with a thermocouple. Therefore, 36 specimens were fabricated during each of the four evaluations conducted at the plants for a total of 144 specimens.

Three 4 in x 8 in cylinders cured on top of the member and three cured alongside were tested in compression at the time the prestress strands were cut, which typically was at an age of 16 to 20 hr.

Following the accelerated curing period, the remaining specimens were transported to the Research Council and stored in the lab until tests were conducted. Three ambient cured 4 in x 8 in cylinders were tested in compression at 7 days and three 4 in x 8 in cylinders cured at each of the three locations were tested in compression at 28 days. The rapid permeability tests, which were conducted on sections cut from two 4 in x 8 in cylinders cured at each location, and the freeze-thaw tests, which were conducted on three 3 in x 4 in x 16 in prisms cured at each location, were started at an age of about 3 weeks.

RESULTS

Properties of Plastic Concrete

The properties of the plastic concrete are shown in Table 3. The requirement for slump is 0 to 4 in except when an HRWR admixture is used, in which case a slump of up to 7 in is acceptable. The requirement for air content is 2% to 6% except when the member will serve as the bridge deck riding surface or be covered with a bituminous overlay; then the requirement is 5% to 8%.

Compressive Strength

The compressive strength data are summarized in Table 4, and Figure 1 shows the relationship between compressive strength and curing temperature for specimens prepared in the laboratory.

It is obvious from Figure 1 that the 22-hr strength increased as the curing temperature increased up to about 150°F. The 28-day strength was the greatest for the ambient moist cured specimens and the specimens cured with live steam at 150°F. The air content had a greater effect on strength than did curing temperature.

Examination of the data in Table 4 reveals that strength was reduced as the cement content was reduced, and the strength was increased by the addition of an HRWR admixture because of the cement-dispensing characteristics of the admixture and the lower water-to-cement ratio that can be achieved. It is obvious from the data in Table 4 that the 4,000 lbf/in^2 minimum strength required before the strands are cut was not achieved at 22 hr for some of the mixtures cured at the lower temperatures and with less than 8 $bags/yd^3$ of cement. Similarly, the 5,000 lbf/in^2 requirement at 28 days was not achieved by some of the same mixtures. At the plant, specimens cured on top of the members cured with radiant heat did not achieve 4,000 lbf/in^2 at the time the strands were cut.

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Table 4

Compressive Strength, lbf/in²

Group	Batch No.	Cure Temp. °F	22 Hours x	22 Hours s	7 Days x	7 Days s	28 Days x	28 Days s	28 Days[a] / 22 Hour
L1	2,10,15	73	3270	150	4770	180	5640	130	1.72
	6,13,28	130	3490	170			4890	190	1.40
	4,9,26	150	3980	150			5300	110	1.33
	7,14,29	170	4040	130			5260	210	1.30
	3,11,30	200	4020	80			5280	150	1.31
	8,16,27	150(S)	4270	240			5670	350	1.33
L1L	1,17,32	150	4710	160			6170	200	1.31
	5,12,31	200	4650	140			5940	170	1.28
L2	18,24	150	3460	240			4590	250	1.33
	20,22	200	3650	170			4790	320	1.31
	19,25	150	3080	100			4140	60	1.35
	21,23	200	3170	70			4210	90	1.33
L3H	47,50,53	100	4550	50			6430	110	1.41
	46,48,54	100	3870	40			5720	200	1.48
	45,49,55	150	3640	110			5380	120	1.48
	51,52,56	150	4830	80			6850	120	1.42
P1	Box 3/2/1983	Top≤106	3750[b]				6320		1.69[b]
		Bottom ≤118	4360[b]				5940		1.36[b]
		Ambient ≤74			6780		7390		
P2	Box 3/9/1983	Top≤133	3980[c]				5560		1.40[c]
		Bottom ≤154	4180[c]				5520		1.32[c]
		Ambient ≤64			5840		6970		
P4	Type III 4/27/1983	Top≤169	5100[d]				7710		1.51[d]
		Bottom ≤169	4710[d]				7450		1.58[d]
		Ambient ≤83			5580		7480		

[a]Air Cure at 73° in Lab except batches 2, 10, 15. [b]20 hr [c]19 hr [d]16 hr

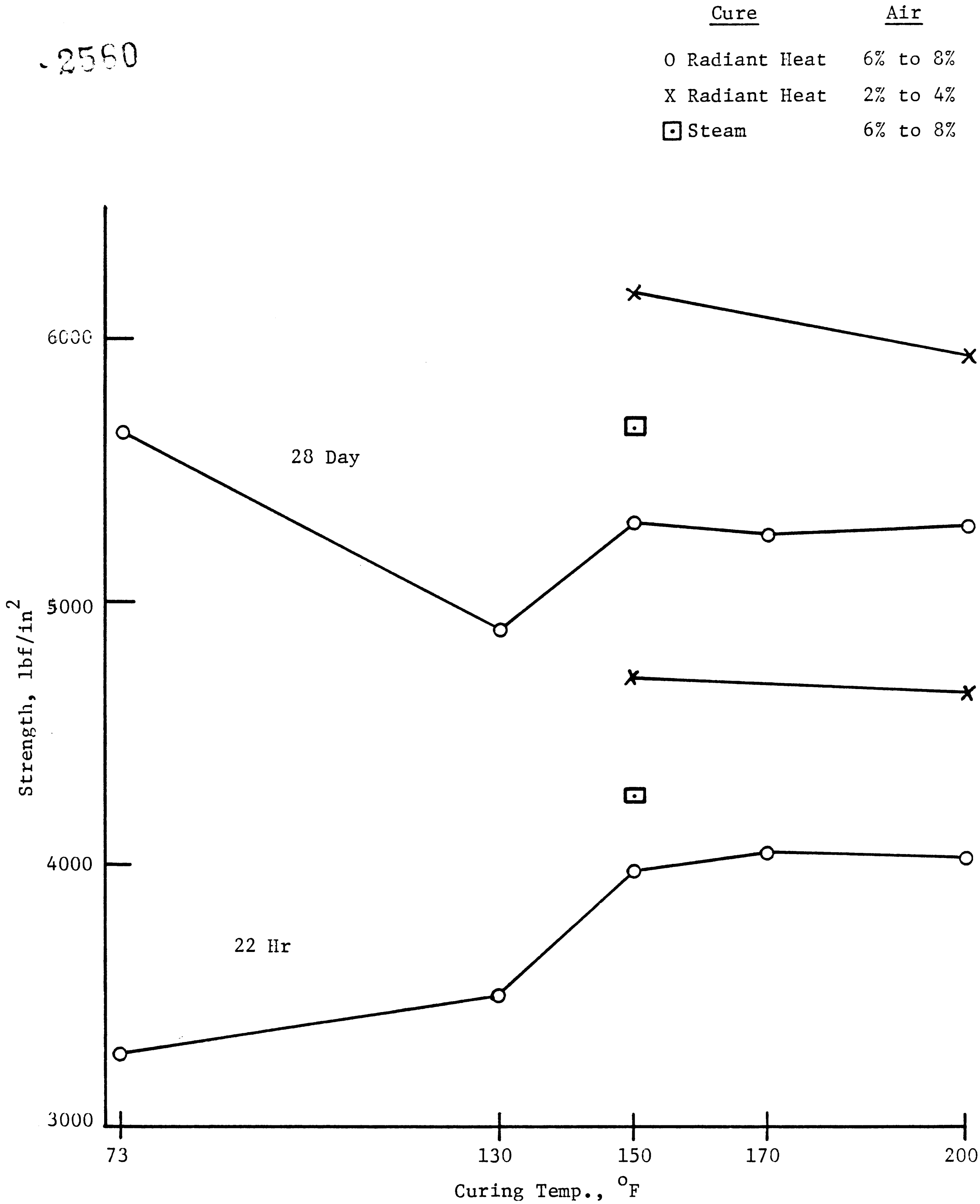

Figure 1. Relationship between compressive strength and curing temperature.

On several occasions, the 5,000 lbf/in^2 minimum strength requirement for shipping members was not achieved at 28 days based on tests of cylinders cured alongside the radiant heat cured box beams, even though the 4,000 lbf/in^2 requirement at release was satisfied by tests on cylinders temperature matched for curing. Subsequent compression tests on cores taken at mid-depth of the members indicated that many of the box beams had 5,000 lbf/in^2 strength.(7) The difference in strength between the cylinders and the cores was probably due to several factors, including the following. For one thing, strength at later ages is a function of early age curing and strength. Obviously, the cylinders cured alongside the member were not cured at the same temperature as the concrete in the member, and one can speculate that they were cured at a lower temperature. Also, while the concrete in a given group of cylinders was obtained from only one batch, the cores may have represented a number of batches and it is reasonable to expect some differences in strength between batches. The way to minimize the difference in strengths between cores and cylinders due to the former factor is to temperature match cure all cylinders, those used to assure that release strengths are satisfied as well as those used to assure that shipping strengths are achieved. The difference in strengths that can be attributed to the latter problem is a part of all concrete production and can be minimized by quality control that minimizes between batch variability.

