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INFLUENCE OF TEMPERATURE ON THE STRENGTH OF CONCRETE

BY

A. B. McDANIEL

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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INFLUENCE OF TEMPERATURE ON THE STRENGTH OF CONCRETE

BY A. B. MCDANIEL, ASSISTANT PROFESSOR OF CIVIL ENGINEERING.

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INFLUENCE OF TEMPERATURE ON THE STRENGTH OF CONCRETE

I. Introduction.

1. *Preliminary.*—The general use of concrete in various kinds of construction and at all seasons of the year renders important a knowledge of the effect of temperature upon the strength of this material. It is of special economic importance to the contractor or the builder to be informed concerning the strength of concrete at early ages under different temperature conditions so that he may know when to remove forms and what loads may be safely applied to the different parts of a structure.

2. *Scope of Bulletin.*—It is the purpose of this bulletin to furnish some information concerning the influence of temperature on the attainment of strength in concrete.

Three groups of tests were made, viz.; forty-five 6 by 6-in. cylinders; fifty-one 6-in. cubes; and sixty 8 by 16-in. cylinders.

The temperature conditions were limited by available facilities.

3. *Acknowledgment.*—The tests reported herein were made in the Laboratory of Applied Mechanics of the University of Illinois. The work was done under the supervision of the writer. Special acknowledgment is due to the Department of Theoretical and Applied Mechanics for the use of material and apparatus. The writer is indebted to A. N. Talbot, Professor in Charge of Theoretical and Applied Mechanics, and to Ira O. Baker, Professor of Civil Engineering, for their co-operation in planning the tests and in interpreting the data.

The tests of Groups I and II—1913 Series—were made by J. Albert Anderson and W. J. Bublitz, senior civil engineering students of the class of 1914; and furnished the subject matter of their baccalaureate thesis. The tests of Group III—1914 Series—were made by J. Albert Anderson, a graduate student in the Department of Civil Engineering; and special credit is due Mr. Anderson for the preparation of the tables and diagrams. All the tests were made with painstaking care and faithful attention to uniformity and accuracy of manipulation.

II. Materials, Form of Test Pieces, and Methods of Storing and Testing.

4. *Materials.*—The materials were of the same character and quality as those used for other concrete and reinforced concrete specimens made and tested by the Engineering Experiment Station during the past five years. The quality of the materials may be taken as representative of that used in first-class concrete work in the Middle West.

Cement. All of the test specimens were made with Universal portland cement. Samples were taken at the beginning of each series and were tested for fineness, soundness, and tensile strength. The cement passed the requirements of the Standard Specifications of the American Society for Testing Materials. The tensile strength tests of neat and 1:3 mortar briquettes made of a sample of the cement used in Group III of the 1914 Series gave average values of 542 and 609 lb. per sq. in. for the neat cement at seven and twenty-eight days, respectively; and 174 and 295 lb. per sq. in. for the 1:3 mortar at seven and twenty-eight days, respectively.

Sand. The sand used came from a deposit of glacial drift near the Wabash River at Attica, Indiana. The sand was clean and well graded. The sand of the 1913 Series was somewhat coarser than that of the 1914 lot. The sand used in Group III—1914 Series—gave a density of 1.79, a specific gravity of 2.65, and contained 32 per cent voids.

Stone. The crushed limestone came from Kankakee, Illinois. The stone used in the 1913 Series contained 87 per cent material smaller than one-half inch and 46 per cent material smaller than one-fourth inch. The stone used in the 1914 series was well graded. It contained 49 per cent voids, and had a density of 1.35 and a specific gravity of 2.65. It was carefully screened over a ¼-in. screen before use, and contained 10 per cent of material smaller than one-fourth inch.

5. *Concrete.*—All the concrete was composed of one part cement, 2 parts sand, and 4 parts broken stone, by weight; corresponding to 1 part cement, 2.2 parts sand, and 3.6 parts broken stone, by volume. The materials for each specimen were weighed out separately and then mixed.

The mixing of the concrete for the 1913 series was done with a trowel in a large galvanized iron pan. The cement and sand were first mixed dry to a uniform color and spread out in a layer of uni-

TABLE 1.

DESCRIPTION OF TEST SPECIMENS

Series	Group	Set	Specimens		Number and Age of Specimens When Tested
			Number	Form	
1913	I	A	15	6 x 6-in. cylinders	5 specimens of each set; at 7, 14, and 28 days.
		B	15		
		C	15		
1913	II	D	15	6-in. cubes	3 specimens of each set; at 4, 7, 11, 14, and 28 days.
		E	18		
		F	18		
1914	III	G	15	8 x 16-in. cylinders	3 specimens of each set; at 3, 7, 10, 14, and 28 days.
		H	15		
		I	15		
		M	15		

form thickness over the bottom of the pan. The stone was then added, and the whole mass given four complete turnings, which secured thorough incorporation of the dry materials. Water was added, and the material turned until thoroughly mixed. The concrete was gathered together in a compact mass, in one end of the mixing pan, so as to reduce evaporation losses to a minimum. The time of mixing of each specimen was kept as nearly constant as possible.

The concrete used in the 1914 Series was mixed in similar manner to that of the 1913 Series, but was mixed on the concrete floor of the laboratory with shovels.

6. *Molding and Storage of Test Specimens.*—The specimens were classified according to the form of test specimen and storage conditions. Table 1 gives the details of the classification.

TABLE 2.

DATA CONCERNING MOLDING OF SPECIMENS

Type of Specimen	Set	Average Time of Molding, minutes	Average Temperature		Weights of Materials			Water, per cent*
			Air	Concrete	Cement, lb.	Sand, lb.	Stone, lb.	
6-in. cylinders	A	8.5	32°F.	70°F.	2.17	4.34	8.68	10.0
	B	8.5	65	71	2.17	4.34	8.68	10.0
	C	8.5	84	70	2.17	4.34	8.68	10.0
6-in. cubes	D	7.0	77	70	2.42	4.84	9.68	10.0
	E	7.0	75	70	2.42	4.84	9.68	11.0
	F	7.0	71	69	2.42	4.84	9.68	10.0
8 x 16-in. cylinders	G		68	69	10.2	20.4	40.8	9.3
	H							
	I							
	M							

*The concrete used in Groups I and II was of a medium or quaking consistency; while that used in Group III was wet, and was similar in consistency to that used in concrete building construction.

Molding. The specimens of Group I of the 1913 Series were molded in the storage rooms under the following temperatures: Set A at 32°F., Set B at 65°F., and Set C at 84°F. The specimens of Group II of the 1913 Series were molded in the cement laboratory at the following temperatures: Set D at 77°F., Set E at 75°F., and Set F at 71°F. The specimens of Group III—1914 Series—were molded in the concrete room of the Engineering Experiment Station at a temperature of 68°F. The specimens of Group II and Group III were moved to their respective storage rooms after a set of six hours.

