Effects of Curing and Moisture Distribution on Measured Strength of Concrete

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Flexural strength tests are being used to an increasing extent as a basis for specifying concrete quality and determining its acceptability. As a consequence, there is need for re-examining the many factors which affect the test results. One of the most critical of these is curing, not only as it affects the hydration of the cement but also through its influence on stresses induced within the specimen by non-uniform distribution of moisture. This report covers investigations made at the Joint Research Laboratory of the National Sand and Gravel Association and the National Ready Mixed Concrete Association at the University of Maryland.

The study was conducted in several parts involving 384 tests for flexural strength. The principal divisions of the work were as follows:

A. Age-strength relationships for different curing conditions. Two coarse aggregates were used in air-entraining concretes of 3 cement factors. For each of the 6 conditions, specimens were made for flexural strength tests in triplicate at ages of 14, 28, 91 and 364 days for 4 curing conditions as follows: (I) continuously in the moist room; (II) continuously in saturated limewater; (III) 7 days in moist room followed by storage in room air until test; and (IV) 7 days in moist room followed by storage in room air until immersion in water 2 days before test.

B. Study of effect of resaturation on measured flexural strength of dry concrete. Air-entraining concrete with 6 sacks of cement per cubic yard was made with the 2 coarse aggregates. For each aggregate, 2 batches of 4 beams each, made on different days, provided tests in duplicate for all curing conditions. All specimens were cured in the standard moist room for 14 days, dried for 77 days at 100 F and then tested for flexural strength after various periods of soaking, as follows: none; 30 minutes; 1, 2, 4, 8, 16 and 32 days.

C. Study of effect of drying on measured flexural strength of moist-cured concrete. For the same classes of concrete as in Part B, tests were made on specimens continuously moist-cured for 91 days and then air-dried at 100 F for various periods before test, as follows: none; 30 minutes; 1, 2, 4, 8, 16 and 32 days. For each test condition, strengths were secured from 4 batches of concrete mixed on different days.

The data demonstrate the importance of moisture distribution and adequacy of curing to the reliability of tests for flexural strength of concrete.

• FLEXURAL strength is a principal factor in designing concrete highways and airport runways. Tests for flexural strength have long been used as criteria for determining when pavements have attained sufficient strength to permit their being subjected to traffic. More recently, flexural strength tests have been used as a basis for acceptance of the concrete itself.

The latter use of the test has increased the need for knowledge of the factors which influence measured flexural strength. When rejection, and even in some cases replacement, of a concrete slab may hinge upon the results of a few beam tests, it is essential that those tests accurately reflect the quality of the concrete.

It is evident also, from a review of the literature, that too little is known concerning the degree to which the modulus of rupture measured under the highly standardized conditions used for acceptance tests relates to the probable load-carrying capacity of the slab. Kellerman[1] found that measured flexural strength of moist-cured specimens was greatly reduced, in some cases by as much as 60 percent, when partial drying of the exterior was permitted. On the other hand, Woolf[2] found that thorough drying resulted in a marked increase in flexural strength over similarly cured specimens tested moist. He also demonstrated that temperature has an important bearing, the flexural strength being reduced as temperature increased.

These demonstrations of the great dependence of flexural strength on minor variations in moisture and curing conditions indicated the need for further research in this field. This paper describes such an investigation, conducted at the Research Laboratory sponsored jointly by the National Sand and Gravel Association and the National Ready Mixed Concrete Association at the University of Maryland. It constituted one phase of an over-all study of problems related to flexural strength, one portion of which has already been published[3] and other portions of which are under way.

[1] "Tests of Concrete Containing Waylite" by W. F. Kellerman, *Public Roads* Magazine, Vol. 24, No. 9, p. 244 (1946).

[2] "Effect of Temperature and Moisture Content on the Flexural Strength of Portland Cement Mortar" by D. O. Woolf, *Public Roads* Magazine, Vol. 15, No. 10, p. 248 (1934).

[3] "Studies of Flexural Strength of Concrete, Part 1, Effects of Different Gravels and Cements" by Stanton Walker and Delmar L. Bloem, Joint Research Laboratory Publication No. 3, National Sand and Gravel Association and National Ready Mixed Concrete Association.

SCOPE OF INVESTIGATION

The investigation was divided into 3 groups for convenience in scheduling tests under the large number of different conditions. In Series 159A, 2 coarse aggregates, different in physical and mineral characteristics, were used in air-entraining concretes of 3 cement factors — 5, 6 and 7 sacks per cubic yard. For each of the 6 classes of concrete, flexural strength specimens were made for test at ages of 14, 28, 91 and 364 days under 4 different conditions of curing:

I. Stored continuously in the standard moist room at 73 F.
II. Immersed continuously (after the first day in the molds under wet burlap) in saturated limewater at 73 F
III. Cured 7 days in the moist room at 73 F, then stored in air in the laboratory until test.
IV. Treated the same as in III but immersed in water for the final 48 hours before test.

Series 159B was a study of the effect of soaking on the measured flexural strength of concrete which had been thoroughly air-dried. Air-entraining concrete was made with the same 2 coarse aggregates as in Series 159A, but with only one cement factor — 6 sacks per cubic yard. Beams for flexural strength tests were cured in the standard moist room at 73 F for 14 days and then air-dried at 100 F for 77 days. They were then tested after various periods of immersion in water, as follows: none and 30 minutes, and 1, 2, 4, 8, 16 and 32 days.

Series 159C was similar to 159 B except that the purpose was to determine the effect on measured flexural strength of air-drying specimens which had been moist cured for a sufficient period to permit attainment of nearly maximum strength. The concrete was the same as in Series 159B — 6 sack, air-entraining, made with the 2 coarse aggregates. The beams for flexural tests were cured in the standard moist room at 73 F for 91 days and then tested after various periods of air-drying at 100 F, as follows: none and

30 minutes, and 1, 2, 4, 8, 16 and 32 days.