Based on the Virginia Department of Highways and Transportation specifications, concretes which meet but don't exceed the 4,000 lbf/in^2 requirement at release must increase in strength 25% to meet the shipping and in-service minimum strength requirements of 5,000 lbf/in^2. Table 4 shows the ratios of the compressive strengths at 28 days for control cylinders stored in the lab at 73°F to the strengths at 22 hr (to simulate typical release ages) for concretes given accelerated curing at various temperatures. In addition to the ratios in Table 4, ratios of 1.31 and 1.20 were found from tests of two additional cylinders prepared from each of batches 4, 9, and 26 and stored in air at 40°F and 100°F, respectively. In every case except one, for cylinders accelerated cured at 150°F and stored at 100°F the ratio of strengths at 28 days to the strengths at 22 hr was greater than 1.25. Therefore, concretes which satisfy the 4,000 lbf/in^2 requirement at release should typically satisfy the 5,000 lbf/in^2 requirement at 28 days. The fact that cylinders broken at 28 days at the precast plant didn't satisfy the 5,000 lbf/in^2 strength requirement on several occasions provides evidence that cylinders must be accelerated cured by matching the temperature of the cylinder to the temperature of the member.(7) However, when considering the data in Table 4 which show that regardless of curing temperature the ratio of the strength at 28 days to the strength at 22 hr typically exceeds 1.25, one would wonder if the cylinders which tested low at 28 days contained concrete with the same mixture proportions and degree of consolidation as the cylinders which

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were temperature matched cured and exceeded 4,000 lbf/in^2 at release. Since the standard practice is to use the same sample of concrete for all cylinders in a group, the concrete mixture or cement evidently were unusual or consolidation was not satisfactory.

Since it is obvious from the data in Figure 1 and Table 4 that the early age strength is a function of the curing temperature, cylinders must be cured at the same temperature as the least mature concrete in the member to ensure that all concrete in the member has a strength greater than or equal to that of the cylinders. Also, the Department's strength requirements are not easily satisfied when radiant heat curing is used, and the producer must use care in the selection of mixture proportions and the control of air content to ensure that the requirements are met.

Permeability to Chloride Ions

The permeability to chloride ions as determined by the rapid permeability test is shown in Table 5,(8) and Figure 2 shows the relationship between permeability and curing temperature. Clearly, the permeability increased as the curing temperature increased. The permeability decreased somewhat with age, as is evident from the lower values obtained at 38 weeks as compared to those at 3 weeks. However, the permeability of all the concretes given accelerated curing was high relative to that of the other concretes,(9) and this may be attributal to the cracking that occurs during the heating process. The air content has a significant effect on the permeability test results.

It is obvious from Table 5 and Figure 2 that the permeabilities were about the same for steam cured specimens and for radiant heat cured specimens. Lower permeabilities are achieved by keeping air contents low, cement contents high, and water-to-cement ratios low through the use of HRWR admixtures.

Table 5

Permeability to Chloride Ions and Freeze-Thaw Durability

Group	Batch No.	Cure Temp. °F	Permeability, Coulombs (3 weeks)	Permeability, Coulombs (38 weeks)	D.F. %	Wt. Loss %	SR
L1	2,10,15	73	8,402	8,217	105	0.6	0.8
	6,13,28	130	12,707	8,761	114	1.5	1.2
	4,9,26	150	12,690	10,329	110	1.6	1.2
	7,14,29	170	13,987	10,215	108	4.2	1.7
	3,11,30	200	13,422	12,903	107	5.2	2.1
	8,16,27	150(S)	11,389	11,769	107	2.1	1.3
L1L	1,17,32	150	9,409	7,818	111	5.5	2.0
	5,12,31	200	9,783	9,187	61	18.6	4.5
L2	18,24	150	19,578	13,057	112	1.8	1.3
	20,22	200	19,582	14,983	105	4.7	1.9
	19,25	150	21,904	15,608	112	2.4	1.4
	21,23	200	25,594	13,217	107	6.0	2.2
L3H	47,50,53	100	7,478	5,715	111	2.4	1.1
	46,48,54	100	9,366	6,703	110	4.2	1.7
	45,49,55	150	12,805	8,951	124	15.8	3.4
	51,52,56	150	8,344	5,770	100	47.8	7.7
P1	Box 3/2/1983	Top≤106	8,712		102	1.1	1.0
		Bottom ≤118	9,661		101	0.7	1.1
		Ambient ≤74	6,656		101	0.4	0.7
P2	Box 3/9/1983	Top≤133	8,635		104	1.6	1.1
		Bottom ≤154	9,430		100	1.8	1.2
		Ambient ≤64	5,731		101	0.8	0.7
P3	Type III 3/25/1983	Top≤125	7,012		31	3.4	1.8
		Bottom ≤157	7,941		73	7.4	1.5
P4	Type III 4/27/1983	Top≤169	11,437		24	30.9	3.4
		Bottom ≤169	10,040		20	35.0	5.3
		Ambient ≤83	5,972		26	2.3	1.0

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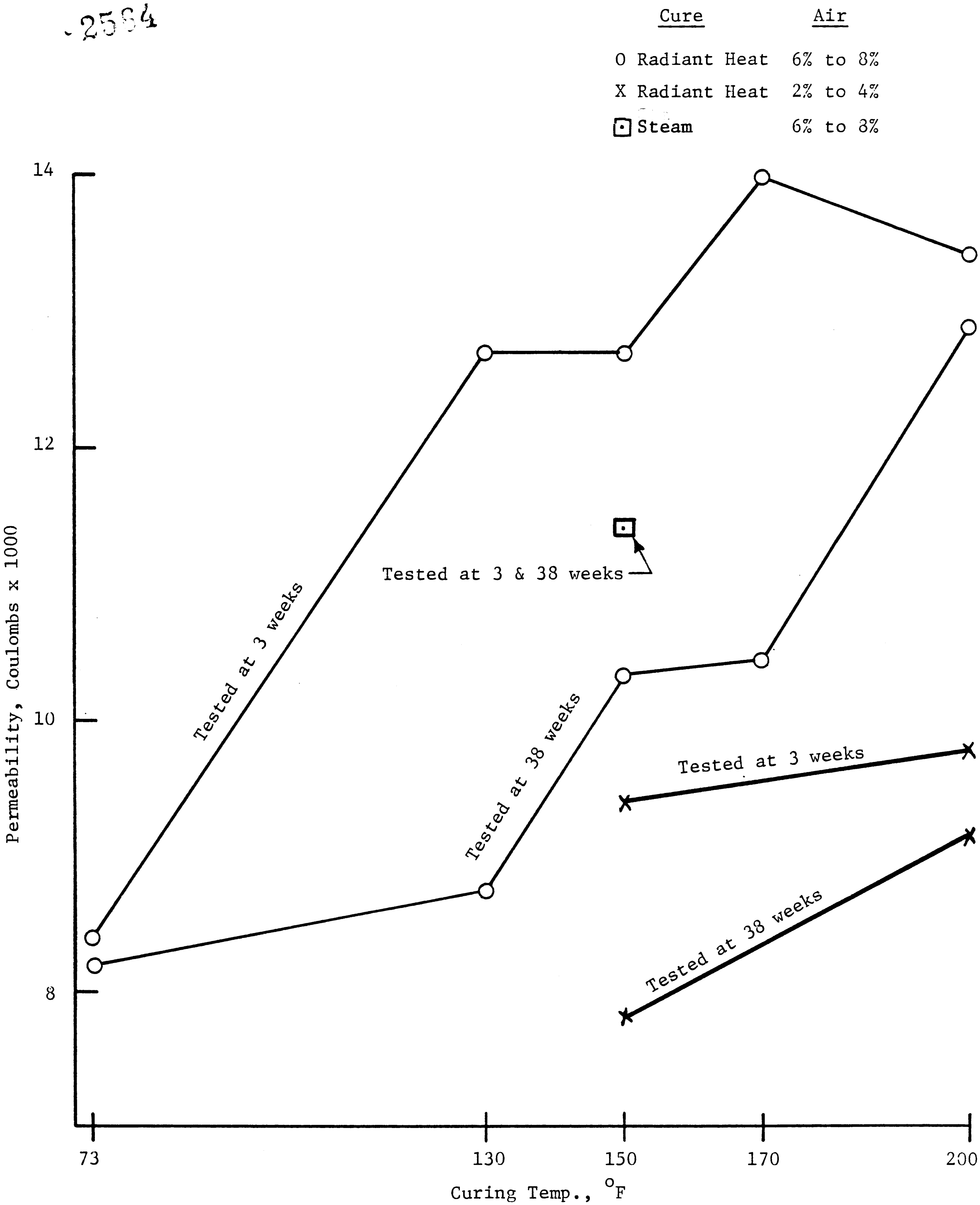

Figure 2. Relationship between permeability to chloride ions and curing temperature.

Freeze-Thaw Performance

The results of freeze-thaw tests conducted in accordance with ASTM C666 Procedure A modified are also shown in Table 5. With the exception of the specimens from batches 2, 10, and 15 that were moist cured for 2 weeks and air dried for 1 week prior to testing, which is the standard practice at the Research Council, all specimens were cured in air for 3 weeks, or sometimes slightly longer, prior to testing. Figures 3, 4, and 5 show the relationships between freeze-thaw performance and curing temperature.