The forms used for Group I were sheet-iron cylinders 6 in. in diameter and 6 in. high. The specimens of Group II were molded in three-gang cube forms made up of two 6-in. channels and plates placed 6 in. apart. The forms for the specimens of Group III were sections of standard 8-in. wrought iron pipe, 16 in. long. The forms were removed from the specimens after a storage of two days.

Table 2 shows the weight of the dry materials, the per cent of water in terms of the total dry materials, the temperature of the room and of the concrete, and the average time of molding.

Storage. The temperature of the storage room was determined by daily readings of the maximum and minimum thermometers. The temperatures for the several groups are shown in Fig. 1–10.

Set A was stored in the ice-storage room of the Smith Ice Company in Urbana, at an average temperature of 30°F. Set B was stored in the meat storage room of the Smith Ice Company in Urbana, at an average temperature of 48.5°F. Set C was stored in the cement laboratory of the University of Illinois at an average temperature of 72.8°F.

Set D was stored in the cement laboratory of the University of Illinois at an average temperature of 68°F. Set E was stored in the ice chest of the Dairy Department of the University of Illinois at an average temperature of 35.5°F. Set F was stored in the ice-storage room of the Twin City Ice and Cold Storage Company of Champaign, at an average temperature of 27.1°F.

Set G was stored in the ice-storage room of the Twin City Ice and Cold Storage Company at Champaign, at an average temperature of 26.5°F. Set H was stored in the ice chest of the Dairy Department of the University of Illinois at an average temperature of 34.7°F. Set I was stored in an interior heated room of the Twin City Ice and Cold Storage Company of Champaign, at an average temperature of 71.8°F. Set M was stored in a chamber of the conduit tunnel under the Floriculture building of the University of Illinois, at an average temperature of 95.6°F.

All the specimens while in storage were covered with several layers of moist sacking, which was sprinkled daily.

7. *Method of Testing.*—All the specimens of Group I were taken from their storage places to the Laboratory of Applied Mechanics of the University of Illinois the day before they were tested. They were measured and weighed, their bearing surfaces coated with plaster of paris, and then were left in the open air of the laboratory for about twenty hours under a temperature of about 70°F.

The specimens of Group II were tested after about one hour from the time of their removal from the storage rooms. Two specimens of Set F, designated as F_{17} and F_{18}, after being stored under an average mean daily temperature of 27.1°F. for forty-four days, were stored in the testing laboratory under an average mean daily temperature of 70°F., the former for seven days and the latter for twenty-one days.

The specimens of Group III were brought to the testing laboratory from their storage places, weighed, measured, plastered, and tested within one hour. The specimens of Set G, which were stored under freezing temperatures, were allowed to thaw out before being tested.

In the tests a spherical-seated bearing block was used.

III. The Data.

8. *Observed Results.*—The results of the tests are given in Tables 3 to 11, pages 8 to 16, and in Fig. 1–10.

9. *Standardized Strength.*—Since a cube or a cylinder having a height equal to its diameter, tested for compressive strength, may be expected to give a value which is higher than the representative compressive strength of the material, it seems desirable for the purposes of comparison to reduce the observed values for the cubes and short cylinders of Groups I and II to what may be considered as the equivalent values which would be obtained from cylinders of height equal to twice their diameter. To do this the values for the cubes and cylinders have been multiplied by 0.73, which is the ratio of strength of prisms to strength of cubes determined by the Committee on Specifications and Methods of Tests for Concrete Materials of the American Concrete Institute. The reduced values are designated as the standardized strengths in Table 3 to 11, and are shown by the lower curve in Fig. 1–10.

TABLE 3.

COMPRESSIVE STRENGTH—AGE 7 DAYS

Group I. 6 x 6-in. Cylinders

Set	Average Diameter, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
A	6.0 6.18 6.06 6.06 6.06	29 240 27 670 24 890 22 450 24 450	1030 930 870 780 850	890	650	Cracked uniformly around circumferential area.
B	6.12 6.00 6.00 5.87 5.87	36 130 34 770 31 660 25 030 26 950	1230 1230 1120 930 980	1100	800	Cracked uniformly " " " " Skewed "
C	5.87 5.81 5.94 5.87 6.00	27 080 35 830 37 660 31 140 32 250	1000 1350 1370 1150 1140	1200	880	Visible voids

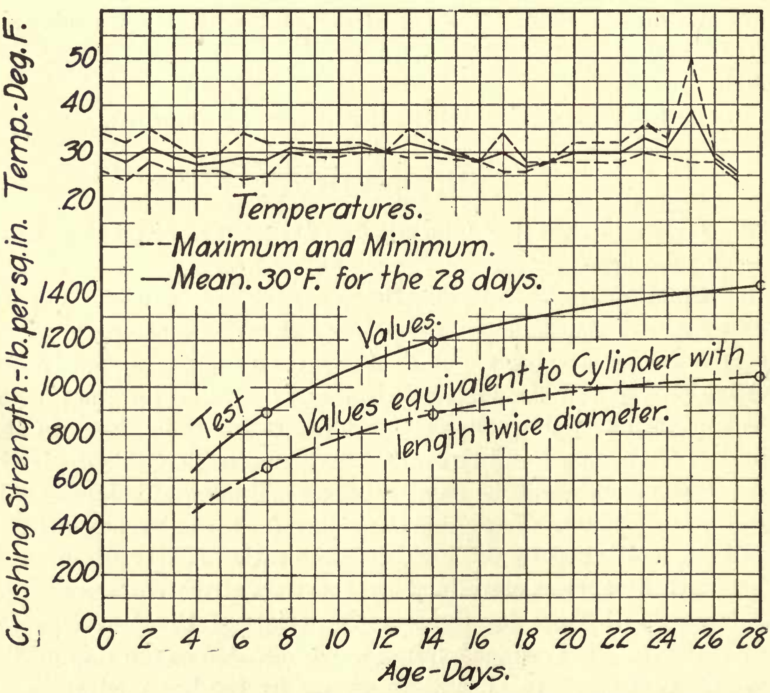

FIG. 1. SET A, GROUP I—1913 SERIES—6 x 6-IN. CYLINDERS.

TABLE 4.

