U. S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

RESEARCH PAPER RP799

Part of Journal of Research of the National Bureau of Standards, Volume 14, June 1935

BEHAVIOR OF HIGH-EARLY-STRENGTH CEMENT CONCRETES AND MORTARS UNDER VARIOUS TEMPERATURE AND HUMIDITY CONDITIONS

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ABSTRACT

Data were obtained on the properties of 12 commercial high-early-strength cements, and on various mortars and concretes made from them.

All of the cements gave early strengths higher than those of ordinary portland cements. The strength of 1:2:4 concrete with C/W ratio of 1.50 by weight varied from 560 to 1,120 lb/in.^{2} at 1 day, and from 1,590 to 2,590 lb/in.^{2} at 3 days. Concrete stored during the first 24 hours at 90 and 110° F was greater in strength than concrete stored at 70° F. Damp-stored specimens gave the highest strengths after 28 days. Concrete subjected to 300 alternations of freezing and thawing had slightly lower strengths than concrete stored 1 year in the damp room. Freezing and thawing combined with drying and soaking caused severe spalling on mortars and concretes made from some of the cements.

Certain mortar specimens made with the same C/W ratio as concrete cylinders were about equal in strength to the cylinders at early ages.

The heat evolved by the cements was computed from the rise in temperature of concrete in an adiabatic calorimeter. At 90 days the heat evolved varied from 104 to 130 cal/g of cement.

No definite relation was found between cement compound composition and strength, length changes, or resistance to freezing, thawing, drying, and soaking of mortars and concretes.

CONTENTS

I. INTRODUCTION

The compressive strength of the high-early-strength cements in various concretes hardened at normal temperatures is known. Information regarding the strength when hardened at higher temperatures, and comparison of the composition and fineness of the cements with such physical properties as strength, volume changes, resistance to freezing and thawing, heat evolution during hardening, etc., are lacking

The studies included in this investigation were undertaken to secure data for making these comparisons.

II. OUTLINE OF TESTS

1. CEMENTS AND MORTARS

Twelve samples of cement were received from different mills, but some of the samples were of the same brand. Each sample of about 8 barrels was well mixed and then stored in metal drums sealed with paraffin.

The weight per cubic foot of the cement, time of set, amount retained on sieves nos. 200 and 325, and on a specially prepared sieve designated no. 450, specific surface (by the Wagner turbidimeter), soundness, and chemical composition were determined. The following mortar specimens were made: (1) standard briquets, (2) 2-inch cubes made of a 1:3 mortar using standard Ottawa sand, (3) 2-inch cubes made of a 1:2.74 mortar, using quarry-run Ottawa sand, with cement-water ratio of 1.89, equivalent to 6 gallons per sack, (4) 2-inch cubes of a 1:5 by weight mix of cement with an aggregate proportioned 1 part quarry-run Ottawa sand, 2 parts standard Ottawa sand, 3 parts of Potomac River sand retained on a no. 8 and passing a no. 4 sieve, and (5) prisms 1½ by 1½ by 4 inches, of the same mix as (3). One set of the prisms was tested in compression, with the load parallel to the long axis, and one set tested transversely on a 3-inch span with the load applied at the midspan. The halves from the transverse test were tested in compression by applying a load through steel plates 1½-inches wide, placed on opposite sides of the specimen, so that the loaded area was a square 1½ inches on a side. Two ends of the specimen in this test projected somewhat beyond the loading plates. The load was perpendicular to the original long axis of the prism. This type of test has been used in Europe,[1] and is now being considered by Committee C-1 of the American Society for Testing Materials.

2. CONCRETES

(a) MIXING AND STORAGE

The 6- by 12-inch concrete cylinders were made of cement, Potomac River sand, and Potomac River gravel. The sand had a fineness modulus of 2.8. The proportions of cement, sand, and gravel are given in table 1.

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[1] Proc. Int. Soc. Testing Materials, 6th Congress, 2nd sec. part 13 (1912).

TABLE 1.—*Proportions of cement, sand, and gravel in 6- by 12-inch concrete cylinders*

Material	Proportions by—			Remarks
	Weight		Volume	
Cement		1.00	1.00	94 lb of cement, assumed equal in bulk to 1 cu ft.
Sand		2.28	2.00	Dry-rodded volume.
Gravel ¼ to ⅜ inch	4.51	1.94	4.00 combined	Do.
Gravel ⅜ to ¾ inch		1.535		
Gravel ¾ to 1 inch		1.035		

Specimens were made using cement-water ratios (C/W ratio) of 1.73, 1.50, and 1.33, by weight (6.5, 7.5, and 8.5 gallons of water per 94 pounds of cement), except that for the adiabatic storage, only the 1.50 cement-water ratio was used. Specimens were made in triplicate.

The materials for each cylinder were mixed dry by hand, the water added, and then mixed for 2 minutes. Flow and slump tests were made on those batches which were mixed at 70° F. The temperature of the mixes and the conditions of storage during the first 24 hours after making were:

(1) Mixes at 70° F, stored in air at 70° F.
(2) Mixes at 90° F, stored in air at 90° F.
(3) Mixes at 110° F, stored in air at 110° F.
(4) Mixes at 70° F, stored in a thermally insulated cabinet.
(5) Mixes at 70° F, stored adiabatically.

After the first 24 hours, under the first four conditions, specimens for compressive-strength and linear-change determinations were treated as follows: (1) Stored in a damp room at 70° F, (2) stored in the air of a laboratory maintained at 70° F, (3) stored outdoors until tested at the end of 1 year, and (4) subjected to 300 cycles of alternate freezing and thawing (each cycle being completed in 24 hours).

Temperatures during the first 24 hours after making were measured on one of each set of three cylinders by a copper-constantan thermoelement, consisting of three couples in series. Each set of three junctions was tied together. One set was inserted at the center of the cylinder, the other in melting ice. In the 90 and 110° F storages the temperatures were measured by a recording galvanometer, and in the 70° F and insulated storages by a recording potentiometer. The use of three couples in series was for the purpose of securing greater accuracy where the temperature rise was small. For the specimens stored at 90 and 110° F during the first 24 hours, the temperature within the storage box was automatically maintained by electric heaters over which the air of the cabinet was continually circulated.

The cylinders to be stored at 70, 90, and 110° F were cast in steel molds, with steel top and bottom plates. Those for storage in the insulated cabinet were cast in paraffined paper molds, and the filled mold placed in a metal cylinder surrounded by a thickness of 9 inches of diatomaceous silica. The cylinders to be stored adiabatically were cast in tinned sheet-iron molds which were hermetically sealed.

(b) EXPANSION MEASUREMENTS

The apparatus for expansion measurements consisted of a metal cradle into which the cylinder was so placed in a definite horizontal position that a fine line scratched on a glass plate cast in one end of the cylinder was in contact with a blunt-pointed screw attached to the stand, while the stem of a dial micrometer touched a glass plate in the other end. Measurements were made on two such sets of glass plates that were placed in the ends of each cylinder. Readings on the cylinders in the 90° F, 110° F, and insulated storages were taken both on the removal from the molds and after cooling to 70° F. The temperature within the cylinders, which were stored in air at 70° F, was generally slightly higher than 70° F at the end of 24 hours; no measurements were made before these cylinders had cooled to 70° F. All specimens were then placed in the designated storages for subsequent tests. After the initial measurements were made the cylinders stored in the damp room and in the laboratory air were measured at the ages of 7 and 28 days, 6 months, 1 year, etc.; those stored outdoors were measured only at 1 year (after storing for the last 10 days in the air of the laboratory at 70° F). The specimens subjected to freezing and thawing were measured at 1 year and at 300 cycles. All expansions and contractions were based upon the length of the cylinders at 1 day, measured at 70° F.

(c) FREEZING, THAWING, DRYING, AND SOAKING TESTS

Three- by six-inch concrete cylinders, with a C/W ratio of 1.50 (7.5 gallons of water per sack) were made for determining the effect of cycles of drying and soaking, and of freezing, thawing, drying, and soaking on the strengths of the concretes of the different cements. The mix was the same as for the 6- by 12-inch cylinders, except that the aggregate had a maximum size of ¾ inch, and for a unit weight of cement was proportioned as follows:

Size of gravel	Proportions, by weight
¼ to ⅜ inch	2.52
⅜ to ¾ inch	1.99

The ratio of the weights of the ¼- to ⅜-inch gravel and ⅜- to ¾-inch gravel was the same as in the 6- by 12-inch cylinders.

All specimens were kept in the molds for 48 hours, then in water for 24 hours, and then started in the specified treatment.

For each cement, cylinders were made for three different treatments:

(1) One freezing and one thawing daily for 3 successive days, then 3 days' drying at 150° F, then 1 day storage in water.
(2) Drying 3 days at 150° F, soaking 4 days.
(3) Damp storage.

The drying took place in an oven maintained at 150° F, through which air was blown after passing through heaters. Fresh air was continuously drawn into the oven.

Specimens were tested in compression after 15, 25, 50, and 100 cycles of treatments (1) and (2), and after damp storage for corresponding ages.

Specimens for expansion measurements, subjected to the same treatments as the 3- by 6-inch cylinders, were made from each cement, in the form of 2- by 12-inch cylinders with glass plates as reference marks set in the ends. The mix used was the same as that used in the 1:5 mortar cubes (see cements and mortars). This gave a mortar of about the same consistency as the mix used for the 3- by 6-inch cylinders. The expansion measurements were made in an apparatus similar to that used for the 6- by 12-inch cylinders. Observations were taken after each set of three freezings and thawings, after drying, and after soaking. The damp-stored specimens were measured at the same ages as the corresponding specimens in the other treatments. All specimens were allowed to reach 70° F before measuring.

(d) COMPRESSIVE STRENGTH

The loads were applied at the rate of approximately 1,000 lb/in.^{2} per minute. The specimens in damp storage and those subjected to freezing and thawing were tested in the wet condition. The specimens stored outdoors were stored in the air of the laboratory at 70° F for 10 days before testing. The air-stored specimens were tested without further treatment.

Most of the specimens were prepared for testing by grinding the ends. In those cases where the cylinder ends could not be trued by grinding, as those with glass plates inserted in the ends, plaster caps were applied.

III. TEST RESULTS

1. TESTS OF CEMENTS AND SMALL SPECIMENS

The chemical composition, calculated compound composition, fineness, specific surface, time of setting, and weight per cubic foot of each cement are given in table 2.

The calculated compound compositions of the cements differ widely. The tricalcium-silicate content ranges from 34 to 70 percent, dicalcium silicate from 0 to 38 percent, the tricalcium aluminate from 7 to 17 percent, and the tetracalcium alumino ferrite from 6 to 10 percent. It is noteworthy that one of the cements (no. 12) contains more dicalcium silicate than tricalcium silicate.