Freeze-thaw performance tended to become worse as the curing temperature increased and the air content decreased. All concretes passed the freeze-thaw tests with the following exceptions.

1. The mixtures having an air content of 3.5% and a cement content of 8 bags/yd^3 and cured at 200°F -- failed on weight loss, >6%, and surface rating, >3

2. The mixtures having air contents of 6.9% and 3.7%, only 6-3/4 bag/yd^3 of cement, and an HRWR admixture and cured at 150°F -- failed on weight loss and surface rating

3. The mixtures containing an HRWR admixture cured by radiant heat along with a type III beam -- failed on durability factor <60%, or weight loss

4. The mixtures containing an HRWR admixture and cured with live steam along with a type III beam or at ambient temperature, and having an air content of 2.0% -- all failed on durability factor and those cured with live steam also failed on weight loss and surface rating.

The usual explanation for failures is a poor air void system. Acceptable freeze-thaw durability is usually achieved when spacing factors are less than 0.008 in and air contents exceed 3.5% for A4 concrete and exceed 6.0% for A4 concrete containing HRWR admixtures.(11) Elevated curing temperatures may also contribute to freeze-thaw deterioration if they cause microcracking in the concrete due to the expansion of moist air in the pores, since water and air have coefficients of thermal expansion 20 and 200 times greater than cement and aggregates.(1)

Petrographic data for 7 specimens are shown in Table 6.(12) The polished surface examined was the bottom face of the top 2 in thick section cut from the 4 in x 8 in cylinders from which permeability specimens were prepared. Since all of the specimens exhibited acceptable spacing factors, the freeze-thaw failures must be attributed to some other factor. The cracks found in the specimens from batches 5, 11, and 12 indicate that to minimize cracks, concrete should not be cured at 200°F. The severe cracking found in the specimens from batches 5 and 12 may have contributed to the freeze-thaw failure. But if this is true, why didn't the concretes which contained 6.7% air (batches 3, 11, and 30) and were also cured at 200°F fail the freeze-thaw test? Likewise, there is no logical explanation for the failure of the specimens from batches 45 and 55. The concretes had an acceptable spacing factor. These contained an HRWR admixture, but batches 46 and 48 also contained an HRWR admixture yet passed the test. In fact, all batches that contained an HRWR admixture and were cured at 150°F failed the freeze-thaw test, whereas batches cured at 100°F passed the test.

Field performance suggests that HRWR concrete is durable, yet when tested by ASTM C666 Procedure A, as conducted at the Research Council, it may or may not pass. Prior work has shown that concrete containing HRWR admixtures and having an air content in excess of 6.0% can pass the test when cured at 73°F in the lab.(11) The present study supports those findings. Unfortunately, it also showed that concrete containing HRWR admixtures and cured at elevated temperatures failed the test, even when the air contents were above 6.0%. The significance of this finding needs to be determined, and the National Cooperative Highway Research Program is awarding a contract to evaluate the durability of HRWR concrete.(10)

Clearly, not enough is known about the relationships between freeze-thaw performance as determined by ASTM C666 Procedure A modified and other combinations of factors such as air content, curing temperature, and the presence of HRWR admixtures. Perhaps it would be well to closely examine the freeze-thaw test rather than the materials being tested.

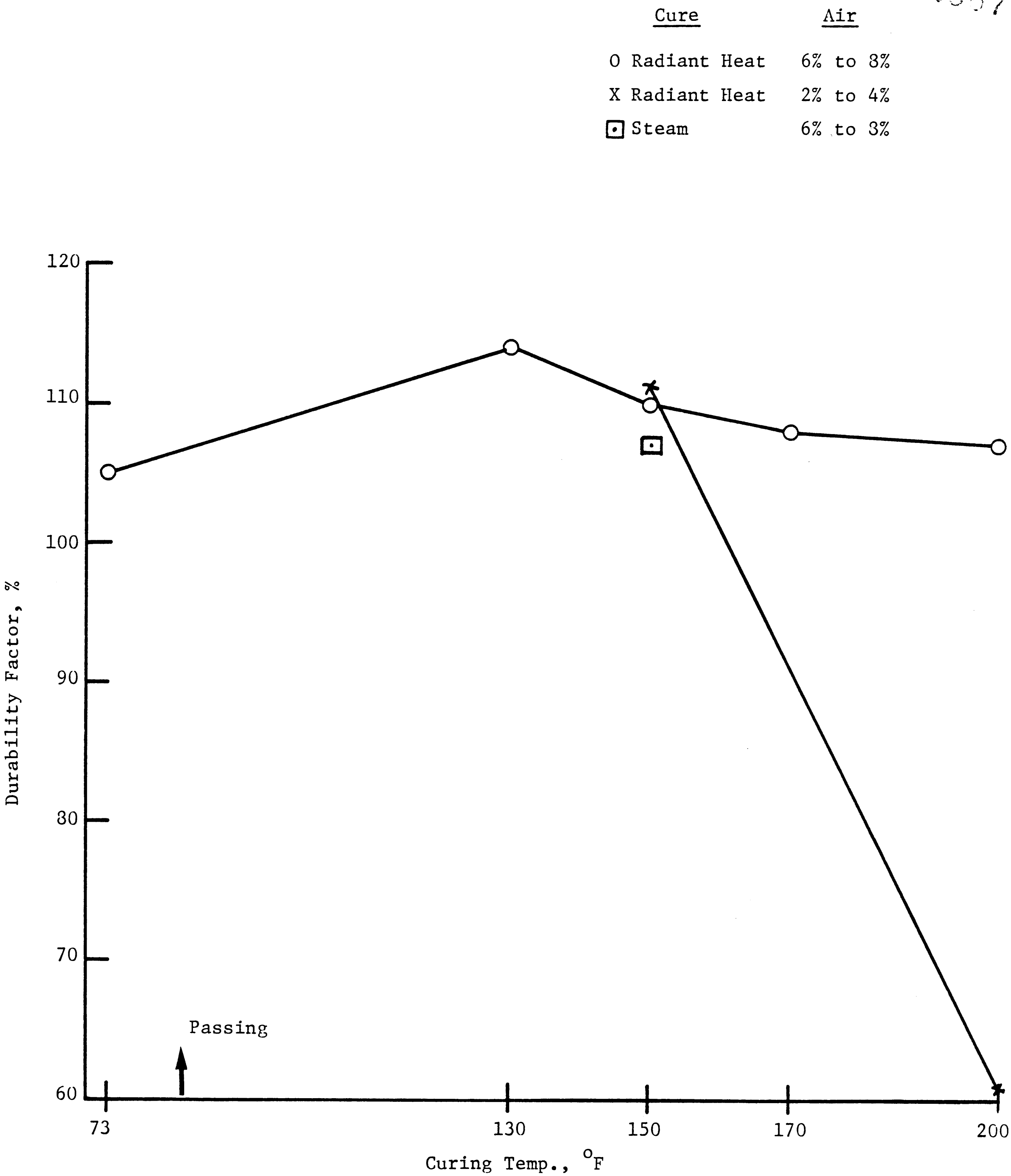

Figure 3. Relationship between durability factor and curing temperature.

