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16. ABSTRACT
The studies reported herein were planned to yield preliminary information on the effect of the early curing of concrete in an atmosphere of saturated steam at temperatures in the range of 125 to 170*F. Concrete proportions were selected to be typical of those used in the manufacture of prestressed concrete products.

All concrete contained 3/4-inch maximum size aggregate from the American River. The cement content was 7-1/2 sacks per cubic yard with water to produce a 3-inch slump. Four cements were used. Three of the cements (Nos. 1, 3 and 5) were finely ground, type II, low-alkali cements, each produced by a mill in northern California. One cement (No. 7) was a normally ground type II, low-alkali cement. To portions of each of these cements, sufficient pulverized gypsum was added in the laboratory to increase the SO3 content by 0.5% making a total of 8 test cements.

Chemical and physical properties of the cements are given in Table 1. Concrete specimens containing each of the 8 cements were cured from the 8th to the 48th hour in a steam chest maintained at four different temperatures; 125, 140, 150 and 170*F. Four rounds were made for each cement and steam curing temperature. Similar specimens were cured in fog at 73*F. Tests were made to measure length change, compressive strength and static modulus of elasticity after varying periods of steam and moist curing at 73*F, and subsequent exposure to air at 73*F and 50 percent relative humidity. A complete schedule of curing variations is given in Table 2. A total of 1600 specimens was tested.

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STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

A Preliminary Report on

THE EFFECT OF STEAM CURING ON THE PROPERTIES OF CONCRETE

60-03

August 1, 1960

State of California
Department of Public Works
DIVISION OF HIGHWAYS

Materials and Research Department

August 1, 1960

Lab. Project
Auth. 56 R 6045

Mr. J. E. McMahon
Assistant State Highway Engineer
Division of Highways
Sacramento, California

Dear Sir:

Submitted for your consideration is:

A Preliminary Report on

THE EFFECT OF STEAM CURING ON THE PROPERTIES OF CONCRETE

Tests made by	Technical Section
Under general direction of	Bailey Tremper
Work supervised by	D. L. Spellman
Report prepared by	W. D. Stewart

Yours very truly

F. N. Hveem
Materials & Research Engineer

cc: JWTrask
IOJahlstrom
ALElliott
DFDowning
M.Harris

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THE EFFECT OF STEAM CURING ON THE PROPERTIES OF CONCRETE

The studies reported herein were planned to yield preliminary information on the effect of the early curing of concrete in an atmosphere of saturated steam at temperatures in the range of 125 to 170°F. Concrete proportions were selected to be typical of those used in the manufacture of prestressed concrete products.

SCOPE OF TESTS

All concrete contained 3/4-inch maximum size aggregate from the American River. The cement content was 7-1/2 sacks per cubic yard with water to produce a 3-inch slump. Four cements were used. Three of the cements (Nos. 1, 3 and 5) were finely ground, type II, low-alkali cements, each produced by a mill in northern California. One cement (No. 7) was a normally ground type II, low-alkali cement. To portions of each of these cements, sufficient pulverized gypsum was added in the laboratory to increase the SO_3 content by 0.5% making a total of 8 test cements.

Chemical and physical properties of the cements are given in Table 1. Concrete specimens containing each of the 8 cements were cured from the 8th to the 48th hour in a steam chest maintained at four different temperatures; 125, 140, 150 and 170°F. Four rounds were made for each cement ~~and~~ steam curing temperature. Similar specimens were cured in fog at 73°F. Tests were made to measure length change, compressive strength and static modulus of elasticity after varying periods of steam and moist curing at 73°F, and subsequent exposure to air at 73°F and 50 percent relative humidity. A complete schedule of curing variations is given in Table 2. A total of 1600 specimens was tested.

TEST METHODS

All tests were made on cylindrical specimens 3 inches in diameter by 6 inches in height containing cadmium plated steel gage studs 1 inch in length, 3/8-inch diameter, threaded full length, and with the exposed end rounded. Molds were constructed of 1/64-inch tin plate with open ends and the seam secured by spot welding. The molds were assembled in groups of 12 and clamped on a treated plywood base plate, fitted with 3-inch diameter masonite discs which were drilled to hold gage plugs. The base plate was clamped to the top of a Syntron vibrating table.

Concrete was mixed in an open tub Lancaster mixer in quantity sufficient for 12 specimens. Each mold was filled to two-thirds capacity and vibration at 3600 cycles per minute was started. The molds were then filled to overflowing and the excess struck off. Caps drilled to accomodate the gage plugs were then placed in position. The gage plug was held in place by means of a small magnet. The amount of vibration used was the same for all groups and was determined by preliminary tests.

The assembly of fabricated specimens was then transferred to the 73°F fog room for 6 hours. The specimens were then removed from the base plate and were weighed and measured for length in a vertical comparator with a 0.0001-inch dial. The sheet metal mold remained in place until the completion of steam curing. The fog cured specimens were stripped at the same time that the steam cured specimens were stripped, at the age of 48 hours. The molds were removed from the specimens by cutting along one element with a band saw.