In each series, it was intended to provide 3 rounds for each test condition, i.e., tests from 3 different batches of concrete made on different days for each combination of type of concrete, curing condition and test age. Because of the large number of curing and age combinations in Series 159A, which required more concrete than could be mixed at one time, 2 batches were required for each round. Specimens for curing environments I and II were made from 1 batch and for III and IV from a second batch. By alternating these batches and using 3 for each condition, it is felt that the direct comparability of curing conditions was preserved.

In Series 159B and 159C, specimens for all curing conditions were made from each batch of concrete. However, in the case of Series 159B, an error in scheduling the removal of specimens from the moist room resulted in only two usable rounds being secured. Specimens intended for the third round were reassigned to Series 159C which, therefore, had 4 rounds.

TABLE 1

CHARACTERISTICS OF FINE AND COARSE AGGREGATES

Sieve Size	Fine Aggregate	Coarse Aggregate A	Coarse Aggregate B
Grading, Percent Passing			
1½ inch	—	100	100
1 inch	—	75	75
¾ inch	—	50	50
⅜ inch	100.0	25	25
No. 4	95.8	0	0
No. 8	83.4	—	—
No. 16	72.3	—	—
No. 30	53.3	—	—
No. 50	14.7	—	—
No. 100	3.6	—	—
No. 200	1.7	—	—
Fineness Modulus	2.77	7.25	7.25
Miscellaneous Tests			
Specific Gravity: (24-Hour Soak)			
Bulk dry	2.59	2.58	2.94
Bulk saturated	2.62	2.61	2.96
Apparent	2.66	2.65	2.99
Absorption, percent	1.0	1.1	0.6
Unit Weight	—	110.7	114.5
Percent Voids	—	31.2	37.6

MATERIALS AND TEST PROCEDURES

Physical characteristics of the 2 coarse aggregates are given in Table 1. They were separated into individual sizes and recombined to the exact grading shown for each batch of concrete. They were weighed dry and immersed in water for 24 hours before incorporation in the concrete.

The fine aggregate, for which data are also given in Table 1, was the same for all concrete. It was a natural siliceous bank sand of excellent quality, conforming to all requirements of typical concrete aggregate specifications. Sand for each day's work was moistened and thoroughly mixed 24 hours in advance.

The cement used in each series was a blend of equal amounts of 5 brands purchased on the local market. The same brands were used throughout but the blend used in Series 159A was prepared at a different time from that used in Series 159B and 159C.

All concrete was proportioned to contain 0.72 cu ft of coarse aggregate, on a dry-rodded basis, per cubic foot of concrete ($b/b_0 = 0.72$). This value is intermediate between usual recommendations for structural and pavement concrete. The concrete was designed to have a slump of 2 to 3 inches. An air content of 4.5 ± 0.5 percent was secured by use of an admixture added at the time of mixing.

The concrete was mixed in 3.3-cubic foot batches in a 3.5-cubic foot capacity tilting mixer. Mixing time was 6 minutes. Each batch was tested for unit weight, from which the air content was calculated gravimetrically, and for slump. Four 6- by 6- by 36-in. beams were molded, each of which provided 2 tests for modulus of rupture using the standard third-point loading on an 18-inch span (ASTM Designation C 78). Thus, each batch provided specimens for 8 different curing conditions. As mentioned earlier, each test condition was represented by an average of 3 batches mixed on different days in Series 159A, 2 batches in Series 159B and 4 batches in Series 159C.

Moist-curing of specimens was in an air-conditioned room, controlled within temperature limits of 73 ± 1 F and equipped with fog nozzles operated by compressed air, which maintained free water on all surfaces of specimens as required by the ASTM Standards. Curing by immersion in water was in a controlled temperature tank maintained at 73 ± 3 F with the water gently circulated to assure uniform temperature throughout. Laboratory air-curing involved no special temperature or humidity control; temperatures averaged approximately 85 F and relative humidity about 50 to 60 percent. In Series 159B and 159C, air-drying was done in a controlled temperature room maintained at 100 ± 2 F with relative humidity averaging about 20 percent.

Methods used in mixing, molding and testing of the concrete conformed to the applicable standards of the ASTM.

TEST RESULTS

The data presented in this paper are averages of the several rounds made for each condition. The details for individual batches have been tabulated and are available in mimeographed form for those interested. Table 2 shows the characteristics of the fresh concrete for all 3 groups of tests — Series 159A, B and C. The design requirements for slump, air content and cement factor were closely maintained, which should insure the accuracy of comparisons among classes of concrete and the various curing conditions.

Series 159A

Tables 3, 4 and 5 present the flexural strength test results through 91 days (the 364-day tests are not yet available) from Series 159A. The data are shown

TABLE 2
CHARACTERISTICS OF FRESH CONCRETE

For characteristics of aggregates, see Table 1.
Cement was a blend of equal amounts of 5 brands.
All concrete designed for b/b_0 of 0.72, slump 2 to 3 inches and air content of 4.5 ± 0.5 percent.
Each value average of 3 batches mixed on different days.