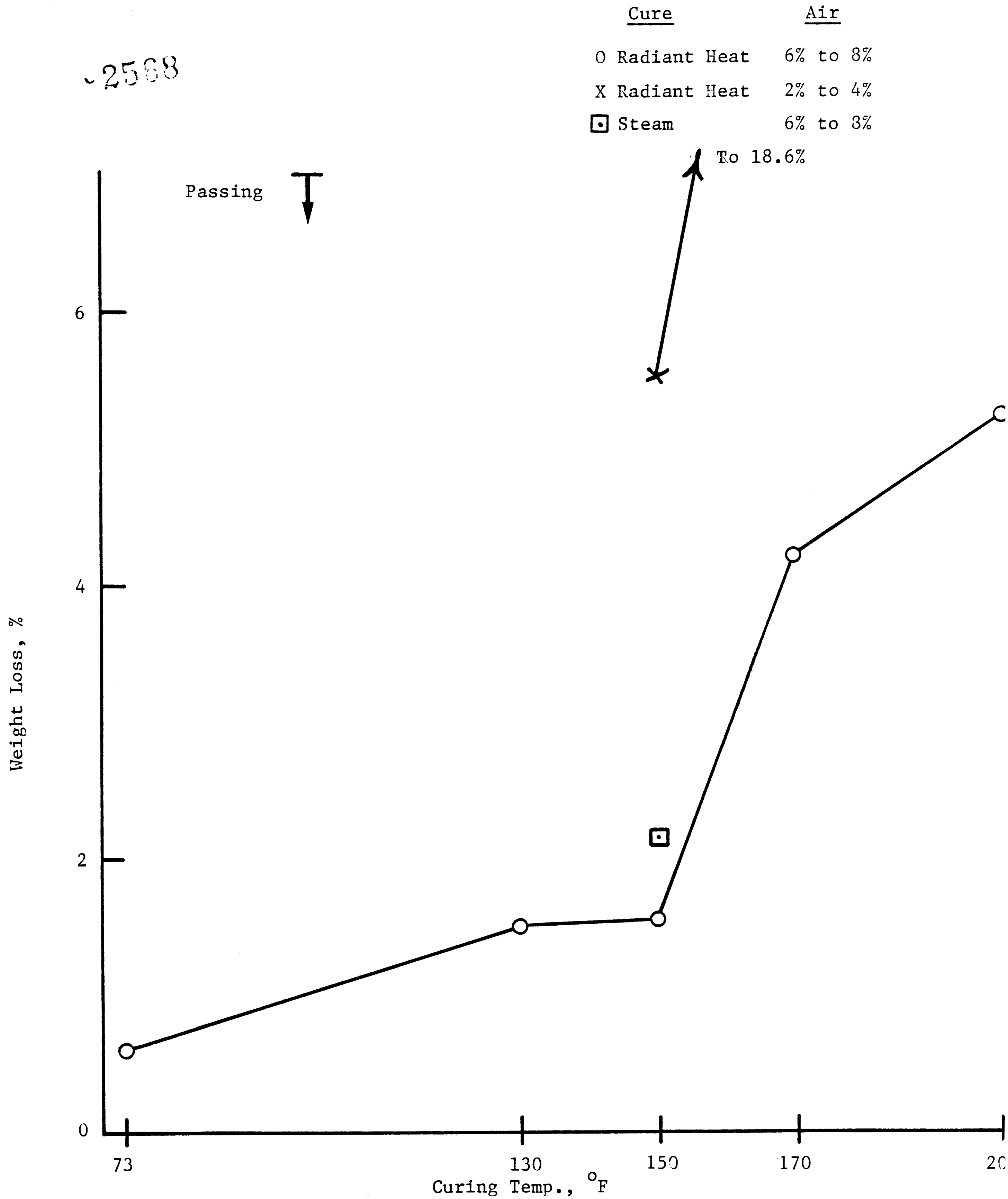

Figure 4. Relationship between weight loss and curing temperature.

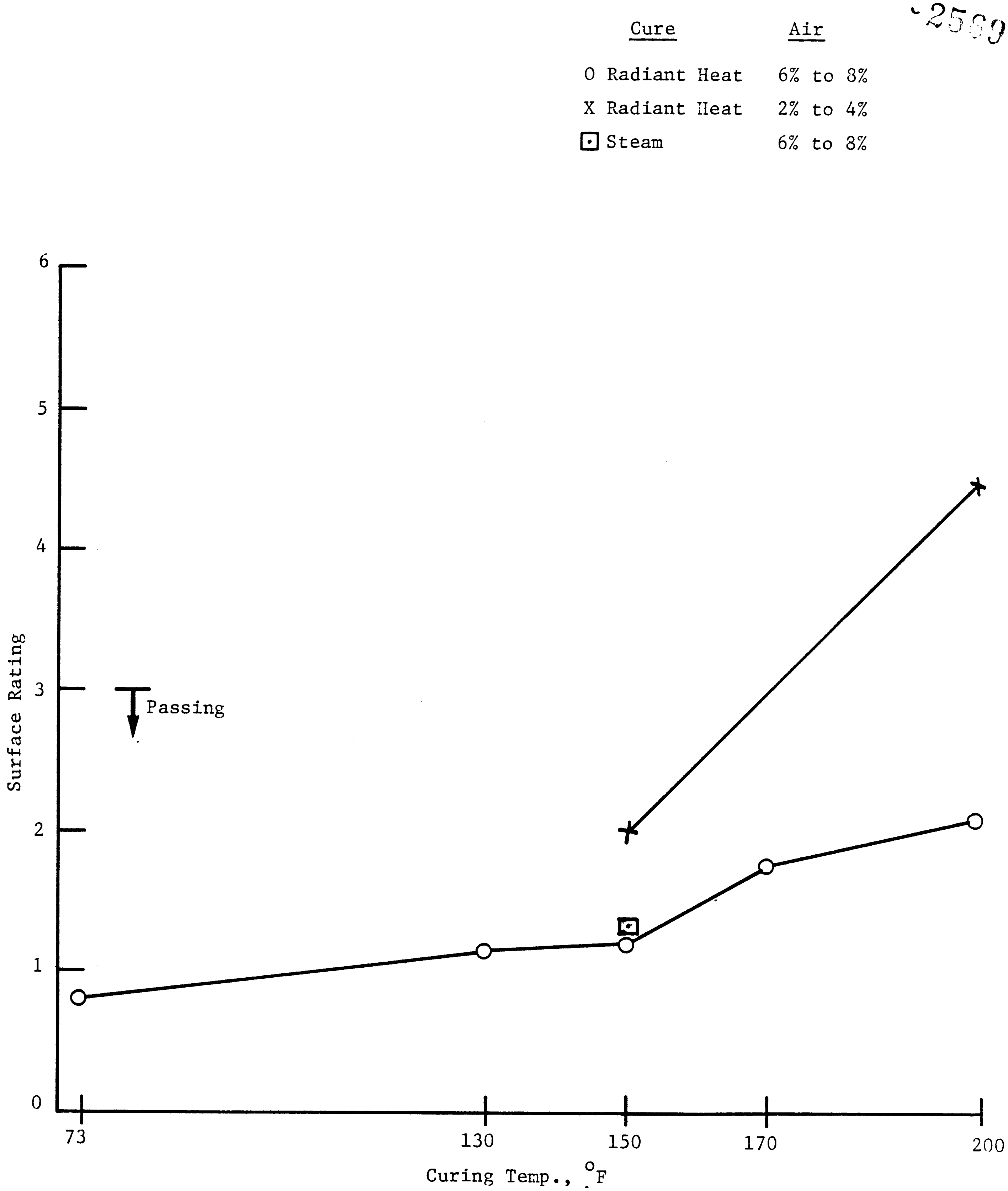

Figure 5. Relationship between surface rating and curing temperature.

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Table 6

Petrographic Data(12)

Batch No.	Cure Temp., °F	HRWR	Freeze-Thaw Results	Voids,% <1mm	Voids,% Total	Specific Surface, in^{-1}	Spacing Factor, in	Petrographer's Comments
5	200	No	Fail	3.3	4.2	886	0.0058	Badly cracked, paste dull
12	200	No	Fail	3.0	4.5	847	.0059	Badly cracked, paste dull
11	200	No	Pass	6.8	8.2	1056	.0031	Cracked, paste normal
45	150	Yes	Fail	10.6	14.9	634	.0029	Normal
55	150	Yes	Fail	3.5	4.9	660	.0073	Paste weak
46	100	Yes	Pass	4.6	6.5	724	.0057	Paste dull
48	100	Yes	Pass	6.1	9.5	535	0.0053	Paste weak

Temperature Distribution in Members

Figures 6, 7, 8, and 9 show the distribution of temperature from top to bottom at the center of members cured by radiant heat and with live steam. When steam was used, the temperature increased throughout the depth of the member, with the more massive parts of the type III beam lagging behind at early ages. When radiant heat was used, the temperature of the concrete on the bottom of the bed was always higher than the temperature of the concrete in the top of the member and the temperature decreased from bottom to top and tended to be a function of location relative to the heat source.

Figure 10 is a copy of the strip chart from the plant's thermocouple recorder which shows a continuous plot of time and temperature for thermocouples located at five locations during the production of a box beam on March 9 and 10, 1983. Thermocouples 2, 8, and 10 were located approximately 3 in from the top surface; approximately 13 in from the top surface, and approximately 1 in above the bottom surface, respectively, of a solid section of the box beam. The data indicate that temperatures decreased from bottom to top during the accelerated curing period.

Thermocouple #7 was located in a 6 in x 12 in cylinder cured under the tarp and on the bottom of the form alongside the box, and it can be seen that it had a temperature less than that of the member at the early ages of cure, but approximately 9 hours after the concrete was placed the temperature of the cylinder was between the temperatures of the top and middle of the box beam. Although the maturity of the cylinder can be related to the maturity of the member based on the time-temperature data, it would be difficult for an inspector to establish a day-to-day routine, except through the use of maturity concepts, for deciding when the cylinder should be broken and when the maturity of the top or least mature part of the member is equal to the maturity of the cylinder at the time it is broken.

Thermocouple #9 was located in one of two 4 in x 8 in molds that were temperature matched to the top of the member at the same location as thermocouple #2. From the data it can be seen that the concretes represented by thermocouples #2 and #9 were cured at the same temperature and would have the same maturity.

Inspection at the Precast Plant

Since accelerated curing with radiant heat may provide a less uniform cure than that attained with live steam, more careful inspection will be required at the precast plant to ensure that an acceptable product is produced. Special attention will have to be directed to the matching of the curing of the cylinders to the curing of the least mature part of the member.

Whereas cylinders cured by live steam under the tarp at the temperature of the steam would have a maturity similar to that of the member, cylinders cured by radiant heat under the tarp would be representative of but one part of the member. Therefore, when radiant heat curing is used, the temperature under which the cylinders are cured must be the same as that applied to the part of the member of most concern. Typically, cylinders would be cured at the same temperature as the top or least mature part of the member to ensure that the least mature concrete has adequate strength. When a new mixture is introduced, it would be advisable to cure some cylinders at the same temperature as the more mature portion of the member to ensure that the maturity concept is applicable and that all strengths are greater than or equal to that of the least mature concrete to which the cylinders are matched.