COMPRESSIVE STRENGTH—AGE 14 DAYS

Group I. 6 x 6-in. Cylinders

Set	Average Diameter, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
A	6.0	38 020	1340	1190	870	Cracked uniformly around circumferential area.
	6.12	33 340	1140			
	6.0	39 220	1390			
	6.0	31 390	1110			
	5.87	26 700	980			
B	6.0	47 090	1670	1540	1130	Cracked uniformly
	5.94	50 460	1820			" "
	5.97	45 850	1640			" "
	5.94	30 000	1090			Badly skewed
	5.87	40 640	1500			Slightly skewed
C	5.87	46 170	1700	1660	1210	Uniform throughout
	6.0	50 000	1770			
	6.12	44 190	1510			
	6.0	44 420	1570			
	5.87	47 100	1740			

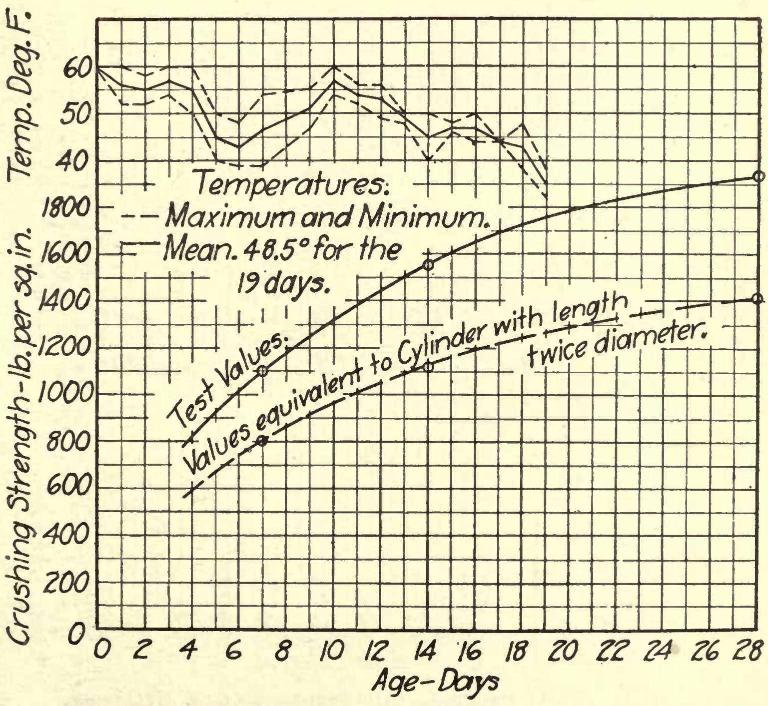

FIG. 2. SET B, GROUP I—1913 SERIES—6 x 6-IN. CYLINDERS.

TABLE 5.

COMPRESSIVE STRENGTH—AGE 28 DAYS

Group I. 6 x 6-in. Cylinders

Set	Average Diameter, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
A	6.06	39 340	1370	1430	1040	All uniform.
	6.06	37 730	1320			
	5.94	48 450	1750			
	6.12	37 660	1280			
	6.00	40 300	1430			
B	6.06	56 240	1960	1940	1410	Area reduced by visible voids.
	6.0	55 300	1950			
	6.06	54 600	1900			
	6.0	34 670	1230			
	6.0	40 000	1420			
C	5.97	55 720	2000	2090	1530	
	5.94	63 650	2310			
	5.87	60 260	2220			
	5.87	49 760	1840			Slightly skewed
	6.0	40 390	*1430			Badly skewed

*Not used in calculating average.

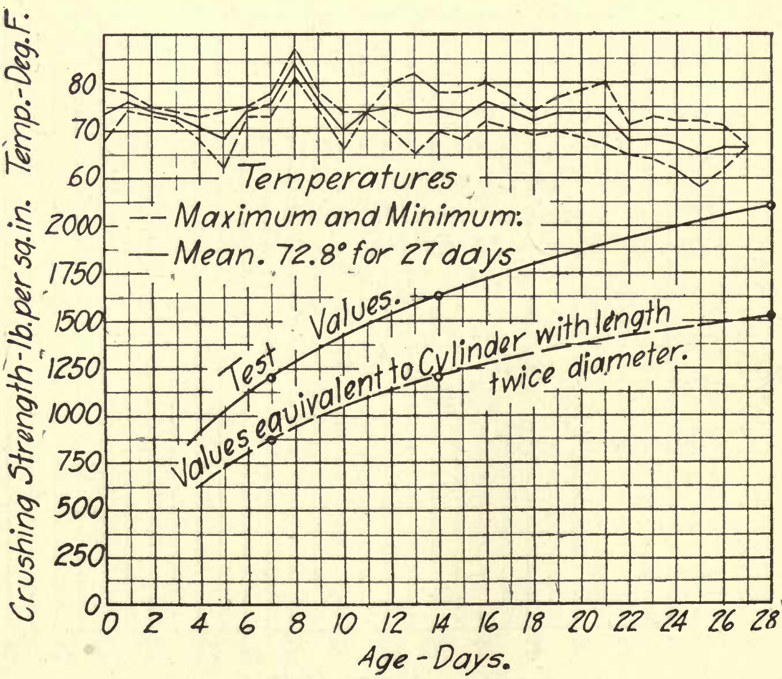

FIG. 3. SET C, GROUP I—1913 SERIES—6 x 6-IN. CYLINDERS.

TABLE 6.

COMPRESSIVE STRENGTH—AGE 4 DAYS

Group II. 6-in. Cubes

Set	Weight lb.	Size, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
D	18.50	6x6x6	28 400	790	780	570	
	18.50	"	22 450	620			
	18.50	"	33 340	920			
E	19.00	"	16 690	460	450	330	
	19.00	"	10 000	280			
	18.75	"	21 300	590			
F	18.75	"	15 680	440	390	280	Slight coating of frost, but all had uniform break.
	18.75	"	13 050	360			
	18.75	"	13 000	360			

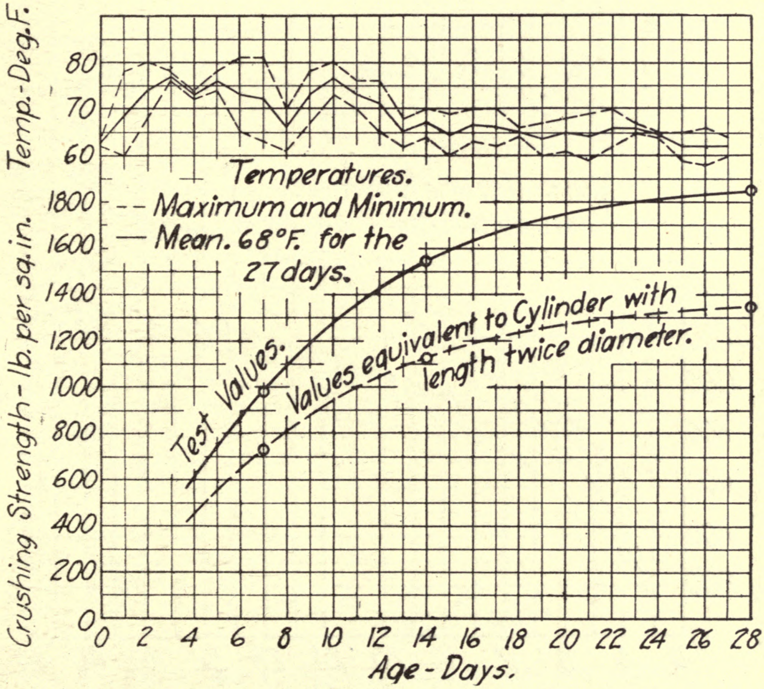

FIG. 4. SET D, GROUP II—1913 SERIES—6-IN. CUBES

TABLE 7.

