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EFFECT OF TEMPERATURE ON THE STRESS-DEFORMATION OF CONCRETE

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ABSTRACT

A number of important investigations have provided information relative to the elastic and plastic properties of concrete. In order to obtain additional information on these properties, a series of tests were made to determine the effect of change of temperatures within the range 26 to 123° F on the elastic and plastic deformations of portland cement concrete when subjected to sustained compressive stress. Tests were made on concretes of two greatly different strengths and under three conditions of moisture content. The specimens were subjected to sustained compressive stress for periods of 3 days, deformation readings being taken both immediately before and after loading, at intervals during the 3-day period of loading, immediately after unloading, and thereafter at intervals during the 3-day period following unloading. For all tests the applied stress was held at an estimated 20 percent of the strength of the specimens. Characteristic trends of the elastic and plastic behavior of the concretes were determined.

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I. INTRODUCTION

Several important investigations [1] have provided information on the elastic and plastic properties of hardened portland cement concretes. In order to determine the effect of temperature on these properties, the tests described in this paper were undertaken. Two concretes, differing greatly in strength, were subjected for 3 days to sustained compressive stresses estimated at approximately 20 percent of their ultimate strength. During the period while under load, and for a period of 3 days following the release of load, deformation readings were taken at regular time intervals. The specimens were maintained during a test at a constant temperature within the range 26 to 123° F, and in one of three moisture conditions, namely, saturated, partially dry, or oven dry.

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[1] See, for example, R. E. Davis, et al., *Plastic flow of concrete under sustained stress,* Proc. Am. Soc. Testing Materials **34** II, 354 (1934); W. H. Glanville, *The creep or flow of concrete under load,* Tech. Pap. 12, British Building Research Board (London), and bibliographies in Proc. Am. Soc. Testing Materials **30** I, 635 and 661 (1930), and **28** II, 337 (1928).

II. APPARATUS

Details of the loading apparatus,[2] as well as the method of mounting the gages and of sealing the concrete cylinders in rubber tubing to reduce, as far as possible, changes in moisture content, are illustrated in figure 1.