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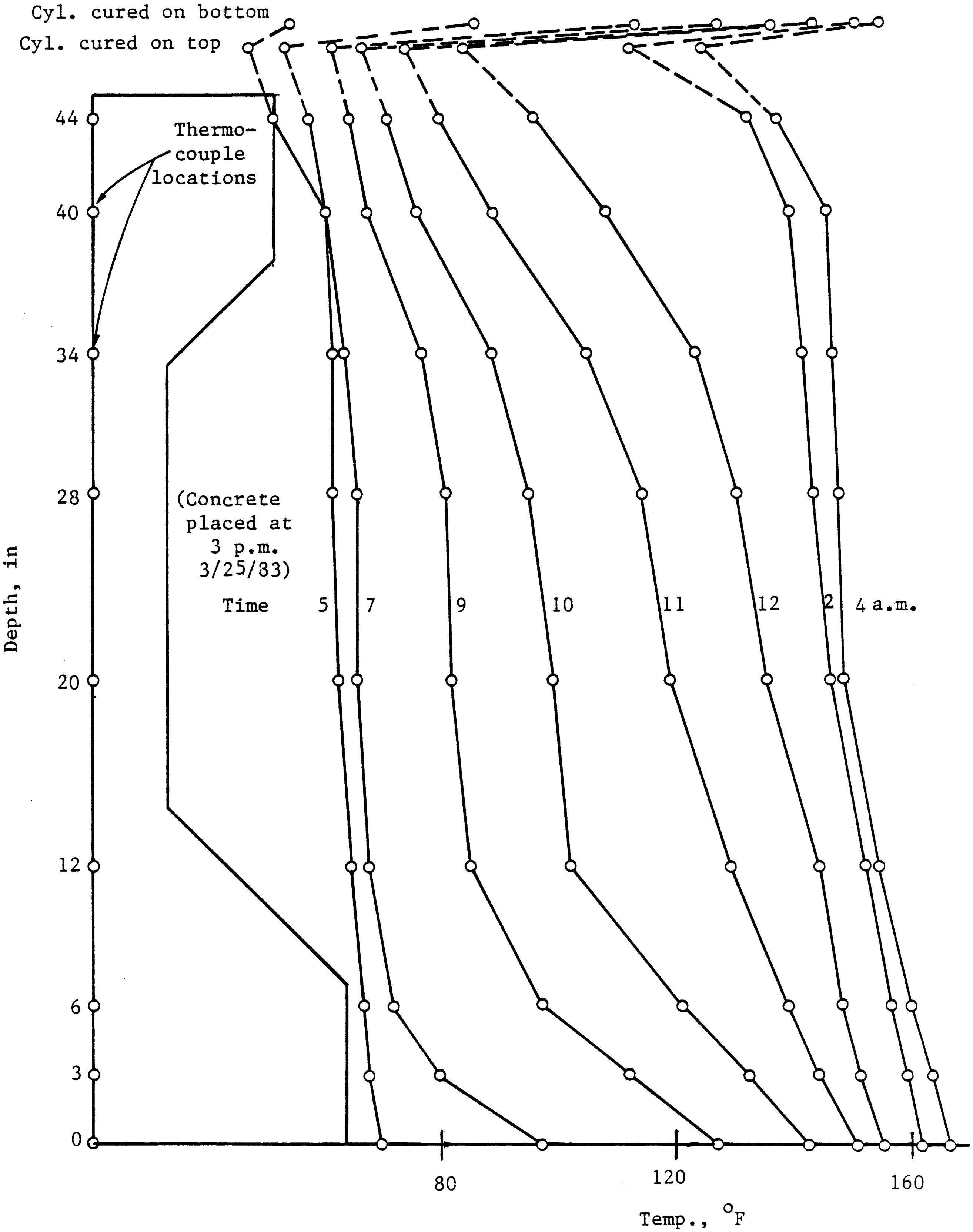

Figure 6. Temperature distribution in type III beam cured with radiant heat.

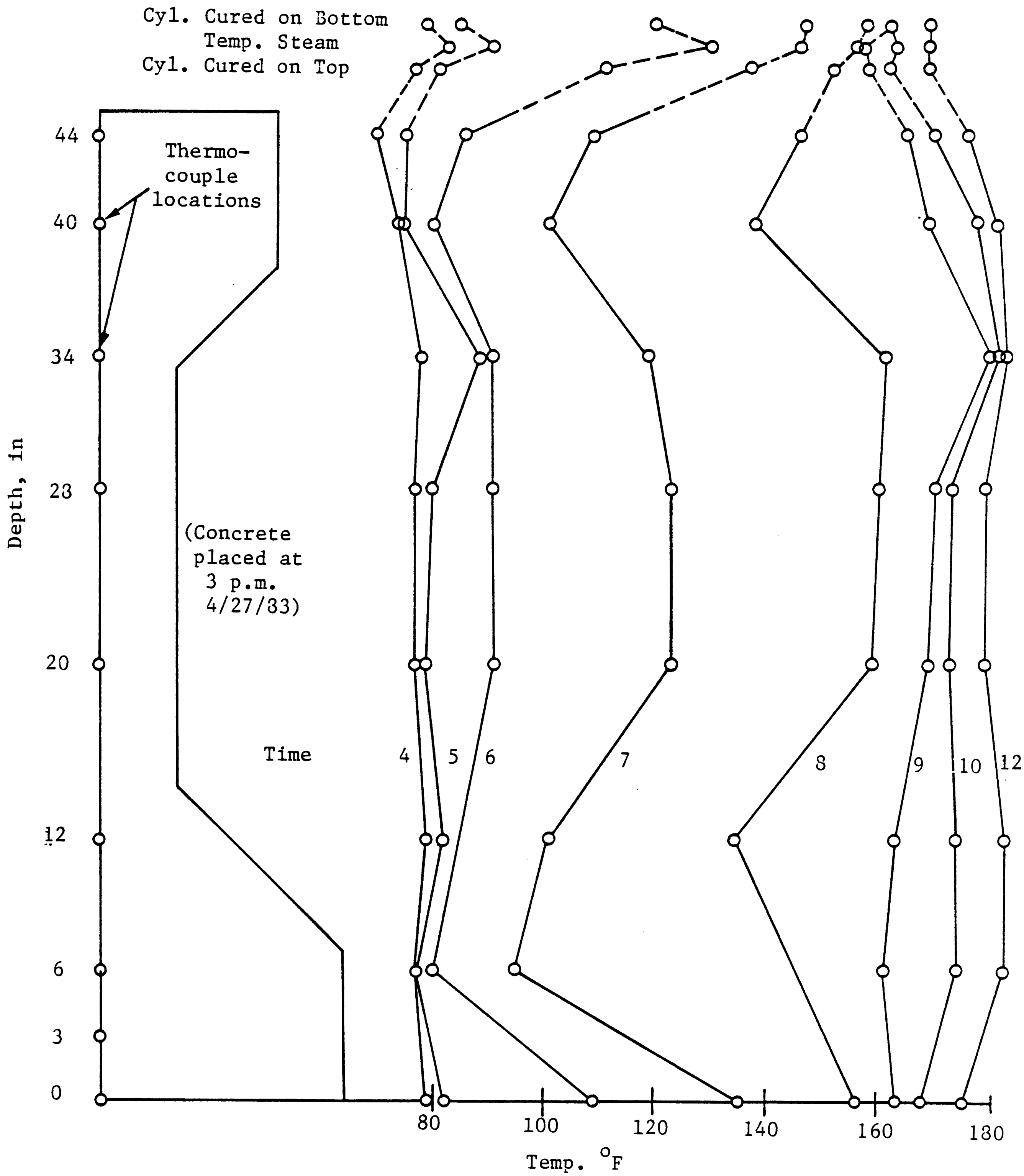

Figure 7. Temperature distribution in type III beam cured with steam.