Coarse Aggregate	Curing Conditions*	Cement, sacks per cu. yd.	Water		Sand Per cent Total Aggregate	Fineness Modulus Total Aggregate	Slump, in.	Percent Air	Weight, lb. per cu. ft.
			Gallons per cu. yd.	Gallons per sack					
				Series 159A					
A	I, II	5.03	28.2	5.61	31.4	5.84	2.3	4.4	144.6
	III, IV	5.01	28.4	5.67	31.4	5.84	2.7	4.7	144.4
A	I, II	6.03	29.1	4.82	29.2	5.94	2.7	4.6	144.6
	III, IV	6.00	29.0	4.83	29.2	5.94	3.0	5.1	143.8
A	I, II	7.05	30.2	4.27	26.8	6.05	2.8	4.3	145.1
	III, IV	7.06	30.1	4.26	26.8	6.05	2.7	4.2	145.2
B	I, II	4.99	30.8	6.17	37.0	5.59	2.3	4.6	152.8
	III, IV	5.03	31.0	6.16	37.0	5.59	2.7	4.0	153.8
B	I, II	6.06	30.8	5.09	35.7	5.65	2.7	4.2	154.1
	III, IV	6.06	31.0	5.12	35.7	5.65	2.5	4.2	154.2
B	I, II	7.07	31.9	4.51	32.8	5.78	2.6	4.2	154.4
	III, IV	7.08	31.9	4.51	32.8	5.78	2.9	4.1	154.5
				Series 159B					
A	All	6.08	29.0	4.77	29.2	5.94	2.4	4.0	145.7
B	All	6.04	30.8	5.10	35.7	5.65	2.6	4.5	153.8
				Series 159C					
A	All	6.05	28.6	4.73	29.2	5.94	2.6	4.5	144.7
B	All	6.04	30.7	5.08	35.7	5.65	2.6	4.7	153.3

* In Series 159A, the batches of concrete used for curing condition I and II were mixed independently of those used for conditions III and IV; in Series 159B and 159C, sufficient beams could be secured from each batch to provide for all curing conditions.

graphically in Figures 1 through 10. Table 3 also reports compression tests of cubes sawed from broken ends of beams cured continuously for 28 days in the moist room or in limewater. Figures 1, 2 and 3 show relationships between age and flexural strength for the 4 different curing conditions. Figure 1 gives the results for the 5-sack concrete for both aggregates A and B; Figure 2 for the 6-sack concrete; and Figure 3, the 7-sack.

For the 2 wet-curing conditions (I and II), age-strength relationships are typical and the strengths and rates of increase in strength are about the same for both aggregates. However, aggregate B gave consistently higher strengths than aggregate A. As discussed later, the differences between the 2 aggregates were significantly less for other curing conditions.

Specimens cured in air after 7 days moist (condition III) showed greatly reduced flexural strength at 14 and 28 days. At 14 days, the reductions averaged, for the two aggregates, about 23 percent for the 5-sack concrete and 30 and 36 percent for the 6- and 7-sack concrete, respectively. At 91 days, reductions in strength were much less; for the 5-sack concrete there was a slight increase and for the 6- and 7-sack concretes the decreases averaged only 10 and 15 percent.

Resoaking the dried concrete (condition IV) appeared to affect beams made with the 2 aggregates somewhat differently. For aggregate A, the resoaking restored the measured strength to substantially the same as found for moist curing. For aggregate B, the results were less consistent; the 14- and 28-day strengths were slightly lower than for

TABLE 3

STRENGTH TESTS FROM SERIES 159A

Curing conditions: I, in standard moist room at 73 F; II, in saturated limewater at 73 F; III, 7 days in standard moist room followed by storage in air of laboratory until test; IV, same as III except specimens immersed in water 48 hours before test.

Nominal Cement Factor, sacks per cu. yd.	Curing Conditions	Measured Modulus of Rupture, psi						28-Day Compressive Strength of Cubes, psi	
		Aggregate A			Aggregate B				
		14 days	28 days	91 days	14 days	28 days	91 days	Aggregate A	Aggregate B
Aggregates A and B shown separately									
5	I	542	593	605	559	610	635	5460	5215
	II	554	581	602	570	614	676	5245	5385
	III	423	447	631	434	500*	684	—	—
	IV	539	599	604*	588	567	588	—	—
6	I	583	582	645	660	705*	723	5915	6170
	II	586	597	646	655	674	727	5895	6050
	III	420*	469	618	444	486	624	—	—
	IV	615	614	634	661	677	616	—	—
7	I	608	634	688	721	777	790	6165	6875
	II	634	649	683	703	728	778	6395	6925
	III	419	417	596	450	479	632	—	—
	IV	612	639	659	671	712	640	—	—
Average of Aggregates A and B									
5	I				550	600	620	5340	
	II				562	597	639	5320	
	III				430	474	657	—	
	IV				564	583	596	—	
6	I				622	644	684	6040	
	II				620	635	686	5970	
	III				432	477	621	—	
	IV				638	645	625	—	
7	I				664	705	739	6520	
	II				668	688	730	6660	
	III				435	448	614	—	
	IV				641	675	650	—	

* One of three values omitted on basis of 90 percent confidence limit.

moist curing, while the 91-day strengths were substantially lower.

Although the effect of curing on strength was found to differ somewhat for the 3 cement factors and the 2 aggregates, Figures 1, 2 and 3 indicate that a clearer picture of the over-all effects in relation to age can be shown by averaging the data for the 6 conditions. This average relationship is given in Figure 4. It shows the significant decreases in strength due to partial drying of specimens cured moist 7 days, averaging 30 percent at 14 days, 27 percent at 28 days, and 7 percent at 91 days. The resoaked specimens, on the other hand, gave about the same strengths as those continuously moist cured at 14 and 28 days and 8 percent lower at 91 days. Note that curing conditions I and II, which have been combined, show an average increase in strength from 14 to 91 days of about 10 percent. For the dry curing condition, III, the increase for this period was great, being 46 percent. The resoaked speci-