Steam curing was conducted in insulated chambers fed with steam from a boiler. Entry of steam was controlled manually at a rate such that the temperature as indicated by a thermocouple embedded in one of the specimens increased at the rate of 15 to 20°F per hour. After the desired temperature was reached, further control of temperature was by automatic means.

Specimens were placed in the steam chest at the age of about 6 to 8 hours. They were removed from the steam at the age of 48 hours calculated from the time of mixing the concrete. The 48-hour steaming period was adopted because preliminary tests indicated that a shorter steam period did not produce strengths comparable to those obtained by moist curing at 73°F for 28 days.

After completion of steam curing, the specimens were placed in water at 120°F for about 1/2-hour. They were then transferred to water at 73°F where they remained for an additional period of at least 1/2-hour, or until thermocouples in companion cylinders indicated that the temperature of cylinders had come to equilibrium with the temperature of the water, 73° ± 3°F. The cylinders were then weighed and measured for length. The molds were removed and the cylinders were again weighed and measured for length. They were then subjected to the curing and drying schedule as shown in Table 2.

Preliminary data indicated that the measurement for length at 6 hours was reasonably reproducible for specimens containing fine grind cements, and that the cooling schedule effectively eliminated length changes due solely to temperature effects, after removal from the steam chamber. Weight and length changes were measured periodically during the moist curing and drying periods. Length changes are expressed as a percentage of the effective gage length, assumed to be 4-1/2 inches, the distance between inner ends of the studs.

Cylinders were prepared for compression testing by capping with molten sulfur compound of such thickness that the gage studs projected about 1/8-inch. Testing machine bearing plates contained drilled holes to receive the stud ends during the compression tests.

Preliminary tests indicated that the presence of the gage studs in the cylinder did not affect the observed compressive strength.

Cylinders were tested in a hydraulic machine equipped with load capsule and pacing disc. The load was applied at the rate of 50 psi per second. A recording stress-strain recorder with a gage length of 4 inches was attached to each specimen and a complete stress-strain graph up to the point of failure was obtained. All specimens were tested for compression and strain in the moisture condition reached during the moist curing or drying period.

All of the rounds for one steam temperature were fabricated before the rounds for another temperature were started. Molding of specimens was started on January 5, 1959 and completed on April 7, 1959. Certain anomalies that appear in the test data for different steam temperatures may have resulted from the scheduling of the work.

DATA OF THE TESTS

Complete test data are not given in this report. The data are presented by means of graphs, Figures 1, 2 and 3, showing average trends. The performance of each of the cements was studied and it was concluded that there was no significant difference between any of the three finely ground cements with or without added gypsum. All data for these 6 cements are presented as average values. The normally ground cement gained strength at a lower rate and its effects are discussed separately. In some cases the average results for the 8 cements are used in order to obtain more significant values.

DISCUSSION

A. FINE GRIND CEMENTS

Effect of Steam Curing on Strength

Figure 1 shows the development of strength as related to different curing conditions and temperatures.

The average effect of temperature of curing to the age of 48 hours as shown by results of the three finely ground cements (with and without added gypsum), is that each degree F increase in temperature increased the strength by 12 psi. After moist curing, subsequent to steaming, the strength at 7 days is increased at the average rate of 7 psi per degree increase in temperature. At later ages when tested in the as-dried condition, strengths for all steam curing temperatures tend to be about equal and are about the same as obtained by 28-day moist curing at 73°F.

It should be noted that all temperatures refer to that of the specimen. In the case of large members, the temperature within the concrete may exceed that of the surrounding vapor by 10 to 15 degrees.

Effect of Steam Curing on Static E

The stress-strain curves were used to derive values of static E at loads of 0.3 and 0.6 of the ultimate compressive strength. The value of E is expressed as the secant modulus of elasticity from zero to the selected proportion of ultimate compressive strength.

The values relative to ultimate strength were not affected greatly by the temperature of steaming.

The average results are plotted in Figure 2.

Values of static E as an average of all cements and all steam temperatures, also after 28 days of fog cure at 73°F, are shown below.

	$E \times 10^{-6}$ at 0.3 Ult.Str.	$E \times 10^{-6}$ at 0.6 Ult.Str.
28 days fog at 73°F	5.1	4.5
48 hours steam	4.2	3.7
48 hours steam plus 26 days fog at 73°F	5.0	4.4
48 hours steam plus 5 days fog at 73°F plus 112 days drying at 73°F and 50% RH	4.5	4.0

These results show a slightly lower value of E after 48 hours of steam than specimens continuously moist cured to 28 days. When subsequently moist cured to the age of 28 days, values of E increased to values comparable to those obtained by continuous moist curing to the age of 28 days. When steamed and then fog cured at 73°F to the age of 7 days and subsequently dried, values of E were reduced about 0.5×10^6 below that obtained by 28 days of continuous fog or steam and fog curing combined.

