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Effect of Mixing and Curing Temperature on Concrete Strength

BY

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By PAUL KLIEGER†

SYNOPSIS

Comprehensive study was made of compressive and flexural strengths produced by different types of portland cement used in concretes mixed, placed, and cured at various temperatures between 25 F and 120 F. Tests indicate that there is a temperature during the early life of concrete which is considered optimum with regard to strength at later ages.

Effect of calcium chloride on strength at varying temperatures of mixing, placing, and curing is reported. Effect of cement temperature was found unimportant, except as it affected concrete temperature after mixing. More air-entraining agent was required for given air content as concrete temperature increased and slump decreased.

INTRODUCTION

This study was prompted by the need for more detailed information on the influence of temperature during mixing, placing, and curing on concrete strength development. The necessity for continuing concreting operations despite high temperatures during the summer and low temperatures during winter is increasing. Although it is known that high temperatures increase the rate of hydration of cement, the effect of this increase on strength development needs investigating.

Specific information was sought on compressive and flexural strengths produced by different types of portland cement when used in concretes mixed, placed, and cured at various temperatures ranging from near the freezing point to 120 F. Information on the effects of an accelerator under these different conditions was also desired.

Recent tests of the influence of cement temperature on concrete strength are reported also.

SCOPE OF TESTS

Part I of this study embraced temperatures from 73 F to 25 F; Part II covered temperatures from 73 F to 120 F. Mixing, placing, and curing of concretes were conducted at temperatures of 120, 105, 90, 73, 55, and 40 F. In addition, some concretes mixed and placed at 40 F were cured at 25 F.

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TABLE 1—CHEMICAL COMPOSITION AND POTENTIAL COMPOUND COMPOSITION OF CEMENTS

Chemical analyses made in accordance with ASTM methods of test current in October, 1953, for Part I and June, 1954, for Part II. Sodium oxide and potassium oxide by flame photometry, ASTM C 228-49T. Compounds corrected for free CaO.

Cement		Major components, percent							Minor components, percent						Calculated compound composition, percent					
												Alkalies								
Lot No.	ASTM type	SiO_2	Al_2O_3	Fe_2O_3	Total CaO	MgO	SO_3	Ignition Loss	Mn_2O_3	Free CaO	Insoluble residue	Na_2O	K_2O	Total as Na_2O	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	Free CaO
Part I, 73 F and below																				
18827*	I	21.20	5.93	2.64	63.12	2.46	2.12	1.26	0.29	0.90	0.12	0.22	0.67	0.66	42.5	28.8	11.3	8.0	3.61	0.90
19012	III	19.88	5.57	2.62	65.08	1.90	2.63	1.67	0.21	1.71	0.10	0.19	0.42	0.47	58.2	13.1	10.3	8.0	4.47	1.71
18830	II	23.13	4.45	3.36	62.50	2.01	1.75	2.01	0.41	1.22	0.14	0.14	0.21	0.28	33.9	40.7	6.1	10.2	2.98	1.22
Part II, 73 F and above																				
18922†	I	21.25	5.86	2.76	63.17	2.43	2.15	1.11	0.24	1.07	0.13	0.23	0.63	0.64	41.8	29.4	10.9	8.4	3.66	1.07
18931†	III	20.12	6.04	2.65	64.67	0.54	2.74	1.23	0.19	1.08	0.20	0.18	0.47	0.49	53.8	17.1	11.5	8.1	4.65	1.08
18925†	II	22.27	4.89	3.41	62.50	2.91	1.79	1.30	0.19	0.84	0.17	0.20	0.47	0.51	39.1	34.4	7.2	10.4	3.04	0.84

*Results for Lot 18827 are averages of tests of the four individual brands used to make this blend.
†Results are averages of tests on individual cements comprising each blend: 18922, four brands; 18931, two brands; 18925, two brands.

TABLE 2—PHYSICAL TESTS OF CEMENT AND MORTARS

Cement		Fineness			Normal consistency, percent	Time of setting, hr and min				Autoclave expansion, percent	Air content, percent, 1:4 mortar	Tensile strength, psi, 1:3 standard sand mortar briquets				Compressive strength, psi, 2-in. plastic mortar cubes			
		Specific surface, sq cm per g		Passing 325 mesh, percent		Vicat		Gillmore											
Lot No.	ASTM type	Wagner	Blaine			Initial	Final	Initial	Final			1 day	3 da	7 da	28 days	1day	3days	7days	28days
Part I, 73 F and below																			
18827	I	1690	3310	90.4	25.0	4:00	6:55	4:30	7:10	0.13	9.7	205	365	410	515	790	1970	3150	4530
19012	III	2350	4840	98.4	29.0	1:45	4:00	2:55	4:20	0.16	6.3	360	465	540	580	2310	4030	5780	6850
18830	II	2020	3910	93.4	25.0	5:05	8:45	5:45	9:15	0.02	6.8	115	240	380	495	520	1180	1910	3730
Part II, 73 F and above																			
18922	I	1650	3120	89.6	24.5	3:00	—	3:55	6:15	0.11	8.5	195	365	400	450	780	1910	2910	4620
18931	III	2360	4730	98.1	28.5	2:00	4:00	2:35	4:30	0.10	6.6	360	485	505‡	530	2090	4010	5440‡	6780
18925	II	2010	3880	92.5	24.0	3:30	5:00	4:10	5:25	0.05	7.8	170	330	400‡	495	680	1510	2600‡	4550

*Tests made in accordance with ASTM Standards current in May, 1954. †Tests made in accordance with ASTM Standards current in June, 1954. ‡Average of two specimens.

ASTM Types I, II, and III cements were used. Concretes were made both with and without calcium chloride as an accelerator. An air-entraining agent was added at the mixer to entrain a prescribed amount of air in all of the concretes.

Concretes were tested at ages ranging from 1 day to 1 year. Included were both compressive and flexural strength tests. In a number of tests the temperature of cement at the time of mixing was varied to determine the influence on the strength of concretes produced.

MATERIALS

Cement

ASTM Types I, II, and III cements were used in this study. For both Parts I and II, the Type I cements were blends of four different brands and the Type III blends of two different brands. One brand of Type II was used in Part I, while a blend of two brands of Type II was used in Part II. Chemical analyses, calculated potential compound composition, and results of miscellaneous physical tests of these cements are shown in Table 1. The results of strength tests of mortars made with these cements are shown in Table 2.

Aggregates

Sand and gravel from Elgin, Ill., were used in the gradings shown in Table 3. These aggregates are partly siliceous and partly calcareous natural sand and gravel.

Admixtures

Neutralized Vinsol resin in solution, added at the mixer, was the air-entraining agent. The accelerator was commercial flake calcium chloride dissolved in a portion of mixing water prior to use.

MIXING, PLACING, AND CURING TEMPERATURES

Concretes were mixed and placed at temperatures of 40, 55, 73, 90, 105, and 120 F. Specimens were prepared for test at ages of 1, 3, 7, and 28 days, 3 months, and 1 year.

In Part I, all specimens were cured continuously moist (100 percent relative humidity) at the mixing and placing temperature for 28 days or less depending on the test age. After the initial 28-day period, half of the specimens remaining for tests at 3 months and 1 year were stored at 73 F and 100 percent relative humidity and the remaining half at 73 F and 50 percent relative humidity. Additional concretes were mixed and placed at 40 F and then, immediately after placing, the specimens in their molds were stored at 25 F. Surfaces of the specimens were covered with a double thickness of damp burlap (not in direct contact with the concrete surface) and a waterproof tarpaulin. After removal from the molds at 1 day, these specimens stored at 25 F were covered with a double thickness of initially damp burlap for 28 days or less depending upon test age. After 28 days, specimens remaining for tests at 3 months and 1 year were treated like those stored at other temperatures.