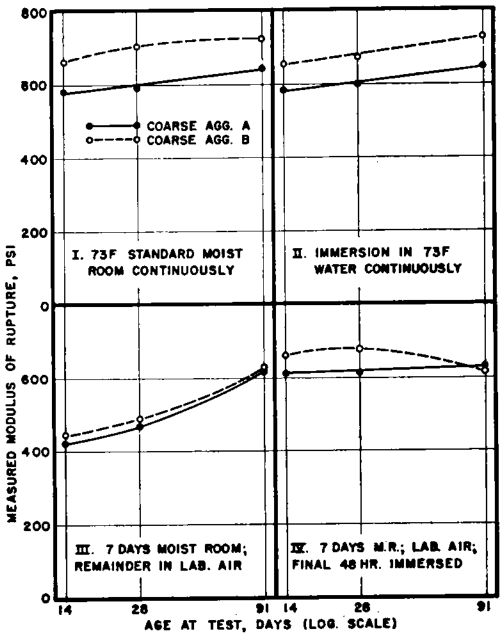

Figure 2. Effects of various curing conditions on measured flexural strength of concrete (series 159A; cement factor 6 sacks per cu. yd.).

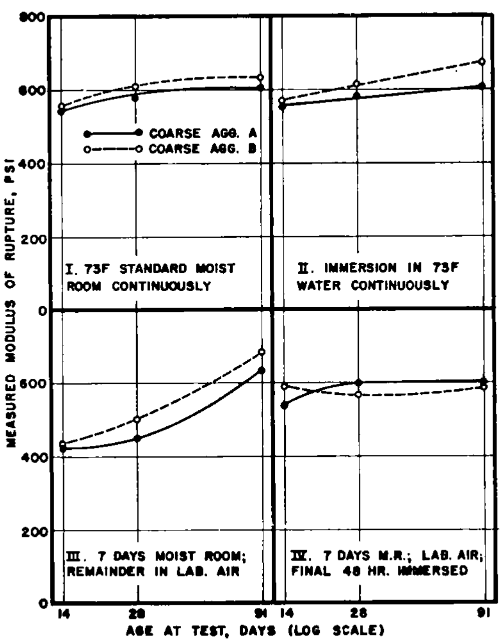

Figure 1. Effects of various curing conditions on measured flexural strength of concrete (series 159A; cement factor 5 sacks per cu. yd.).

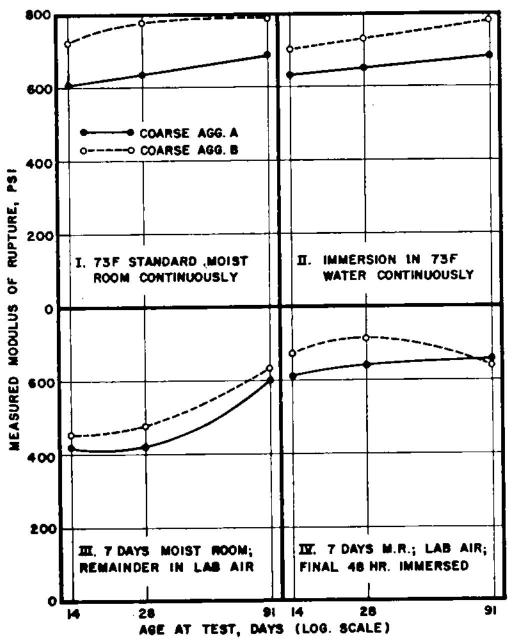

Figure 3. Effects of various curing conditions on measured flexural strength of concrete (series 159A; cement factor 7 sacks per cu. yd.).

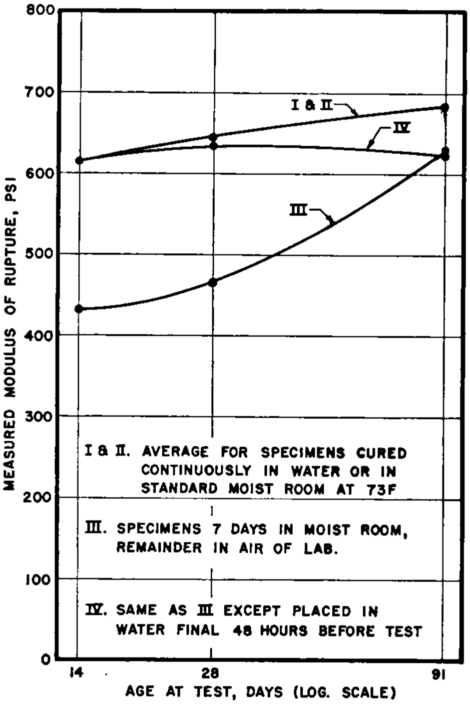

Figure 4. Average age-strength relationships for various curing conditions (series 159A).

mens gave substantially the same strengths at all 3 ages.

Mention has been made of the differences in strength between concretes made with aggregates A and B. In Table 4, age-strength data have been averaged for the 3 cement factors to permit comparing the two aggregates. They are shown graphically in Figure 5, with curing conditions I and II averaged because of the close agreement between them. For curing conditions I and II, aggregate B produced consistently higher flexural strengths than aggregate A, the difference amounting to 11 percent at 14 days, 13 percent at 28 days, and 12 percent at 91 days. However, for the other two curing conditions, the difference between the two aggregates largely disappeared. For condition III, with specimens tested dry, strengths for aggregate B exceeded those for aggregate A by only 5 percent at 14 days, 10 percent at 28 days, and 5 percent at 91 days. For condition IV, where specimens were soaked before test,

TABLE 4

AVERAGE AGE-STRENGTH RELATIONSHIPS FOR ALL CEMENT FACTORS SERIES 159A

See Table 3 for strength data for individual cement factors.

Each value average of 9 strength tests representing 3 batches for each of 3 different cement factors, except as noted.

