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on

EFFECT OF TYPE OF AGGREGATE ON SHRINKAGE AND CRACKING CHARACTERISTICS OF CONCRETE

by

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EFFECT OF TYPE OF AGGREGATE

ON

SHRINKAGE AND CRACKING CHARACTERISTICS OF CONCRETE

Reported herein are the results of an investigation on the effect of type of aggregate and of continued mixing and retempering of concretes on their shrinkage and cracking characteristics. This investigation was made for the Division of Architecture, Department of Public Works, State of California under the conditions of State of California Standard Agreement Number 2379. These studies were carried out in the Engineering Materials Laboratory of the University of California, Berkeley, California during the period June 1961 to January 1962.

Results clearly demonstrate that type and source of aggregate is a major factor influencing shrinkage and cracking of concrete, that continued mixing and retempering increases shrinkage and aggregate breakdown, and that air entrainment somewhat reduces shrinkage.

SCOPE OF PROGRAM

The main purpose of these studies was to determine the effect of type of aggregate on the magnitude of shrinkage and the tendency towards cracking of a typical concrete mix that might be employed in the construction of reinforced concrete buildings. The mix used had a cement content of 5-3/4 scy and a maximum slump of 4 inches, and contained 1 1/2-in. maximum-size aggregate.

Continued mixing and retempering of concrete was included in this study to evaluate its effects on degradation of aggregates and on shrinkage and cracking of concretes. Data were obtained for continued mixing times of 3/4, 1 1/2, and 3 hours. Although specifications usually require that a concrete mix be discharged from a truck mixer within 45 minutes, sometimes concretes are agitated for longer periods prior to discharge.

Also included in this investigation was a limited study of the effect of air entrainment on shrinkage and cracking characteristics. These tests included only standard-mixed concretes not subjected to continued mixing and retempering.

Four concrete aggregates were included in this study. Two of these aggregates were representative of the Livermore Valley and of the Niles Valley deposits. The other two aggregates included Fair Oaks gravel and Watsonville crushed granite. The Livermore Valley coarse aggregate was also employed in one mix after being beneficiated by heavy-liquid separation.

For the shrinkage and cracking study, all concretes were moist-cured for a period of seven days prior to exposure to drying at 70°F and 50 percent relative humidity.

CONCRETE MATERIALS AND MIXES

Portland Cement

A Santa Cruz Type II cement was used in all concretes of this investigation. The chemical analysis is given in Table 1. The alkali content of this cement was 0.5 percent and its C_3A content only 4 percent.

Aggregates

The four aggregates included in these tests were:

(1) Fair Oaks gravel and Prattco sand, supplied by the Pacific Cement and Aggregate Company of San Francisco.

(2) Livermore Valley fine and coarse aggregate used with a small amount of Felton sand, all supplied by the Henry J. Kaiser Company of Oakland. The Livermore materials came from the company's Radum plant

and the Felton sand from their plant in Olympia near Felton.

(3) Niles Valley coarse aggregate and sand, supplied by the Pacific Cement and Aggregate Company from their plant west of Niles on the Alameda Creek.

(4) Watsonville crushed granite and Olympia sand, supplied by the Granite Rock Company, Watsonville, California. The crushed granite is produced by the Granite Rock Company in their Watsonville plant. The Olympia sand is produced by the Central Supply Company at their Olympia plant.

Also submitted for test was a small sample of the Livermore Valley coarse aggregate which was processed by heavy-liquid separation to remove material of specific gravity lower than 2.60. This material, prepared by the Henry J. Kaiser Company, was employed in only one of the test conditions.

The above-described combinations of aggregates are designated in this report as Fair Oaks, Livermore Valley, Niles Valley, and Watsonville. The Livermore Valley aggregate subjected to heavy liquid separation is desmated as beneficiated Livermore Valley aggregate.

Physical Properties. -- The physical properties of the aggregates are given in Table 2.

The fineness modulus of the concrete sands ranged from 2.85 for the Prattco sand used with the Fair Oaks gravel to 3.11 for the Niles Valley sand. Both the Fair Oaks and Watsonville aggregates had substantially higher sand equivalent and cleanness values than did the Livermore Valley and Niles Valley aggregates.

As judged by the specific gravities and absorption capacities of the aggregates, the Fair Oaks and Watsonville aggregates would be considered of superior quality in comparison with the Livermore Valley and Niles Valley aggregates.