In Part II, half of the specimens were cured for 7 days moist at the fabrication temperature while the remainder of the specimens were cured for 28 days moist at the fabrication temperature. At the end of the 7 and 28-day preliminary curing periods, each half was subdivided into two groups, one cured at 73 F and 100 percent relative humidity, and the other at 73 F and 50 percent relative humidity.

TABLE 3—AGGREGATE GRADING

Elgin sand		Elgin gravel	
Sieve No.	Percent passing	Sieve No. or size	Percent passing
4	100	1½-in.	100
8	82	¾-in.	50
16	67	⅜-in.	25
30	43	No. 4	0
50	13		
100	5	Fineness modulus of sand = 2.90	

CONCRETES

The cement content of all of the concretes was held constant at 5½ sacks per cu yd. In Part I, the net water-cement ratio for each concrete (particular cement type with or without accelerator) was such as to produce a slump of approximately 3 in. at a concrete temperature of 55 F. For concretes mixed at 40 and 73 F, the net water-cement ratio was held fixed at the value determined at 55 F, and the slump was permitted to change. In Part II, the net water-cement ratio for each concrete was such as to produce a slump of approximately 3 in. at a concrete temperature of 90 F. For the concretes mixed at 73, 105, and 120 F, the net water-cement ratio was held at the value determined at 90 F, and the slump was permitted to change. Within each part of this study, this procedure permitted a direct comparison of strengths produced at different temperatures without having to consider changes in net water-cement ratio. Continuity between Parts I and II is provided by a repetition of all of the concretes at 73 F; therefore comparisons on a percentage basis are valid despite a small difference in net water-cement ratio between the concretes in Parts I and II.

Neutralized Vinsol resin in solution was added at the mixer to entrain 4½ ± ½ percent air in all of the concretes. Changes in the amounts of air-entraining agent were necessary to maintain this constant air content when changing type of cement or concrete temperature, or when $CaCl_2$ was used.

In those mixes containing an accelerator, 2 percent flake calcium chloride (by weight of the cement) was used. The calcium chloride was dissolved in part of the mixing water prior to mixing.

CONCRETE MIXING AND FABRICATION OF SPECIMENS

All materials used in the concretes were stored at the required temperature for sufficient time prior to mixing to enable them to reach this temperature. The aggregates were weighed in the air-dried condition (moisture content

TABLE 4—CONCRETE MIX DATA

Cement content of all mixes, 5½ sacks per cu yd. Net W/C constant for each cement type. Sand percentage, all mixes, 35 percent by absolute volume of total aggregate.

Cement		Fabrication and curing temperature, deg F first 28 days	No $CaCl_2$				2 percent $CaCl_2$, by weight of cement			
Lot No.	ASTM Type		Concrete temperature after mixing, deg F	Average slump, in.	Net *W/C*, gal. per sack	Air content, percent	Concrete temperature after mixing, deg F	Average slump, in.	Net *W/C*, gal. per sack	Air content, percent
			Part I, 73 F and below							
18827	I	73	75	2.4	4.82	4.5	76	2.1	4.73	4.6
		55	57	3.0	4.81	4.4	58	2.8	4.71	4.4
		40	41	3.8	4.77	4.9	43	3.8	4.70	4.7
		25*	41	4.1	4.81	4.7	43	5.1	4.71	4.6
19012	III	73	73	1.6	5.09	4.5	75	1.8	5.10	4.7
		55	59	1.7	5.08	4.8	59	2.8	5.09	5.0
		40	44	1.3	5.06	4.5	44	1.7	5.08	4.8
		25*	45	1.7	5.07	4.6	46	1.7	5.09	4.5
18830	II	73	74	2.7	4.78	4.6	75	2.0	4.47	4.7
		55	57	3.2	4.77	4.5	57	3.3	4.50	4.7
		40	41	5.3	4.75	4.8	42	5.5	4.46	4.9
		25*	40	5.4	4.77	4.3	42	5.4	4.46	4.5
			Part II, 73 F and above							
18922	I	73	75	3.4	5.13	4.6	76	3.6	5.09	4.5
		90	93	3.1	5.10	4.5	95	3.1	5.08	4.7
		105	107	1.9	5.10	4.7	108	2.9	5.10	4.3
		120	121	1.3	5.11	4.4	124	1.3	5.13	4.5
18931	III	73	76	3.2	5.57	4.6	77	2.9	5.42	4.6
		90	94	3.2	5.57	4.5	96	3.2	5.42	4.5
		105	107	3.1	5.57	4.6	108	3.5	5.42	4.5
		120	121	2.2	5.55	4.6	122	2.0	5.43	4.5
18925	II	73	75	3.6	4.93	4.6	76	4.1	4.98	4.8
		90	92	3.2	4.93	4.4	94	3.1	4.98	4.6
		105	104	2.3	4.93	4.4	106	3.0	4.99	4.4
		120	121	1.2	4.93	4.5	121	1.7	4.97	4.8

*Fabricated at 40 F and placed immediately in room at 25 F.

known) and, 18 to 20 hr prior to use, inundated with a known amount of water. Excess water was drawn off and weighed immediately prior to mixing.

Each batch contained sufficient concrete to cast two 6 x 6 x 30-in. beams. The batches were mixed for 2½ min in a 1¾ cu ft capacity Lancirick mixer (horizontal open tub). Slump, air content by the pressure method, and concrete temperatures were determined immediately after mixing.

The specimens were cast in watertight steel molds, following the procedure outlined in ASTM C 192-52T. Sufficient batches were mixed (duplicates on two different days) so that two specimens were available for each test age and curing condition.

STRENGTH TESTS

Beams were tested in flexure with load applied at the third-points of an 18-in. span. Two flexural breaks were obtained for each beam. The two beam ends were tested in compression as 6-in. modified cubes. (For this particular aggregate, the ratio of 6 x 12-in. cylinder strength to 6-in. modified cube strength is 0.93.) For each test age, concrete mix, and curing procedure, two beams were tested yielding four flexural and four compressive test results for averaging.

TABLE 5—COMPRESSIVE STRENGTHS OF CONCRETE. PART I—73 F AND BELOW

Cement content of all mixes, 5½ sacks per cu yd. Net W/C constant for each cement type. Compression, 6-in. modified cubes.