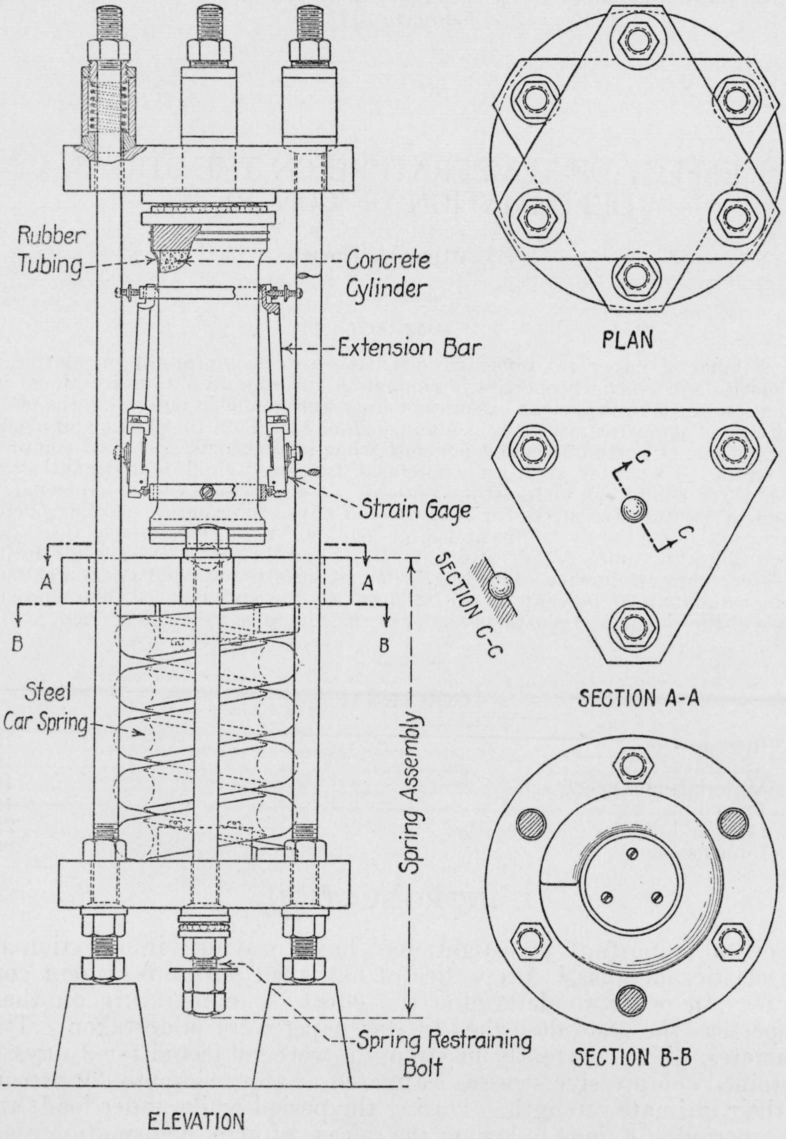

FIGURE 1.—*Loading apparatus assembled for test with specimen in place and gages mounted.*

The spring assemblies were calibrated in a beam type of testing machine. The relation between load and length of spring was first

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[2] The loading apparatus was designed by Dr. S. Springer, of Budapest, Hungary, while at the National Bureau of Standards.

determined in a series of preliminary tests. This relation was also determined before and after each test. The data obtained indicated that the spring loads as applied to the concrete cylinders could be determined to within an accuracy of 0.5 percent.

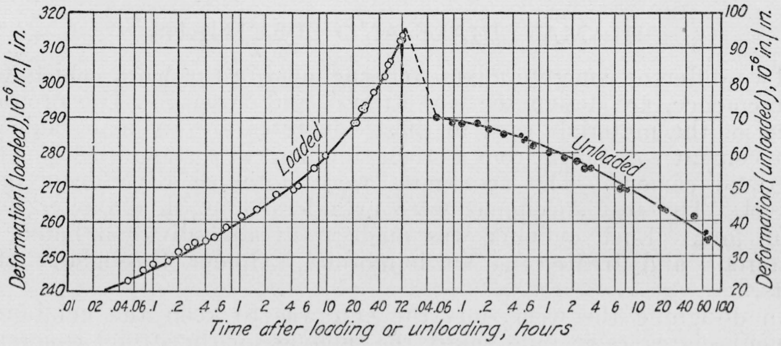

FIGURE 2.—*Time-deformation relation for cylinder 2W (strong saturated concrete) representing a complete loading and unloading cycle.*

This graph was plotted through points taken from the original test data. The zero deformation point is the gage reading immediately before the application of load.

Deformations of the concrete cylinders were measured by means of Tuckerman optical strain gages and autocollimator.[3]

The fixed ends of the gages rested on small aluminum plates placed directly against the cylinder. The other ends of the gages rested on a collar fixed to the cylinder by means of three setscrews bearing against small aluminum plates. These gages may be read directly to 2×10^{-6} in./in. in a 2-in. gage length. This degree of accuracy could not be obtained, however, in the tests owing to small rapid fluctuations in the temperature of the surrounding air with the

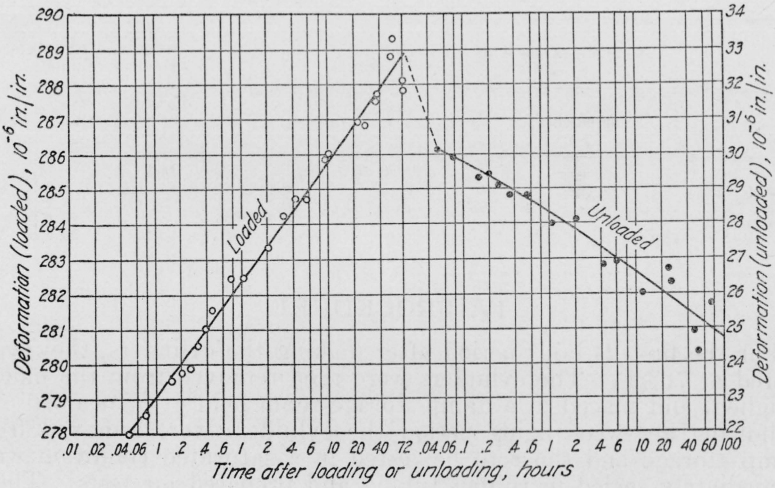

FIGURE 3.—*Time-deformation relation for cylinder 7D (strong dry concrete) representing a complete loading and unloading cycle.*

This graph was plotted through points taken from the original test data. The zero deformation point is the gage reading immediately before the application of load.