The beneficiation of Livermore Valley coarse aggregates by heavy-liquid separation improved somewhat the quality of the material by increasing its specific gravity and reducing its absorption capacity.

Petrographic Analyses. -- Petrographic analyses of concrete aggregates as reported in U. S. Corps of Engineers, Technical Memorandum No. 6-370, "Test Data Concrete Aggregates in Continental United States", are summarized as follows:

1) Fair Oaks gravel from the American River consists of basic igneous rocks (24%), basic meta-igneous rocks (42%), andesite (14%), sandstone (11%), quartzite (5%), slate (2%), vein quartz, chert, and schist (2%).

The sand used with this gravel was Prattco, a dune sand from the Monterey Bay. This sand is composed of granitics, sandstone, chert, and meta-volcanic rock types with quartz, feldspar, biotite, magnetite, amphibole garnet, and antigorite minerals.

2) Livermore Valley aggregate is a river sand and gravel from Radum, California. The coarse aggregate is composed of sandstone and graywacke (61%), vein quartz (14%), basic igneous rocks (6%), basic meta-igneous rocks (9%), and jasperoid type chert (10%).

The sand is composed of graywacke and sandstone, quartz, basic igneous rocks, meta-basic igneous rocks and chert (jasperoid type).

In addition to this sand, a small amount of Felton sand was used. This sand is from the Zayante Creek at Olympia near Felton, California. Its mineral constituents consist largely of quartz (50%) and feldspar (50%), with trace quantities of biotite.

3) Niles Valley aggregate is from the Alameda Creek west of Niles. The coarse aggregate consists of sandstone and graywacke (84%), vein quartz (8%), basic igneous rocks (4%), basic meta-igneous rocks (3%), jasperoid type chert (1%), and a trace of shale.

The sand consists of sandstone, graywacke, vein quartz, basic igneous rocks, basic meta-igneous rocks, chert and shale.

4) Watsonville crushed coarse aggregate comes from a quarry near Watsonville, California. It is composed of a dark-colored granite which has an abundance of amphibole.

The concrete sand used with this crushed granite was Olympia sand from a deposit at Olympia on Zayante Creek. This sand is composed of quartz (50%) and feldspar (50%), with a trace of biotite and magnetite.

Concrete Mixes

Concrete mixes employed in this investigation had a cement content of 5-3/4 scy and a slump of 4 inches. This type of concrete mix is typical of that which could be used in the construction of reinforced concrete buildings. Mix proportions for the concretes containing the aggregates investigated are given in Table 3. Since both the Livermore Valley and the Niles Valley coarse aggregates are quite similar materials, the same basic mix design was employed for concretes containing these two materials. The mix selected was the one suggested by the Henry J. Kaiser Company to be used with their Livermore Valley aggregate.

Concrete mixes used were based on the mix proportions shown in Table 3, except that the water contents were adjusted slightly to produce the desired 4-inch slump. Actual water contents used are given in Table 4.

Three of the aggregates (Fair Oaks, Livermore Valley, and Watsonville) were also used in air-entrained concretes. The air-entraining admixture Darex was added in sufficient quantity to produce an air content of about 4.5 percent. As shown in Table 4, the sand-to-total aggregate ratio (S/A) of the air-entrained concretes was reduced by 0.03.

As shown in Table 4, the water-cement ratios of the plain concretes ranged from 5.53 gal/sk for Fair Oaks aggregate to 5.83 gal/sk for Livermore Valley aggregate. For the air-entrained concretes the water-cement ratio ranged from 4.92 gal/sk for Fair Oaks aggregate to 5.22 gal/sk for the Livermore Valley aggregate.

The one concrete mix containing beneficiated Livermore Valley coarse aggregate was of similar proportions to those of the concrete containing the unprocessed material. Its S/A ratio was slightly reduced (from 0.39 to 0.38), and its water-cement ratio was also slightly lower.

MIXING PROCEDURES AND TEST SPECIMENS

Mixing of Concretes

All concretes were mixed in a tilting-type, 3-cubic-foot capacity drum mixer. The mixer was equipped with an adjustable speed motor. The aggregate and cement were placed in the mixer first, and were mixed together for half a minute. Water was added, and mixing was continued at a mixing speed of 17 rpm for 2 minutes. Mixing was then stopped for 3 minutes, after which the concrete was mixed for an additional 2 minutes. The concrete was then discharged into a wheelbarrow, slump and air content were determined, and specimens were cast.