Cement		Fabrication and curing temperature, deg F first 28 days	Compressive strength, psi							
							3 months†		1 year†	
Lot No.	ASTM Type		1 day	3 days	7 days	28 days	100 percent relative humidity	50 percent relative humidity	100 percent relative humidity	50 percent relative humidity
No $CaCl_2$										
18827	I	73	1410	3120	4490	6050	6360	7070	7190	7100
		55	580	1930	3750	6250	7550	7990	8100	7720
		40	80	730	2140	5180	7120	7010	7730	6600
		25*	40	460	620	1580	6290	4300	7360	4560
19012	III	73	2640	3930	4780	5750	6320	7290	6910	7070
		55	1440	3180	4010	5470	6490	6680	6880	6740
		40	360	2000	4160	6260	7740	8090	8570	8260
		25*	140	1360	2540	4020	6430	6500	6940	6720
18830	II	73	860	1860	2760	5050	6480	7070	7440	6760
		55	400	1140	1990	4720	7190	7720	8150	7170
		40	60	560	1320	3290	7150	6360	7900	6430
		25*	40	220	640	680	6360	2780	7800	3020
2 percent $CaCl_2$, by weight of cement										
18827	I	73	2530	3970	4960	6170	6980	7590	8340	7520
		55	1390	3210	4610	6300	7450	7840	8040	8220
		40	430	1940	3470	5350	7420	7920	8550	7540
		25*	200	950	1930	4080	6550	6530	7910	6200
19012	III	73	4440	5900	6820	7310	7820	8050	8680	8370
		55	3030	5120	5780	6740	8100	8230	8500	8280
		40	1640	3880	5320	6660	7970	7780	8040	7630
		25*	1320	3240	4400	6460	7880	7400	8210	8020
18830	II	73	1870	3300	4180	5690	7210	7640	8160	7280
		55	1030	2640	3870	5620	7470	7840	8280	7460
		40	290	1440	2740	4960	7220	7400	8460	6800
		25*	220	920	1870	3180	6920	6400	9020	5840

*Fabricated at 40 F and placed immediately in room at 25 F.
†Cured at 73 F and either 100 percent or 50 percent relative humidity after first 28 days.

All strength tests were made at a concrete temperature of 73 F. Specimens stored at temperatures other than 73 F were placed in the 73 F moist-room for temperature conditioning 1½ hr before testing. This length of conditioning period, determined on trial specimens containing thermocouples, was required specifically for those beams stored at 25 F.

DISCUSSION OF RESULTS

Tests of cements and mortars

All of the ASTM chemical and physical requirements were met by these cements (Tables 1 and 2).

Effect of temperature on slump and water requirements

Maintaining the net water per cu yd constant in both Parts I and II generally resulted in different slump at the different concrete temperatures. Fig. 1 shows an idealization of the average effect of concrete temperature on the slump of the various concretes made with the Type I and II cements. The *broken* line in this figure shows the idealized slumps as a function of concrete temperature. Approximately 1-in. decrease in slump resulted for each

20-F increase in temperature. As seen in Table 4, the slump of the concretes made with the Type III cements was not influenced by temperature. The reason for this behavior is not now apparent.

Auxiliary tests were made at some of the different temperature levels to determine the changes in water content necessary to effect a 1-in. change in slump (either increase or decrease). The *solid* line in Fig. 1 shows that as concrete temperature was increased, a greater percentage increase in water was required to effect a 1-in. change in slump than was required at lower temperatures. For example, at 73 F a 2½ percent change in water content will change the slump 1 in., while at 120 F a 4½ percent change in water content will be required.

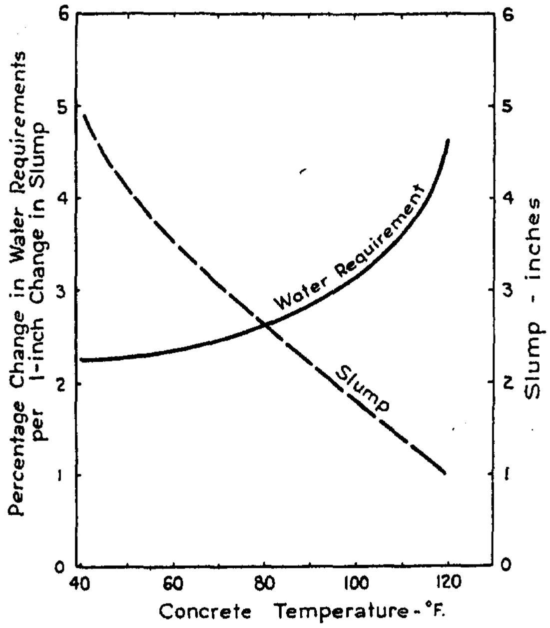


Fig. 1—Effect of concrete temperature on slump and on water required to change slump

Cement content: 5½ sacks per cu yd; 4½ ± ½ percent air; maximum size of aggregates, 1½ in.; *average of data for Types I and II cements*

In a concrete mix with proportions of solid ingredients fixed, changes in water content to maintain slump necessitated by changes in concrete temperature would result in concomitant changes in net water-cement ratio. These changes in net water-cement ratio would influence the strengths developed by these concretes. For example, based on the data in Fig. 1, the additional water required to maintain the 73 F slump would result in an increase in net water-cement ratio of about 0.6 gal. per sack for the 120-F concretes. In order to maintain the original water-cement ratio, and thereby not sacrifice strength, an increase of about 0.6 sacks of cement per cu yd would be required for the 120-F concretes. This point will be discussed further later in this report.

Effect of initial and curing temperature on strength development

In order to facilitate the presentation and discussion of the large amount of strength data (Tables 5, 6, 7, 8) obtained, Fig. 2 and 3 have been prepared using the strengths expressed as percentages of the 73-F strengths. Fig. 2 shows the effect of temperature on compressive strength, Fig. 3 the effect on flexural strength. These data are for concretes cured moist the first 28 days. In Part II, a 7-day moist-curing period at the fabrication temperature was included for comparison with the 28-day moist-curing period at the fabrication temperature. The qualitative interpretation of the results for this 7-day group is similar to that for the 28-day group.

TABLE 6—COMPRESSIVE STRENGTHS OF CONCRETES MADE AT DIFFERENT TEMPERATURES. PART II—73 F AND ABOVE

Cement content of all mixes, 5½ sacks per cu yd. Net W/C constant for each cement type. Specimens, 6-in. modified cubes.

Cement		Fabrication and curing temperature, deg F, first 7 or 28 days	Compressive strength, psi													
			Moist at fabrication temperature				28 days moist at fabrication temperature, remainder at 73 F				7 days moist at fabrication temperature, remainder at 73 F					
							3 months		1 year		28 days		3 months		1 year	
							Relative humidity, percent				Relative humidity, percent					
Lot No.	ASTM Type		1 day	3 days	7 days	28 days	100	50	100	50	100	50	100	50	100	50
							No $CaCl_2$									
18922	I	73	1150	2600	4060	5440	6000	6840	6450	7230	5440	5700	6000	6190	6450	6270
		90	1490	3090	4160	5240	5700	6480	6240	6180	4820	5380	5460	5710	6320	5640
		105	1850	3200	3850	4720	5250	5820	5860	6160	4200	4700	4920	5600	5820	5690
		120	2040	2840	3440	4110	4730	5510	5320	5300	4080	4340	4320	5020	5410	5030
18931	III	73	2210	3460	4610	5460	5970	6430	6440	6800	5460	6280	5970	6120	6440	6580
		90	2760	4290	5010	5710	5910	6950	6860	7040	5610	6030	5940	6500	6920	6220
		105	3010	3900	4580	5120	5660	6750	6190	6660	5210	5660	5300	5980	6060	6110
		120	3280	3850	4160	4720	5040	6140	5420	5880	4490	5040	5000	6010	5720	5760
18925	II	73	990	2180	3680	5230	6570	7070	7620	6940	5230	5840	6570	6460	7620	6160
		90	1250	2720	3900	5780	6400	7150	6610	6890	5190	5470	6090	5880	6400	5780
		105	1500	3070	4420	5330	6120	6740	6630	7020	4990	5570	5760	5850	6490	5880
		120	1950	3060	3930	4820	5760	6460	5780	6190	4720	5040	5300	5690	5630	5620
							2 percent $CaCl_2$									
18922	I	73	2300	3490	4420	5420	6460	7420	7730	7360	5420	6620	6460	6940	7730	6940
		90	2540	4010	4810	5720	6350	6980	7010	7000	5400	5960	6350	6740	7000	6640
		105	2800	3660	4630	5410	6020	6760	6730	7050	5030	5790	5400	5900	6660	6280
		120	3060	3720	4320	5130	5720	7090	6320	6510	4930	5420	5440	6230	6280	5990
18931	III	73	3890	4940	5870	6450	7200	8040	7680	7700	6450	7410	7200	7640	7680	7040
		90	4490	5380	6070	6790	6500	7190	6880	7580	6800	7620	7300	6910	7690	7030
		105	4410	5200	5940	6170	6940	7970	6930	7680	6070	6750	6200	7020	7000	7100
		120	4410	4940	5600	6010	6780	8060	6730	7540	5970	6850	6240	7120	6920	7040
18925	II	73	1960	3300	4280	5590	6680	7400	7700	7200	5590	6190	6680	6630	7700	6220
		90	2350	4110	4820	6120	6970	7430	7730	7610	5540	6020	6490	6850	7510	6580
		105	2510	3630	4610	5620	6400	7360	6940	7290	5200	5830	5760	5750	6930	6280
		120	2580	3660	4820	5740	6320	6660	6580	7440	4780	5850	5850	6830	6720	6140