COMPRESSIVE STRENGTH—AGE 7 DAYS

Group II. 6-in. Cubes

Set	Weight, lb.	Size, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
D	18.75	6x6x6	39 390	1090	980	720	
	19.00	"	35 930	1000			
	18.75	"	31 300	860			
E		"	17 100	470	470	340	Broke uniformly
		"	19 820	550			
		"	14 060	390			
F	18.50	"	20 880	580	560	410	
	18.75	"	19 230	530			
	18.75	"	20 760	580			

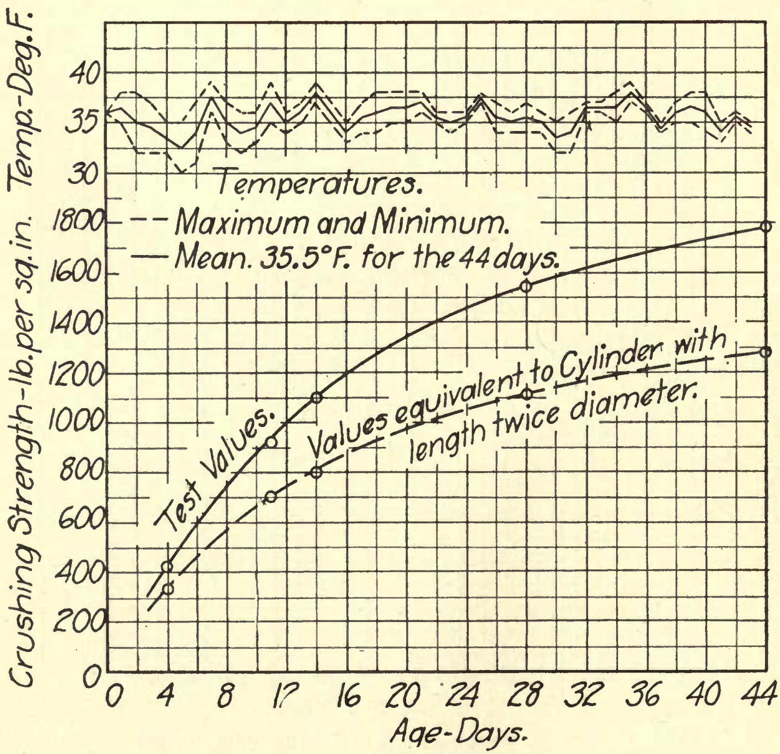

FIG. 5. SET E, GROUP II—1913 SERIES—6-IN. CUBES.

TABLE 8.

COMPRESSIVE STRENGTH—AGE 11 DAYS

Group II. 6-in. Cubes

Set	Weight lb.	Size, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
D	18.75 18.75 18.75	6x6x6 " "	43 420 52 440 47 300	1200 1460 1300	1320	970	
E	19.00 19.00 18.75	" " "	42 310 31 060 26 000	1180 860 720	920	670	Visible voids Broke at one corner
F	18.75 18.75 18.75	" " "	15 080 17 760 21 820	420 490 610	500	370	

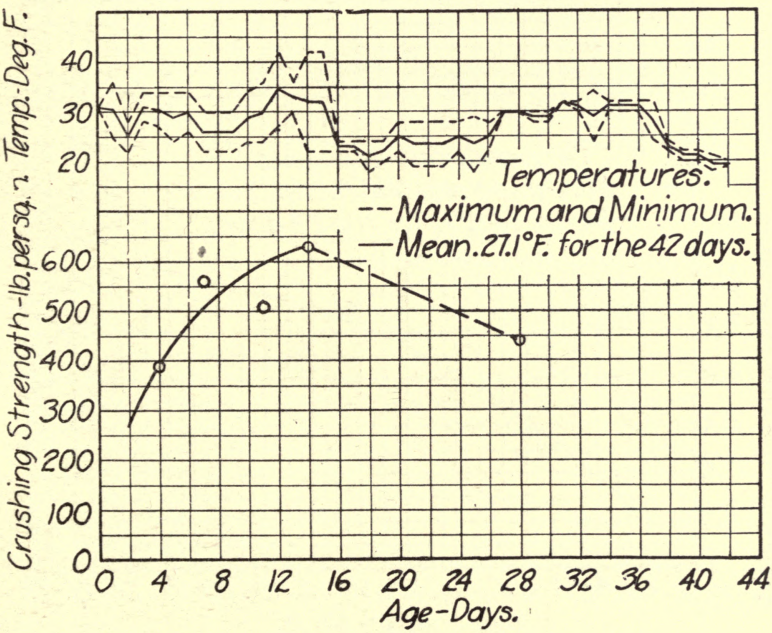

FIG. 6. SET F, GROUP II—1913 SERIES—6-IN. CUBES.

TABLE 9.

COMPRESSIVE STRENGTH—AGE 14 DAYS

Group II. 6-in. Cubes

Set	Weight, lb.	Size, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
D	19.00 19.00 18.75	6x6x6 " "	58 710 62 810 45 530	1630 1740 1260	1540	1130	
E		" " "	38 630 40 300 40 280	1070 1120 1120	1100	800	
F	18.75 18.75 18.75	" " "	19 330 26 350 22 900	540 730 650	640	470	