Concrete to be subjected to continued mixing and retempering was initially mixed following the procedure just described. After completion of this initial mixing, at a mixer speed of 17 rpm, the mixing was continued at a mixer speed of only 5 rpm. During this slow continued mixing the opening of the drum mixer was sealed with a sheet of plastic to prevent evaporation of water. Tests were made on concretes which were subjected to continued mixing periods of 3/4, 1-1/2, and 3 hours. All concretes subjected to continued mixing were retempered to bring the slump to 4 inches. For the concretes subjected to 3/4 hours of continued mixing, the retempering water was added just prior to discharging of the concrete. For the concretes subjected to 1-1/2 hours of continued mixing, retempering was done at 1 hour and just prior to discharge. For the 3-hour mixing period, retempering was done at 1 and 2 hours and just prior to discharge.

The entire procedure of mixing was carried out in a specially constructed room (wood frame and plastic cover) maintained at 70°F and 90 percent relative humidity.

Aggregate Breakdown Tests

To determine the degradation of aggregates in concretes subjected to continued mixing and retempering, a sieve analysis was made on the entire batch before and after mixing. The sieve analysis prior to mixing was made on air-dry aggregates. For the analysis after mixing, the concrete was wet-screened through successively smaller sieves. All cement and fines passing the No. 100 sieve were washed away from the aggregate. Materials retained on the individual sieve sizes were air-dried and then rescreened through the set of sieves used for the analysis of the aggregate prior to mixing.

Test Specimens

For each test condition there were cast two 4-7/8 by 6 by 16-inch shrinkage bars, two 4-7/8 by 6 by 40-inch crack-resistance bars and six 6 by 12-inch compressive-strength cylinders. In Fig. 1 are shown the details of the two types of concrete bars employed.

The molds used for casting of shrinkage specimens had 1/2-inch-diameter brass plugs secured in the ends of the molds for embedment in the concrete. These plugs projected 1/2 inch out of the concrete specimens to permit length measurements.

In order to produce the restraining effect for the crack-resistance bars, a steel rod of 1-1/2-inch diameter was secured in the mold longitudinally along the centerline of the mold. As shown in Fig. 1, this steel rod was threaded at each end for a distance of 3 inches to provide anchorage. To prevent bond along the remaining 34-inch length, the bar was covered with 1/8-inch-thick soft rubber tube. To permit length measurements, the steel bar projected 1/2 inch out of the concrete at each end.

Compressive-strength specimens were cast in 6 by 12-inch cardboard molds.

Casting of Specimens

The molds for shrinkage and crack-resistance bars were filled in two successive layers, each consolidated by the use of a laboratory-size internal vibrator. Immediately after casting, specimens were stored in the curing room. They were stripped after 24 hours, and remained in the curing room (70°F and 100 percent relative humidity) for 7 days.

Standard procedure was employed for the casting of the 6 by 12-inch compressive-strength specimens.

Measurements

After completion of the 7-day moist-curing period, initial measurements were taken on both the shrinkage and the crack-resistance bars. The bars were then transferred to the drying room (70°F and 50 percent relative humidity), where length measurements were taken every 24 hours for the first two weeks and then every 2 days until a crack occurred in the crack-resistance bars. Shrinkage measurements were then continued, at weekly intervals, for three months. Crack-resistance bars which did not crack within 30 days were thereafter measured at weekly intervals.

Shrinkage.-- The shrinkage, in millionths of an inch per inch of length, was computed by dividing the total change in length by the effective length (15 inches) of the concrete bar.

Crack Resistance. -- The resistance of concrete to cracking is the tensile stress developed in the concrete due to restrained drying shrinkage (Fig. 1). Crack resistance of a concrete is evaluated on the bases of (1) tensile stress developed prior to formation of crack and (2) the drying period (in days) required to produce a crack. The tensile stress in the concrete was calculated from the observed length change of the steel bar, using the following equation:

$$S_c = \frac{\Delta L}{L} \cdot E_s \cdot \frac{A_s}{A_c}$$

where:

S_c = Average tensile stress in concrete, psi

ΔL = Measured deformation of steel rod, in.

L = Effective length of steel rod = 37 in.

E_s = Modulus of elasticity of steel rod = 30 x 10^6 psi.

A_s = Area of steel rod = 1.77 sq. in.