Fig. 2 shows all of the compressive strength data for the three types of cement with and without accelerator expressed as percentages of the strengths developed at 73 F for each test age. This figure shows the accelerating effect of temperatures above 73 F on the early-age strengths with a sacrifice however in strengths at the later ages. On the other hand, the concretes placed and cured at temperatures below 73 F, while showing lower strengths at the

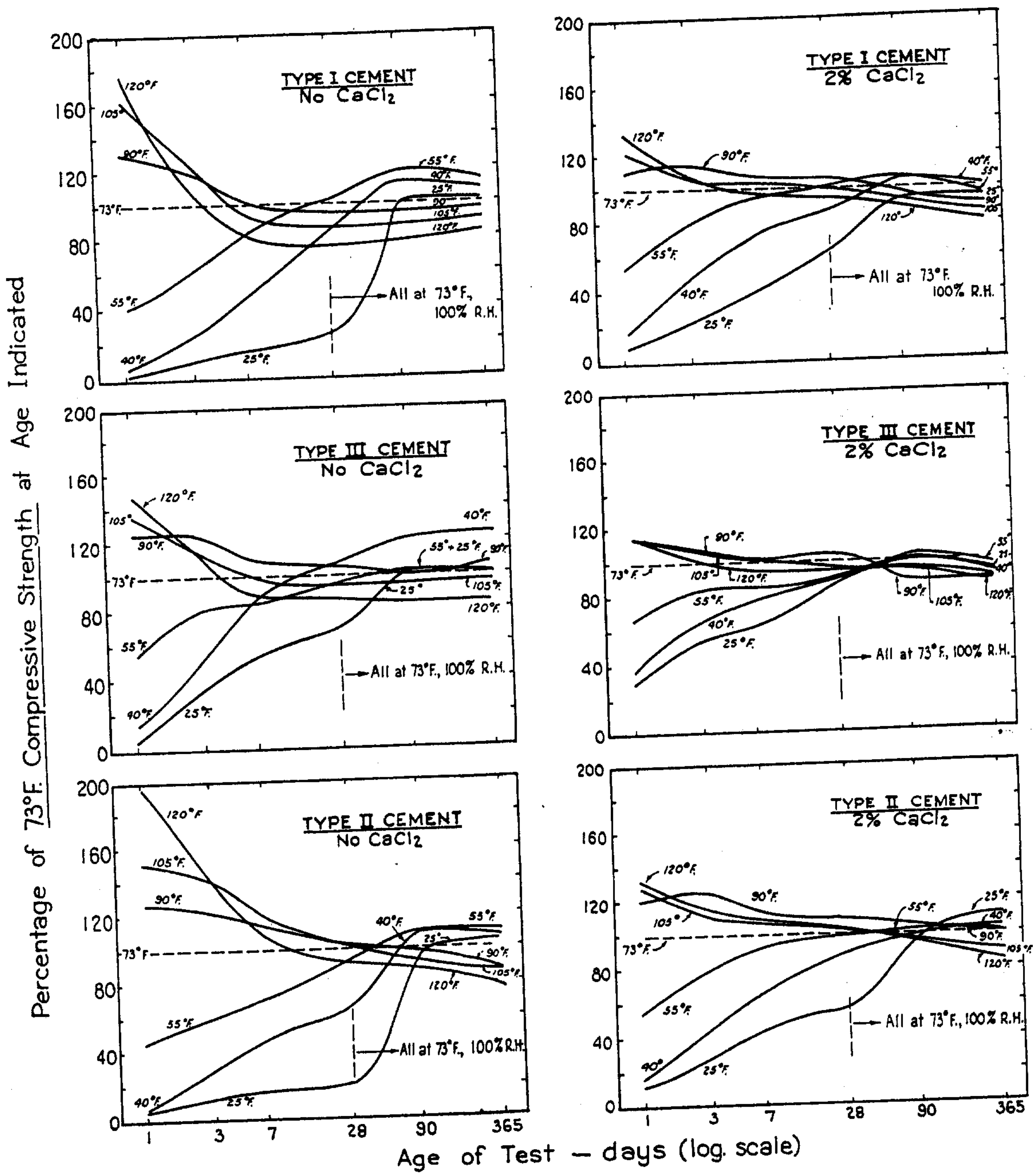


Fig. 2—Effect of temperature on compressive strength of concretes made with different types of cement with and without an accelerator

Air content of all concretes, 4½ ± ½ percent (neutralized Vinsol resin solution added at mixer); cement content of all concretes, 5½ sacks per cu yd. Within the individual boxes, the net water-cement ratios of the concretes are approximately equal (see tabulated data on mix characteristics)

TABLE 7—FLEXURAL STRENGTHS OF CONCRETE. PART I—73 F AND BELOW

Cement content of all mixes, 5½ sacks per cu yd. Net W/C constant for each cement type. Flexure, 1/3-point loading on 18-in. span.