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[3] For a description of these gages see Proc. Am. Soc. Testing Materials **23**, II, 602 (1923).

resulting effect of varying the lengths of the gages almost instantaneously and the concrete scarcely at all. The accuracy of a single reading is very near to $\pm 5 \times 10^{-6}$ in./in. The accuracy of the observations may be judged by the two curves, figures 2 and 3.

III. MATERIALS AND SPECIMENS

Two different concrete mixes were included in this work, which, for convenience, are designated as "strong" and "weak." The proportions of the materials used in these concretes are given in table 1. The cement was taken from a stock shipment of a standard brand of portland cement. The aggregates were Potomac River sand and gravel. The test specimens were cylinders 3 in. in diameter and 8 in. long. Each cylinder was made from an individual batch of materials and treated as an individual cylinder throughout the tests.

In designing the weak mix the aim was to keep the combined cement-aggregate grading nearly the same as for the strong concrete, a decrease in strength being secured by replacing a certain amount of the cement by aggregate while still retaining the desirable workability and uniformity in finished product.

The concretes were mixed by hand for a period of 4 minutes, and were placed in the molds in four layers, each layer being rodded 50 times. The molds were designed to be practically watertight to keep evaporation losses to a minimum.

TABLE 1.—*Concrete and aggregate*

Concrete proportions (by weight)			Grading of combined cement and aggregate (by absolute volume)		
Ingredients	Strong	Weak	Passed sieve no.—	Strong	Weak
			Inch		
Cement	1.00	1.00	3/8	100.0	100.0
Water	.40	.80	4	73.2	75.6
Aggregate	3.00	6.37	8	62.5	62.0
			16	53.5	53.0
			50	32.1	30.3

IV. PROCEDURE

For the first 24-hour period after making the cylinders, they were stored at 70° F. The cylinders were then removed from the molds, weighed, and placed in a damp-storage room held at or near 70° F.[4] Following a 4-week aging period the cylinders were removed from damp storage and those to be tested in a saturated condition were immediately sealed in rubber tubing and prepared for tests. Those to be tested dry were placed for a period of 1 week in an oven held at 230° F, before being sealed for test; and those to be tested in a semidry condition were placed in an oven held at 104° F until their loss of moisture fell within the ranges 22 to 37 and 50 to 70 percent, respectively, of the loss of the strong and weak cylinders dried at 230° F before being sealed for test. The cylinders dried at 230° F are designated hereafter as "dry", and those dried at 104° F as "semidry." All data pertaining to moisture losses and gains are included in table 2.

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[4] Temperatures 8 to 10° F below normal were recorded in the damp-storage room for nearly a week each, on two occasions. A part of the variation in the strength of certain of the test cylinders is believed to be caused by this difference in storage temperature.

TABLE 2.—*Percentage weight loss or gain in moisture during the time the test specimens were being cured, dried, and under test*

[All values for gain or loss are percentages of water content at start of exposure]