A_c = Net area of concrete bar = 26.85 sq. in.

The effective length L of 37 inches was determined on the assumption that the tensile stress in the concrete, over the 3-inch threaded portion of the steel bar, varies linearly from 0 at the free surface to its maximum at 3 inches from the surface. Therefore one half of the threaded portion of the steel bar can be considered to be subjected to the average tensile stress and the effective length becomes (34 + 1-1/2 + 1-1/2) = 37 inches.

Crack-resistance bars made with a concrete mix of low shrinkage characteristics and of high tensile strength might not develop a crack during the drying period. In this investigation concretes containing the Fair Oaks and the Watsonville aggregates did not develop a crack within the 90-day drying period, after which time the tests were discontinued.

Compressive Strength. --Compressive-strength tests on 6 by 12-inch cylinders at ages of 7 and 28 days were made in accordance with ASTM Specification C39. Hydrostone was used for capping the ends of the cylinders.

TEST RESULTS

Properties of Concretes

Properties of fresh concretes and compressive strengths at ages 7 and 28 days are given in Table 4.

Water Requirement. -- As shown in Table 4, the water-cement ratio for plain concrete containing Fair Oaks gravel was 5.53 gal/sk, for Watsonville crushed granite 5.65 gal/sk, and for the Livermore Valley and Niles Valley aggregates 5.83 and 5.71 gal/sk respectively. The water-cement ratio of the concrete containing the beneficiated Livermore Valley coarse aggregate was 5.68 gal/sk as compared to 5.83 gal/sk for the concrete containing the unprocessed material.

The water-cement ratios of the air-entrained concretes were lower by about 0.6 gal/sk than those for the corresponding plain concretes. This reduction in water-cement ratio was due not only to the improved workability produced by the air-entrainment but also to the reduction of the sand content in mixes containing the air-entraining admixture (Darex).

Compressive Strength. --Compressive strengths at ages of 7 and 28 days are shown in the last two columns of Table 4. Data given are the average of three cylinders per test condition.

All plain concretes produced 28-day compressive strengths in excess of 4000 psi. The 28-day compressive strengths of air-entrained concretes were somewhat lower than those of the corresponding plain mixes. The Livermore Valley and the Niles Valley aggregates produced concretes of lower compressive strengths than did the Fair Oaks or Watsonville aggregates.

Compressive strengths of concrete containing the beneficiated Livermore Valley coarse aggregate were about 10 percent higher than those of the concrete mix made with the unprocessed material.

Breakdown of Aggregates

Tests to determine degradation of aggregates caused by continued mixing for 0, 1-1/2, and 3 hours were made on concretes containing three of the aggregates, namely Livermore Valley, Niles Valley, and

Watsonville. As described earlier, the concrete was mixed for a total of 4 minutes at a mixing speed of 17 rpm and mixing was then continued at a mixer speed of 5 rpm. Concretes subjected to this continued mixing were retempered to bring the slump to 4 inches. The 0-hour continued mixing condition represents a concrete mix subjected only to the initial 4-minute mixing time.

Gradations of aggregates were determined before mixing and after completion of continued mixing. The change in grading, expressed in terms of change in fineness modulus, is shown in the bar diagrams of Fig. 2. In this figure the degradation is shown separately for the sand and for the coarse aggregate. Also shown is the degradation for the combined aggregate.

A study of these diagrams (Fig. 2) reveals that the major part of the aggregate breakdown occurs within the sand fraction. The change in fineness modulus of the sand ranged from 0.04 (Livermore Valley) to 0.22 (Niles Valley) for 0 hours of continued mixing and from 0.17 (Livermore Valley) to 0.50 (Niles Valley) after 3 hours of continued mixing. After 3 hours of continued mixing the sand fraction of the Watsonville aggregate changed its fineness modulus by only 0.15.

The breakdown of the coarse aggregate was in all cases very small. The inconsistencies in the change in fineness modulus of the coarse aggregate, for the three periods of continued mixing, are considered to have no significance. A few pieces of coarse aggregate passing a given screen would produce the small differences observed. The maximum change in fineness modulus observed was only 0.05.

By studying the degradation of the combined aggregate (last set of bar diagrams of Fig. 2), it will be observed that about 40 to 60 percent of breakdown of aggregate occurred during the initial 4 minutes of mixing. After this initial large degradation, further breakdown of aggregate was approximately proportional to mixing time.