Cement		Fabrication and curing temperature, deg F first 28 days	Flexural strength, psi							
							3 months†		1 year†	
Lot No.	ASTM Type		1 day	3 days	7 days	28 days	100 percent relative humidity	50 percent relative humidity	100 percent relative humidity	50 percent relative humidity
No $CaCl_2$										
18827	I	73	250	460	555	665	740	685	740	810
		55	110	320	495	640	790	790	850	790
		40	10	135	335	580	710	705	845	660
		25*	10	95	125	265	720	490	790	510
19012	III	73	360	510	535	660	710	725	670	670
		55	230	435	515	600	735	730	715	640
		40	60	290	530	650	735	815	770	760
		25*	20	190	340	415	665	635	725	535
18830	II	73	160	315	445	645	735	730	820	790
		55	75	205	335	530	795	780	860	750
		40	10	100	245	460	760	725	790	700
		25*	10	50	135	165	705	400	820	335
2 percent $CaCl_2$, by weight of cement										
18827	I	73	340	500	540	630	750	705	795	800
		55	215	385	480	570	745	770	820	805
		40	80	265	435	550	750	745	760	735
		25*	35	170	270	425	690	660	780	710
19012	III	73	435	580	625	690	720	800	745	705
		55	390	520	560	645	720	755	755	655
		40	240	440	570	585	715	720	745	630
		25*	220	390	490	520	715	690	770	645
18830	II	73	305	400	460	585	730	750	800	795
		55	180	330	425	565	770	780	800	750
		40	60	240	340	475	720	700	840	685
		25*	45	160	265	350	710	630	880	590

*Fabricated at 40 F and placed immediately in room at 25 F.
†Cured at 73 F and either 100 percent or 50 percent relative humidity after first 28 days.

early ages, show strengths at the later ages in excess of those developed at 73 F. This was true even for the concretes mixed and cast at 40 F and stored immediately after casting at 25 F for the first 28 days. For example, the concrete made with Type I cement (no accelerator) developed during 28 days at 25 F only 26 percent of the strength developed at 73 F. However, subsequent moist curing at 73 F resulted in a compressive strength at 1 year 102 percent of that resulting from continuous moist curing at 73 F, while the concretes at 120 F for the first 28 days showed only 82 percent of the 1-year strength at 73 F. For those concretes cured initially at low temperatures followed by curing at 73 F, 1-year strengths close to or exceeding those for the concretes cured continuously moist at 73 F were attained only when moist curing was employed. Air drying during this subsequent 73-F period generally resulted in lower strengths, particularly for concretes made with Type I and II cements.

The concretes made with the three different types of cement reacted to temperature in a similar manner, but differed somewhat in degree of reaction particularly at the earlier ages. For example, the 120-F concrete made with Type II cement had a 1-day compressive strength 197 percent of that at 73 F,

TABLE 8—FLEXURAL STRENGTHS OF CONCRETES MADE AT DIFFERENT TEMPERATURES. PART II—73 F AND ABOVE

Cement content of all mixes, 5½ saks per cu yd. Net W/C constant for each cement type.
Specimens, 6 x 6 x 30-in. beams. Third-point loading on an 18-in. span.

Cement		Fabrication and curing temperature, deg F, first 7 or 28 days	Flexural strength, psi															
			Moist at fabrication temperature				28 days moist at fabrication temperature, remainder at 73 F				7 days moist at fabrication temperature, remainder at 73 F							
							3 months		1 year		28 days		3 months		1 year			
							Relative humidity, percent				Relative humidity, percent							
Lot No.	ASTM Type		1 day	3 days	7 days	28 days	100	50	100	50	100	50	100	50	100	50		
									No $CaCl_2$									
18922	I	73	220	405	530	675	780	725	790	830	675	585	780	745	790	725		
		90	265	420	520	585	720	640	675	735	610	525	705	670	690	685		
		105	285	420	505	610	705	540	710	760	600	505	640	625	690	660		
		120	295	400	450	545	585	485	645	665	550	410	570	530	615	590		
18931	III	73	340	450	515	600	725	680	700	740	600	595	725	715	700	700		
		90	400	525	545	615	725	695	720	815	660	540	660	710	710	670		
		105	400	455	465	565	630	560	690	680	575	495	610	625	640	630		
		120	385	430	485	510	605	445	605	600	575	465	610	550	635	605		
18925	II	73	190	360	490	635	740	725	855	735	635	580	740	755	855	695		
		90	215	390	540	600	735	670	790	750	645	505	740	675	770	645		
		105	265	410	515	660	730	640	780	770	650	510	720	635	745	660		
		120	320	390	480	560	640	500	690	720	605	470	610	525	660	630		
									2 percent $CaCl_2$									
18922	I	73	295	440	515	605	750	710	760	805	605	570	750	700	760	740		
		90	335	435	525	620	725	675	730	780	640	560	700	700	750	680		
		105	345	390	460	605	665	585	695	685	585	495	630	600	645	645		
		120	375	395	440	545	625	625	680	700	560	500	610	600	635	655		
18931	III	73	410	490	560	640	705	720	725	715	640	630	705	695	725	665		
		90	410	485	560	625	740	790	720	740	630	630	690	730	750	655		
		105	420	465	480	540	630	685	690	735	600	620	645	665	660	665		
		120	450	430	460	580	665	645	675	765	630	580	650	665	675	695		
18925	II	73	290	430	475	590	705	720	715	740	590	595	705	680	715	665		
		90	340	440	495	665	740	725	800	780	625	575	670	730	765	705		
		105	350	400	420	605	700	690	750	740	595	555	665	660	730	665		
		120	320	395	440	590	680	655	695	760	620	540	655	655	710	660		

while the 120-F concrete made with the Type III cement had a 1-day compressive strength 148 percent of that at 73 F. At 1 year, however, the strengths of these same concretes were 77 percent and 84 percent, respectively, of the 73-F strengths.

The concretes made with and without the accelerator reacted similarly to temperature; however, the effect of temperatures above 73 F on the early