Effect of Steam Curing on Expansion

Measurements of length before and after placing the specimens in the steam chest and after cooling the specimens in water to room temperature yield data for estimating the length change produced by steaming. These results are compared to those of similar specimens cured continuously moist to the age of 28 days. The measured values were small because of the short gage length employed and are rather erratic between supposedly similar specimens. The results of all specimens involving 8 cements and all four steam temperatures have been averaged with the following results:

Expansion of Moist Cured Specimens from 6 hrs. to 28 days, percent	Expansion of Steam Cured Specimens from 6 hrs. to 48 hours, percent
0.008	0.014

The smallest expansion that occurred in the steam cured specimens was 0.010% at the 155°F curing temperature, which is larger than the .008% expansion of the moist-cured group. The average expansion for the 125°F, 140°F, and 170°F group combined, was 0.015%, or nearly double the expansion of the moist-cured group.

Effect of Steam Curing on Drying Shrinkage

The results of steam curing on shrinkage during drying are shown in Figure 3.

When compared to the drying shrinkage of specimens moist-cured at 73°F for 7 days, steaming at 125°F had little effect. Higher steam temperatures progressively reduced drying shrinkage as the temperature was increased. At steam temperatures of 170°F, the reduction in shrinkage below that obtained at 73°F was about 15 percent after 7 and 14 days of drying, 25 percent after longer periods. The longer periods probably represent a state of dryness greatly in excess of that to be expected in large members exposed outside in California. Members exposed in closed, heated buildings however, would be expected to dry eventually to the state represented by long-time drying of the test specimens.

B. REGULAR GRIND CEMENT

Effect of Steam Curing on Strength

Average compressive strengths of test specimens fabricated with regular grind cements cured continuously in the 73°F fog room up to 28 days, were from 17 to 23 percent less than the specimens made with the fine grind cements at the same ages. The strength of these cements, when subjected to steam curing, ranged from 17 to 33 percent less than the strength of the fine grind cements.

Effect of Steam Curing on Static E

Static E values of the 2-day steam cured specimens cured at 125°F, 140°F and 155°F fabricated with regular grind cements were approximately 0.5 x 10^6 psi less than the specimens fabricated with the fine grind cements. This difference in static E gradually decreased in value as the specimens aged. The average difference in static E of the specimens cured at 170°F appeared to be slightly greater than at the other curing temperatures, (0.7 x 10^6 psi) and did not appear to diminish as rapidly as the specimens aged.

Effect of Steam Curing on Expansion

It was not possible to secure accurate length readings on the specimens fabricated with the regular grind cements at the age of 6 hours; therefore, no expansion comparison was made between the two different grinds of cement.

Effect on Drying Shrinkage

The regular grind cements, when subjected to 7 days moist curing in the 73°F fog room prior to being placed in the 50% relative humidity room, showed considerably less shrinkage than the fine grind cements. The numerical difference in shrinkage between the regular and fine grind cements was substantially constant after all periods of drying. On a relative basis however, the ratio decreased with length of drying as shown below.

$$\text{Relative Drying Shrinkage of Moist Cured Specimens} = \frac{\text{Fine Grind}}{\text{Regular Grind}}$$

Days Dried	7	14	28	56	112
Ratio	1.43	1.33	1.23	1.15	1.09

In general, the total amount of drying shrinkage of the regular grind cements when steam cured, was less than the fine grind cements for any one given steam curing temperature. Also, increasing the curing temperature reduced the drying shrinkage. The greater reductions being noted at the higher temperatures.

CONCLUSIONS

The validity of conclusions reached from the test results is subject to some question because of the small size of the test specimens, lack of randomization among the four steam temperatures and the fact that the large number of specimens made it necessary that different operators perform similar tests and measurements at different times. Notwithstanding certain anomalies appearing in the results, the following general conclusions with respect to performance of the fine grind cements appear to be warranted.

1. Steam curing accelerated the rate of strength gain. Although higher steam temperatures produced greater strength at the age of 48 hours than did the lower steam temperatures, the difference was not very great and amounted to only about 120 psi for each 10 degree increase in temperature. Temperature of steaming had little effect on final strength of the concrete.

2. Although steaming to the age of 48 hours produced relatively high strengths, the static modulus of elasticity at this age was lower than that resulting from 28 days of fog curing at 73°F. Additional fog curing at 73°F to the age of 28 days produced values of E comparable to continuous fog curing at 73°F. Prolonged drying reduced values of E by about 0.5×10^6.

3. During steam curing, the concrete expanded and retained an expansion after cooling in an amount that was about 175 percent as great as resulted from continuous moist curing at 73°F for 28 days.

4. Steaming tended to reduce shrinkage upon drying progressively with increase in temperature. The reduction in shrinkage below that obtained after moist curing at 73°F was of the order of 15 to 25 percent with steam temperatures of 170°F. Relative shrinkage of full size members exposed outside are expected to be in accordance with the lower range in reduction whereas those exposed in closed, heated buildings may be expected to correspond to the higher ranges in reduction.