Wet			Dry				Semidry			
Cylinder no.	Gain in weight during 4 weeks of curing	Loss in weight during test	Cylinder no.	Gain in weight during 4 weeks of curing	Loss in weight on drying 1 week at 230° F	Gain in weight during test	Cylinder no.	Gain in weight during 4 weeks of curing	Loss in weight on drying at 104° F	Gain in weight during test
STRONG CONCRETE										
1W	−1.7	1.0	*7D*	7.3	66.3	2.0	*15SD*	5.6	22.6	−0.9
2W	−2.0	1.0	*8D*	7.3	66.8	1.4	*16SD*	7.8	19.9	−.8
3W	.5	4.9	*9D*	4.1	65.6	7.5	*17SD*	8.3	15.3	.5
4W	.5	4.9	*10D*	2.4	64.7	6.5	*18SD*	8.3	15.5	.0
5W	4.6	1.2	*11D*	5.4	67.1	.0	*19SD*	4.6	23.8	.0
6W	4.4	1.2	*12D*	6.8	69.4	.7	*20SD*	5.1	23.9	.6
--------	--------	--------	*13D*	5.4	64.8	.0	*21SD*	6.3	14.9	−.8
--------	--------	--------	*14D*	6.8	70.3	--------	*22SD*	6.8	16.5	−.5
--------	--------	--------	--------	--------	--------	--------	*23SD*	6.8	15.7	−.5
WEAK CONCRETE										
24W	7.0	0.7	*34D*	3.0	77.7	2.0	*44SD*	6.5	43.5	−1.5
25W	6.7	.7	*35D*	3.7	78.0	1.0	*45SD*	6.5	41.5	−.7
26W	6.7	.0	*36D*	.0	74.4	3.6	*46SD*	6.3	51.6	−.9
27W	7.0	.4	*37D*	.0	80.0	8.1	*47SD*	6.5	49.3	.0
28W	−2.3	5.0	*38D*	6.1	77.4	1.0	*48SD*	4.4	43.8	−.8
29W	−2.6	4.8	*39D*	6.3	76.1	1.8	--------	--------	--------	--------
30W	.0	.0	*40D*	5.4	74.6	2.6	--------	--------	--------	--------
31W	.9	.0	*41D*	5.6	72.9	1.6	--------	--------	--------	--------
32W	7.7	5.2	*42D*	.7	84.0	4.4	--------	--------	--------	--------
33W	6.7	5.0	*43D*	1.6	82.8	9.3	--------	--------	--------	--------

The cylinders were subjected to a sustained compressive stress for a period of 3 days; deformation readings were taken both immediately before and after loading the cylinders, at intervals through the 3-day period of loading, immediately after unloading, and thereafter for a period of 3 days. The method of applying the sustained stress to the cylinders was as follows: For each test the springs were first compressed in the testing machine under a load corresponding to that desired for a particular test. The spring was then secured between the two end plates by means of three restraining bolts. After the cylinder had been placed above the spring, as shown in figure 1, the spring load was transferred from the restraining bolts to the cylinder.

During the 6-day period while under test and for at least 1 day previous to the commencement of the test, the cylinders were kept at as nearly a uniform temperature and moisture content as possible. Variations in the moisture content during the tests are given in table 2, and variations in temperature during the test are given as maximum deviations in table 3. Uniform temperature of concrete during the tests was obtained by resort to constant-temperature rooms and uniform moisture content by means of sealing the concrete specimens in rubber bags (fig. 1).

In order to obtain a measure of the deformations caused by temperature and shrinkage changes, deformation readings were always taken on an unloaded cylinder at the same time that readings were taken on the loaded cylinders. The magnitude of the deformations occurring on the unloaded cylinders and applied as a correction to the data for the loaded cylinder averaged about 5×10^{-6} in./in., with 12×10^{-6} in./in. as a rather extreme value. Differential effects between the steel gages and concrete specimens with relatively rapid temperature changes usually constituted a major portion of these changes.

TABLE 3.—*Deformation values at six successive intervals after loading and unloading*

W, specimens tested as taken from damp storage.
D, specimens dried at 230° F.
SD, specimens dried at 104° F.