The fineness also varies considerably; the specific surface values are considerably higher than similar values for standard portland cement. For example, in one cement, the weight of the fraction containing particles less than 10 microns in diameter exceeded 40 percent of the total weight of the sample. With the possible exception of an earlier final set, the setting characteristics are similar to those of the slower-hardening cements. The weights per cubic foot show how much these depart from the commonly accepted figure of 94 pounds.

TABLE 2.—*Chemical and compound composition, fineness, time of set, and weight of the cements*

All of the cements were satisfactory in the steaming test for soundness

$C_3S=3CaO.SiO_2$; $C_2S=2CaO.SiO_2$; $C_3A=3Ca.O.Al_2O_3$; $C_4AF=4CaO.Al_2O_3.\ Fe_2O_3$

Cement no.	Chemical compositions										Calculated compound compositions					Fineness				Weight		Mixing water for normal consistency (% of dry cement, by weight)	Time of setting (Gilmore method)	
																Retained on sieve no.—			Specific surface (by Wagner turbidimeter)					
	CaO	MgO	Al_2O_3	Fe_2O_3	SiO_2	SO_3	Cl	Insoluble in HCl	Loss on ignition	Free CaO[a]	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	200	325	450[b] (wet method)		Rodded[c]	Loose[d]		Initial	Final
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	cm ^{2}/g	lb/ft ^{3}	lb/ft ^{3}		hr	hr
1	66.2	1.1	8.3	3.1	17.0	2.4	0.0	0.2	1.7	[e] 0.4	65	0	17	10	4.1	3.7	8.5	15.7	1990	78.3	67.8	25.0	2.5	4.5
2	66.6	1.0	6.2	1.9	20.6	2.5	.0	.5	1.1	1.6	57	16	13	6	4.2	3.1	8.3	16.3	1910	74.6	63.6	27.0	3.0	6.0
3[f]	65.6	2.5	4.7	3.1	20.6	1.3	.3	.5	2.4	.3	70	7	7	9	2.2	2.8	8.8	16.6	1770	78.7	69.8	25.6	4.5	6.5
4	65.7	2.5	5.6	2.3	19.3	2.2	.02	.6	2.1	2.7	62	8	11	7	3.7	3.1	8.7	13.2	2030	74.8	65.6	26.0	3.5	5.5
5	64.2	3.4	7.2	2.5	18.5	2.4	.04	.2	1.8	.6	61	7	15	8	4.1	1.7	5.3	14.2	1760	74.8	62.7	25.0	3.5	6.0
6	62.9	2.9	7.0	2.3	20.3	2.6	.08	2.3	1.6	.1	45	24	15	7	4.4	2.7	8.4	15.2	2050	75.8	64.6	25.4	4.5	6.5
7	65.7	1.5	6.6	2.7	19.3	2.1	.03	.4	1.8	1.5	57	14	13	8	3.5	1.3	5.8	11.8	1970	74.2	63.4	26.0	3.0	5.5
8	65.4	2.7	6.4	1.9	19.3	2.3	.0	.2	1.7	4.2	51	17	13	6	3.9	1.7	9.6	13.6	2180	76.1	63.1	24.4	1.75	3.5
9	66.2	2.2	4.4	2.8	21.6	1.9	.0	.1	1.2	.4	65	13	7	9	3.2	1.7	7.5	12.2	2120	75.6	67.2	24.0	3.0	5.5
10	62.3	3.4	7.1	2.8	18.5	2.5	.0	.5	2.7	1.9	47	18	14	9	4.2	3.8	8.8	20.4	1930	79.5	67.8	25.0	2.5	6.0
11	63.3	3.5	6.4	2.5	19.1	2.6	.07	.4	1.9	1.2	54	14	13	8	4.4	2.1	5.1	11.2	2150	75.0	63.2	25.0	3.0	5.0
12	60.6	4.8	4.8	2.4	21.9	2.7	.0	.7	2.5	.9	34	38	9	7	4.6	3.9	6.6	7.7	2490	74.3	63.8	25.0	3.0	5.5

[a] Free CaO determined by the method of Emley, Trans. Am. Ceram. Soc. **17,** 720 (1915).

[b] Sieve no. 450 was produced by electroplating the cloth of a no. 325 sieve, which reduced the average size of opening from .044 mm to .031 mm. If the standard sieve series were extended the .031 size would correspond to a no. 450 sieve.

[c] According to ASTM Standard Method of Test for Unit Weight of Aggregate for Concrete C29–27.

[d] According to Rogers' method, BS J. Research **13,** 811 (1934) RP 746.

[e] The value for the free CaO for cement no. 1 was analytically determined. However, in calculating the compound composition it was found that the excess CaO over that required for the compounds was 1.9 percent.

[f] Contains a water-repellent material.

TABLE 3.—*Strength of small test specimens*

[All values are given in lb/in.^{2}]

Cement no.	Tensile strength of 1:3 standard-mortar briquets					Compressive strength of 1:3 standard mortar. (2-in. cubes.)					Compressive strength of plastic mortar.[a] (2-in. cubes.)					Compressive strength of 1:5 mortar.[b] (2-in. cubes.) C/W=1.50					Compressive strength of plastic mortar.[a] (1½- by 1½- by 4-in. prisms.) Loaded parallel to long side					Transverse strength of plastic mortar.[a] (1½- by 1½- by 4-in. prisms.) Modulus of rupture—3-in. span					Compressive strength of halves from transverse test.[a] Loaded on 1½-in. square area[c]				
	Tested at					Tested at					Tested at					Tested at					Tested at					Tested at					Tested at				
	1 day	3 days	7 days	28 days	1 year	1 day	3 days	7 days	28 days	1 year	1 day	3 days	7 days	28 days	1 year	1 day	3 days	7 days	28 days	1 year	1 day	3 days	7 days	28 days	1 year	1 day	3 days	7 days	28 days	1 year	1 day	3 days	7 days	28 days	1 year
1	330	400	400	455	375	2550	3710	4120	5010	5090	1380	3310	3800	4450	3920	780	2040	2510	2980	2990	1630	3060	3440	3930	4020	620	795	895	945	860	1730	3230	3610	4230	4370
2	250	390	395	450	415	1750	4060	5650	5860	5690	965	3500	4690	5030	4850	710	2220	3490	4320	4820	1150	3380	4700	5590	6350	380	770	945	1040	1000	1250	3800	5190	6290	6530
3	185	300	365	385	395	1260	2580	3550	4690	6560	925	2650	3950	4350	5490	565	1580	2250	2870	4290	[d]1140	[d]2450	[d]3410	[d]4890	[d]5390	[d]360	[d]665	[d]820	[d]985	[d]1000	[d]1290	[d]2970	[d]3590	[d]5000	[d]6330
4	280	390	400	410	370	2100	4030	4890	5990	6310	1150	4090	5660	6440	6720	740	2360	3730	4810	4850	1380	3660	5000	5860	5910	465	780	950	960	935	1590	3840	5310	6080	6090
5	255	385	515	445	425	1730	3870	5420	6960	7430	1360	4010	5500	6830	7470	630	2430	3840	5180	5260	1130	3610	4840	6180	6110	380	810	1060	1100	1020	1310	3830	5380	6320	6750
6	225	370	425	475	465	1740	3670	5130	6220	6310	1130	3420	4680	5280	6210	540	1700	2680	4270	5090	905	2620	3730	5620	6600	365	710	885	1160	1085	935	3020	4380	5670	6530
7	245	390	375	500	400	1860	3430	5260	4290	6130	1570	3140	5080	5110	6200	765	2150	3160	4920	5750	1370	3590	4880	5780	5650	445	825	1000	1110	1000	1570	3910	5180	6200	6340
8	215	360	370	440	420	1720	4040	4880	6170	6170	1030	3430	4790	5790	6090	820	1970	3330	4620	4840	1270	3320	4620	6050	4980	395	755	1020	1180	985	1350	3510	4810	6560	5610
9	255	395	465	470	460	2000	4320	5240	8050	7420	1400	3860	5670	6970	6650	1010	2280	3730	5010	5480	1020	3380	4040	5920	5870	415	730	935	1080	1070	1260	3280	4930	6660	7160
10	250	350	360	420	400	1700	3030	4110	5490	5110	1240	2990	3820	4970	6340	710	2020	2830	3970	4730	950	2310	2410	4320	4430	395	750	920	1030	1040	1370	2720	3660	4630	5280
11	295	380	485	435	385	2660	4550	6210	7270	7010	1450	3900	4910	6060	5950	1000	2560	3760	4910	5020	1420	3340	4830	5320	5950	550	885	1070	1080	1020	1870	3790	4900	6190	5900
12	230	320	410	500	455	2160	3650	5110	5850	6990	1220	2810	4080	6410	7540	630	1440	2250	4350	5690	880	1920	2860	3990	6410	370	650	885	1080	1170	1100	2430	3450	5550	6900
Avg	250	370	415	450	415	1940	3740	4960	5990	6350	1230	3430	4720	5640	6120	740	2060	3130	4350	4900	1190	3050	4060	5290	5640	430	760	950	1060	1010	1380	3360	4530	5780	6150

[a] 300 g of cement, 822 g of pit-run Ottawa sand, 159 ml of water. C/W=1.89. Fineness modulus of sand about 1.8.

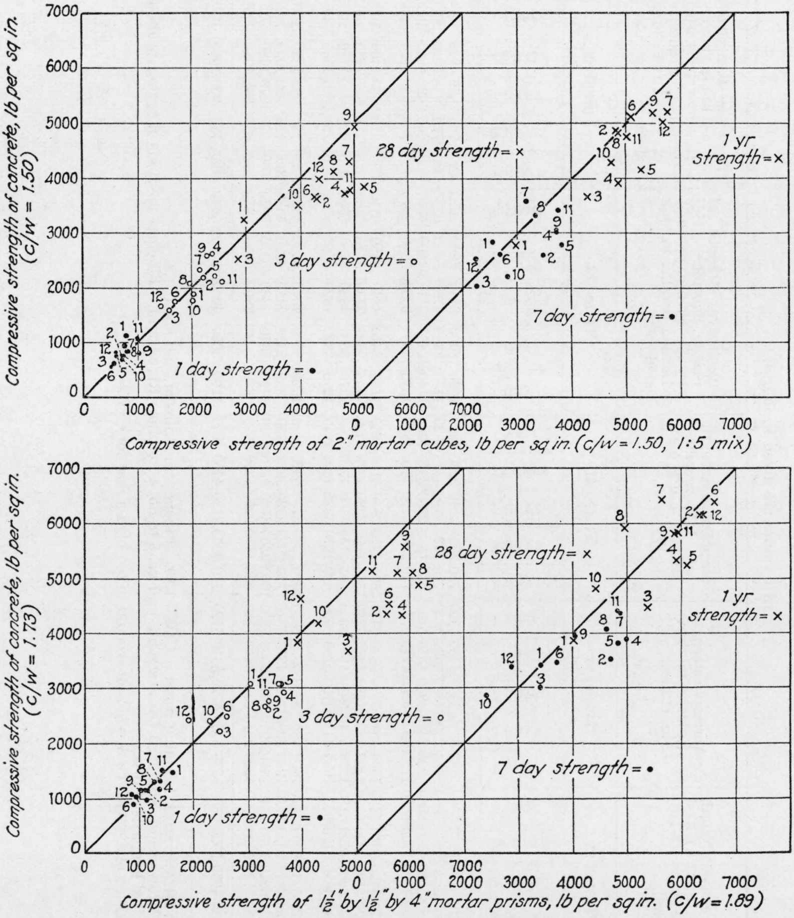
[b] Aggregate 1:2:3 mix of pit-run Ottawa sand, Standard Ottawa sand, and no. 8 to no. 4 Potomac River sand. Fineness modulus of aggregate about 3.8.