Table 1

Chemical and Physical Properties of Cements
Used in Steam Curing Tests

	Cement Number*			
	1	3	5	7
Oxide Analysis				
SiO_2	23.0	22.7	24.0	22.2
Al_2O_3	4.1	3.8	2.7	4.6
Fe_2O_3	4.3	2.6	2.9	2.6
CaO	64.1	64.7	66.0	64.8
MgO	1.5	1.6	0.7	1.7
SO_3	2.1	2.3	2.1	1.8
Ignition Loss	0.6	1.6	1.5	2.0
Insoluble Residue	0.02	0.16	0.06	0.30
Na_2O	0.27	0.36	0.03	0.31
K_2O	0.15	0.22	0.15	0.34
Equiv. Na_2O	0.37	0.51	0.13	0.53
Compound Composition				
C_4AF	13	8	9	8
C_3A	4	6	2	8
C_3S	46	55	58	55
C_2S	31	24	25	22
Compressive Strength, 2-inch cubes				
3 day	2017	2183	2540	1465
7 day	2993	3298	3533	2087
Autoclave Expansion	-0.017	-0.022	-0.050	+0.041
Setting Time:				
Initial Set (hrs. & mins.)	2:55	3:00	3:15	3:10
Final Set	4:10	4:05	7:00	4:15
Specific Surface (Blaine)	3855	3904	4079	3035
% Air	7.8	10.0	10.7	7.4
Expansion and Contraction (Test Method No. Calif. 527-A)				
Expansion (As Rec'd), %	0.0082	0.0090	0.0130	0.0030
" (0.5% added SO_3) %	0.0065	0.0130	0.0137	0.0072
Contraction (As Rec'd), %	0.0425	0.0460	0.0500	0.0357
" (0.5% added SO_3) %	0.0332	0.0572	0.0620	0.0488
Calculated Optimum SO_3, %	2.8	1.9	1.6	1.3

*Nos. 2, 4, 6 and 8 were assigned to the cements containing added gypsum.

Table 2

Schedule of Curing Variations Used
for Steam Cure Tests

Schedule for each round				
Spec. No.	No. days in Steam*	No. Days (fog) Standard Cure	No. days in Air	Age at Str.Test
1(a)**	0	3	0	3
1(b)	0	7	0	7
2(a)	0	14	0	14
2(b)	0	28	0	28
3(a)	0	7	14	21
3(b)	0	7	28	35
4(a)	0	7	56	63
4(b)	0	7	112	119
5	2	0	0	2
6	2	5	0	7
7	2	26	0	28
8	2	5	14	21
9	2	5	28	35
10	2	5	56	63
11	2	5	112	119
12	Thermocouple			

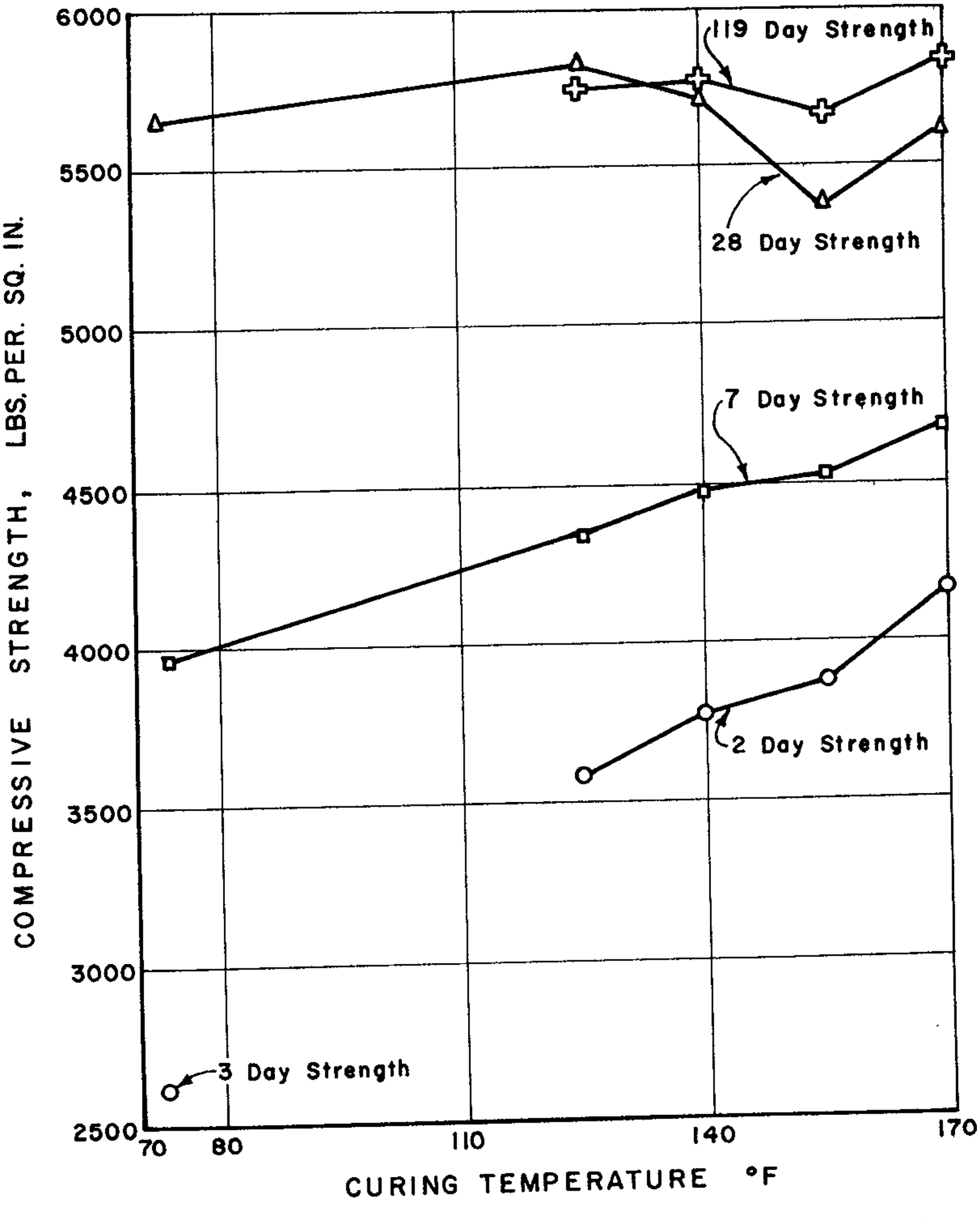
*Time in steam includes 6 to 8 hrs. delay time before steam