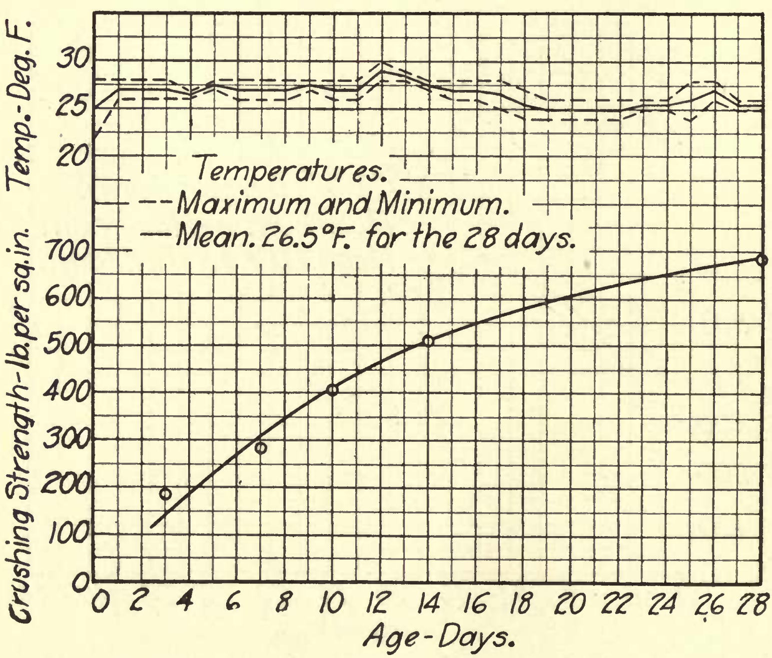

FIG. 7. SET G, GROUP III—1914 SERIES—8 x 16-IN. CYLINDERS.

TABLE 10.

COMPRESSIVE STRENGTH—AGE 28 DAYS

Group II. 6-in. Cubes

Set	Weight, lb.	Size, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
D	19.00 19.00 19.00	6x6x6 " "	64 000 67 460 68 440	1780 1870 1900	1850	1350	
E	18.75 18.75 18.75	" " "	52 590 58 270 56 350	1460 1620 1560	1550	1130	
F	19.00 19.00 18.75	" " "	16 540 15 160 10 400	460 420 *290	440	320	

*Specimen in bad condition; not included in average.

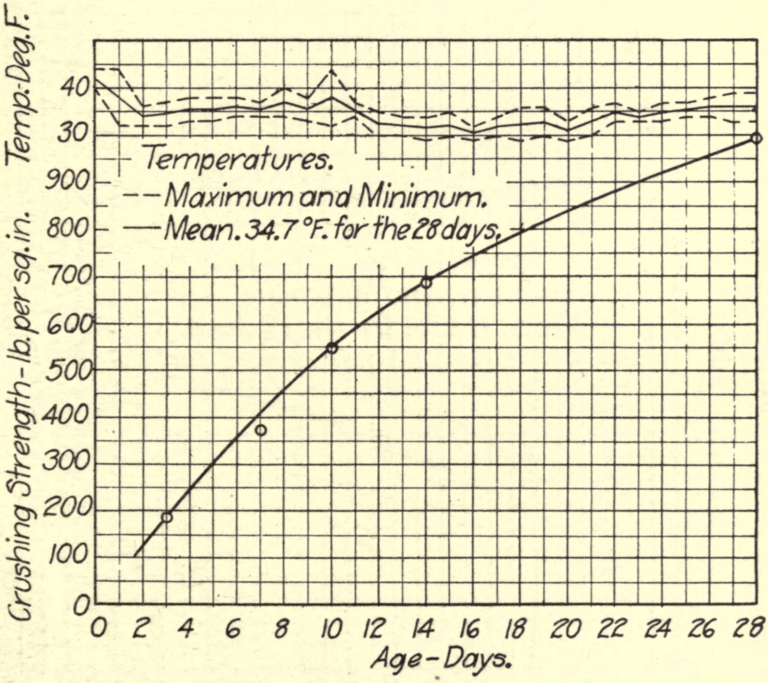

FIG. 8. SET H, GROUP III—1914 SERIES—8 x 16-IN. CYLINDERS.

TABLE 11.

COMPRESSIVE STRENGTH—AGE 42 DAYS

Group II. 6-in. Cubes.

Set	Weight, lb.	Size, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Standardized Strength, lb. per sq. in.	Remarks
E	18.75	6x6x6	66 710	1850	1780	1300	Broke uniformly
	18.75	”	62 880	1740	1780	1300	One corner broke
	18.75	”	62 240	1740			Slightly skewed
F	18.00	”	15 240	420			Specimens in a soft and crumbling condition
		5x5x6	31 720	1270*			
		4x5x6	8 040	400†			

*Age when tested, 49 days.
†Age when tested, 63 days.

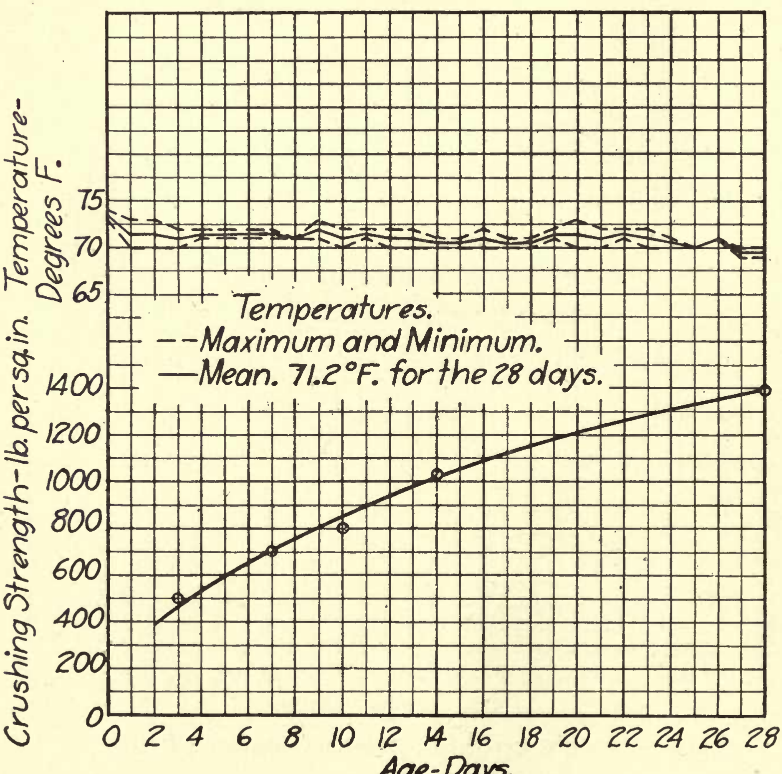

FIG. 9. SET I, GROUP III—1914 SERIES—8 x 16-IN. CYLINDERS.

TABLE 12.