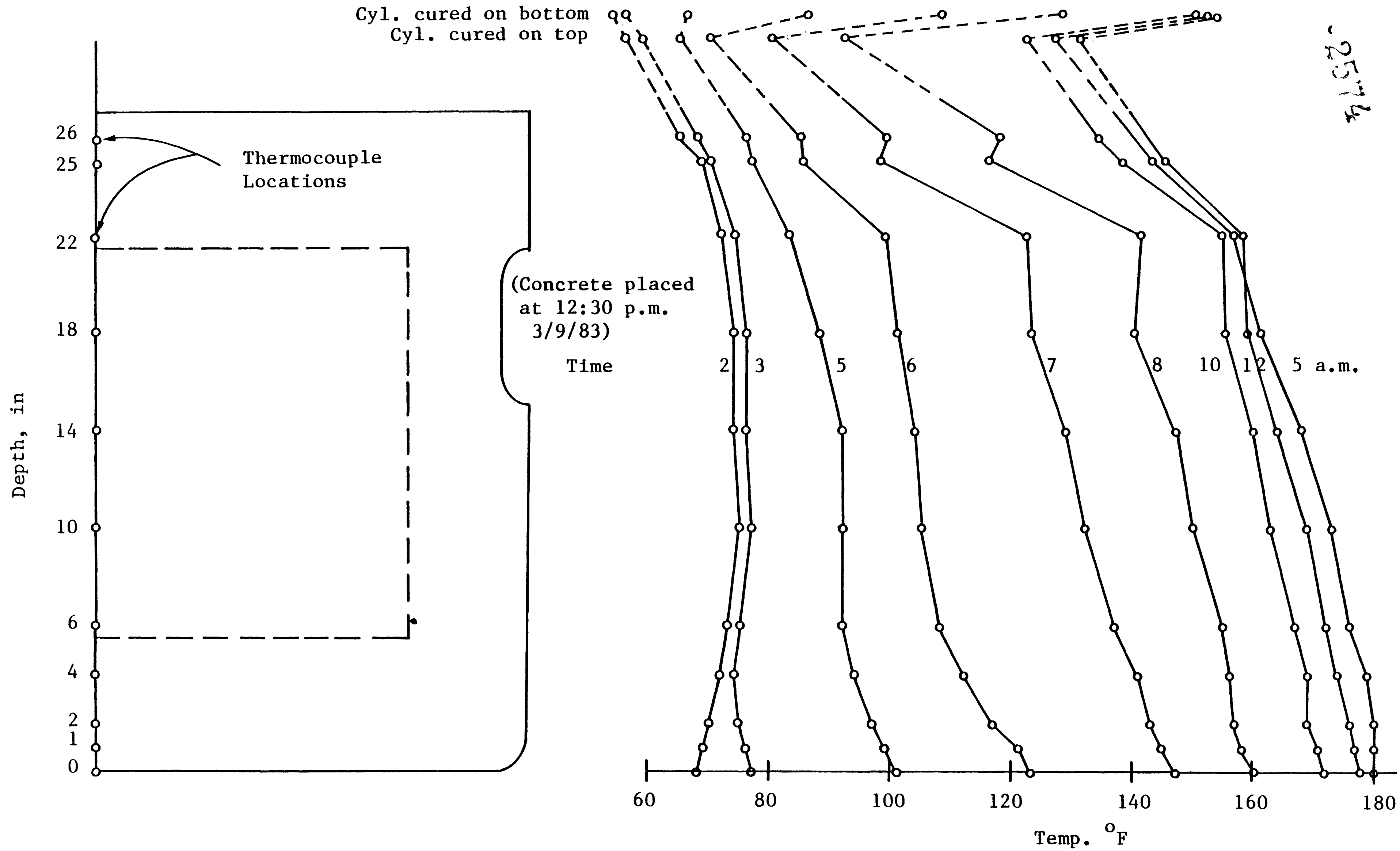

Figure 8. Temperature distribution in box beam cured with radiant heat.

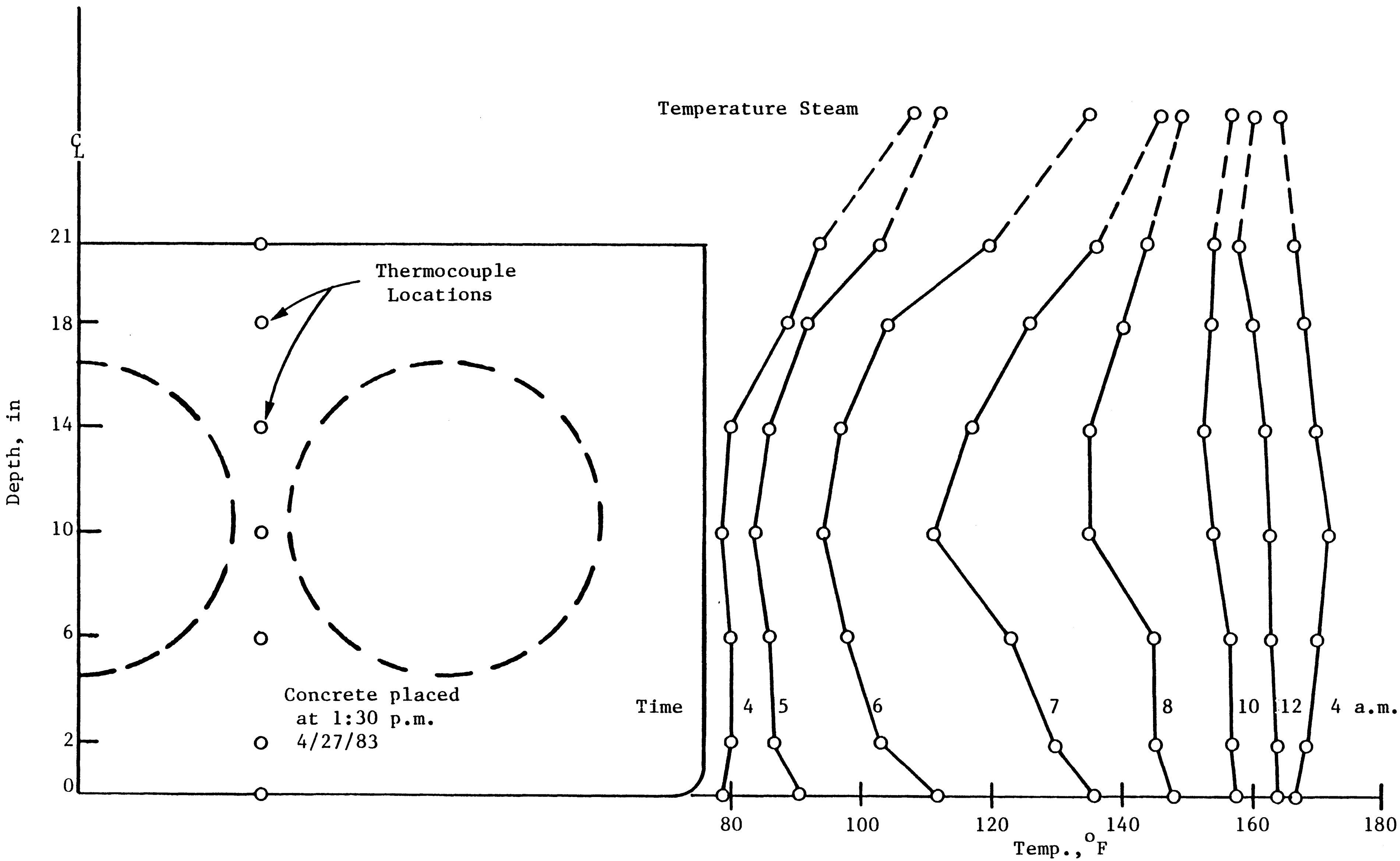

Figure 9. Temperature distribution in voided slab cured with steam.

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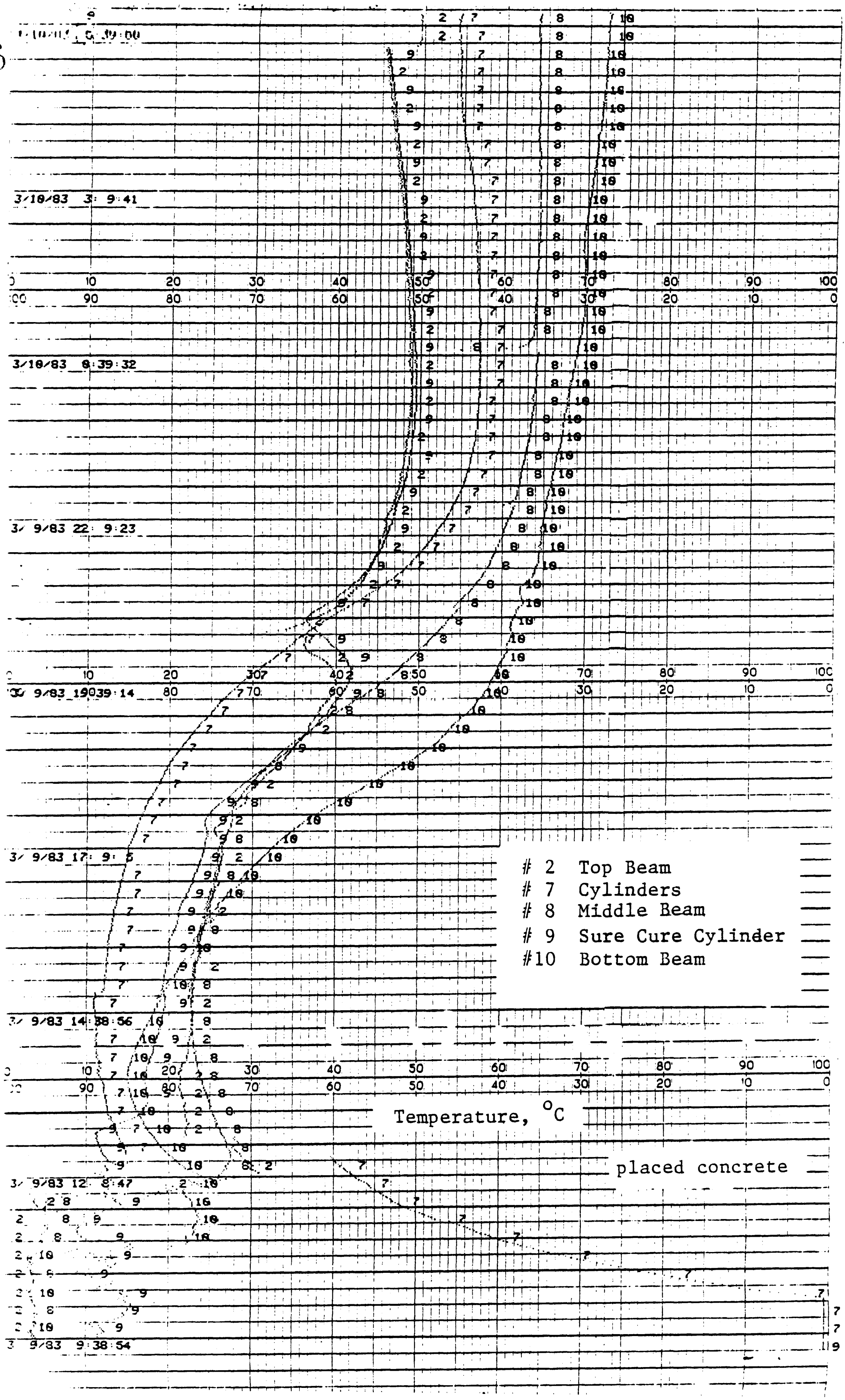

Figure 10. Strip chart from plant using radiant heat curing to produce box beam.