Shrinkage and Crack Resistance

Shrinkage and crack-resistance tests were made on concrete specimens moist-cured for 7 days prior to drying at 70°F and 50 percent relative humidity. Tests were made on concretes containing the four aggregates investigated. Also included for three of the aggregates (Livermore Valley, Niles Valley, and Watsonville) were shrinkage and crack-resistance tests of concretes subjected to continued mixing for 3/4, 1 1/2, and 3 hours. Effect of air-entrainment on shrinkage and crack-resistance was evaluated for concretes containing Fair Oaks, Livermore Valley, and Watsonville aggregates.

Shrinkage.--Shrinkage data for selected ages up to 90 days for concretes moist-cured for 7 days are given in Table 5, and various comparisons are made in Figs. 3 to 8.

Effect of type of aggregate on shrinkage up to 90 days is shown in Fig. 3. Data of Fig. 3 are for concretes not subjected to continued mixing (0 hours). Concretes containing Fair Oaks or Watsonville aggregates exhibited substantially lower shrinkage than concretes containing Niles Valley or Livermore Valley aggregates. For example, the shrinkage after 21 days of drying (Table 5 and Fig. 3) for the concrete containing Fair Oaks aggregate was 220 millionths (0.0220 percent) as compared to 420 millionths (0.0420 percent) for the concrete containing Niles Valley aggregate. Shrinkage of concrete containing Watsonville aggregate was even slightly lower than that containing Fair Oaks aggregate. The Livermore Valley aggregate concrete had a somewhat lower shrinkage than the concrete containing the Niles Valley material.

It should be pointed out that the shrinkages observed for the Fair Oaks and for the Watsonville aggregate concretes are to be considered as being exceptionally low. There are not many aggregates that will produce concretes of such low shrinkage characteristics.

Effect of air entrainment on shrinkage of concretes containing Fair Oaks, Livermore Valley, or Watsonville aggregates is shown in Fig. 4. Data of Fig. 4 are for concretes not subjected to continued mixing (0 hours). In all cases the use of air-entrainment reduced somewhat the shrinkage characteristics of the concretes. The reduced water-cement ratios of the air-entrained mixes are primarily responsible for this reduction in shrinkage. For example, the shrinkage after 21 days of drying (Table 5 and Fig. 4) for the plain concrete containing Fair Oaks aggregate was 220 millionths as compared to 190 millionths for the corresponding air-entrained concrete mix. Even a greater effect was observed for the concrete mix containing Livermore Valley aggregates. On the other hand air-entrainment had little effect on the shrinkage characteristics of concrete containing Watsonville aggregate.

Shrinkage data up to 90 days of drying for concretes subjected to continued mixing (for 3/4, 1-1/2, and 3 hours) and retempering are given in Table 5 and plotted in Fig. 5 (Livermore Valley aggregate), Fig. 6 (Niles Valley aggregate), and in the lower half of Fig. 7 (Watsonville aggregate). Also given are the water-cement ratios for the different periods of continued mixing. As described earlier, all concretes were retempered to maintain a 4-inch slump. Shrinkage of concretes subjected to continued mixing and retempering was greater than that of the corresponding mixes not subjected to continued mixing.

The longer the period of continued mixing, the larger was the increase in shrinkage. For example, after 21 days of drying, the increase in shrinkage ranged from 15 to 20 percent for concretes subjected to 1-1/2 hours of continued mixing and from 30 to 40 percent for those subjected to 3 hours of continued mixing. Continued mixing had a somewhat greater effect on shrinkage of concretes containing Niles Valley aggregate (Fig. 6) than on concretes containing Livermore Valley aggregate (Fig. 5); as earlier discussed and as shown in Fig. 2, continued mixing produced a more severe degradation of aggregate for concretes made with the Niles aggregate than for those containing Livermore aggregate.

Increases in shrinkage observed in these concretes subjected to continued mixing and retempering are primarily due to increases in water-cement ratios. This increase in water-cement ratio ranged from 0.2 to 0.3 gal/sk for 3/4 hour of continued mixing and from 0.8 to 1.2 gal/sk for 3 hours of continued mixing. These results clearly justify the usual requirement that concrete be discharged from the truck mixer within 45 minutes and that no retempering be permitted.