[c] Load axis perpendicular to original long axis of prism.

[d] Cement no. 3 plastic-mortar prisms made with C/W=2.02 on account of too high a flow for C/W=1.89.

Table 3 presents the results of the strength tests of the mortar specimens. The average values for each type specimen are also given.

Although tension and compression tests only are required in the United States in strength specifications for cement, transverse tests also are being used or considered in some countries. In these studies transverse tests were made, and the resultant halves of the specimens were tested in compression.



Lines drawn arbitrarily at 45°

FIGURE 1.—*Relation of compressive strength of concretes and mortars.*

The results of the tensile tests are typical in that there is in all but one case a retrogression after 28 days, a phenomenon not typical of cement mortars or concrete tested in compression at corresponding ages. It is to be noted that eight of the cements do not meet the 1-day requirement of the ASTM tentative specification (C74–30T) for high-early-strength cement and five do not meet the 3-day requirement. Some manufacturers are now producing cements with greater tensile strengths, but, as shown by data collected in another investigation, the requirements of 275 and 375 lb./in.^{2} at 1 and 3 days, respectively, are not being exceeded by an appreciable margin. The transverse-test results are somewhat similar to those for the tension tests in that there is frequently a retrogression at the later ages.

Two-inch cubes of plastic mortar have been proposed as test specimens for portland cement, on the assumption that they will have the same strength as concrete when made with the same cement-water ratio and of about the same consistency as the concrete. While most of the mortar specimens tested approximately justify this assumption the 1:5 cubes and the 1½- by 1½- by 4-inch prisms tested in compression with the load parallel to the long axis gave strengths more nearly equal to the concrete strength at all ages. If the concrete and mortar strengths at all ages were identical, the points for each cement in figure 1 would lie on the lines drawn at 45°. The average strength of the prisms tends to be higher than the average strength of the concrete after 1 day, the difference increasing up to 28 days, but becoming negligible at 1 year. The cement-water ratio of the prisms could not be changed to bring the strengths at all ages into equality. Although the 2-inch cubes and the concrete cylinders under discussion were of the same cement-water ratio and the strengths of the two are in better accord than the strengths of the concrete and the mortar prisms, the cube strengths also tend to be higher at the later ages than those of the concrete. The values obtained on the halves from the transverse-test specimens at any age, were, on the average, about 10 percent higher than the strengths of the corresponding prisms tested with the load parallel to the long axis. Compared to the 2-inch cubes of the same mortar, the strengths of the halves were, on the average, about equal in strength to those of the cubes; but individual differences were often large, and were not consistent.

2. FLOW AND SLUMP

The flow and slump measurements are given in table 4. There is no apparent relation between the flow or slump and composition or

TABLE 4.—*Flow and slump*

Cement no.	Flow and slump of concrete for 6- by 12-inch cylinders						Flow[a] of concrete for 3- by 6-inch cylinders; C/W 150	Flow[b] of quarry-run sand mortar; C/W 1.89
	C/W 1.73		C/W 1.50		C/W 1.33			
	Flow	Slump	Flow	Slump	Flow	Slump		
	%	in.	%	in.	%	in.	%	%
1	16	0.3	40	3.6	84	6.7	36	103
2	30	.2	51	1.3	83	5.0	45	101
3	46	.4	81	4.4	107	6.7	75	141 [c] 103
4	29	.2	51	2.4	80	5.5	54	102
5	30	.2	53	1.6	72	3.6	43	114
6	31	.2	54	3.9	78	5.5	56	104
7	28	.2	43	1.1	67	4.6	48	129
8	22	.2	39	1.4	66	5.6	49	113
9	28	.2	50	1.5	77	5.9	58	113
10	27	.2	51	1.4	80	5.8	50	102
11	35	.4	57	2.3	93	7.2	66	124
12	19	.3	43	1.9	79	6.9	58	123

[a] Using large flow table and fifteen ⅛-inch drops.

[b] Using small flow table and twenty-five ½-inch drops.

[c] C/W=1.89 was too wet for this cement. The values for flow of 103 and those given for strength in table 3 are for C/W=2.02, which gives a flow value nearer to that of the other cements.

fineness (table 2). Cement no. 3 has a flow markedly greater than any of the others, because the water repellent therein increases the flow.

3. TEMPERATURE RISE

The data on temperature rise of the concrete under the different storage conditions are given in table 5. The concretes with different cement-water ratios did not differ much in temperature rise. In insulated storage, the average temperature rise for the lowest

TABLE 5.—*Rise in temperature of the concrete*

Cement no.	STORED AT 70° F DURING FIRST 24 HOURS						STORED AT 90° F DURING FIRST 24 HOURS					
	C/W=1.73		C/W=1.50		C/W=1.33		C/W=1.73		C/W=1.50		C/W=1.33	
	Max rise in temp	Time to reach max temp	Max rise in temp	Time to reach max temp	Max rise in temp	Time to reach max temp	Max rise in temp	Time to reach max temp	Max rise in temp	Time to reach max temp	Max rise in temp	Time to reach max temp
	° F	hr	° F	hr	° F	hr	° F	hr	° F	hr	° F	hr
1	15	9	10	9	12	11	16	4.5	12	4.5	13	4
2	6	13.5	5	13	6	14	9	7.5	8	8	8	8
3	4	8.5	3	11	2	12.5	7	6.5	6	7.5	7	7
4	5	10.5	4	10	4	11.5	14	6.5	11	6.5	11	6.5
5	5	11	5	11.5	6	12.5	6	5.5	6	6	6	7
6	8	12.5	6	13	8	13.5	6	7	4	7	4	8
7	5	9	4	14	7	13	7	5.5	5	6	5	7
8	6	12	4	12	4	12	11	7	9	7	6	7.5
9	3	12	3	13	4	13.5	9	8	8	8	7	8.5
10	7	10.5	5	11	6	12	11	5	10	6	10	6
11	4	12	6	12	4	12.5	7	7	5	7.5	5	8.5
12	4	14	4	18	4	15	6	7	5	8	4	8
	STORED AT 110° F DURING FIRST 24 HOURS						THERMALLY INSULATED DURING FIRST 24 HOURS					
1	12	3.5	7	3	10	3.5	31	8	30	8	27	7.5
2	10	5	7	5	10	5.5	25	15	23	13	22	13
3	11	5.5	10	6	11	7	17	14	17	13	16	16
4	11	3.5	8	4	8	4	23	14	21	11	19	14
5	11	4	10	4	9	4.5	23	14	21	13	22	15
6	10	5.5	8	5	7	5	21	12	18	13	20	12
7	10	4	8	4	5	4	22	16	21	17	19	18
8	12	3	10	3	9	3	25	12	24	12	22	12
9	10	6	9	6	10	6.5	20	16	19	17	18	18
10	11	4	9	5	9	4	21	10	21	12	19	13
11	11	4.5	9	5	10	5	22	12	21	13.5	18	14
12	9	5	7	5	7	5	18	15	18	15.5	17	15

STORED ADIABATICALLY

Cement no.	C/W=1.50			Cement no.	C/W=1.50		
	Temp rise at 24 hr	Temp rise at 87 days	Ratio of 24-hr rise to 87-day rise		Temp rise at 24 hr	Temp rise at 87 days	Ratio of 24-hr rise to 87-day rise
	° F	° F			° F	° F	
1	78	102	0.77	7	57	95	0.60
2	46	87	.54	8	69	90	.76
3	46	85	.56	9	56	92	.61
4	59	96	.61	10	60	85	.64
5	67	97	.61	11	64	94	.69
6	55	86	.65	12	48	80	.60

TABLE 6.—*Compressive strength* (lb/in.^{2}) *of 6- by 12-inch concrete cylinders*