Cylinder no.	Compressive strength at 42 days f_c	Stress σ	Ratio, stress to strength σ/f_c	Temperature		Total deformations in 10^{-6} in./in. at time, t, after												Residual deformation
				Average T	Maximum deviation R	Loaded (total deformation)						Unloaded (recovery)						
						0.05 hr	0.2 hr	1 hr	6 hr	24 hr	72 hr	0.05 hr	0.2 hr	1 hr	6 hr	24 hr	72 hr	
STRONG CONCRETE																		
	lb/in²	lb/in²		° F	° F													
1W	6,040	1,125	0.1862	72	1.6	253	259	269	290	306	318	246	252	257	270	279	285	33
2W	6,080	1,128	.1856			243	250	260	273	290	312	242	247	252	263	272	279	33
3W	6,610	1,124	.1700	125	1.4	255	267	278	305	345	377	203	205	208	220	241	265	112
4W[a]	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
5W	5,880	1,123	.1910	43	1.8	242	248	256	271	281	288	237	240	247	256	260	264	24
6W	5,870	1,120	.1909			245	251	259	275	283	291	240	243	250	259	264	267	24
7D	6,970	1,128	.1618	73	1.4	278	280	282	285	287	289	259	260	261	262	263	264	25
8D	6,380	1,128	.1767			304	306	310	314	316	317	299	300	302	303	303	303	14
9D	6,530	1,128	.1726	123	1.4	310	318	323	328	329	332	310	311	314	316	317	319	13
10D	6,300	1,128	.1790			318	328	334	336	337	339	324	325	330	333	334	235	4
11D	5,830	1,128	.1935	49	2.9	325	329	331	334	336	337	310	312	313	315	317	319	18
12D	5,770	1,124	.1948			317	320	322	325	327	328	292	294	295	297	298	299	29
13D	6,390	1,125	.1761	40	4.5	310	313	317	320	322	323	293	294	296	297	298	299	24
14D	6,730	1,128	.1675			308	310	314	317	320	321	289	290	291	293	294	295	26
15SD	7,090	1,130	.1594	104.5	1.8	285	293	308	330	364	399	252	257	266	276	287	298	101
16SD	7,050	1,125	.1596			288	296	310	333	366	402	256	260	268	278	290	301	101
17SD	6,990	1,128	.1614	58.5	1.5	290	297	305	318	334	354	262	267	273	280	286	291	63
18SD	7,090	1,124	.1586			292	300	308	322	338	357	264	268	274	281	288	295	62
19SD	7,120	1,128	.1584	102	4.5	311	321	330	354	384	421	266	274	280	292	302	313	108
20SD	7,050	1,122	.1591			299	311	320	344	372	408	265	272	277	288	299	310	98
21SD	7,140	1,130	.1583	86.5	.5	278	290	303	324	351	381	242	248	254	263	274	284	97
22SD	7,780	1,130	.1452	40.5	1.0	266	273	280	294	310	329	244	249	254	261	267	273	56
23SD	7,470	1,130	.1513			252	259	264	276	291	307	234	239	243	250	256	262	45
WEAK CONCRETE																		
24W	2,650	432	0.1630	72	1.3	118	121	126	135	142	148	115	117	120	126	130	134	14
25W	2,740	435	.1587			119	122	128	137	144	150	114	115	118	124	128	132	18
26W	2,520	592	.2350	72	1.9	168	173	179	192	202	210	162	164	170	179	183	186	24
27W	2,650	589	.2222			164	168	174	188	198	206	159	162	167	175	180	183	23
28W	3,040	591	.1945	122	2.2	167	178	190	227	256	280	---	170	171	---	---	198	82
29W	3,080	592	.1922			172	184	199	236	264	287	---	182	184	---	---	214	73
30W	2,370	591	.2494	56	5.2	164	169	176	190	200	207	150	161	166	173	179	182	25
31W	2,560	580	.2266			156	160	167	180	188	195	153	156	160	167	172	175	20
32W	2,630	592	.2250	96	1.8	178	186	197	213	232	255	168	172	179	187	197	204	51
33W	2,620	590	.2253			180	188	198	215	234	262	185	190	195	204	213	220	42
34D	2,850	584	.2050	72	1.1	242	243	246	250	252	253	214	216	218	221	222	223	30
35D	2,850	591	.2074			233	236	240	244	246	247	209	210	212	215	216	218	29
36D	2,920	582	.1994	122	1.8	216	218	226	230	231	232	201	203	207	210	211	212	20
37D	2,720	591	.2172			248	250	255	259	261	262	228	229	231	235	237	238	24
38D	2,740	590	.2153	26	6.0	222	224	226	230	232	234	198	199	201	204	205	205	29
39D	2,700	592	.2193			225	228	231	234	237	238	207	208	210	212	213	214	24
40D	2,420	587	.2427	41	2.0	256	257	260	264	266	268	223	224	227	230	231	232	36
41D	2,760	590	.2138			236	237	240	244	246	248	206	208	212	214	215	216	32
42D	2,550	594	.2330	95	2.6	259	263	266	270	273	276	235	237	238	240	242	244	32
43D	2,630	590	.2243			250	253	256	259	261	264	214	216	218	220	221	222	42
44SD	3,110	590	.1898	105	2.7	193	199	212	233	261	297	184	190	196	205	215	226	71
45SD	3,230	592	.1833			181	188	201	223	254	293	169	172	178	186	198	206	87
46SD	2,910	590	.2027	44	.8	197	200	202	206	209	212	180	181	183	184	186	188	24
47SD	3,090	590	.1910			188	190	193	195	197	199	174	175	177	179	181	182	17
48SD	3,090	590	.1910	86	.5	184	193	200	217	240	270	168	174	178	184	191	198	72

[a] Bag broken during test.