COMPRESSIVE STRENGTH—AGE 3 DAYS

Group III—1914 Series—8 x 16-in. Cylinders

Set	Weight lb.	Average Diameter, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Remarks
G	67.75 67.25 70.25	7.94 7.87 8.06	8 880 9 720 9 340	180 200 180	190	Crumbled Crumbled badly
H	65.0 66.0 65.0	7.94 7.87 8.0	9 950 8 250 9 250	200 170 180	180	Plaster loose on one end
I	69.0 70.25 69.75	8.0 8.06 8.06	29 650 23 750 22 600	600 460 440	500	
M	64.0 65.0 65.0	8.0 7.94 7.94	24 000 30 850 20 000	480 620. 400.	500	

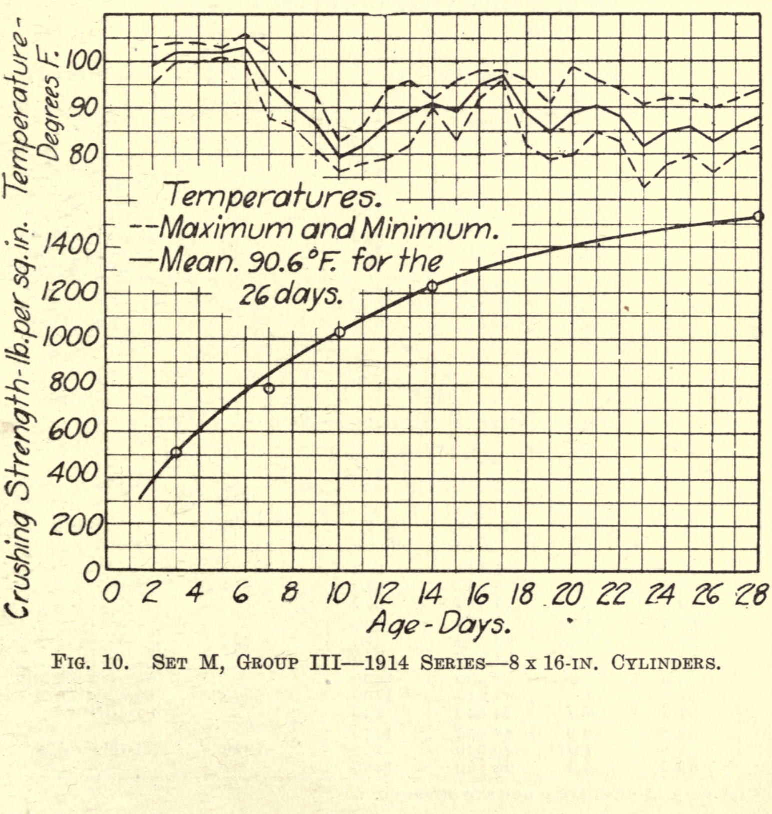

FIG. 10. SET M, GROUP III—1914 SERIES—8 x 16-IN. CYLINDERS.

Table 13.

Compressive Strength—Age 7 Days

Group III—1914 Series—8 x 16-in. Cylinders

Set	Weight, lb.	Average Diameter, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Remarks
G	67.75 67.25 65.50	8.0 8.0 8.0	17 200 14 750 10 700	340 290 210	280	
H	66.0 69.5 65.5	7.87 8.06 7.94	14 450 18 920 18 530	300* 370 370	370	Skewed one inch, horizontal crack
I	67.75 67.25	8.0 7.94 8.12	40 800 31 630 34 340	810 640 660	700	
M	68.0 69.0 69.0	8.0 8.06 8.06	44 500 40 250 35 150	890 790 690	790	

*Not used in calculating average strength.

Table 14.

Compressive Strength—Age 10 Days

Group III—1914 Series—8 x 16-in. Cylinders

Set	Weight, lb.	Average Diameter, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Remarks
G	66.5 67.5 70.5	8.0 7.87 8.0	18 670 18 280 23 630	370 370 470	400	
H	68.0 68.5 69.0	8.0 8.12 8.06	25 000 30 680 26 830	500 600 530	540	2—8x8 forms
I	67.5 68.0	8.06 8.0	44 700 36 050	880 720	800	Top crumbled Skewed Fractured in transit
M	68.0 69.0 69.5	7.94 8.06 8.06	59 620 46 700 49 540	1200 920 970	1030	2—8x8 forms

Table 15.

Compressive Strength—Age 14 Days

Group III—1914 Series—8 x 16-in. Cylinders

Set	Weight, lb.	Average Diameter, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Remarks
G	70.0 68.5 69.5	8.0 7.94 8.06	26 430 25 330 25 420	520 510 500	510	
H	67.5 64.5 66.5	7.94 8.06 8.0	30 550 35 100 37 750	620 690 750	690	
I	66.0 69.5 67.0	7.94 8.0 8.0	51 000 63 230 41 430	1030 1260 820	1040	Skewed slightly Bearing faces not parallel
M	67.5 66.5 66.5	8.0 7.94 8.0	58 000 40 650 65 000	1150 820* 1290	1220	Visible voids

*Not used in calculating average strength.

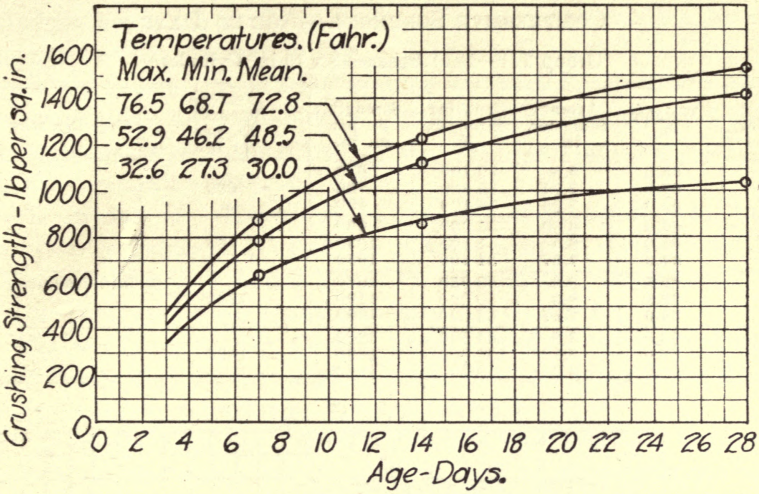

FIG. 11. GROUP I—1913 SERIES—6 x 6-IN. CYLINDERS. STANDARDIZED VALUES.