Cement no.	C/W (by weight)	Storage during first 24 hr	Subsequent storage condition									Storage during first 24 hr	Subsequent storage condition								
		70° F	Damp				Laboratory air			Outdoors	Freezing and thawing	90° F	Damp				Laboratory air			Outdoors	Freezing and thawing
		Tested at—																			
		1 day	3 days	7 days	28 days	1 year	7 days	28 days	1 year	1 year	300 cycles	1 day	3 days	7 days	28 days	1 year	7 days	28 days	1 year	1 year	300 cycles
1	1.73	1470	3100	3430	3840	3880	3170	3930	4190	3020	3890	2150	2760	3330	3100	3650	3280	3780	3880	3820	3750
	1.50	1120	1880	2830	3240	2780	2480	3390	3140	2930	3430	2000	2600	3010	2880	3140	2560	3050	2990	2710	2870
	1.33	550	1250	1570	1980	2120	1740	2350	2230	1990	2220	1280	1520	1810	1930	2100	1920	2310	2400	1990	2090
2	1.73	1150	2610	3510	4340	6140	3210	3900	4090	4110	4950	1940	2760	3350	3750	5070	3350	2850	3940	4450	4710
	1.50	760	2200	2600	3620	4850	2570	2890	2950	3070	3950	1380	2050	2780	2930	3690	2510	3450	2920	3670	4130
	1.33	470	1320	1940	2620	3050	1730	2330	2150	2570	2650	890	1320	1680	2140	2880	1640	2640	2180	2850	2770
3	1.73	990	2220	3010	3690	4490	2930	3660	3150	3860	4120	1780	2450	2860	3790	4310	2800	3720	3280	4520	3960
	1.50	620	1590	2050	2520	3660	2050	3010	2450	3030	3660	1140	1540	1890	2800	3290	2040	2680	2490	3430	3250
	1.33	410	990	1510	1930	2640	1470	2030	1620	1980	2710	700	1020	1290	2010	2280	1150	1660	1500	2200	2810
4	1.73	1190	2940	3900	4310	5340	4020	4660	4320	4970	5010	2180	3060	3750	4590	5150	3460	4270	4160	5340	4870
	1.50	760	2360	3030	3720	3910	2880	3960	3010	3990	4310	1540	2230	2610	3270	3640	2800	3020	2730	3880	3800
	1.33	460	1540	2390	2820	3010	2220	2880	2070	2910	3270	1100	1790	1770	2640	2720	1960	2350	1930	2610	2660
5	1.73	1160	3080	3810	4880	5240	3270	4600	4370	5100	5010	1990	2840	3390	4140	4260	2750	4160	4210	4790	4340
	1.50	770	2200	2800	3840	4150	2470	3740	3400	4470	3600	1410	2100	2740	3260	3570	2690	3230	2950	4210	3690
	1.33	530	1710	2470	3180	3130	2130	2830	2600	3460	2840	960	1750	2030	2560	3170	2090	2480	2180	3410	2770
6	1.73	900	2480	3470	4520	6370	3050	4030	4280	4970	5340	1520	2840	3540	4650	5830	3300	4700	4600	4680	4760
	1.50	560	1750	2630	3650	5110	2200	3140	3080	4340	4370	1150	1890	2540	3570	4850	2390	3380	3120	4330	4320
	1.33	390	1230	2090	2900	3860	1760	2470	2070	3500	3160	770	1460	2090	3000	3990	2000	2600	2310	3570	3680
7	1.73	1320	3090	4370	5100	6410	3710	4360	3970	5560	4900	2210	3180	4310	4000	4800	4030	4200	4080	4990	4650
	1.50	950	2330	3600	4300	5200	2810	3530	3290	4670	4210	1630	2470	3390	3920	4320	3290	3770	3570	4640	4190
	1.33	590	1740	2760	3320	4280	2210	2650	2360	3960	3250	1130	1760	2410	2950	3490	2250	2370	1960	3120	3360
8	1.73	1320	2670	4070	5100	5910	3550	4370	4290	5300	5700	2000	3190	3600	4690	5210	3660	4480	4260	5520	4890
	1.50	840	2090	3320	4100	4380	2720	3410	3490	4960	4510	1440	2140	2680	3810	4520	2670	3430	3200	4250	4210
	1.33	570	1430	2440	3440	3890	2060	2710	2710	3620	3040	970	1560	2460	3220	3340	2110	2470	2450	3300	3340
9	1.73	1150	2780	3940	5560	5800	4150	4830	4300	4730	5470	2430	3560	4100	4840	6000	3880	4850	4120	6100	5380
	1.50	820	2590	3050	4930	5190	2570	3550	3050	4340	4970	1570	2310	2920	3880	4010	2830	3350	3000	4570	4350
	1.33	560	1530	2290	3450	3510	1820	2440	2120	3670	3170	1060	1610	2260	2700	3400	2030	2600	2020	3540	3050
10	1.73	1040	2410	2860	4190	4800	2690	3760	3790	5400	4580	1590	2160	3050	3670	5170	2890	3650	3790	4840	4230
	1.50	700	1770	2210	3500	4300	2190	2850	2720	4110	4090	1240	1800	2140	2990	4040	1970	2710	2810	4100	3830
	1.33	390	1210	1790	2500	3100	1490	2300	2070	3260	2920	710	1160	1330	2430	2990	1430	1980	2010	2990	3140
11	1.73	1520	2940	4400	5130	5810	3750	4920	4920	5770	5600	2230	3610	3750	5300	5980	3930	4910	4790	5390	5510
	1.50	1070	2120	3440	3770	4780	2870	3480	3570	4570	4600	1560	2360	3070	3980	5050	2900	3760	3370	4580	4420
	1.33	630	1600	2470	3040	3430	2290	2670	2790	3890	2990	890	1440	2220	2620	3450	1950	2730	2580	3650	3060
12	1.73	1090	2420	3390	4640	6130	3080	3960	4230	6320	5660	1810	2070	3060	4670	6240	3320	4000	4260	6020	5260
	1.50	820	1680	2540	3990	5020	2310	2890	3070	5310	5200	1160	1890	2350	3020	4700	2120	2890	3170	4640	4530
	1.33	560	1230	1790	2770	3660	1650	2200	2250	4320	3490	760	1200	1670	2460	3480	1480	2430	2230	3540	3660

Cement no.	C/W (by weight)	Storage during first 24 hr	Subsequent storage condition									Storage during first 24 hr	Subsequent storage condition									Stored adiabatically for 87 days		
		110° F	Damp				Laboratory air			Outdoors	Freezing and thawing	Insulated	Damp				Laboratory air			Outdoors	Freezing and thawing			
		Tested at—																						
		1 day	3 days	7 days	28 days	1 year	7 days	28 days	1 year	1 year	300 cycles	1 day	3 days	7 days	28 days	1 year	7 days	28 days	1 year	1 year	300 cycles	90 days	1 year	
																							Sealed	Stored unsealed in damp room after 87 days
1	1.73	[a] 1620	2080	2350	2350	3420	2170	2430	3050	3380	3460	2380	2880	3140	3480	3500	3120	3890	3820	3420	3790	------	------	------
	1.50	1780	2190	2680	3100	3550	2310	2910	2960	3540	3490	1800	2100	2430	2660	2720	2550	2890	2930	2420	3320	2780	2760	2720
	1.33	1410	1800	2090	2200	2630	1980	2290	2140	2430	2580	1070	1490	1510	1970	2090	1740	2100	2180	1830	2150	------	------	------
2	1.73	2330	2980	2980	3020	4890	3320	3660	3890	4040	4450	1690	2600	3160	3470	4430	3080	3620	3710	4170	4210	------	------	------
	1.50	1610	2110	2550	2670	4100	2440	3140	2690	3520	3770	1260	2070	2120	2890	3140	2080	2510	2420	3520	3380	3450	3880	4010
	1.33	1480	1630	1960	2120	3540	2060	2220	2180	2910	2960	820	1430	1730	1930	2340	1470	1770	1600	2340	2530	------	------	------
3	1.73	2470	3010	3360	3520	4610	3490	4160	4080	4570	4810	1270	1990	2430	3020	4140	2670	3060	2670	3860	4210	------	------	------
	1.50	1650	2440	2630	2710	3750	2420	2810	2940	3740	3610	830	1400	1540	2130	3040	1640	1980	1750	2870	3540	3530	3560	3810
	1.33	1250	1550	1910	2080	2640	1710	2220	2060	2750	3100	480	860	1140	1610	2160	1030	1650	1190	2090	2570	------	------	------
4	1.73	2360	2490	3070	4390	4380	3540	4090	3830	5560	3930	2150	3010	3280	3700	4270	3180	3850	3730	4510	4450	------	------	------
	1.50	1900	2290	2540	3420	3980	2720	3680	3250	4120	3870	1180	2080	2590	3230	3560	2640	2780	2560	4010	3680	3830	3510	3880
	1.33	1430	1810	2150	2330	3170	2020	2920	2320	3480	3340	870	1610	1860	2580	2760	2080	2510	1800	2660	2830	------	------	------
5	1.73	2300	2850	2720	3530	3760	2620	3580	3380	3500	3420	1600	2790	2910	3590	4240	3080	3690	3620	5090	4510	------	------	------
	1.50	1660	2130	2430	3010	3520	2560	3010	3120	4020	3570	1280	2020	2760	3050	3300	2430	3200	2740	4030	3820	3630	4020	3380
	1.33	1240	1560	1900	2480	2980	1740	2410	2410	3760	3050	830	1670	2200	2480	2690	1880	2550	2080	3320	2710	------	------	------
6	1.73	[a] 1640	1530	2240	3070	3460	3170	2910	2840	4390	3250	1350	2460	3030	3590	4990	2930	3580	3530	4680	4990	------	------	------
	1.50	1740	2280	2700	3390	4650	2600	3480	3040	4190	4200	1000	1950	2420	3400	3890	2300	2910	2530	4160	4130	3490	3840	3850
	1.33	1250	1840	2170	3030	4250	2120	2610	2320	3630	3780	640	1140	1910	2600	3000	1650	2070	2050	3000	3090	------	------	------
7	1.73	[a] 1690	2490	2580	2740	3070	2410	4140	3740	3310	3020	2040	3100	3850	4160	5180	3800	4370	4050	4650	4960	------	------	------
	1.50	2240	2850	3360	3840	4970	3260	3870	3390	4390	3860	1470	2300	3150	4000	4080	2790	3380	2940	4440	3360	3910	4580	4000
	1.33	1600	2120	2690	3140	4010	2530	2930	2650	3480	3420	1020	1730	1600	2070	2120	2180	2660	2030	3230	3180	------	------	------
8	1.73	[a] 2010	1650	2560	3580	4650	3220	3300	3430	5080	3160	1870	2670	3450	3840	4820	3150	4460	3840	5600	4810	------	------	------
	1.50	1970	2170	3010	3760	4470	3050	3730	3710	4680	4180	1270	2050	3340	3820	3720	2120	3350	3050	4350	3900	3660	3970	4180
	1.33	1460	1960	2230	3160	3740	2380	2780	3000	3830	3360	910	1710	2290	3170	3160	1950	2710	2350	3800	2470	------	------	------
9	1.73	2680	3680	4010	4980	5330	3880	4930	4710	6140	5320	2120	3350	3640	4210	4290	3720	4560	3320	5460	5390	------	------	------
	1.50	2290	2840	3500	3650	4580	3500	3910	3750	5840	4550	1030	2070	3130	3800	4480	2240	3240	2960	4420	4620	4310	4760	4720
	1.33	1620	2320	2750	3400	4060	2880	3220	2830	4130	3220	660	1420	2110	2970	3370	1750	2430	1730	3090	3350	------	------	------
10	1.73	1760	2060	2690	3180	3960	2770	3220	3600	4490	3700	1420	1920	2810	2930	4280	2240	3200	3150	4420	4450	------	------	------
	1.50	1650	1770	2170	2560	3330	2140	2730	3210	4110	3470	940	1560	1870	2530	3460	1770	2640	2240	3370	3030	2910	3190	3610
	1.33	1020	1370	1610	2070	2770	1440	2020	2190	3240	2330	660	1110	1340	2250	2610	1370	1750	1680	2660	2260	------	------	------
11	1.73	2900	3160	3870	4940	5520	3980	4730	4350	5470	3910	1930	2850	3590	4010	4590	3610	3950	3670	4770	5110	------	------	------
	1.50	2080	2670	3340	3900	4760	3770	3670	3820	4290	4230	1250	1930	2770	3520	4090	2170	3090	2970	3940	4130	3640	3850	3880
	1.33	1520	2100	2420	3180	3540	2380	2940	2810	3600	3450	700	1280	1920	2460	2610	1740	2670	2140	3050	3120	------	------	------
12	1.73	[a] 1330	1600	1940	2470	4340	2110	2690	2750	3560	3200	1310	2130	2960	4240	5460	2450	3850	3890	4860	5040	------	------	------
	1.50	1560	2100	2310	3570	5180	2570	3210	3590	5450	4480	940	1520	2200	3340	4320	1920	3080	3200	4170	4000	3980	4450	4750
	1.33	1030	1470	1880	2890	4070	2020	2560	2700	4430	3680	580	1140	1650	2910	3430	1410	1740	1930	3350	3280	------	------	------

[a] Cylinders for this cement, made at 110° F, C/W=1.73, were honeycombed.