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Since early strength is directly related to curing temperature, and therefore to maturity, it is imperative that temperature records be maintained to allow the inspector to assure that the cylinders are cured at the same temperature as the top or least mature part of the member. If the cylinders are cured at a temperature higher than that of the least mature part of the member at release, they will likely show a strength greater than that of the less mature concrete in the member. Also, since strength at a later age can be affected by the accelerated curing period, it is necessary to match the accelerated curing of all cylinders to the curing of the top or least mature concrete in the member. Periodically,the curing temperature of some cylinders should also be matched to that of the more mature part of the member to ensure that strengths at release and at 28 days are being achieved in all the concrete in the member.

RECOMMENDED PRACTICE FOR RADIANT HEAT CURING

Prestressed Concrete Institute, American Concrete Institute, and American Association of State Highway and Transportation Officials Specifications

The Manual for Quality Control for Plants and Production of Precast Prestressed Concrete Products stresses that cylinders be cured as nearly as possible in the same manner as the members, that moisture be retained through the use of a membrane curing compound or other means, and that curing procedures be well established and carefully controlled.(13) The Manual also indicates that test cylinders shall be cured with and by the same methods as the members they represent or that they may be cured in curing chambers correlated in temperature and humidity with the beds. The Manual notes that if there is any indication of variable heat, cylinders shall be placed in the coolest area. The Manual notes that ACI Standard 308-81 "Standard Practice for Curing Concrete" describes various curing procedures in detail.(14) ACI Standard 308 directs the reader to ACI Standard 517.2R-80 "Accelerated Curing of Concrete at Atmospheric Pressure -- State of the Art".(15) ACI 517.2R indicates that the properties of concrete cured by circulating hot oil through cavities provided in steel forms should not differ from those cured with electrically heated forms. Both methods apply dry heat to fresh concrete, and as long as sufficient moisture is retained in the concrete through the use of a curing compound or externally applied moisture, adequate cure should be attained.

AASHTO specifications on radiant heat curing indicate that it shall be done under a suitable enclosure to contain the heat, and the moisture loss shall be minimized through the use of a plastic sheeting

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or a membrane curing compound.(16) The relevant parts of the AASHTO specs(16) and the PCI Manual(13) are reproduced in the Appendix.

Practices of Other States

Colorado, North Carolina, Tennessee, Maryland, Pennsylvania, New York, West Virginia, and Kentucky were contacted to determine their practices with regard to the use of radiant heat to produce prestressed concrete products for highway applications. All of these states allow the use of radiant heat, but there is very little in their specifications concerning radiant heat curing. The specifications usually indicate that it can be used with approval of the engineer, and that the curing must be done under a suitable enclosure to prevent the loss of heat and moisture as indicated by the AASHTO specs.(16) They were not aware of a problem with significantly different curing temperatures throughout the depth of a member, and most were satisfied to cure the cylinders along the bed as is done with steam curing. It seems that live steam is used at most of the plants in the states contacted.

Personnel from the Colorado Department of Highways indicated that Stanley Structures has successfully used radiant heat curing to produce highway members for more than 10 years. The beds are well insulated because they are underground, and a uniform environment is achieved. Temperature matched curing of cylinders has been done but is not considered necessary.

One producer in North Carolina has used hot water radiant heat to produce 12 in square piles and 20 in octagonal piles for approximately 20 years in forms that are aboveground. DOT personnel there were not aware of any problems with obtaining a uniform cure of the concrete.

No plants that produce prestressed concrete members for use by the Tennessee Department of Transportation use radiant heat curing.

Shockey's Prestressed Concrete Products is the only plant that uses hot oil radiant heat to produce members for the Maryland Department of Transportation.

Hot oil radiant heat is used at one plant that produces members for the Pennsylvania Department of Transportation. The plant is outside, is closed from November 15 to March 15, and has successfully produced box beams and I-beams for approximately 20 years. The Department of Transportation personnel were not aware of any problems with significantly different curing temperatures, and cylinders are cured along the bed, moisture is retained through the use of wet burlap and water spray, and heat loss is prevented by using insulated mats.

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None of the 10 plants that produce prestressed concrete products for the New York Department of Transportation use radiant heat. Likewise, plants that produce members for the West Virginia Department of Transportation don't use radiant heat.

One plant that produces members for the Kentucky Department of Highways uses hot water in conjunction with live steam. Cylinders are stored at a high level along the bed, and no problems have been encountered.

The Virginia Bed

Evidently some of the nonuniformity of cure that was found in Virginia is unique to the bed studied and is not typical of beds that use radiant heat curing. The bed apparently is not adequately enclosed to retain the heat necessary to provide a fairly uniform cure, particularly in winter months. It is believed that the difference in maturity between the concrete in the top and bottom of a member typically is less pronounced than that found in the bed evaluated. Beds that are better insulated (such as beds below ground or inside), or beds where the outside ambient temperature is not cold (beds inside or used in only warm months), or beds which have the heating medium flowing through cavities throughout the form rather than below the form would provide a much more uniform cure.

However, the information obtained from this study indicates that when radiant heat curing is used, temperature matched curing should be used for all cylinders, unless the prestressed concrete producer can document that his bed and procedures provide a uniform enough cure to allow the cylinders to be cured along the bed as is done when low pressure steam is used.

CONCLUSIONS

1. During the accelerated curing with radiant heat the temperature of the concrete in a member is influenced by its proximity to the heat source, and at the time the prestressed strands are cut, the concrete may, depending upon the design of the bed, exhibit a greater range of maturities than does concrete cured by low pressure steam.

2. The compressive strengths of concrete cylinders, particularly the strength at early ages, is related to the curing temperature. The less mature concrete has a lower strength.

3. The permeability to chloride ions is related to the curing temperature and the entrained air content. The highest permeabilities are exhibited by concrete cured at relatively high temperatures and concretes with relatively high entrained air contents. Accelerating the cure of concrete increases its permeability to chloride ions.

4. Most specimens cured by radiant heat passed the freeze-thaw test. The only specimens to fail the test were those with a low air content of approximately 2% to 4% and those containing an HRWR admixture and cured at elevated temperatures.

5. The membrane curing compound does an acceptable job of retaining the moisture in the concrete during accelerated curing. Compressive strengths were only 7% greater for specimens cured with steam as compared to those cured with radiant heat and covered with a curing compound. The freeze-thaw performance was about the same for specimens cured by both methods. The permeability was greater at early ages but less at later ages for specimens cured by radiant heat as compared to those cured with steam.

6. The requirements in Section 405.09 of the Virginia Department of Highways and Transportation Road and Bridge Specifications[2] listed below will apply to curing with radiant heat with the indicated modifications:

    c) Test specimens used to determine initial set will be stored and maintained in an environment equivalent to that of the coolest section of the member.

    d) All concrete shall be cured at a concrete temperature of 165°F or less.

    e) Delete.

    f) The curing enclosure shall be designed and protected so as to minimize the loss of heat and moisture and to provide reasonably uniform curing of all portions of the member. Moisture loss shall be minimized by covering all exposed surfaces with a plastic sheeting or by applying an approved liquid membrane curing compound.

    g) All concrete test cylinders will be subjected to accelerated curing by matching the temperature of the cylinders to the temperature of the portion of the member that will achieve the lowest maturity.

7. Table II-15 of the specifications should be modified to require an air content of 4% to 7% for class A5 concrete members that will be subjected to an environment in which they will undergo cycles of freezing and thawing in the presence of moisture.

ACKNOWLEDGEMENTS

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The study was conducted with HPR funds as a type B study under the direction of Harry E. Brown, group leader, and Howard Newlon, research director.

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APPENDIX

RELEVANT PARTS OF AASHTO SPECIFICATIONS

AND

PCI MANUAL

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4.33.5.5 Curing with Radiant Heat (16)

Radiant heat may be applied by means of pipes circulating steam, hot oil or hot water, or by electric heating elements. Radiant heat curing shall be done under a suitable enclosure to contain the heat, and moisture loss shall be minimized by covering all exposed concrete surfaces with a plastic sheeting or by applying an approved liquid membrane curing compound to all exposed concrete surfaces. Top surfaces of concrete members to be used in composite construction shall be clear of residue of the membrane curing compound so as not to reduce bond below design limits. Surfaces of concrete members to which other materials will be bonded in the finished structure shall be clear of residue of the membrane curing compound so as not to reduce bond below design limits.