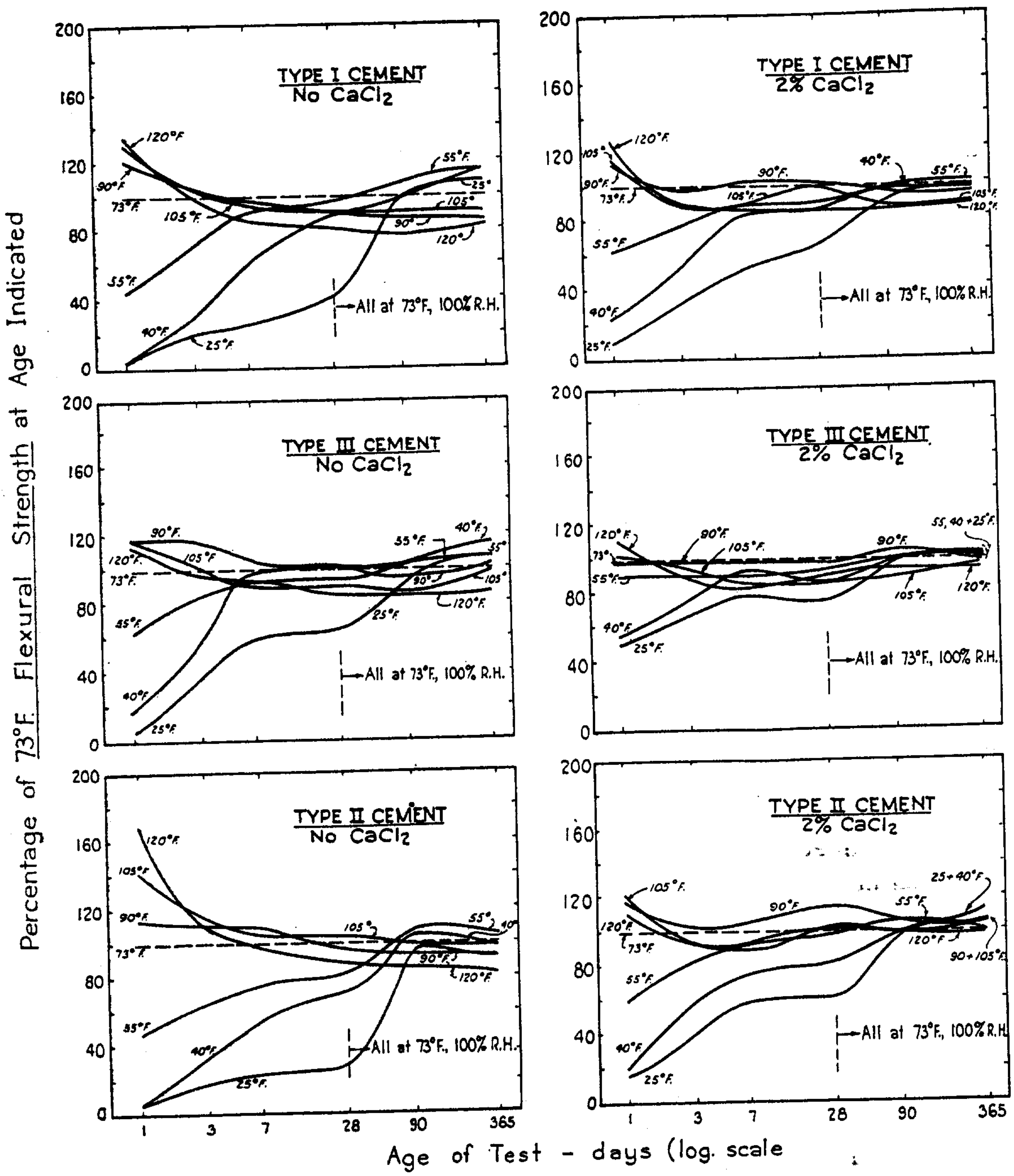


Fig. 3—Effect of temperature on flexural strength of concretes made with different types of cement with and without an accelerator

Air content of all concretes, 4½ ± ½ percent (neutralized Vinsol resin solution added at mixer); cement content of all concretes, 5½ sacks per cu yd. Within the individual boxes, the net water-cement ratios of the concretes are approximately equal (see tabulated data on mix characteristics)

and ultimate strengths was somewhat moderated by the use of calcium chloride.

The data indicate that there is a casting and curing temperature which may be considered optimum with regard to the ultimate strength developed. For the Type I and II cements without accelerator this optimum is 55 F. For the Type III cement without accelerator, the optimum is 40 F. With calcium chloride as an accelerator, these optimum temperatures appear somewhat lower.

Temperature seems to affect the hydration and hence development of strength in two ways. First, there is the known effect of temperature on any chemical reaction, the rate of reaction increasing as temperature increases. Since in a general sense the strength of like concrete mixes is proportional to the amount of hydration, this greater rate of reaction at the higher temperatures accounts for the higher strength at early ages. However, a second factor may be that the type of hydration product obtained or the physical make-up of the product is influenced by the temperature during this hydration. Lower temperatures may be conducive to a better hydration product or better physical structure of the product. The role of gypsum as a function of temperature needs further investigation in this regard.

Fig. 3 shows the flexural strength data for these same concretes. The preceding discussion of compressive strength data applies equally to the flexural strength data. Flexural strengths at early ages increased with increase in temperature. At later ages, the effect of temperature was reversed. Those concretes made and cured at the lower temperatures showed highest flexural strengths at 1 year. The optimum temperatures for flexural strength development appear to be the same as those for compressive strength.

Effect of age and temperature on strength

Many investigators have proposed that differences in curing temperature can be accounted for in interpreting strength development data by the use of a parameter which includes both age and temperature.* This has led to the use of the term "degree-days." The number of "degree-days" representing a particular amount of curing is obtained by multiplying the curing time in days by the temperature, in deg F, *above* the minimum temperature for hydration. The choice of this minimum temperature for hydration is somewhat arbitrary, however, since it is influenced by the characteristics of the cement used, initial concrete temperature, mix proportions, and amount of protection afforded by forms. Some exploratory tests indicated that the concretes in this study mixed and placed at 40 F and then immediately stored at 10 F were capable of developing a small amount of strength during 28 days at this temperature. On the basis of these tests, this temperature of 10 F was selected as the minimum temperature for hydration for these concretes.

*Nurse, R. W., "Steam Curing of Concrete," *Magazine of Concrete Research* (London), V. 1, No. 2, June 1949. pp. 79-88.

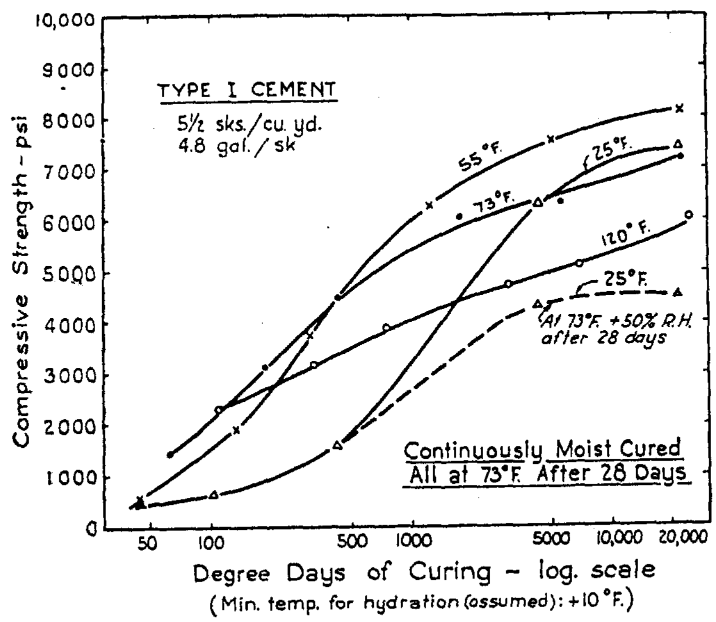


Fig. 4—Relationship between degree-days of curing and compressive strength

Air content of concretes, 4½ ± ½ percent. No $CaCl_2$. Strengths of 120-F concretes corrected for difference in water-cement ratio between these concretes and the 55 and 73-F concretes

Fig. 4 shows the relationships between degree-days of curing and the compressive strength of the 25, 55, 73, and 120-F concretes made with Type I cement. The separate relationships for each initial concrete temperature indicate poor correlation of strength with this parameter. The fact that the 55-F concretes produced higher strengths at the later ages than the 73-F concretes and still higher strengths than the 120 F concretes precludes significant correlation on a basis as simple as degree-days.

The data for the Types II and III cements and for flexural strengths are similar to those shown in Fig. 4. For the concretes containing calcium chloride as an accelerator, somewhat better correlation of strength with degree-days was obtained.

A factor not considered in this type of correlation is the presence or absence of water during curing. Data for the concretes at 25 F for the first 28 days indicate clearly that strength developed during subsequent curing at 73 F depends considerably upon the presence of water during this period. This was more marked for these 25 F concretes than for the concretes made and cured at 40 F and higher. Tables 5, 6, 7, and 8 show strength data for the 50 percent relative humidity storage condition along with the data for the continuously moist-cured concretes.