C/W ratio was about 10 percent less than for the highest C/W ratio. This is to be expected, since the heat capacity of the concrete was increased only about 10 percent by increasing the water from the highest to lowest cement-water ratio.

The average temperature rise of all cements in storage under three temperatures was in the order of the temperature of storage, the highest storage temperature giving the greatest rise of temperature in the concrete. For the concretes with a C/W ratio of 1.50 the average temperature rise for the different conditions of storage was as follows: 70° F storage, 5° rise; 90° F storage, 7.4° rise; 110° F storage, 8.5° rise; thermally insulated, 21° rise; and adiabatic storage, 59° rise. It is to be noted that cements nos. 1 and 4 were exceptions in that the highest temperature rise was obtained in 90° F storage.

The data in tables 2 and 5 may be studied to obtain some idea regarding the effect of composition and fineness on the temperature rise produced by the reaction of the cements and water. Maximum temperatures attained in the insulated storage seem to depend mainly on the tricalcium-aluminate content. The low-aluminate cements (nos. 3, 9, and 12) gave the lowest maximum temperatures. No doubt the fineness of the cements also influences the temperatures attained during the first 24 hours. Under the section devoted to strength, the results of the use of an equation derived from similar data will be presented in some detail.

4. COMPRESSIVE STRENGTHS OF CONCRETES

The results of the compression tests on concrete cylinders are given in tables 6, 7, and 8.

(a) EFFECT OF TYPE OF STORAGE DURING THE FIRST TWENTY-FOUR HOURS

The storage temperature during the first 24 hours greatly affects the 1-day strength (table 7). Cylinders stored at 90° F during the first 24 hours have strengths nearly twice those of cylinders stored at 70° F. Storing at 110° F further increases the early strength, while cylinders thermally insulated, where the maximum temperature averaged approximately 90° F, gave compressive-strength values somewhat lower than those of the cylinders kept for the entire 24 hours in the 90° F cabinet. The higher temperatures during the first 24 hours do not affect the strength appreciably beyond 3 days. Indeed, the average strength of the specimens stored in the damp room is greater at 1 year for those stored at 70° F than for those exposed to higher temperatures during the first-day storage. The results obtained on specimens stored adiabatically are discussed in section III–6.

(b) EFFECT OF TYPE OF STORAGE AFTER THE FIRST TWENTY-FOUR HOURS

With a few exceptions the specimens stored in the damp room, at 70°±3° F and relative humidity not less than 95 percent, developed the highest strengths. Cement no. 1 showed practically no gain after 28 days. Most of the other cements showed considerable increase in strength up to 1 year, when stored in a damp atmosphere.

TABLE 7.—*Compressive strength of 6- by 12-inch cylinders*

(Average for 12 cements)

COMPRESSIVE STRENGTH—AGED 1 DAY

C/W ratio	Type of storage after first 24 hr[a]	Initial storage			
		70° F	90° F	110° F	Insulated
		lb/in.²	lb/in.²	lb/in.²	lb/in.²
1.73		1190	1990	2090	1760
1.50		815	1440	1840	1190
1.33		510	935	1360	770

COMPRESSIVE STRENGTH—AGED 1 YEAR OR AFTER 300 CYCLES OF FREEZING AND THAWING

1.73	D	5530	5140	4280	4520
	OD	4930	5040	4460	4620
	FT	5020	4690	3800	4660
	LA	4160	4110	3640	3580
1.50	D	4440	4070	4240	3650
	OD	4150	4080	4320	3810
	FT	4240	3970	3940	3740
	LA	3100	3030	3290	2690
1.33	D	3310	3110	3450	2690
	OD	3260	3060	3470	2870
	FT	2980	3030	3190	2790
	LA	2250	2150	2470	1900

[a] D=damp storage; OD=outdoor storage; FT=freezing and thawing; LA=laboratory air at 70° F.

TABLE 8.—*Results of tests of 3- by 6-inch concrete cylinders after certain treatments*

Cement no.	Compressive strength (lb/in.²) after freezing and thawing, drying and soaking				Compressive strength (lb/in.²) after drying and soaking				Compressive strength (lb/in.²) after continuous damp storage				Effect of freezing and thawing, drying, and soaking
	Cycles at which tested				Cycles at which tested				Weeks at which tested				
	15	25	50	100	15	25	50	100	15	25	50	100	
1	1670	2060	2200	Spalled	2080	2400	2400	3110	2930	3040	3310	3610	Began spalling at about 35 cycles. Considerable spalling from 50 to 70 cycles.
2	2950	3010	3170	[a] 3120	2930	3090	3290	3550	3490	3640	3590	3870	Showed slight spalling at about 70 cycles. Considerable spalling at 90 cycles.
3	2660	2550	2780	3200	2550	2630	3030	3710	2730	3010	3730	4020	No spalling up to 90 cycles.
4	2820	2860	3180	Spalled	3300	2980	3560	3920	3370	3450	4060	4210	Showed slight spalling at about 70 cycles. Considerably spalled at 90 cycles.
5	2960	3470	3700	[a] 4420	3300	3280	3780	4070	3940	3960	4370	4400	Showed slight spalling at about 70 cycles. Considerable spalling after 80 cycles.
6	3220	3620	3850	4030	3550	3780	3810	3950	3890	4280	4490	4460	Slight spalling after 80 cycles.
7	2880	2990	3460	Spalled	3370	3000	3480	3770	3730	3890	4620	3930	Began spalling at about 40 cycles. Considerable spalling from 50 to 70 cycles.
8	3140	3310	4650	5300	3360	3440	4210	5450	4510	4230	3950	4750	Slight spalling after 75 cycles.
9	3090	5420	Spalled	Spalled	3260	3410	4120	3870	4240	4570	4540	4300	Severe spalling from about 35 to 50 cycles.
10	2070	2620	[a] 2220	Spalled	2600	2680	3320	3370	3250	3460	3320	3560	Began spalling at about 35 cycles. Considerably spalled a 40 cycles.
11	3470	2560	Spalled	Spalled	3660	3170	3580	3930	4220	3940	4340	4170	Severe spalling from about 35 to 50 cycles.
12	3610	3130	3600	3490	3410	3360	3820	4130	4120	4020	4380	4940	No spalling up to 80 cycles.
Avg	2880	2970	2560	---------	3110	3100	3530	3900	3700	3790	4060	4190	

[a] Only 1 specimen tested—others too badly spalled.

It has been assumed that this type of cement is characterized by a strength at early ages indicative of its name, but not by good gains with age. If the concrete is stored in a humidity that permits hardening without drying, there is considerable gain in strength with age.

In the majority of cases specimens stored in the air of the laboratory at 70°±3° F had nearly the same strengths at 7 days as those stored in the damp room. The air-stored specimens gain relatively little with age after 28 days because of the lack of water.

The average compressive strengths of the concrete test specimens stores outdoors for 1 year under natural conditions of temperature, humidity, and precipitation were but little different from those of specimens stored in the damp room for the same length of time, with the exception of those made with a C/W ratio of 1.73, and stored at 70° F for the first 24 hours (table 7). The specimens stored outdoors for 1 year gave strengths distinctly higher than those stored in the air of the laboratory.

The specimens subjected to freezing and thawing were given 300 freezings at 0 to 20° F, alternated with thawings in water at 50 to 80° F. While it was originally hoped that the 300 cycles of freezing and thawing would require about a year and therefore data obtained would be directly comparable with the 1 -year tests of specimens in other storages, interruption because of the necessary periodic defrosting of the freezing room extended the time required to carry out these tests about 3 months. The treatment, as shown in tables 6 and 7, did not markedly reduce the strength of any of the concrete below that of specimens stored damp. In fact, of the specimens thermally insulated during the first 24 hours, those frozen and thawed had slightly greater strengths than those stored in the damp room.

It had been noted in other studies that a drying out of the concrete, even if carried out below the boiling point of water, between the freezing and thawing cycles, tended to materially increase the severity of so-called freezing tests. In some cases, freezing tests showed that although a temperature of 10° to 15° F below freezing was attained, no typical freezing curve was obtained. There was no indication through a rise of temperature that later the supercooled water froze. But this phenomenon was not always noted; in general, a typical freezing curve was indicated. The reason for this is not certain. Also it should be remembered that water with considerable amounts of salts in solution, as in concrete, seldom freezes to a solid mass, but tends to freeze more as slush of small ice crystals in the salt solution. However, during a cycle of drying, the salts, especially the hydrated lime, would crystallize out of solution. When the concrete is reimmersed in water, the amount of these salts which would dissolve in the first 24 hours of soaking will probably be less than had crystallized during the drying. A freezing immediately following a drying and soaking would therefore be more characteristic of a true freezing of pure water with the development of large crystals.

From such reasoning, plus the additional fact that most structures submitted to the weather undergo drying as well as freezing, the drying cycles have been included in the freezing and thawing tests. Three- by six-inch cylindrical specimens were prepared, which were submitted only to drying and soaking, and these alternations carried out so that the number was equal to the number of dryings undergone by the freezing, thawing, drying, and soaking specimens. A third set of test pieces was stored continuously in the damp-room. Other work had shown that it is not necessary to carry out such tests to destruction, but that testing in compression from time to time would yield valuable data. Hence, in the present study, sets of concrete cylinders were tested at 15, 25, 50, and 100 cycles (each cycle requiring 1 week) of freezing, thawing, drying, and soaking. Damp-stored specimens were tested at the same ages.

The wide variations in results for different cements under the freezing, thawing, drying, and soaking treatment cannot be adequately explained by differences in composition or early strength, as can be seen from a comparison of tables 2, 6, and 8. Cements nos. 3 and 12 were among the few giving excellent results. Cement no. 3 has a high C_3S content, the lowest C_2S; cement no. 12 the highest C_2S and lowest C_3S content; the C_3A content of neither is high. Cement no. 6, one of the most resistant, had a very high C_3A content, namely, 15 percent.