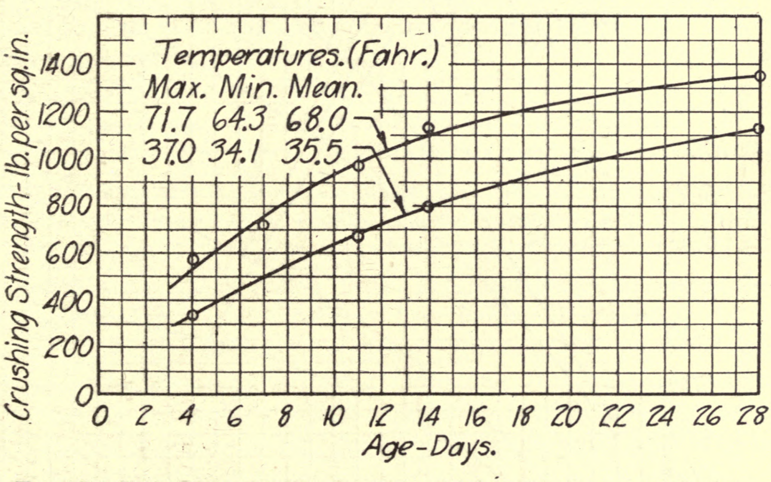

FIG. 12. GROUP II—1913 SERIES—6-IN. CUBES. STANDARDIZED VALUES.

TABLE 16.

COMPRESSIVE STRENGTH—AGE 28 DAYS

Group III—1914 Series—8 x 16-in. Cylinders

Set	Weight, lb.	Average Diameter, in.	Crushing Strength, lb.	Strength, lb. per sq. in.	Average Strength, lb. per sq. in.	Remarks
G	68.0 67.5 65.0	8.0 7.94 7.94	32 100 35 900 34 100	630 730 690	680	
H	65.0 65.0 64.0	8.06 8.0 7.87	45 900 51 600 51 400	900 1030 1050	990	
I	68.5 68.5 66.0	8.0 8.0 7.87	83 950 60 000 63 900	1670 1190 1290	1380	Odd fracture
M	66.0 66.0 66.0	8.0 8.12 8.0	63 500 101 900 68 200	1260 1960 1360	1530	

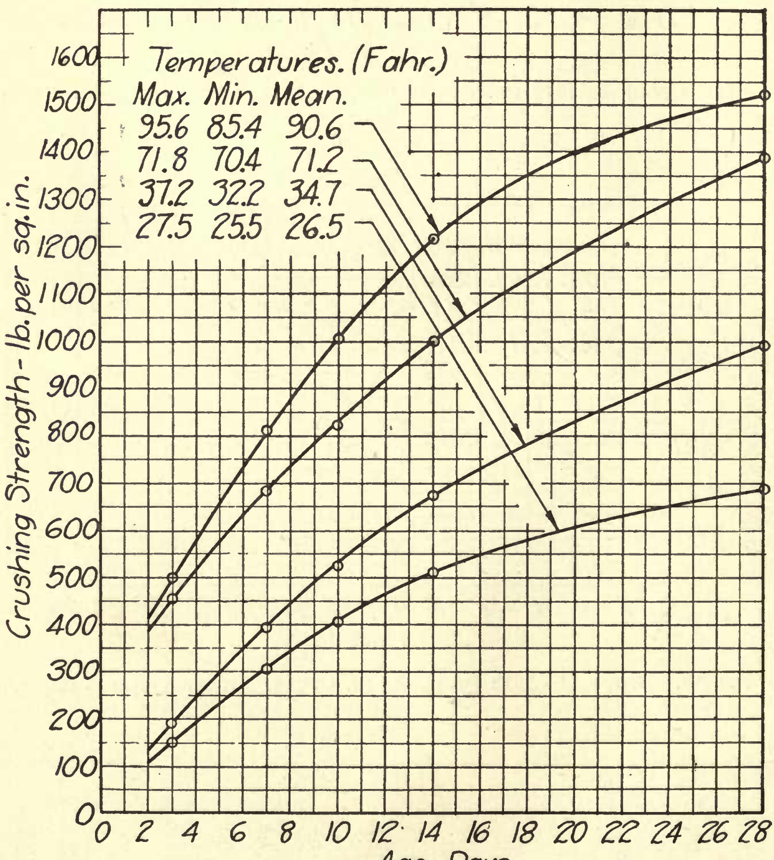

FIG. 13. GROUP III—1914 SERIES—8 x 16-IN. CYLINDERS.

10. *Group I.*—The results of the tests of Group I, 6 by 6-in. cylinders, are given in Table 3, 4, and 5; and the relation between strength and age is shown in Fig. 1, 2, and 3, pages 8, 9, and 10. The curves are drawn through the average values for each group of five specimens for 7, 14, and 28 days. At the top of each figure is shown the temperature conditions for that set; the maximum, the minimum, and the mean temperatures.

11. *Group II.*—The results of the tests of Group II, 6-in. cubes, are given in Tables 6–11; and the relation between strength and age is shown in Fig. 4, 5, and 6, pages 11, 12, and 13. The strength and temperature curves are drawn as stated for Group I.

The Sets D and E, Fig. 4 and 5, pages 11 and 12, were stored under substantially uniform temperature conditions, and give results of practically the same character as those of Group I.

The specimens of Set F were stored in a room where it was known the temperature would not be uniform. All of the specimens tested at 11 days were slightly disintegrated on the surface, and those tested at 28 days were badly disintegrated; while of those reserved to be tested at 42 days only one could be tested at that date, the remaining specimens, F_{17} and F_{18}, being very badly disintegrated. Specimen F_{17} was tested at 49 days, and F_{18} at 63 days. Since there was only one specimen at each of these ages, and since none of the other groups contained specimens at corresponding ages, the results of these two tests are not plotted in Fig. 6, and are not further considered.

The results of Set F, indicate that the low temperature retarded the hardening action of the concrete, and that the alternations above and below freezing caused a softening and crumbling of the material.

12. *Group III.*—The results of the tests of Group III, 8 by 16-in. cylinders, are given in Tables 12–16; and the relation between strength and age is shown graphically in Fig. 7–10. It is noteworthy that under a temperature slightly below freezing the concrete gained strength continuously, see Fig. 7, page 14. It is also interesting to note that the curve for a mean temperature of 26.5°F. is substantially of the same character as that for a mean temperature of 71.2°,—compare Fig. 7 and Fig. 9.

13. *Summary.*—The results for the three sets of Group I are presented in Fig. 11, page 19; and the corresponding values for Groups II and III are given in Fig. 12 and 13. Fig. 11–13 show the relation between strength and age for the several mean temperatures.

In Group I the test specimens were cylinders 6 inches in diameter and 6 inches high, and in Group II the specimens were 6-inch cubes;

and owing to the effect of the restraint of the pressing surfaces of the testing machine, the results of these tests are not further considered.