Method of Curing	Modulus of Rupture, psi, at indicated test age					
	Coarse Aggregate A			Coarse Aggregate B		
	14 days	28 days	91 days	14 days	28 days	91 days
I—Continuous moist-curing	578	603	646	650	697*	715
II—Continuous immersed curing	591	609	644	643	672	726
III—7 days moist; remainder in laboratory air	421*	444	614	443	488*	647
IV—7 days moist plus laboratory air plus 48 hours soaking	589	617	632*	640	652	614

* Average of 8 tests only; one value rejected on basis of 90 percent confidence limit.

aggregate B gave higher strengths by 9 and 6 percent at 14 and 28 days, respectively, but was 3 percent lower than aggregate A at 91 days.

Figures 6 through 10 report the information given in Figures 1 through 5, but in different form. They emphasize the effect of cement content, whereas the first group emphasizes effect of age.

Figures 6, 7 and 8 show normal increases in the flexural strength with additional cement for curing conditions I and II. The 3 ages show about the same relationships; for aggregate A, the increase is about 6 percent per sack of cement, and for aggregate B, about 11 percent. Curing condition III, which showed the largest increase in strength with age, showed no benefit to strength due to increased cement — with some slight decrease being shown for the 28- and 91-day tests. The decreased spread in strength between the 2 aggregates for the less favorable curing condition is shown here as in the case of the earlier presentation of the data. The data for the 3 ages are averaged in Table 5 and in Figure 9 the data are further consolidated by averaging the 2 aggregates.

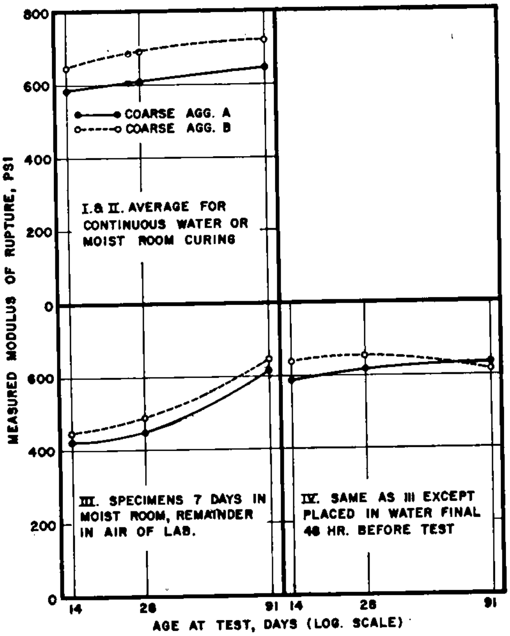

Figure 5. Effects of various curing conditions on measured flexural strength of concrete (series 159A, averages for 3 cement factors).

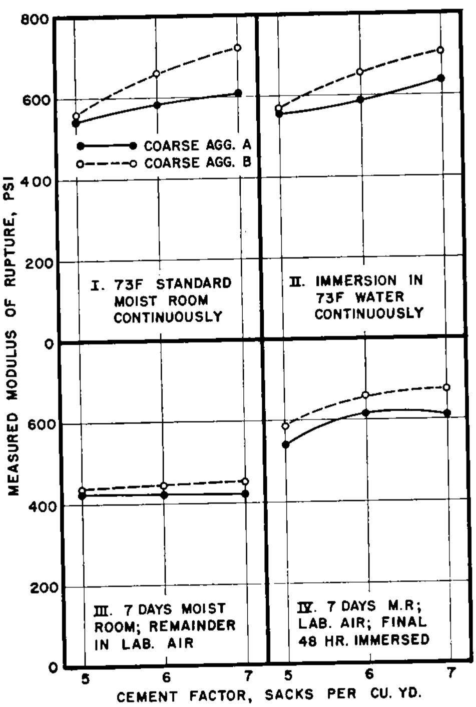

Figure 6. Relationships of cement content to flexural strength for various curing conditions (series 159A, 14-day tests).

Figure 10 compares the two aggregates, showing average strengths for all test ages, as given in Table 5. The spread between the 2 aggregates was greatest for the conditions of continuous moist curing, as shown previously. For the average of conditions I and II, aggregate B gave strengths averaging about 5 percent higher than aggregate A for the 5-sack concrete, 14 percent for the 6-sack, and 15 percent for the 7-sack. For curing condition III, the average spreads in favor of aggregate B were only 8, 3 and 9 percent, respectively, for the 5-, 6-, and 7-sack concrete, with no consistent relation to cement factor being shown. For the resoaked specimens (condition IV), the spreads were still further reduced, with aggregate B showing the same strength as aggregate A at 5 sacks, and only 5 and 6 percent higher at 6 and 7 sacks, respectively.

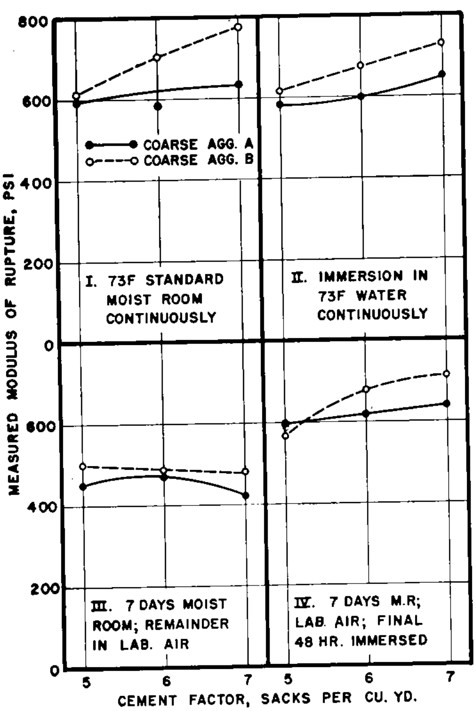

Figure 7. Relationships of cement content to flexural strength for various curing conditions (series 159A, 28-day tests).