After completion of the load-deformation test the cylinders were stored in a sealed condition at a temperature of 70° F until tested for compressive strength at the age of 6 weeks.

V. DATA AND DISCUSSION OF RESULTS

Data on the compressive strength of the cylinders, stress and temperature of the concrete during the load tests, and deformation values of the specimens at six successive intervals of time after loading and unloading are given in table 3. All deformation values given in this table, excepting the deformation value at the 0.05-hour interval, have been taken from smooth curves drawn through points plotted from the original test data (corrected for shrinkage and temperature changes, as indicated by the readings on the unloaded cylinder). The original test data usually included 20 or more time-deformation observations. Two representative curves of this type, plotted with semilogarithmic coordinates, are included as figures 2 and 3. The values for the deformations under load given in table 3 were taken directly from such curves; those for deformations after unloading are the differences between the total deformations immediately before unloading and the residuals shown by the curves. The data of the table give, therefore, the compressive deformations at various periods after loading and the amounts of the recoveries at the same periods after unloading.

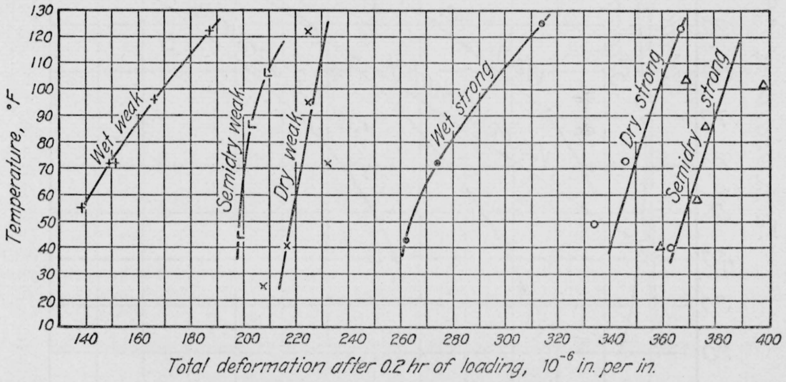

FIGURE 4.—*Relation between the total deformation at 0.2 hour after the application of load and the temperature of the concrete.*

Plotted points represent the average of the adjusted observations made on two cylinders tested simultaneously. The adjustment was made by multiplying the deformations by the factor $\frac{0.2 f_c}{\sigma}$.

The temperature-deformation relations for three arbitrarily defined deformations are represented in figures 4, 5, and 6. The three deformations represented are as follows: The instantaneous deformation or that part of the total deformation which occurs within 0.2 hour after application of load (fig. 4); the time deformation or that part of the total deformation that occurs in the interval 0.2 to 72 hours of sustained loading (fig. 5); and finally, the residual deformation, which is the total deformation that occurs after 72 hours of sustained loading minus the recovery that has taken place within 72 hours after release of load (fig. 6). The plotted points in these three figures represent the adjusted averages for the observations made on two cylinders tested simultaneously. The adjustment was made on the assumption that for small differences in strength, the deformation value will be proportional to the ratio of stress to strength, and for the tests considered, is an estimate of the deformation which would have occurred if the stress upon loading had been 0.2 of the compressive strength of the concrete.

The data of table 3 and figure 4 for deformations at 0.2 hour show that the instantaneous deformations for the wet concrete were less than for dry or semidry concrete and that they increased with an increase in temperature. These deformations were greater for the dry cylinders than for the semidry ones of weak concrete, whereas they were greater for the semidry than for the dry cylinders of strong concrete. However, as the time-deformation graphs showed that the rate of compression under constant load was much greater (except at the lowest temperatures used) for the semidry than for the dry concrete, it is possible that the deformations at the instant of loading for the dry strong concrete (except at the lowest temperatures) were as large as for the semidry concrete. They show also that the instantaneous deformations were larger for the strong than for the weak concretes when the compressive stresses were equal to 0.2 of the compressive strength.