In Group III the test specimens were cylinders 8 inches in diameter and 16 inches high, and the interpolated results for these tests are presented in Fig. 14 to show the relation between strength and temperature for the several ages. Fig. 14 may be employed to determine (1) the strength which the concrete attained at different ages under a constant temperature, (2) the age at which a particular strength was gained under the different temperatures, and (3) the strength which may be expected at different ages under different temperatures. The relative strength attained by concrete at different temperatures during hardening and at different ages may be expected to vary somewhat with differences in cements, aggregates, and consistencies; but

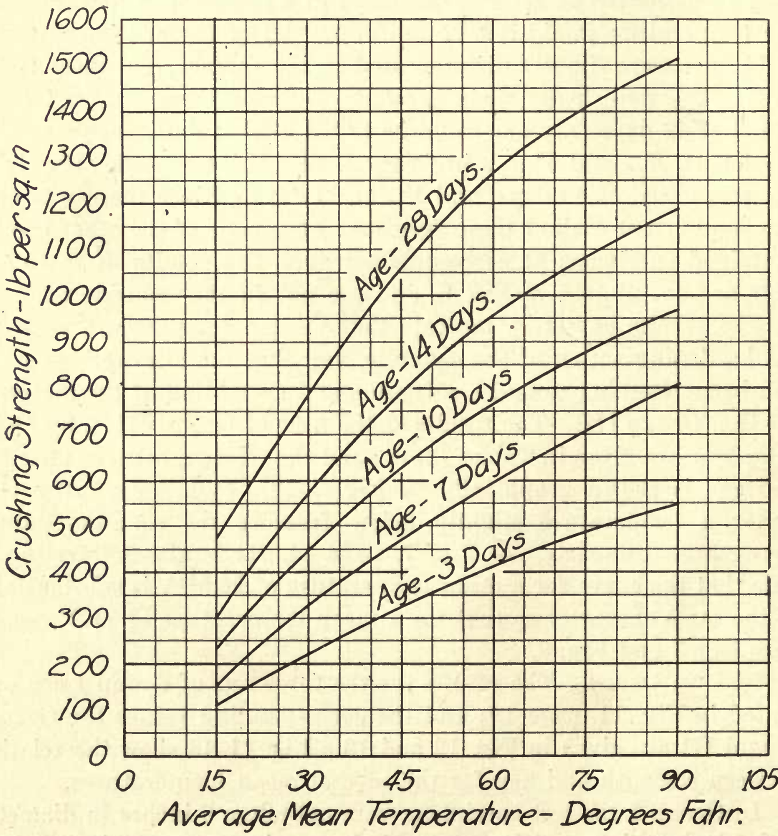

FIG. 14. RELATION OF STRENGTH TO TEMPERATURE FOR DIFFERENT AGES.

it is thought that the values in Fig. 14 may be taken to represent the effect of the variation in the temperatures during hardening upon the strength.

Fig. 15 has been drawn by taking values from the curves in Fig. 14. It shows in a general way, the relation between the strength at 28 days under 70°F. and the strength attained at various ages under varying temperatures. Fig. 15 can be used in substantially the same way as Fig. 14.

The tests summarized in Fig. 14 and 15 cover a wide range of temperature conditions, the average temperature varying from 20.4°F. to 90.6°F., and are fairly consistent; and hence it is believed these values are sufficiently accurate to furnish suggestive information which may be useful in determining the time when forms may be removed and loads applied.

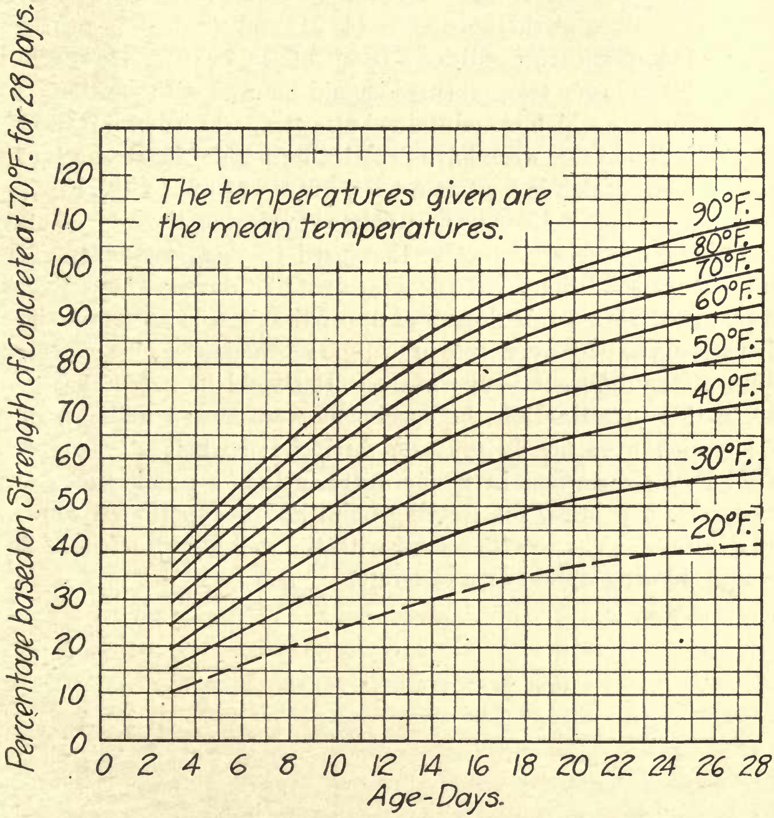

FIG. 15. PERCENTAGES OF STRENGTH FOR DIFFERENT TEMPERATURES.

IV. Conclusions

14. *General Conclusions.*—It is believed the following general conclusions are justifiable.

1. Under uniform temperature conditions, there was an increase of strength with age within the limits of the tests. For any temperature the rate of increase decreases with the age of the specimen; and this rate of increase is less correspondingly at the lower temperature conditions. For the specimens tested, under normal hardening temperature conditions of from 60 to 70°F., the compressive strength of the concrete subjected to a uniform temperature at the ages of 7, 14, and 21 days may be taken as approximately 50 per cent, 75 per cent, and 90 per cent of the strength at twenty-eight days, respectively. For lower temperatures the percentage values are less; and for higher temperatures the percentages are higher. The relation between the percentage values at the ages of 7, 14, 21, and 28 days is nearly the same for temperature conditions from 30° to 70° F. However, the values for the lower temperatures should be used with caution.

2. Concrete which is maintained at a temperature of 60° to 70° F. will at the age of one week have practically double the strength of the same material which is kept at a temperature of 32° to 40° F.

3. Fig. 14 and 15 may be used to determine the representative strength of concrete similar to that used in these tests, for various temperature conditions and for ages up to 28 days. These diagrams may be used with a fair degree of approximation to ascertain the relative strengths which concrete of ordinary practice may be expected to attain at the different temperatures. It should be noted that generally in this investigation the specimens were stored under temperatures which were nearly uniform during the whole storage period. In set F the variations in temperature include a number of alternations above and below the freezing point and the specimens were seriously injured. The results accord with the well-known effect of freezing and thawing upon green concrete.

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