Effect of addition of water to maintain slump

In discussing the effect of temperature on slump and water requirements, it was pointed out that the addition of water to concrete at 120 F to obtain the same slump as at 73 F would increase the net water-cement ratio of the mix, unless additional cement were added to offset this increase in water. Fig. 5 shows the compressive strength developed by the 55, 73, and 120-F concretes at the same net water-cement ratio. The strengths of the 120-F concretes were corrected for the slight difference in water-cement ratio between these concretes and the 55 and 73-F concretes, this procedure being

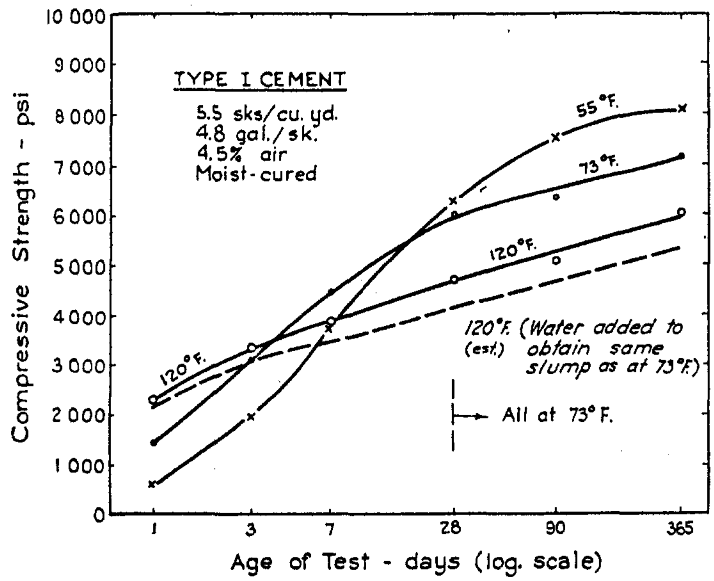


Fig. 5—Effect of curing temperature and addition of water to maintain slump on the compressive strength

Strengths of 120-F concretes corrected for difference in water-cement ratio between these concretes and the 55 and 73-F concretes. Dashed line illustrates effect of addition of water to obtain same slump as at 73 F, without addition of cement required to maintain same net water-cement ratio

possible since the 73-F concretes were prepared in Parts I and II. The effect on strength of adding water to the 120-F concretes in order to obtain the same slump as the 73-F concretes is shown by the dashed line in this figure. The strengths shown in the dashed line were estimated from the change in net water-cement ratio which would result from this procedure, the change being based on the water-requirement data in Fig. 1. At 28 days, the effect of this added water is to reduce strength 500 psi below that of the original 120-F concrete. While this is approximately a 10 percent reduction, it is worth noting that the original 120-F concrete shows 1250 psi less strength at 28 days than the 73-F concrete at the same net water-cement ratio. Occurrence of low strengths during hot weather may therefore be attributed to a large extent to two factors: increasing water without a concomitant increase in cement, and the effect of initial temperature on strength at the later ages.

Effect of cement type on strength development

The effect of type of cement on compressive and flexural strength development at the various test ages at the different temperatures can be determined from data shown in Tables 5, 6, 7, and 8.

Concretes made with Type III cements showed higher strengths at early ages than concretes made with Type I cements, while concretes made with Type II cements showed lower strengths at early ages than concretes made with Type I cements. These strength differences tended to disappear at the later ages, however.

These data afford a means of comparing the strength development of the concretes made with Type II and Type III cements with those made with Type I cements. For example, at 40 F for concretes made without calcium chloride the 7-day compressive strength of the concrete made with Type III cement (4160 psi) is 195 percent of that made with Type I cement (2140 psi), while for the Type II cement (1320 psi) 62 percent of the Type I strength is developed. For flexural strengths, the respective percentages are 158 percent

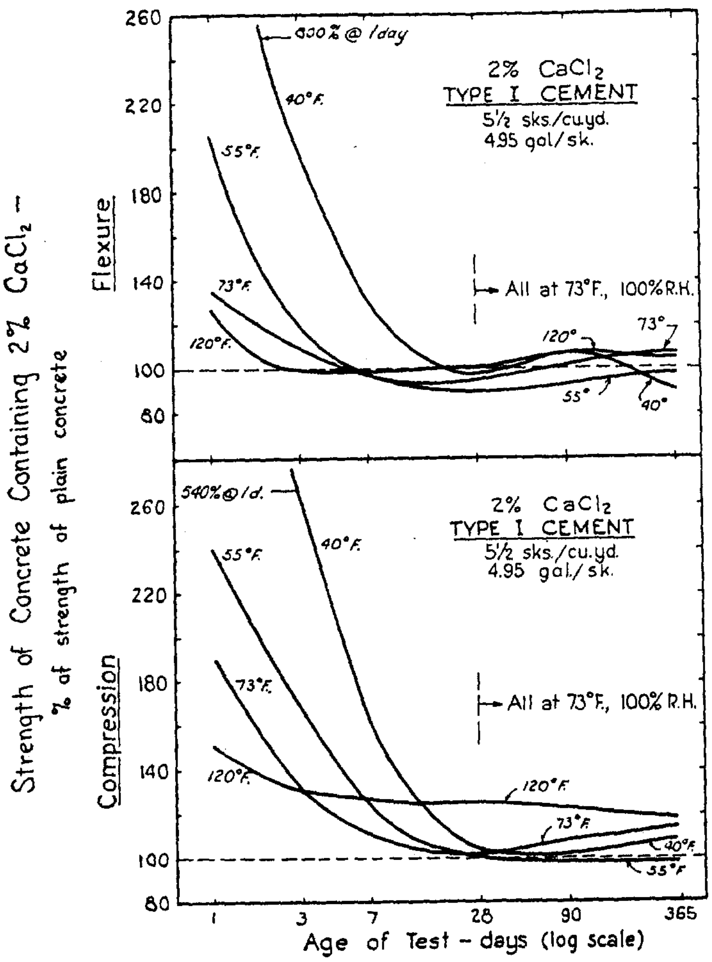


Fig. 6—Effect of calcium chloride on strength development of concretes made with Type I cement

Air content, 4½ ± ½ percent (neutralized Vinsol resin solution added at mixer); average net water-cement ratio 4.95 gal. per sack

and 73 percent. These data provide typical information on strength development as affected by cement type over a rather wide temperature range.

Effect of calcium chloride on strength development

Information on the effect of calcium chloride on flexural and compressive strengths of these concrete can be determined from data in Tables 5, 6, 7, and 8.

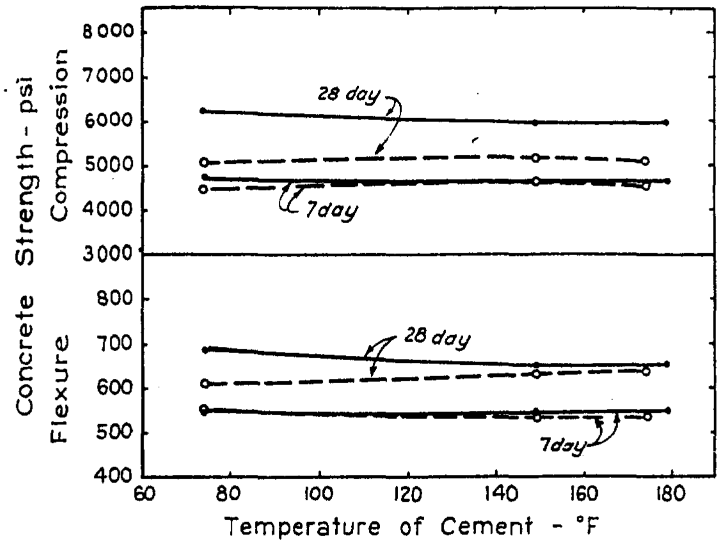
Fig. 6 shows the effect of calcium chloride on flexural and compressive strengths of the 40, 55, 73, and 120-F concretes made with the Type I cements. Each solid line is a comparison by itself with the dashed 100-percent line, which represents the strength attained without calcium chloride. For example, at 1 day for the 55-F concretes, the compressive strength of the concrete made with 2 percent calcium chloride was 240 percent of that of the mix without calcium chloride. For the 120-F concretes, the use of calcium chloride produced a compressive strength 150 percent of that of the mix without calcium chloride. This means that at 55 F, the calcium chloride produces a proportionately greater increase in strength than it does at 120 F.