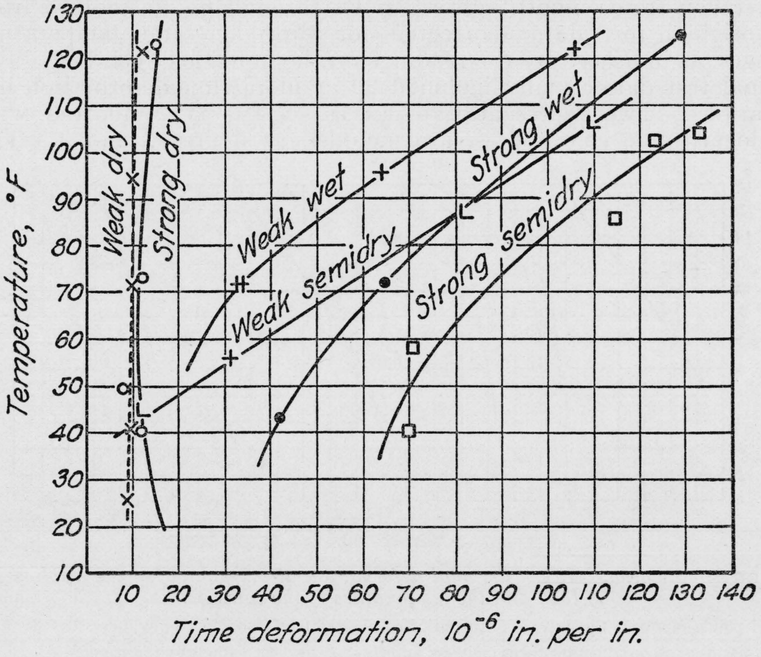

FIGURE 5.—*Relation between time deformation and temperature of concrete.*

The time deformation is that part of the total deformation occurring between 0.2 and 72 hours after the application of the test load. The plotted points represent the average of the adjusted observations made on two cylinders tested simultaneously. The adjustment was made by multiplying the deformations by the factor $\frac{0.2f_c}{\sigma}$.

As shown by figure 5, the time deformation of the oven-dried concretes was small and did not differ significantly at the various temperatures, whereas the time deformation of the wet and semidry concretes was greater the greater the temperature of the concrete, and was greater for the strong than for the weak concrete.

The relation between the residual deformation and the test temperatures for the two concretes under three conditions of moisture content are shown in figure 6. For both concretes when dry the residual deformations are small and very nearly independent of the test temperatures. In the semidry and saturated conditions the residual deformations for both concretes increase rapidly when tested at successively higher temperatures, and was greater for the strong than for the weak concrete.

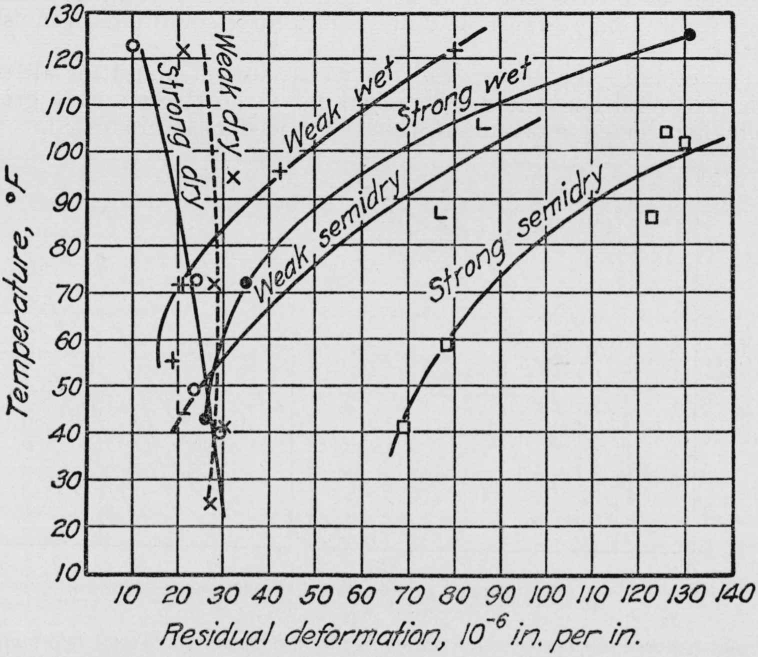

FIGURE 6.—*Relation between the residual deformation and the temperature of the concrete.*