3.4 Curing Concrete (13)

3.4.1 General

Proper curing of fresh concrete by any method requires moisture be retained for complete hydration of cement to take place and to prevent formation of surface cracks due to rapid loss of water while the concrete is plastic. For all prestressed concrete operations, the curing procedure shall be well established and properly controlled.

Various methods commonly used include leaving forms in place, sprinkling, ponding, using moisture-retaining covers, or applying a liquid seal coat of thin water-impervious membrane. Curing shall be commenced as soon as possible following completion of surface finishing.

For accelerated curing, heat shall be applied at a controlled rate following the initial set of concrete in combination with an effective method of supplying or retaining moisture.

The actual curing of concrete depends on many variables, including the mass of the member, type and properties of cement, air temperature, humidity and other variables. As the properties of concrete in members are usually judged by the strength of test cylinders, cylinders shall be cured, as nearly as possible, in the same manner as the members.

Curing of products used for architectural appearance shall be a well established method that precludes strains or discoloration.

To determine effects of curing, it is critical that cylinders be cured at concrete temperatures of the product represented. Cylinders shall be monitored in their curing environment or controlled by thermocouples to ensure consistent curing with the products.

3.4.2 Accelerated Curing Temperature Controls

Accelerated curing shall be developed based on efficiency of concrete strength development without damaging concrete. Temperature guidelines for accelerated curing, no matter which method is used, are as follows:

1. The temperature gains and controls outlined are concrete temperatures, not ambient temperatures of the curing area.
2. Application of heat gains over placed concrete temperatures shall begin only after concrete has reached its initial set as determined by ASTM C 403. Heat application to the curing area may be required immediately in cold weather (below 50 °F) to maintain or regain placed concrete temperatures.
3. Heat gain of not over 80 °F per hour is acceptable for the curing concrete as long as a proper delay period is used (ASTM C 403).
4. Maximum concrete temperature during the curing cycle shall be 190 °F.
5. Delay periods in excess of 10 hours result in the loss of effectiveness of accelerated curing.
6. Recording thermometers shall be provided showing the time-temperature relationship through the curing period from placing concrete to transfer of prestress. At least one recording thermometer per product line shall be used to monitor the product at appropriate locations.

3.4.3 Curing with Live Steam

Steam curing shall be under a suitable enclosure to retain the live steam to minimize moisture and heat losses. The enclosure shall allow free circulation of the steam. Steam jets shall be positioned so they do not discharge directly on the concrete, forms or test cylinders.

After placement and vibration, the concrete shall be allowed to attain its initial set before steam is applied; otherwise the elevated temperature may have a detrimental effect on the concrete strength. During the period between placement of concrete and application of steam, provision shall be made to prevent surface drying by means of a coating of membrane curing compound, moisture retention covers, or equally effective methods.

3.4.4 Curing with Radiant Heat and Moisture

Radiant heat may be applied to beds by means of pipes circulating steam, hot oil or hot water, by electric blankets or heating elements on forms, or by circulating warm air under and around forms. Pipes, blankets or heating elements shall not be in contact with test cylinders.

During the cycle of radiant heat curing, effective means shall be provided to prevent rapid loss of moisture in any part of the member. Moisture may be applied by a cover of moist burlap, cotton matting, or other effective means. Moisture may be retained by covering the member with an impermeable sheet in combination with an insulating cover, or by applying a liquid seal coat or membrane curing compound.

Due to the slow rise of ambient temperatures with radiant heat, application of the heat cycle may be accelerated to meet climatic conditions. However, in all cases, the curing procedure to be used shall be well established and carefully controlled.

3.4.5 Curing by Moisture Retention Without Heat

For curing without heat, the surface of the concrete shall be kept covered or moist until such time as the compressive strength of the concrete reaches the strength specified for detensioning or stripping. Acceptable methods of curing are:

1. Leaving side forms in place and keeping top surfaces continually moist by fogging, spraying or covering with moist burlap or cotton mats, or by covering top surfaces with impermeable covers or membrane curing compound.
2. Removing side forms and preventing loss of moisture from the sides and top surfaces by applicable methods described above.

3.4.6 Membrane Curing Compound

In the use of membrane curing compound, the following precautions shall be observed:

1. The coating of membrane shall cover the entire suface to be cured with a uniform film which will remain in place without gaps or omissions until the full design strength of the concrete is reached. To detect omissions, means shall be taken to ensure membrane is uniformly coating surfaces.
2. Membrane curing compound shall be applied at a rate of coverage not in excess of the manufacturer's recommendations and generally not in excess of 400 to 450 sq. ft. per gallon.
3. Membrane curing compound shall be applied to the top surface as soon after casting as the surface water sheen disappears.
4. Top surfaces of concrete members to be used in composite construction shall be clear of the residue of the membrane curing compound so as not to reduce bond below design limits, unless suitable mechanical means for full bond development are provided.
5. Membrane curing compounds shall be compatible with coatings or other materials to be applied.

6.1 Testing

6.1.1 General

In order to manufacture products having uniformly predictable properties, it is necessary that they be composed of component parts having known and acceptable characteristics. To this end, the properties of all materials used in the manufacture of prestressed concrete members shall be demonstrated by adequate testing.

Given materials of acceptable properties must be combined and utilized in accordance with prescribed practices. The adequacy of manufacturing methods requires constant confirmation through regular and adequate testing.

Component materials entering into precast and prestressed concrete shall be restricted to those of established manufacture for which satisfactory performance records are available. Manufacturers shall be required to furnish certified test reports for cement, aggregates, admixtures, curing materials, tendon materials, headed studs, deformed bars, and reinforcing steel showing compliance with the applicable specifications listed in Article 6. These reports shall be retained by the precast and prestressed concrete producer. No component materials shall be used in the manufacture of concrete members until their correct properties have been demonstrated either by manufacturer's certified test reports or by plant testing.

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It is important that plants be properly equipped and have an adequate program for testing of concrete specimens so concrete strengths can be readily and accurately determined at the time of stress transfer and at design age. Each precast plant shall be equipped with adequate testing equipment and staffed with personnel trained in its use to ensure proper control of concrete, testing of specimens and the design and control of concrete mixes.

Manufacturer's operating instructions shall be obtained for all testing equipment and applicable industry standards, national standards, etc. for materials and testing. These instructions shall be kept on file and shall be generally understood by all testing personnel.

6.1.2 Concrete Test Cylinders

Testing of concrete strengths by means of test cylinders is a critical part of the quality control program at all precast plants. In order for the cylinder testing to provide valid results, specimens must represent the prototype concrete within close limits. Concrete shall be sampled and cylinders made in accordance with the following specifications except as modified herein:

ASTM C 31 — Specification for Making and Curing Concrete Test Specimens in the Field

ASTM C 172 — Specification for Sampling Fresh Concrete

ASTM C 192 — Specification for Making and Curing Concrete Test Specimens in the Laboratory

Sizes of specimens made and cured in accordance with ASTM C 31 are modified to permit use of 4 × 8 in. test cylinders.

A minimum of two test cylinders shall be made to verify stress transfer strength tested in accordance with Article 6.1.8, and a minimum of two test cylinders per day or per 75 cu. yd. of concrete shall be made for each mix design to indicate 28-day strength, or strength at an earlier age if specified. In the case of individual forms for small units having the same mix, but non-continuous batching or dissimilar curing, a minimum of two test cylinders shall be made for each 20 cu. yd. or fraction thereof to verify handling strength or strength at stress transfer.

6.1.3 Purpose of Cylinders

Cylinders made to evaluate design mixes are generally cast and cured under carefully controlled laboratory conditions. Before acceptance and establishment of a standard design mix, representative cylinders also shall be cast and cured under plant production conditions.

6.1.4 Cylinder Molds

Molds for making test cylinders shall be in accordance with applicable requirements of ASTM C 31 or C 470.

Cylinder molds shall be kept clean and free from deformations. Any molds that become distorted, or which do not comply with the dimensional requirements of ASTM specifications, shall be discarded.

6.1.5 Cylinder Making

Cylinders shall be made as near as possible to the location where they will be cured and shall not be disturbed in any way from ½ hour after casting until they are either 24 hours old or ready to be tested. Concrete in cylinders may be consolidated by rodding or by vibration as specified in ASTM C 31 or C 192. If external vibrators are used, techniques shall be developed to preclude segregation.

6.1.6 Cylinder Curing

Test cylinders shall be cured with similar methods as the members they represent. In lieu of actual curing with the members, cylinders may be cured in curing chambers correlated in temperature with the beds. In such a case, the correlation shall be constantly verified by use of recording thermometers in the curing chambers and comparison with the temperature records of beds, and by use of the same methods of moisture retention for curing chambers and casting beds.

The 28-day cylinders shall remain with stress transfer cylinders in the bed with the member or in the curing chamber until the member is stripped. At that time, the cylinders may be removed from their molds and placed in storage in a moist condition at 73.4°, ±3°F per ASTM C 192 requirements.