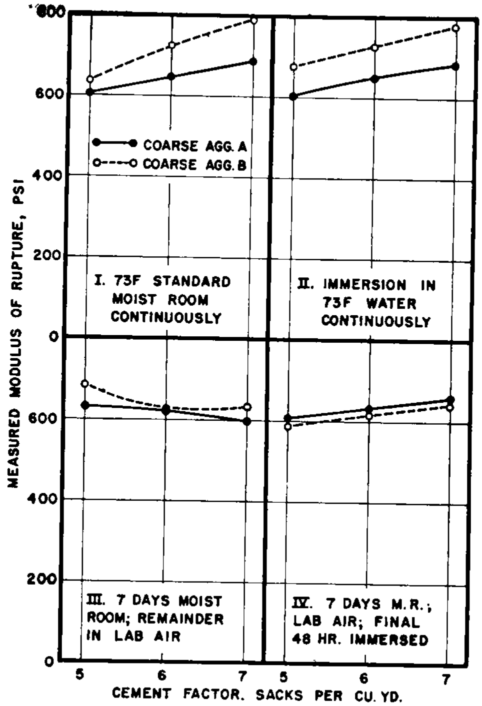

Figure 8. Relationships of cement content to flexural strength for various curing conditions (series 159A, 91-day tests).

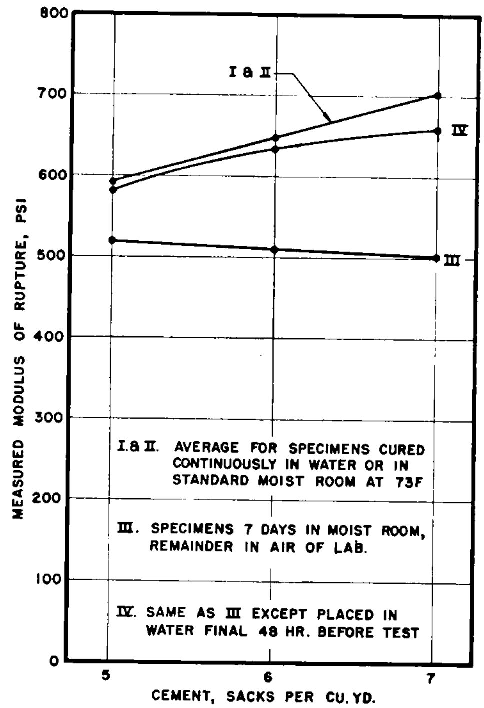

Figure 9. Average relationships of cement factor to flexural strength (series 159A).

TABLE 5

AVERAGE RELATIONSHIPS OF FLEXURAL STRENGTH TO CEMENT FACTOR FOR ALL TEST AGES, SERIES 159A

See Table 3 for strengths at individual ages.

Each value average of 9 strength tests representing 3 batches for each of 3 different test ages, except as noted.

Method of Curing	Modulus of Rupture, psi, for indicated cement factors					
	Coarse Aggregate A			Coarse Aggregate B		
	5 sacks	6 sacks	7 sacks	5 sacks	6 sacks	7 sacks
I—Continuous moist-curing	580	603	643	601	696*	763
II—Continuous immersed curing	579	610	655	620	685	736
III—7 days moist; remainder in laboratory air	500	502*	477	539*	518	520
IV—7 days moist plus laboratory air plus 48 hours soaking	581*	621	637	581	651	674

* Average of 8 tests only; one value rejected on basis of 90 percent confidence limit.

Series 159B

The data on effect of resaturation of dried concrete, from Series 159B, are given in Table 6 and shown graphically in Figure 11. It is apparent from the lower portion of Figure 11 that the specimens had reached a condition of very nearly stable saturation after 4 days' immersion in water although there was a slight weight increase between 4 and 8 days. These data are consistent with observations of the broken surfaces of test specimens, which revealed that a visibly dry core persisted through 8 days of soaking but was not visible after 16 or 32 days. The changes in flexural strength appear to correlate well with the changes in absorbed moisture. The modulus of rupture decreased progressively to the fourth day of soaking and showed a slight upward trend thereafter.

These results at first appear inconsistent with the data from Series 159A which showed that soaking, at least un-

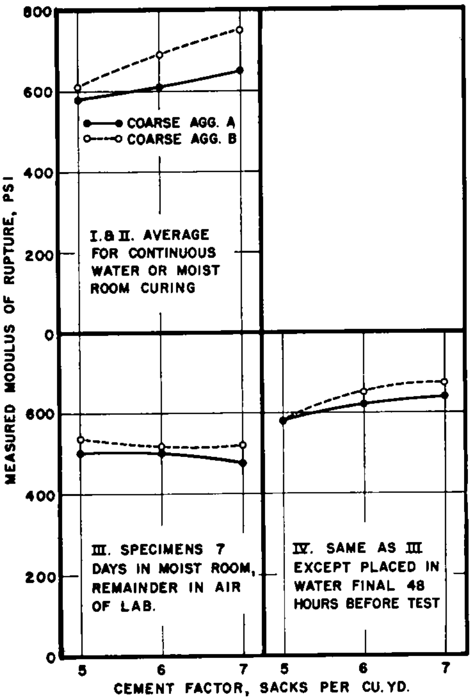

Figure 10. Relationships of cement content to flexural strength for various curing conditions (series 159A; averages for 3 test ages).