Table 8 also shows that after cycles of drying and soaking the strengths are lower than those of specimens of the same age stored in the damp room. The difference in the average strength is approximately 600 lb/in.^{2} at the end of 15 weeks (15 cycles) and less at later ages. The specimens, after cycles of drying and soaking, have greater strengths than specimens subjected to the same number of cycles of freezing, thawing, drying, and soaking.

(c) EFFECT OF CEMENT-WATER RATIO

The data presented in table 7, showing the relation of C/W ratio to compressive strengths of concrete at two different ages, are plotted in figure 2. The strengths decrease with decrease in C/W ratio; and the relation is approximately linear. Concrete specimens made with a C/W ratio of 1.73 and stored at 110° F for the first 24 hours were badly honeycombed, and hence the values for these do not show a linear relationship; this concrete stiffened so rapidly that the specimens could not be properly placed. Approximate linear relationships as given in figure 2 hold also for specimens in other storages at other ages.

From the data of table 7 the increase in strength obtained by high initial storage temperature may be compared with that obtained by increasing the C/W ratio. Using the average strength of concrete specimens at 1 day with a C/W ratio of 1.73 stored at 70° F as a basis of comparison, the average strength of those with a C/W ratio of 1.50, but stored at 90°, was about 20-percent greater; those with a C/W ratio of 1.50 stored at 110° averaged about 55-percent greater; those with a C/W ratio of 1.50 stored in the insulated cabinet were of equal strength. After 1 day, however, the strengths were lower for the C/W ratio of 1.50 even when these specimens were initially stored at higher temperatures.

TABLE 9.—*Relation of observed to calculated compressive strength*

6- by 12-inch concrete cylinders: cement-water ratio=1.5, by weight

3-day strength calculated from equation: strength=40.9 C_3S+24.5 C_2S+22.9 C_3A–123.5 C_4AF.
28-day strength calculated from equation: strength=54.8 C_3S+66.7 C_2S+39.35 C_3A–117.4 C_4AF.
For derivation of equation see text.

$C_3S=3CaO.SiO_2$; $C_2S=2CaO.SiO_2$; $C_3A=3CaO.Al_2O_3$; $C_4AF=4CaO.Al_2O_3.Fe_2O_3$

Cement no.	3-day strength			28-day strength		
	Observed	Calculated	Deviation of calculated from observed in terms of observed	Observed	Calculated	Deviation of calculated from observed in terms of observed
	lb/in.^{2}	lb/in.^{2}	*Percent*	lb/in.^{2}	lb/in.^{2}	*Percent*
1	1880	1860	1.1	3240	3100	4.3
2	2200	2310	4.8	3620	3950	9.0
3	1590	2060	30.0	2520	3460	37.3
4	2360	2150	8.9	3720	3600	3.2
5	2200	2000	9.3	3840	3450	10.0
6	1750	1880	7.4	3650	3830	4.9
7	2330	2000	14.2	4300	3620	15.8
8	2090	2080	0.7	4100	3800	7.3
9	2590	2090	19.4	4930	3700	25.0
10	1770	1610	9.3	3500	3310	5.6
11	2120	1890	10.6	3770	3510	6.9
12	1680	1580	6.2	3990	3830	4.0

(d) EFFECT OF CEMENT COMPOSITIONS

Attempts have been made by several investigators [2] to develop equations that would express the contribution to the strength of the cement of each percent of the four major compounds (C_3S, C_2S, C_3A, and C_4AF) in the cement. A similar attempt was made in this investigation. The equations gave calculated strengths that agreed fairly well with the observed strengths for eight of the cements listed in table 2, but the coefficients as given in table 9 for the individual compounds were widely different from those found by others. Since all portland cements may contain the same four major compounds it is obvious that any equation of this type must be applicable over the whole range of portland-cement compositions to have any real significance. Apparently such variables as fineness, percent ignition loss, insoluble residue, etc., have such an important effect on strength that they cannot be left out of consideration in any such calculation.

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[2] Woods, Starke, and Steinour, Eng. News-Record **109**, 435 (Oct. 13, 1932); R. E. Davis and coworkers Proc. Am. Concrete Inst. **29**, 413 (1933); R. F. Blanks, Proc. Am. Concrete Inst. **30**, 9, (1934); H. F. Gonnerman, Proc. Am. Soc. Testing Materials **34**, part II, 244 (1934).

5. EXPANSION AND CONTRACTION

Table 10 presents some of the data on changes in length of the 6- by 12-inch concrete cylinders. Although measurements were made at several earlier ages, only those obtained at 1 year are given, since the former showed like changes of less magnitude.

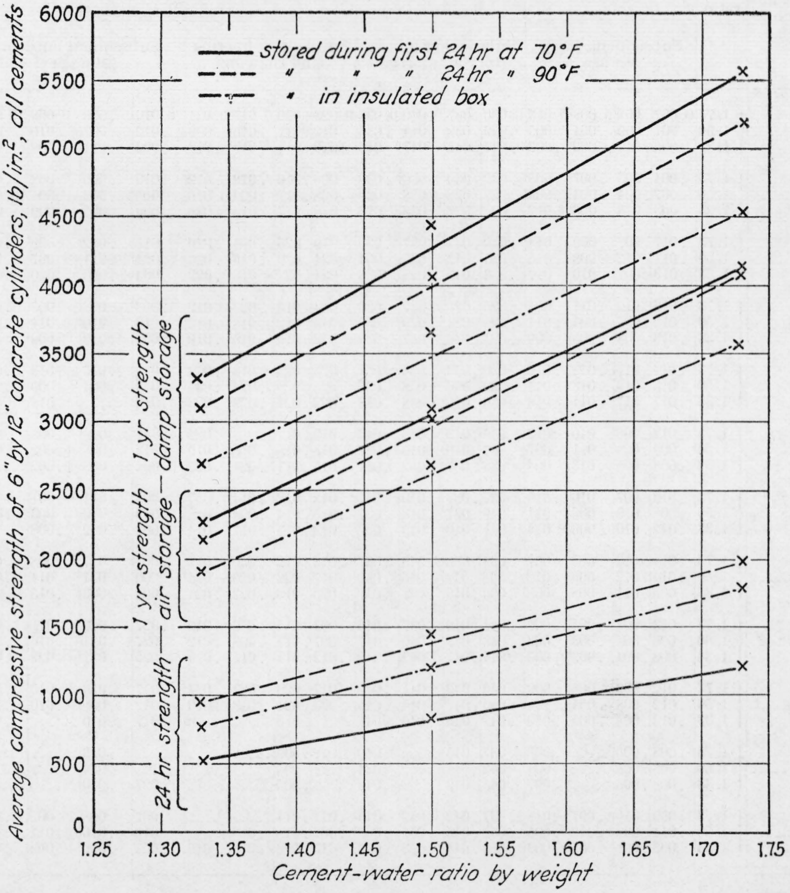

FIGURE 2.—*Relation between* C/W *ratio and average compressive strength of concrete.*

The specimens stored outdoors did not give consistent results. The conditions of temperature and humidity during early hardening or at periods immediately preceding a set of observations may have been markedly different for one set of specimens than for another, affecting the length of the various cylinders differently. Briefly, it can be said that there was a tendency for the concrete so stored to contract.

TABLE 10.—*Expansions or contractions of 6- by 12-inch concrete cylinders at one year*

[Expressed in percent of the length at 24 hours, measured at 70° F.]

Cement no.	C/W ratio	Storage during first 24 hr—															
		70°	90°	110°	Ins.	70°	90°	110°	Ins.	70°	90°	110°	Ins.	70°	90°	110°	Ins.
		Subsequent damp storage				Subsequent laboratory air storage				Subsequent freezing and thawing				Subsequent outdoor storage			
1	1.73	0.007	.008	0.008	0.013	0.030	.037	0.040	0.038	0.023	.020	0.017	0.031	0.010	.006	0.009	0.013
	1.50	.001	.009	.004	.005	.039	.038	.044	.035	.012	.011	.016	.009	.012	.007	.010	.009
	1.33	.006	.010	.002	.003	.044	.041	.047	.040	.012	.011	.019	.013	.022	.011	.009	.013
2	1.73	.004	.003	.007	.005	.032	.030	.030	.030	.008	.016	.012	.012	.010	.009	.003	.000
	1.50	.007	.004	.004	.003	.037	.028	.028	.029	.008	.017	.009	.016	.005	.003	+.001	+.002
	1.33	.003	.013	.006	.012	.031	.027	.033	.026	.018	.017	.015	.020	.009	.005	.009	.000
3	1.73	.017	.007	.009	.014	.040	.037	.037	.035	.019	.025	.014	.020	.015	.002	.009	.011
	1.50	.011	012	.008	.015	.035	.042	.037	.034	.024	.020	.015	.023	.004	.011	.007	.005
	1.33	.013	.007	.010	.017	.033	.040	.028	.038	.024	.022	.018	.022	.003	+.003	.020	.007
4	1.73	.018	.012	.011	.004	.025	.025	.027	.026	.013	.013	.023	.012	.003	.008	.003	.012
	1.50	.012	.007	.004	.011	.028	.034	.029	.035	.015	.012	.018	.012	.010	.010	.014	.008
	1.33	.013	.008	.003	.009	.027	.034	.037	.034	.012	.019	.015	.019	.007	.009	.009	.003
5	1.73	.014	.017	.013	.015	.030	.033	.034	.031	.023	.025	.018	.024	.017	.015	.013	.015
	1.50	.013	.016	.013	.017	.032	.030	.038	.032	.026	.029	.024	.034	.013	.004	.009	.010
	1.33	.017	.017	.011	.018	.030	.030	.038	.037	.022	.021	.022	.023	.012	------	.014	.007
6	1.73	.012	.006	.010	.013	.045	.043	.043	.040	.010	.017	-----	.022	.011	.006	.008	.013
	1.50	.009	.008	.011	.007	.047	.040	.049	.037	.013	.018	.018	.019	.013	.003	+.002	.014
	1.33	.008	.008	.013	.008	.038	.037	.052	.051	.015	.011	.024	.022	+.004	+.008	+.002	-----
7	1.73	.013	.007	.010	.010	.037	.037	.040	.042	.012	.012	.014	.017	.002	.011	.001	.007
	1.50	.008	.010	.008	.011	.040	.037	.043	.037	.015	.014	.004	.018	.009	.010	.003	.009
	1.33	.012	.010	.006	.014	.041	.040	.045	.036	.012	.017	.017	.014	.002	+.002	.000	.010
8	1.73	.014	.013	.005	.007	.034	.039	.043	.037	.013	.012	.030	.017	.007	.017	.008	.003
	1.50	.014	.012	.009	.012	.038	.044	.045	.040	.017	.022	.020	.014	.000	.011	.014	.010
	1.33	.009	.011	.008	.008	.039	.045	.051	.047	.023	.018	.022	.021	.008	.003	.015	.009
9	1.73	.013	.004	.005	.009	.044	.040	.037	.040	.003	.014	.010	.010	.027	.022	.011	.017
	1.50	.006	.004	.003	.003	.043	.047	.040	.047	.007	.011	.008	.012	.027	.021	.016	.022
	1.33	.003	.004	.003	.003	.044	.041	.043	.042	.012	.011	.015	.014	.025	.022	.022	.019
10	1.73	.012	.009	.006	.009	.040	.042	.041	.040	.017	.029	.023	.024	.017	.010	.013	.008
	1.50	.012	.008	.004	-----	.040	.047	.044	.045	.023	.021	.013	.019	.012	.008	.010	-----
	1.33	.012	.008	.005	.010	.042	.045	.046	.047	-----	.016	-----	-----	.017	.010	-----	.008
11	1.73	.003	.005	-----	.006	.037	.045	-----	.040	-----	.009	-----	-----	-----	.013	-----	-----
	1.50	.008	.005	-----	.004	.042	.044	-----	.035	-----	.005	-----	-----	-----	.014	-----	-----
	1.33	.008	.006	-----	.007	.045	.042	-----	.042	-----	.005	-----	-----	.027	.010	-----	-----
12	1.73	.009	.010	.007	.018	.037	.042	.047	.043	.011	.014	-----	-----	.007	.008	.007	.008
	1.50	.011	.008	.010	.005	.039	.045	.051	.048	.007	.018	.016	-----	.012	.010	.011	.002
	1.33	.005	.008	.004	.008	.053	.044	.053	.053	.015	.016	.013	.016	.007	.009	.009	.006