**(a) and (b) alternated for different steam temperatures

4 steam temperatures: 125°F, 140°F, 155°F, 170°F

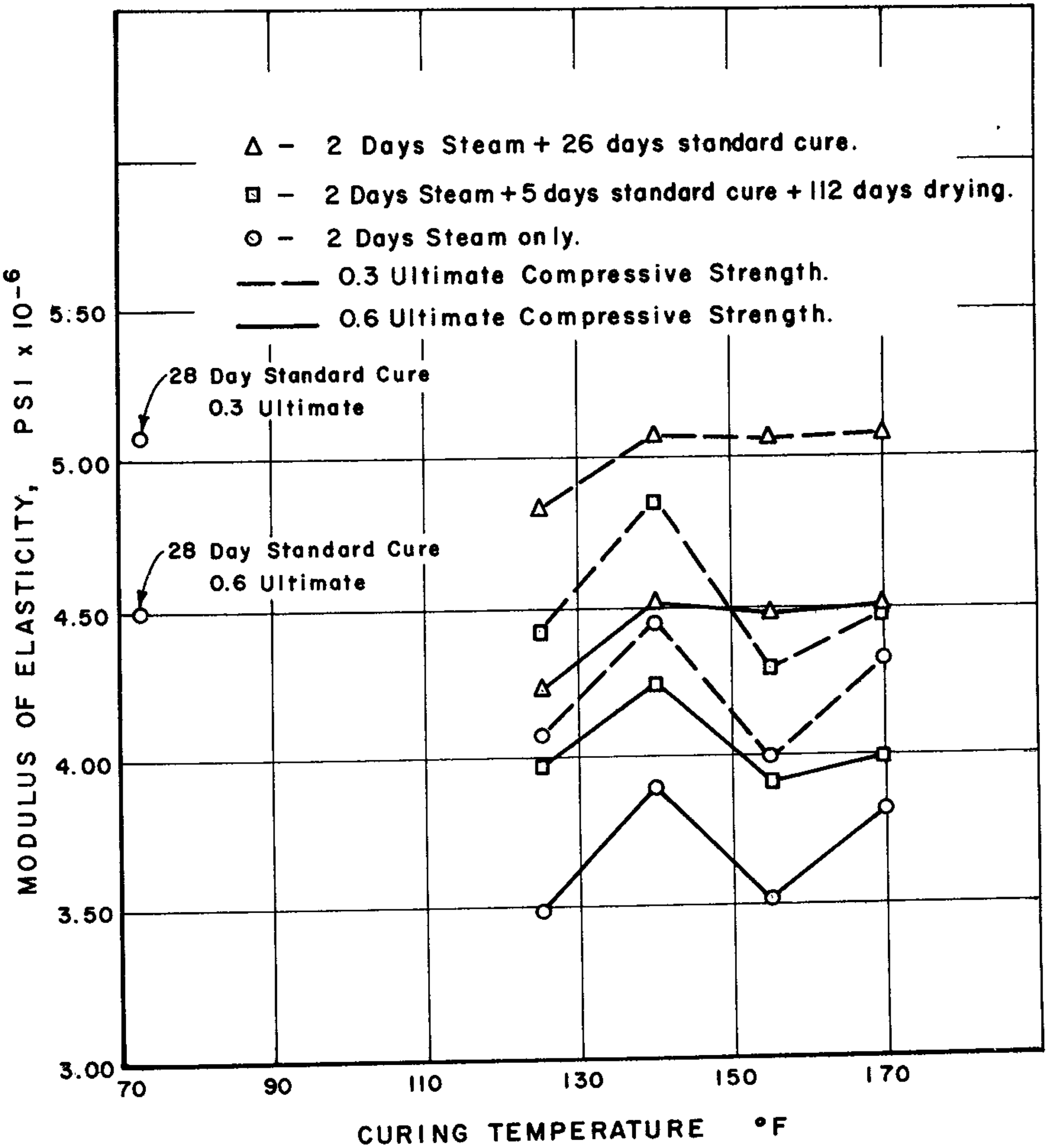
4 rounds each cement

8 cements (3 fine grinds) (1 regular grind) Each cement as received and with added gypsum



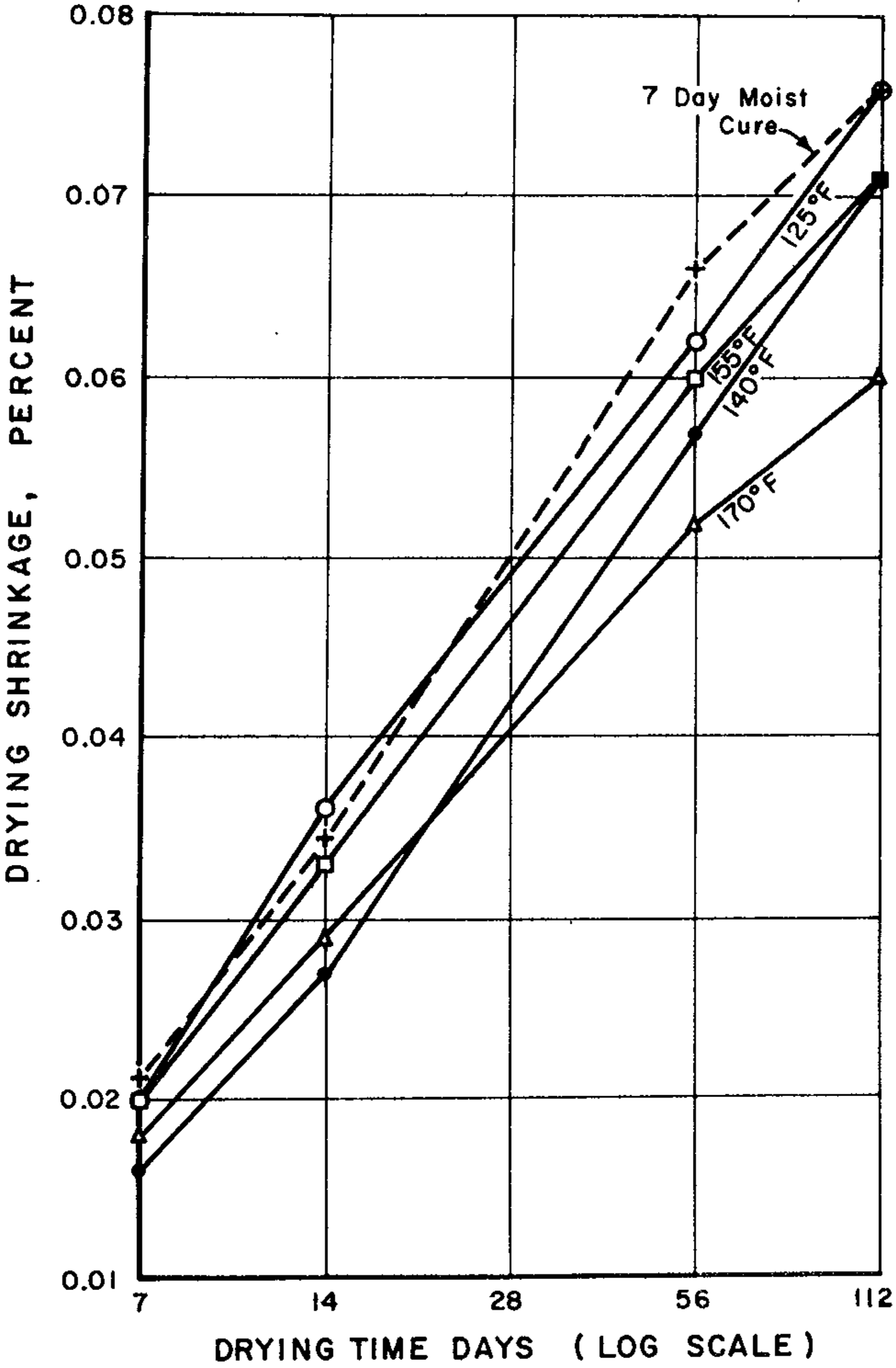
COMPRESSIVE STRENGTH AFTER VARIOUS TYPES AND AMOUNTS OF CURING

AVERAGE OF FINELY GROUND CEMENTS



ULTIMATE STRENGTH FOR VARIOUS CURING CONDITIONS
ALL FINE GROUND CEMENTS

Figure 3



DRYING SHRINKAGE AFTER CURING

Drying at 73° F and 50% Relative Humidity
Specimens cured 2 days in steam plus
5 days Moist Cure before drying.
Cured length = 0.00