The residual deformation is the total deformation occurring after 72 hours of sustained loading minus the recovery that has taken place within 72 hours after the release of load. The plotted points represent the average of the adjusted observations made on two cylinders tested simultaneously. The adjustment was made by multiplying the deformations by the factor $\frac{0.2\,f_c}{\sigma}$.

The magnitude of the residual deformations of the wet and the semidry concretes appeared to be related to the total deformation at 72 hours after loading. This is indicated by the data of figure 7, which show also that the ratio of residual deformation to the total deformation increased with an increase of temperature, but was approximately the same for the weak as for the strong concretes when each was stressed to a value equal to 0.2 the compressive strength.

Neither the deformations under load nor the recoveries after unloading showed a consistent relation with the moisture content of the concrete. As noted previously, the total deformation, the time deformation, and the residual deformation were larger for the semidry than for the wet concretes, but for the dry concretes they were not consistently larger or smaller than for either of the others. The exposure of the dry concrete to a temperature of 230° F for 1 week may have caused changes which would not have occurred in concretes dried at a lower temperature.

VI. CONCLUSIONS

The following conclusions are drawn only with reference to the two concretes of greatly different strength which were tested over the temperature range 26 to 123° F and under three conditions of moisture content.

(1) For both the strong and the weak concretes and for all three moisture conditions the deformations for given stresses were greater the higher the temperatures at which the specimens were tested.

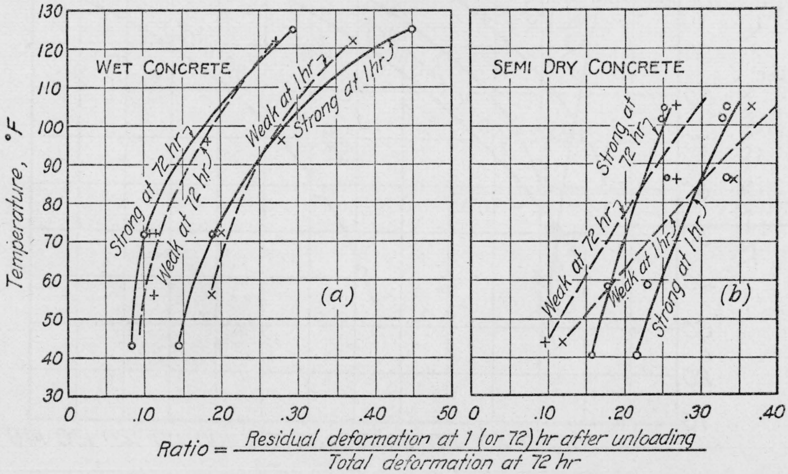

FIGURE 7.—*Relations between the ratio of residual deformation to total deformation at 72 hours, and the temperature of the concrete.*

The plotted points and curves show the values for the ratios of residual deformations (both at 1 and 72 hours after release of load) to the total deformation at 72 hours.

(2) For both concretes, when in a saturated or semidry condition, the time deformations as well as the residual deformations were greater the higher the temperature of the concrete.

(3) For both concretes in an oven-dry condition, the time deformation was relatively small and practically the same at all test temperatures.

(4) For both concretes in the dry condition, the residual deformations were small and very nearly independent of the temperature of the concrete.

(5) The instantaneous deformations of the wet concretes were less than those of the dry or semidry concretes.

(6) For the constant ratio of stress to strength of concrete, the deformations and recoveries at all periods after loading were greater for the strong than for the weak concrete when saturated or semidry; when dry, the instantaneous deformation on loading and that upon unloading likewise were greater for the strong concrete but the time deformations, recoveries, and residuals were nearly equal.

WASHINGTON, December 18, 1936.