NOTES.—
Ins. = Thermally insulated for first 24 hours.
All specimens in damp storage expanded.
All specimens in laboratory air storage contracted.
All specimens subjected to freezing and thawing expanded.
All specimens stored outdoors contracted, except the few indicated by a + sign, which expanded.

Neither the differences in temperature of initial storage (during the first 24 hours) nor the differences in C/W ratio perceptibly affected the change in length; but the conditions of later storage had profound effects. The greatest change in length was the contraction during air storage. The expansion due to alternate freezing and thawing is larger, in general, than that resulting from storage in the damp room.

The changes of length of the 2- by 12-inch cylinders after various treatments are given in table 11 under five subheadings. Under subheading (1) there is given the contraction from the original length to the least dry length. In the case of ten cements this maximum

TABLE 11.—*Length changes (in percent) due to freezing, thawing, drying, and soaking*

(2- by 12-inch cylinders)

FTDS=Freezing and thawing, daily on 3 successive days, then drying at 150° F. for 3 days, then soaking 24 hours before freezing.
DS=Drying 3 days at 150° F. followed by soaking for 4 days.
All values except those under heading (1) are positive (expansion) unless negative (contraction) sign appears.
The figure in parentheses is the number of the cycle at which this contraction occurred.

Cement no.	(1)		(2)		(3)								(4)				(5)	
	Contraction from original length to least dry length		Expansion on soaking following cycle given under heading (1)		Change from original length, when dried after—								Expansion from original length caused by soaking, after drying at—				Expansion from original length in damp storage at—	
					10 cycles		25 cycles		50 cycles		100 cycles		10 cycles		100 cycles			
	FTDS specimens	DS specimens	FTDS	DS	FTDS	DS	FTDS	DS	FTDS	DS	FTDS	DS	FTDS	DS	FTDS	DS	10 weeks	100 weeks
1	(2) 0.050	(2) 0.059	0.024	0.029	−0.031	−0.051	−0.019	−0.029	Spalling	−0.026	Spalling	−.027	0.010	0.016	Spalling	0.003	0.012	0.012
2	(1) .036	(3) .042	.024	.022	−.028	−.033	−.012	−.017	Spalling	−.013	Spalling	−.007	.014	.017	Spalling	.005	.007	.007
3	(2) .031	(1) .034	.026	.020	−.021	−.034	−.017	−.022	−0.007	−.022	−0.002	−.028	.015	.018	0.007	.008	.008	.009
4	(2) .029	(2) .033	.027	.026	−.003	−.022	.006	−.008	Spalling	.000	Spalling	.007	.014	.020	Spalling	.005	.006	.008
5	(3) .042	(3) .042	.030	.024	−.032	−.030	−.012	−.014	.018	.000	Spalling	−.003	.021	.015	Spalling	.006	.005	.010
6	(1) .042	(1) .042	.034	.030	−.019	−.024	−.004	−.008	.015	−.007	.018	−.006	.020	.015	.009	.008	.010	.012
7	(1) .027	(2) .030	.026	.025	.007	−.002	.022	.012	Spalling	.013	Spalling	.017	.012	.010	Spalling	.005	.008	.011
8	(3) .037	(1) .037	.027	.030	−.021	−.024	−.012	−.013	Spalling	−.006	Spalling	−.003	.021	.017	Spalling	.005	.004	.004
9	(1) .035	(1) .039	.023	.028	−.021	−.032	Spalling	−.029	Spalling	−.025	Spalling	−.022	.018	.015	Spalling	.006	−.002	−.001
10	(2) .040	(2) .048	.026	.028	−.024	−.031	−.017	−.014	Spalling	−.001	Spalling	.003	.013	.020	.004	.006	.008	.009
11	(2) .037	(1) .044	.027	.029	−.025	−.031	.015	−.023	Spalling	−.012	Spalling	−.003	.019	.019	Spalling	.004	.007	.006
12	(1) .039	(2) .034	.028	.025	−.005	−.013	.013	−.002	.022	−.003	.025	−.001	.012	.014	.008	.006	.005	.008

contraction occurred either after the first or second drying and in the case of the other two cements after the third drying. Under subheading (2) there is given the percent expansion on soaking after the drying referred to. These data are given for the specimens subjected to freezing, thawing, drying, and soaking, and for those subjected to drying and soaking. In no case did the subsequent soaking bring the specimens back to their length before drying, though in two cases they returned very closely to the original length.

The change from the original length of the specimens dried after 10, 25, 50, and 100 cycles of each of the two treatments is given under subheading (3). It is evident that the contraction decreased as the number of cycles increased; in other words, the effect of the treatment was to cause the specimens to expand. For example, at 25 cycles, even in the dry condition, the specimens of four of the cements subjected to freezing, thawing, drying, and soaking, were longer than originally; one expanded sufficiently to start spalling. At 50 cycles specimens of only one cement were shorter than originally, and the others were either longer or had spalled. The magnitude of the expansion, however, cannot be taken as an indication of the tendency to spall. The changes in length produced by cycles of drying and soaking were in the same direction as those produced by freezing, thawing, drying, and soaking, but the magnitude of the former is much less than the latter.

The data under subheading (4) show the percent expansion during the first soaking after drying at 10 and 100 cycles. It is seen that the magnitude of the expansion due to soaking decreases with successive cycles. The effect of these treatments is that the specimen first contracts and then gradually expands until its final length is almost equal to or greater than its original length.

The changes in length at two different periods under continuous damp storage are given in table 11 for comparison. It is evident that changes in length are much less under this condition than under the cyclic treatments.

There does not appear to be any marked relation between the changes in length of these specimens and the chemical composition or physical properties of the cements from which they are made.

6. ADIABATIC STORAGE

The apparatus for the adiabatic storage was designed by C. H. Jumper and G. Kalousek. All of the tests for this storage were made by them, and their assistance is gratefully acknowledged.

The concrete mix for the adiabatically stored specimens was identical with that used in the other strength tests, but the specimens were made with only one C/W ratio, namely, 1.50. Only enough material was mixed at one time to fill a mold, which was then hermetically sealed. The pan, trowels, tamping rod, and gloves were weighed before and after the molding in order to determine the amount of mortar adhering to them. After separation of the constituents of this mortar by wet sieving, the weights of sand and cement were determined and the amounts of gravel, sand, cement, and water in the mold computed. Table 12 gives the weights and shows the actual change of the proportions from the nominal 1:2:4 mix, and also how the C/W ratio has changed from 1.50.

TABLE 12.—*Data obtained on concrete stored adiabatically*

Cement no.	Heat evolution (calories per gram of cement) after—								Cumulative weight loss (in grams) on drying after 90 days storage			Gain in weight (in grams) on soaking following drying			Concrete proportion in mold (by volume) [1]	Cement-water ratio (by weight) of concrete in cylinder [2]
									At 68° F for 24 hr	Additional storage time at 104° F						
	4 hr	8 hr	12 hr	1 day	3 days	7 days	28 days	87 days		48 hr	6 days	1-hr soaking	24-hr soaking	7-days soaking		
1	16	60	80	100	115	119	125	130	221	366	443	190	404	484	1:2.09:4.26	1.56
2	3	10	31	61	99	107	112	114	177	303	362	149	321	339	1:2.11:4.23	1.47
3	10	27	40	60	86	96	105	110	101	182	239	114	209	249	1:2.08:4.25	1.50
4	4	17	44	77	109	116	125	125	170	307	355	148	356	375	1:2.09:4.23	1.48
5	11	25	50	86	111	117	121	125	179	306	386	193	368	434	1:2.09:4.28	1.53
6	5	12	40	72	104	108	108	111	157	284	331	138	311	332	1:2.10:4.22	1.49
7	6	20	49	73	96	105	116	122	162	286	366	155	314	390	1:2.09:4.25	1.55
8	13	33	63	89	112	116	117	117	167	264	336	162	324	367	1:2.09:4.26	1.55
9	7	23	45	73	100	105	105	105	138	240	305	131	269	318	1:2.09:4.39	1.56
10	10	28	53	78	100	106	110	110	165	262	344	170	330	358	1:2.10:4.29	1.56
11	8	25	49	83	111	116	120	121	163	254	335	160	315	338	1:2.09:4.29	1.57
12	10	23	41	62	78	88	100	104	133	234	297	138	291	324	1:2.07:4.26	1.53

[1] Proportions as weighed out were 1:2:4 by volume.
[2] Cement-water ratio of the concrete as mixed was 1.50.

Twelve specimens for each cement were stored adiabatically at one time. After 87 days, 3 days were allowed for cooling. The molds were then removed from three cylinders, which were tested in compression. Three other cylinders were removed from the molds and weighed. Losses of water were then determined after storage at 68° F for 24 hours and then after storage at 104° F for 48 hours and for 6 days. The specimens were then placed in water, and the absorption determined after 1 hour, 24 hours, and 7 days. The specimens were then placed in the damp room and tested at 1 year. The other six cylinders of each cement were placed in the 70° F storage room; half of these were tested on unsealing at 1 year and the other half are being held sealed for later tests.