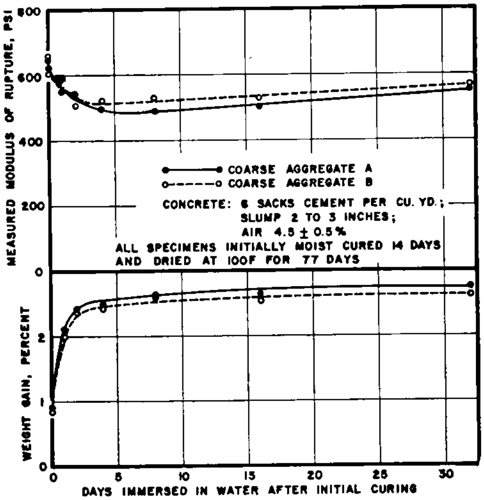

Figure 11. Effect of resaturation on measured flexural strength of dried concrete (series 159B).

TABLE 6

EFFECT OF RESATURATION ON MEASURED FLEXURAL STRENGTH, SERIES 159B

For detailed characteristics of fresh concrete, see Table 2.

All specimens cured in standard moist room to age of 14 days, then air-dried at 100 F for 77 days and tested after the indicated periods of immersion in water at 73 F.

Each value average of tests from two batches of concrete mixed on different days.

Period of Soaking Initially Dried Concrete	Modulus of Rupture, psi		Gain in Weight, percent	
	Coarse Aggregate A	Coarse Aggregate B	Coarse Aggregate A	Coarse Aggregate B
0 (Concrete dry)	650	658	0.00	0.00
30 Minutes	626	604	0.92	0.84
1 day	554	592	2.12	1.99
2 days	544	506	2.42	2.36
4 days	496	523	2.48	2.43
8 days	490	530	2.64	2.59
16 days	503	530	2.65	2.53
32 days	550	568	2.74	2.62

der some circumstances, caused an increase in the measured strength of dried concrete. However, there was evidence there, as discussed earlier, that only the incompletely dried specimens were benefitted by soaking while those which were uniformly dry were either unaffected or reduced in strength. In this series, the concretes were dried at relatively high temperature and low humidity for a long period before being soaked and tested. It can be reasoned that soaking should produce compressive stresses in the outer fibers which, since failure in the flexure test is in tension, should increase the load required for failure. That this was not supported by the test data suggests that wetting of concrete *per se* reduces its strength and that the reduction was more than enough to offset the induced compressive stresses.

The slight upward trend in strength after the 4-day immersion can reasonably be accounted for as due to the effect of additional hydration of cement. The specimens were moist cured only 14 days initially and would be expected to gain strength on resumption of favorable curing. It is again of interest to note the very small difference in strength level between the 2 types of coarse aggregate. This agrees with the indications of Series

159A that the strength advantage displayed by aggregate B under favorable standard curing conditions largely disappears after concrete has been permitted to dry.

Series 159C

Flexural strength and moisture change data for specimens dried for various periods after 3 months of moist curing are given in Table 7 and shown graphically in Figure 12. Figure 12 shows that, unlike soaking, the drying did not produce a condition of stable moisture content in the period employed in the tests. Specimens were apparently still losing significant quantities of moisture even after 32 days of drying at 100 F. This was in spite of the fact that broken surfaces revealed a dry appearance throughout the specimens after only 1 day of drying. The specimens which had been dried 30 minutes exhibited a dried surface shell about ⅛ inch thick. Drying produced a sharp drop in measured flexural strength even after the short period

TABLE 7

EFFECT OF DRYING ON MEASURED FLEXURAL STRENGTH OF MOIST-CURED CONCRETE, SERIES 159C

For detailed characteristics of fresh concrete, see Table 2.
All specimens cured in standard moist room at 73 F to age of 91 days, then tested after indicated periods of air-drying at 100 F.
Each value average of tests from 4 batches of concrete mixed on different days.

Period of Drying Initially Wet Concrete	Modulus of Rupture, psi		Loss in Weight, percent	
	Coarse Aggregate A	Coarse Aggregate B	Coarse Aggregate A	Coarse Aggregate B
0 (Concrete wet)	654*	726	0.00	0.00
30 minutes	593	671	0.12	0.09
1 day	452*	475	0.44	0.46
2 days	435	444	0.60	0.64
4 days	367	423†	0.77	0.74
8 days	433*	445	1.08	1.02
16 days	440	554*	1.34	1.16
32 days	549	532	1.82	1.60

* One of four values omitted from average on the basis of 90 percent confidence limits.
† Two of four values omitted from average on the basis of 90 percent confidence limits.
(With all values included, average was 417 psi.)

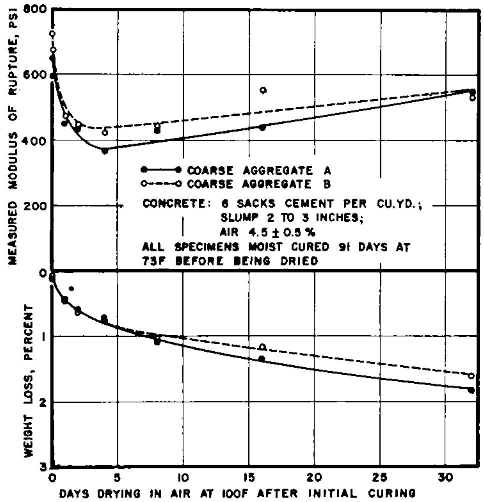

Figure 12. Effect of drying on measured flexural strength of concrete (series 159C).

of only 30 minutes. The strength reached a minimum after 4 days of drying and increased progressively thereafter, apparently not having reached its maximum after the 32 days reached in these tests.

The data are consistent with Series 159A and with work of other investigators in demonstrating the detrimental effect of partial drying on measured flexural strength. It appears that the tensile stresses induced by surface drying reduce the load-carrying capacity of the specimen. The later recovery of strength may be due to the moisture distribution approaching a uniform condition or possibly, as suggested earlier, to the strength of dry concrete actually being greater than that of wet concrete.