For both flexural and compressive strengths, the increases effected by use of calcium chloride decreased with an increase in the age of concrete and became quite small at 28 days and later. For the 120-F concrete, the use of

Fig. 7—Effect of temperature of cement on concrete strength

Solid line represents concrete temperature 76 F, cured at 73 F, 100 percent relative humidity. Dashed line, concrete temperature 104 F, cured 7 days at 105 F and 100 percent relative humidity, remainder at 73 F and 100 percent relative humidity

Type I cement, Lot 18922; 5½ sacks per cu yd, 4.9 gal. per sack
Specimens: 6 x 6 x 30-in. beams
Flexure: Third-point loading, 18-in. span
Compression: 6-in. modified cubes



calcium chloride produced a smaller increase in compressive strength at the early ages; however, this increase appears to persist longer than at the other temperatures. Despite the persistence of the increases effected at 120 F, these 120-F concretes showed lower strengths at 28 days and later than the 55 or 73-F concretes made with calcium chloride, as can be seen in Fig. 2 and Fig. 3. This was true for the three types of cement and for both flexural and compressive strength.

At the later ages, concretes made with calcium chloride showed compressive strengths equal to or somewhat greater than those without the accelerator. The later-age flexural strengths, however, were reduced somewhat when calcium chloride was used. The reductions encountered at 28 days and later ages ranged from negligible values to about 10 percent, these reductions showing no particular relationship with making and curing temperatures. The beneficial effects of the accelerator for the low temperature early-age concretes are relatively more important than these generally small decreases in flexural strength at the later ages.

Effect of temperature of cement on strength

High cement temperature has sometimes been blamed for a lowering of concrete strength, in spite of evidence to the contrary.*

Strength tests were made of concretes prepared with the Type I cement (Lot No. 18922) at three different cement temperatures: 74, 148, and 177 F. Cements at each of these temperatures were used in preparing concretes which had temperatures at the end of the mixing period of 76 F and 104 F. These final concrete temperatures were attained by adjusting mixing water temperatures, using the aggregates maintained at the same temperature as that of the concrete after mixing. The 76-F concretes were cured continuously moist at 73-F. The 104-F concretes were cured continuously moist for 7 days at 105 F followed by 21 days moist at 73 F.

*Report of Working Committee of ASTM Committee C-1, *Proceedings*, ASTM, V. 32, Part I, 1932, p. 298.

TABLE 9—AIR-ENTRAINING AGENT REQUIREMENTS

Cement type	$CaCl_2$, percent by weight	Amount of air-entraining agent, ml per lb cement					
		40 F	55 F	73 F	90 F	105 F	120 F
I	0	1.5	1.6	2.2	2.8	3.0	3.6
	2	1.0	1.2	1.8	2.6	2.9	5.0
III	0	3.6	4.4	4.7	6.4	7.0	9.8
	2	2.8	2.8	3.3	4.9	6.2	11.0
II	0	1.7	1.7	2.4	3.0	3.3	4.5
	2	1.0	1.3	1.7	2.5	3.2	5.2

Fig. 7 shows the flexural and compressive strengths of these concretes at 7 and 28 days as a function of cement temperature at the time of mixing. All of these concretes had the same cement content and the same net water-cement ratio, therefore the strengths are directly comparable. The average slump of the 74-F concretes was approximately 3 in., while for the 104-F concretes the average slump was slightly less than 1 in. It is apparent from Fig. 7 that the cement temperature in itself exerts no significant influence on the strength of the concrete so long as the comparison is made on the basis of equal concrete temperature. The temperature of the concrete during curing has by far more influence than the temperature of the cement, as shown by the 28-day strengths. The concretes made at 104 F and cured 7 days at 105 F and 21 days at 73 F had compressive strengths about 1000 psi lower than the concretes made and cured at normal temperatures. The same conclusions can be drawn from the flexural strength data.

These results show that cement temperature was of concern only insofar as it affected the temperature of the concrete after mixing. However, cement temperature plays only a small role in the final concrete temperature because of the relatively small amount used and its low specific heat. The temperature of the aggregates, by virtue of their large quantity, and the temperature of the water with its high specific heat exert more influence on the final concrete temperature than the cement.*

Effect of concrete temperature on Vinsol resin requirements

The air contents of all of the concretes in this study were maintained within the range of 4½ ± ½ percent. Neutralized Vinsol resin solution was added at the mixer as the air-entraining agent.

Changes in concrete temperature required changes in the amount of air-entraining agent per unit of cement needed to entrain 4½ ± ½ percent air. The amount of agent required increased with an increase in concrete temperature. This increased demand with temperature was accentuated somewhat in these tests since the water content per cu yd was held constant; consequently slump decreased with increased temperature. The amount of air entrained per unit of agent generally increases with an increase in concrete slump up to about 5 or 6 in. The air-entraining agent requirements shown in Table 9 for the different concrete temperatures are therefore influenced by slump in addition to temperature.

*Swayze, M. A., "Hot Cement Effect on Concrete Mix Temperature," ACI Journal, Dec. 1947, *Proc.* V. 44, p. 330.

At all temperatures except 120 F, the concretes made with calcium chloride as the accelerator required slightly less air-entraining agent than those without calcium chloride. At 120 F the reverse was true. The requirements for the Type I and II cements were approximately equal, while the Type III cements required greater quantities of agent than either the Type I or II.

SUMMARY AND CONCLUSIONS

Based on these laboratory tests of air-entrained concretes mixed, placed, and cured at different temperatures, the following statements appear valid:

1. Concrete slump generally decreased with an increase in concrete temperature when the water content was held constant. Increasing the water content of concrete without increasing the cement content is one of the reasons for reductions in strength during hot weather.
2. At 1, 3, and 7 days, concrete strengths increase with an increase in the initial and curing temperature of the concrete.
3. Increasing the initial and curing temperatures results in considerably lower strengths at 3 months and 1 year.
4. Temperature influences flexural strength development in much the same manner as it does compressive strength development.
5. Strengths of concretes made with the three cement types used in this study were influenced in a like manner by temperature; differences were in degree only.
6. These tests indicate that there is a temperature during the early life of the concrete which may be considered optimum with regard to strength at later ages, or more strictly, at comparable degrees of hydration. This temperature is influenced somewhat by cement type. For Types I and II this temperature is 55 F, for Type III it is 40 F.
7. Concrete strengths did not correlate well with the simple index known as "degree-days."
8. For concretes with calcium chloride added, strength increases due to the accelerator are proportionately greater at early ages and lower temperatures. The use of calcium chloride frequently resulted in flexural strengths at later ages somewhat lower than for comparable concretes without calcium chloride. Maximum reductions noted were of the order of 10 percent.
9. In these tests, cement temperature by itself exerted no significant influence on the strength of the concrete except insofar as it affected the final temperature of the concrete after mixing. It is concrete temperature and curing temperature which influence strength development and not cement temperature.
10. To maintain a constant amount of entrained air, greater amounts of air-entraining agent per unit of cement are required as concrete temperature is increased and slump decreased.

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