Figure 4 Molding specimens on vibrating table

Figure 5 View of steam chest showing specimens in racks

Figure 6 Temperature Recorder for steam chest

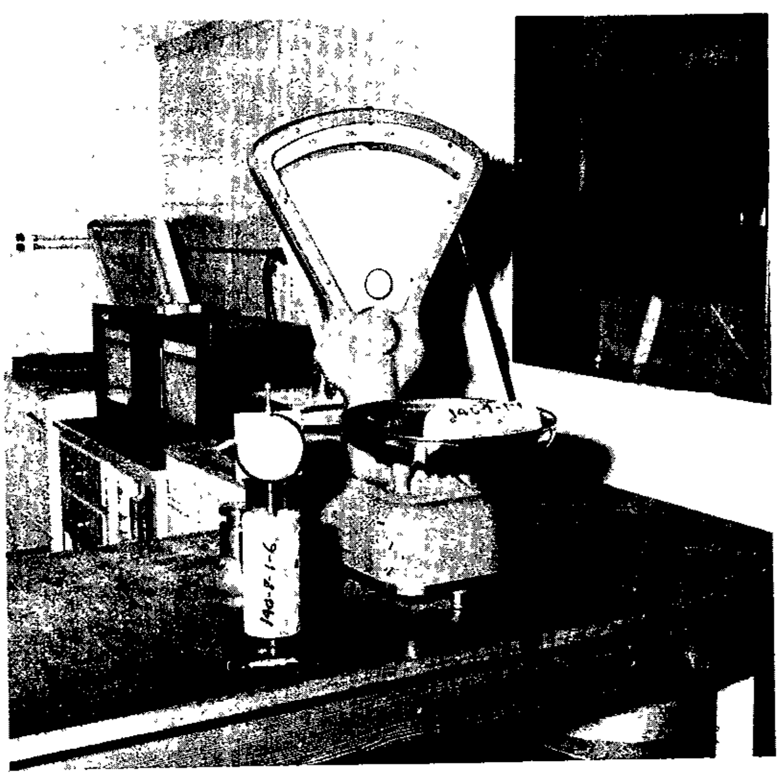


Figure 7 Scales and length comparator

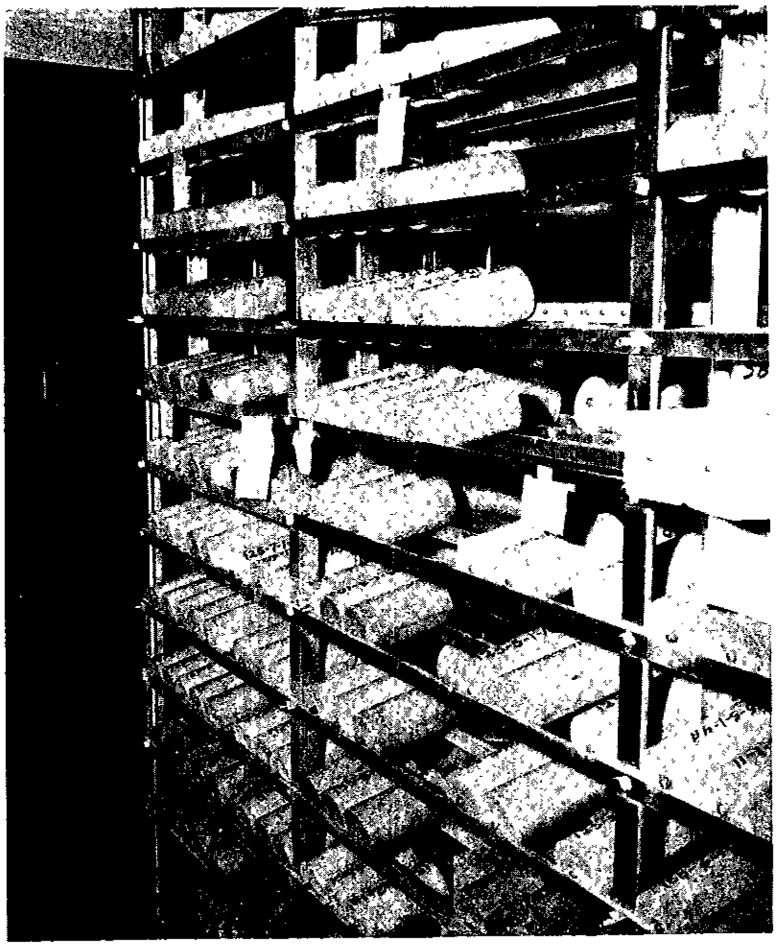