This group of tests lends further support to the findings of the other two portions of the investigation that the strength advantage of coarse aggregate B over aggregate A is significant only for standard laboratory curing. In this case, concrete with aggregate B was about 70 psi stronger after 91 days moist curing but was actually slightly weaker than that with aggregate A after the subsequent 32 days of drying.

Supplementary Tests

In an endeavor to develop further information on the phenomena shown by the tests reported herein, tensile strength tests of briquettes were made for different conditions of curing. They were made from mortar proportioned and mixed in accordance with ASTM Method C 109 (one part cement to 2.75 parts by weight of graded Ottawa sand). The flow was within the range of 105 to 113. Fifteen briquettes were made from each of 5 batches. These provided specimens for tests under 13 curing conditions with 5 rounds for each condition.

Two groups of the 15 were tested after 28 days of standard moist room curing, providing 10 strength values to be averaged. After 28 days, all remaining specimens (13 groups) were stored in 100 F air with relative humidity of about 20 percent. Strength tests were made after 30 minutes, 2 hours, and 1, 2, 4 and 14 days, with 2 of the groups being tested at the 14-day period. The remaining 6 groups (now 42 days old) were then placed in water at 73 F and tested after 15 and 30 minutes, 1 hour, and 1, 2 and 8 days.

The averages of the results are given in Table 8 and Figure 13. They show clearly that, for these tensile tests, strengths were significantly reduced with initial drying, which produced shrinkage, and greatly increased as drying was continued to 14 days. On resoaking, strengths almost immediately were reduced to substantially the same as the original 28-day moist-cured strength and remained at that level or lower as soaking was continued to 8 days. These data support others indicating that the measured tensile strength of dried concrete or mortar is substantially greater than that of wet concrete or mortar.

TABLE 8

RESULTS OF TENSILE STRENGTH TESTS OF MORTAR UNDER VARIOUS CONDITIONS OF SATURATION (SERIES J-104)

Mortar proportioned and mixed in accordance with ASTM Method C 109; briquettes cured to age of 28 days in accordance with ASTM Method C 190 and tested for tensile strength after indicated treatments.

Each value average of 5 tests from separate batches, except as noted.

Successive Periods of Curing			Age at Test, days	Tensile Strength, psi
In Water at 73 F	In Air at 100 F	In Water at 73 F		
28 days	0	0	28	426*
28 days	30 min.	0	28+	374
28 days	2 hours	0	28+	315
28 days	1 day	0	29	392
28 days	2 days	0	30	473
28 days	4 days	0	32	533
28 days	14 days	0	42	652*
28 days	14 days	15 minutes	42+	402
28 days	14 days	30 minutes	42+	428
28 days	14 days	1 hour	42+	411
28 days	14 days	1 day	43	371
28 days	14 days	2 days	44	429
28 days	14 days	8 days	50	383

* Average of 10 tests — 2 from each of 5 batches.

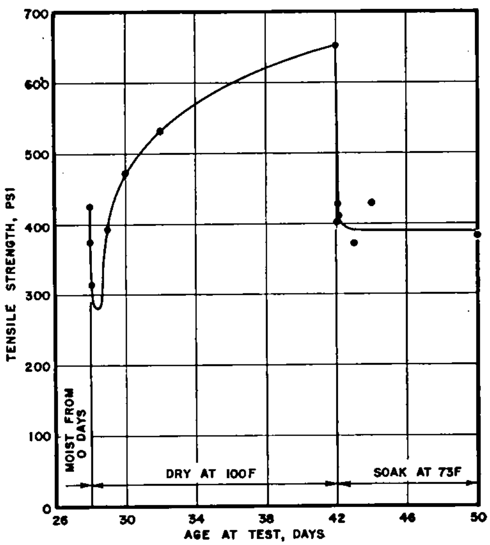

Figure 13. Effect of moisture condition on tensile strength of mortar (series J104).

SUMMARY AND CONCLUSIONS

1. Continuous curing in the moist room and in limewater produced essentially the same strengths in both flexure and compression. Normal increases in strength with age were shown.

2. Drying test specimens in laboratory air after 7-day moist curing produced large reductions in strength for ages at test of 14 and 28 days — up to 36 percent at 14 days. At 91 days, the difference in strength ranged between relatively small increases and relatively small decreases and, on the average, amounted to a reduction of 7 percent below standard moist-curing.

3. Immersion for 48 hours of dried specimens overcame the strength reductions due to drying for test ages of 14 and 28 days. At 91 days the immersed and dried specimens gave the same strength.

4. Coarse aggregate B produced higher flexure strength than coarse aggregate A particularly for moist-curing. The differences between the 2 aggregates were much less for the air-cured specimens, whether or not re-immersed, and completely disappeared in the 91-day tests of the re-immersed specimens.

5. Increases in cement content produced normal increases in measured flexural strength of moist-cured specimens. For the air-dried concrete additional cement resulted in no increase in strength. For the re-immersed specimens, there was some benefit due to adding cement but it was relatively small.

6. Specimens which had been moist cured 14 days and then stored in air at 100 F for 77 days, showed sharply reduced flexural strengths when immersed in water. After 4-day immersion a slight gain in strength was found which continued at a low rate during the 32-day immersion and which may have been due to continuing hydration of cement.

7. Specimens cured moist for 91 days and then dried at 100 F showed large reduction in flexural strength, up to about 40 percent after 4 days of drying. Thereafter, there was a slight increase in measured strength up to the maximum period of 32 days' drying.

8. The tests referred to in Paragraphs 6 and 7 showed that, for specimens which were immersed in water after thorough drying or which were dried after thorough curing, aggregates A and B produced substantially the same strength levels.

The investigation demonstrates the great sensitivity of flexural strength tests to variations in curing and moisture condition of the specimens. It raises the question as to the significance of measured values unless full account is taken of the moisture distribution in the specimen and of its curing.

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