The loss of water during drying of the concrete after the adiabatic storage is of much interest. Taking cement no. 1, there was in the mold approximately 950 g of water. During the first 24 hours after the 90-day storage, the specimen lost about 220 g at a temperature of about 68° F. During the next 6 days at 104° F this loss was doubled. Hence, 440 of the original 950 g of water were lost at a temperature so low that it might be considered as void filling or free water. If it is assumed that the 500 g remaining is combined with the 1,472 g of cement present, then the cement has taken up about one-third of its dry weight in hardening under adiabatic storage. The loss of 440 g of water indicates the creating of 440 cc of voids or about 27 cu in. in 339 (volume of a 6- by 12-inch cylinder).

An attempt to correlate percentage losses of water in drying with the compound composition of the cements used in the concrete leads to contradictions that are apparently irreconcilable. For instance, cement no. 1, which had the greatest loss in water, contained a large amount of C_3S, while cement no. 3, with the greatest amount of C_3S, showed the least loss. Cement no. 9 also showed a small loss, although it contained a large amount of C_3S. There also appears to be no consistent relation between tricalcium-aluminate content and water loss.

The compressive strengths of the concrete specimens stored adiabatically are given in table 6. Since these were the only specimens tested at the age of 90 days, there can be no direct comparison at this age with specimens in other storage conditions. A comparison of the specimens stored in the damp room for 28 days with those adiabatically stored for 90 days shows that for 10 of the 12 cements the strength of the adiabatically stored specimens is less than those stored in the damp room. When the specimens stored adiabatically for 87 days were then stored sealed at 70° F until 9 months further had elapsed, the average gain in strength was slight and the values on the average were about 500 lb/in.² less than those obtained for a full year storage at 70° F in the damp room. The adiabatically stored specimens which were taken out of their sealed molds and placed in the damp room for a further 9 months, changed

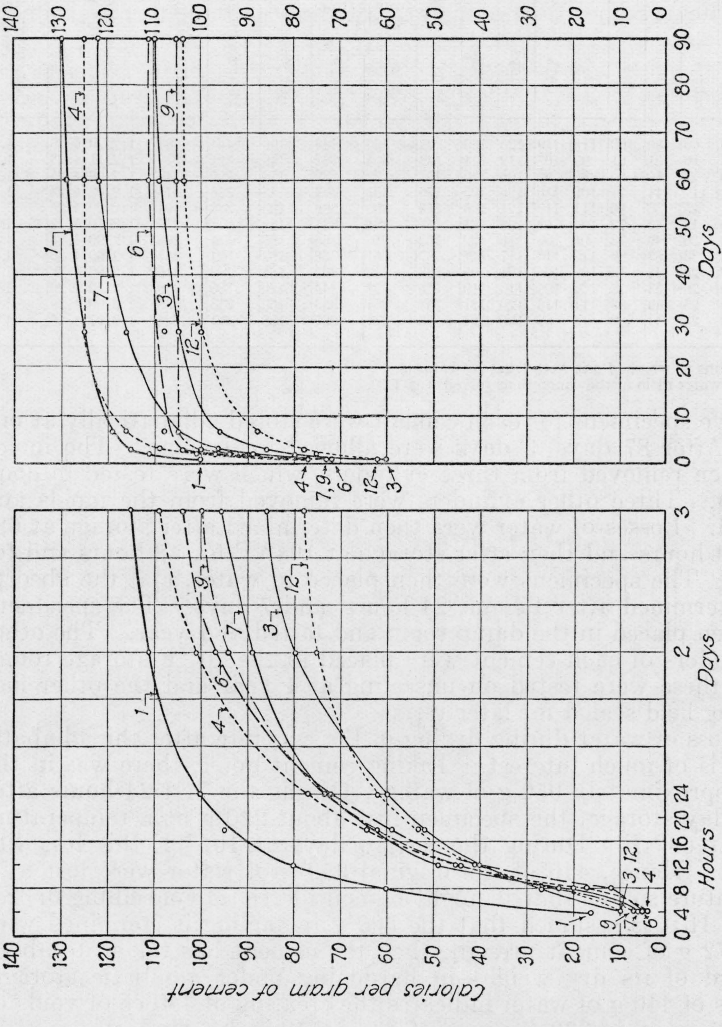

FIGURE 3.—*Heat evolved at different ages by some of the cements in adiabatically stored concrete.*

Numbers on graph refer to cement numbers.

but slightly, and the average strength was still less than that of the 1-year specimens stored in the damp room.

The number of cements used in this investigation was too small to enable the derivation of a satisfactory equation relating heat evolution with composition. The calculated values for some of these cements, using factors obtained by others, may be of interest. Taking the factors used by Woods [3] for calculating the heat evolution from the chemical composition, and assuming that the cements of this investigation were of equal fineness, it is found that cement no. 1 gives a calculated heat evolution at 90 days of 115 cal/g, whereas the observed heat in concrete in the adiabatic calorimeter was 130 cal/g (table 12). Similar differences between calculated and observed values were also found for the other cements. Cement no. 12, which is unusual for a high-early-strength cement in that it contains a large amount of C_2S relative to the amount of C_3S, has a calculated heat evolution of 81 cal/g and an observed heat of 104 cal/g. Cement no. 12 is also of interest because it is much finer than the others. This is perhaps one of the reasons that the observed heat is greater than the calculated. Cement no. 4 has a specific surface 270 cm^2/g greater than that of no. 5. These two cements have nearly the same compositions, and the same observed heats, viz, 125 cal/g. Their calculated heats were 104 and 110 cal/g, respectively. These cements were finer than those used in Woods' studies, which probably explains why the evolved heats were greater than those calculated from compound compositions.

A comparison of the evolved heat with the compressive strengths of concretes made with the same cements (table 6 and fig. 3) shows that it is not a general rule that at any age the cement which has developed the greatest heat will develop the greatest strength.

IV. SUMMARY

(1) Twelve commercial high-early-strength cements were studied in this investigation. The data obtained include the chemical and compound compositions; fineness measured by the turbidimeter and on the nos. 200, 325, and 450 sieves; weight per cubic foot; tensile, compressive, and transverse strengths of one or more kinds of mortars; compressive strength of 1:2:4 concrete of three C/W ratios stored at four different temperatures during the first 24 hours and different conditions of temperature or humidity thereafter; the effect of freezing, thawing, drying, and soaking upon concrete specimens; the length changes in concrete induced by different conditions of storage; the heat of hardening of concrete specimens; and the effect of adiabatic storage.

(2) The calculated compound compositions of the cements varied widely from one containing more dicalcium than tricalcium silicate to one with no dicalcium silicate. The percentage of tricalcium aluminate varied over a wide range.

(3) The amount of material retained by the no. 200 sieve is too small to have significance. Even when sieved wet with a sieve having such small openings as the no. 450, the amount retained was still

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[3] Woods, Steinour, and Starke, *Heat evolved by cement during hardening.* Eng. News-Record (Oct. 6 and 13, 1932, and April 6, 1933).

small, varying from 7.7 to 20.4 percent. The specific surface [4] as determined by the Wagner turbidimeter, ranged from 1,760 to 2,490 cm²/g.

(4) The standard mortar briquets of only three of the cements passed the present tentative ASTM requirement, at 24 hours, of 275 lb; seven met the 3-day requirements.

(5) Of the several kinds of mortars and mortar specimens studied, those which seemed to predict most satisfactorily the strength of concrete at all ages were the 2-inch 1:5-mortar cubes, and the 1½- by 1½- by 4-inch mortar prisms tested in compression.

(6) The proportions and grading of the aggregates used were such as to permit a C/W ratio approaching that used in practice, but avoiding what might be called a "sloppy" or too "wet" mix. Hence, at 24 hours the concrete strengths were relatively low—all under 1,500 lb/in.²—compared with strengths reported as being attained by such cements. The results show all the cements were of the true high-early-strength type and developed early strengths considerably greater than those attained by standard portland cements for corresponding mixes and C/W ratios.

(7) A linear relation was found to exist between the C/W ratio and the strength of the concrete, for any particular age or storage condition, except for some specimens which could not be properly molded.

(8) The weight per cubic foot of the cements varied from 63 to 80 pounds according to the degree of compaction used.

(9) Concrete cylinders stored at 90° F developed nearly double the 1-day strength of specimens stored at 70° F. Storage at 110° F still further increased the 1-day strength. At ages after 3 days the strengths were unaffected or somewhat decreased by the higher initial temperatures. Specimens stored adiabatically for 87 days and then in the damp room gave lower strengths at 1 year than specimens stored at 70° F in the damp room for 1 year.

(10) After the first 24 hours, damp storage gave the highest strengths. Specimens stored in laboratory air gained little or no strength after 28 days. Those stored outdoors had slightly lower strengths than those stored in the damp room.

(11) Three hundred cycles of freezing and thawing reduced the strengths of concrete cylinders of all C/W ratios and kinds of storage during the first 24 hours, on the average, about 10 percent below the 1-year strength of cylinders stored in the damp room at 70° F.

(12) Cycles of freezing, thawing, drying, and soaking produced pronounced effects on concrete cylinders. Less than 100 cycles caused spalling to the extent that compressive tests could not be made on specimens from six of the twelve cements. Specimens subjected to cycles of drying and soaking were lower in strength on the average than those stored in the damp room.

(13) Concrete cylinders in damp storage expanded from 0.001 to 0.018 percent in 1 year. Cylinders in air storage contracted from 0.025 to 0.053 percent in 1 year. Cylinders subjected to alternate freezing and thawing expanded from 0.003 to 0.031 percent in 1 year. Freezing, thawing, drying, and soaking of the 2- by 12-inch cylinders caused so much spalling that few data were obtained after the 25th cycle.

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[4] The fineness of 28 brands of high-early-strength cements of recent manufacture was determined by the turbidimeter and the specific surface was found to vary from 1,990 to 2,860 cm.²/g with an average value of 2,360.

(14) The total heat evolved at the end of 8 hours of adiabatic storage of concrete made with a C/W ratio of 1.5 and hermetically sealed, ranged from 10 to 60 cal/g of cement; at the end of 24 hours, from 60 to 100 cal/g, and at the end of 87 days from 104 to 130 cal/g. In general, the higher the tricalcium-silicate and tricalcium- aluminate content, the greater the amount of the heat developed.

(15) No satisfactory equation could be derived showing the relation between composition and heat evolution, strength, or linear changes of the cements.

(16) Specimens of concrete of all cements hermetically sealed and stored adiabatically for 87 days were all found to contain free water varying in amount from one-quarter to one-half of the original mixing water.

The authors desire to express their appreciation to P. H. Bates, who outlined the investigation and directed the work; and also to G. W. Walker, who initiated the concrete tests.

WASHINGTON, March 6, 1935