Figure 8 Test specimens in drying room

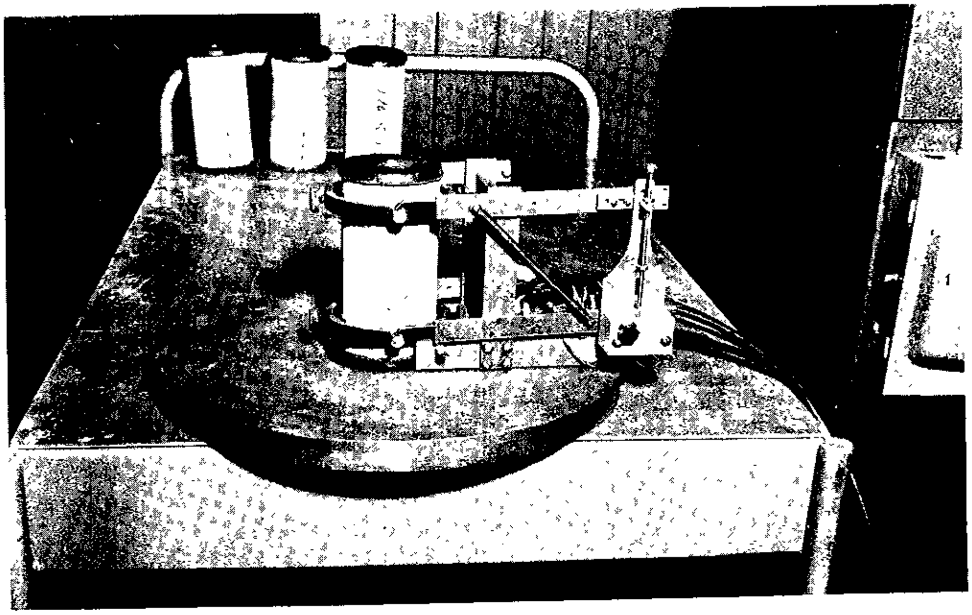


Figure 9 Extensometer for indicating strain of test specimens

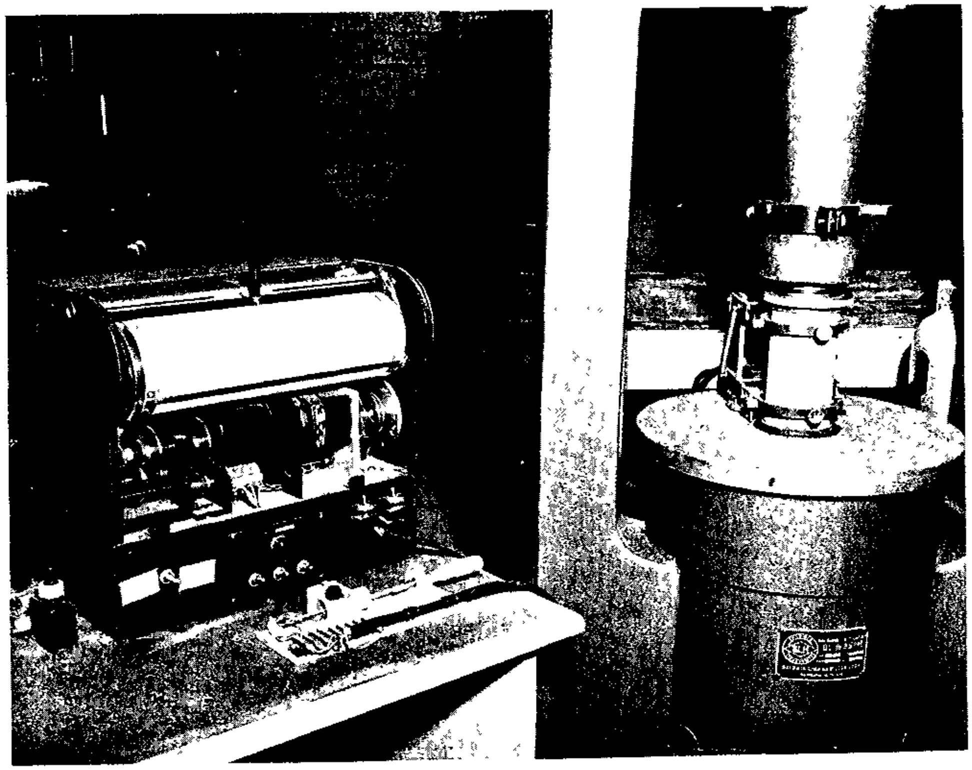


Figure 10 Test specimen in compression test showing extensometer and equipment for recording stress-strain curves