Shrinkage data up to 90 days of drying for the concrete mix containing the beneficiated Livermore Valley coarse aggregate are shown in the lower half of Fig. 8. The shrinkage of concrete containing the beneficiated coarse aggregate was lower by about 20 percent than that of the concrete made with the unprocessed coarse aggregate. Although the water-cement ratio of the concrete mix containing the beneficiated aggregate was slightly lower (0.15 gal/sk), this relatively large reduction in shrinkage must also be due to the improvement in the quality of the coarse aggregate by removal of material of minus 2.60 specific gravity.

Crack Resistance.-- Tensile stresses developed in the restrained-concrete crack-resistance bars are plotted in the top halves of Figs. 7 to 11, and in Fig. 12. The lower halves of Figs. 7 to 11 contain plots of shrinkage observed in specimens of corresponding concretes. The shrinkage data for concretes corresponding to those shown in Fig. 12 (effect of air entrainment) are plotted in Fig. 4.

These data are summarized in Table 6, in which are given the periods of drying to crack formation, the tensile stress at time of cracking, and the shrinkage values for the drying period up to time of cracking. For concretes which did not crack within 90 days, values of tensile stress and shrinkage at 90 days are given.

In evaluating these crack-resistance data it should be realized that several factors influence the tendency towards crack formation. They include shrinkage characteristics, tensile strength, elastic properties, and creep characteristics of the concrete mix. Size of specimen and degree of restraint (size of restraining steel bar) will also influence the cracking tendency of a concrete mix. For this reason, comparisons should be made on a relative rather than an absolute basis. However, the cracking tendency of a concrete mix, as herein evaluated, is far more significant than the drying shrinkage alone.

As shown in Fig. 9 and Table 6, concretes containing Livermore Valley or Niles Valley aggregates cracked after 13 days of drying. No cracking was obtained within 90 days on bars containing Fair Oaks or Watsonville aggregate concretes. It might be pointed out that the longer the elapsed period of drying without formation of a crack, the smaller is the possibility that a crack will form. This is due to creep which reduces the rate of tensile stress development; also tensile strength increases with time.

The effect of continued mixing and retempering on cracking tendency for concretes containing Livermore Valley aggregates is shown in Fig. 10, and for those containing Niles Valley aggregates in Fig. 11. All of these concretes subjected to continued mixing (Table 6) cracked within 8 to 13 days, at tensile stresses ranging from 190 to 265 psi. None of the concretes containing Watsonville granite and subjected to continued mixing (Table 6, Fig. 7) cracked within the 90-day drying period. The tensile stresses of these concretes at 90 days were about 300 psi.

The effect of air entrainment on crack resistance is shown in Fig. 12 and Table 6. In some cases the use of air entrainment appears to have improved the cracking characteristics and the tensile stress development of the concretes. For example, the air-entrained concrete containing Livermore Valley aggregate did not crack until after 28 days of drying, as compared to 13 days for the corresponding plain mix. The tensile stress of the air-entrained concrete mix containing Fair Oaks aggregate was 270 psi, and that of the plain mix 300 psi. Air entrainment did not reduce the 90-day tensile stress developed in concretes containing the Watsonville aggregate. Although the results of the effect of air entrainment are not conclusive it would be expected that because of the lower water contents of these air-entrained concretes their cracking tendency would be improved in comparison to corresponding non-air-entrained mixes.

Beneficiation of the Livermore Valley coarse aggregate (Fig. 8 and Table 6) reduced the cracking tendency of the concrete containing this aggregate in comparison with that of the mix containing the unprocessed material. Concrete containing the beneficiated material cracked after 26 days of drying at a tensile stress of 270 psi, whereas that containing the unprocessed aggregate cracked after 13 days of drying and a stress of 220 psi.

DISCUSSION

Results of this investigation indicate that:

1. The nature of the aggregate is one of the major factors influencing the shrinkage and cracking characteristics of concretes. Greater shrinkage and cracking characteristics were obtained with Livermore Valley and Niles Valley aggregates, which contain a high percentage of sandstone and graywacke, than with Fair Oaks gravel or Watsonville crushed granite. However, the shrinkage of concretes containing Fair Oaks and Watsonville aggregates should be considered as exceptionally low, as very few aggregates would produce comparable low shrinkage characteristics.

2. Concretes subjected to continued mixing and retempering exhibited a larger shrinkage than did corresponding control mixes. Only a small increase in shrinkage was observed for concretes subjected to continued mixing for 3/4 hour. The longer the period of continued mixing and retempering, the greater was the increase in shrinkage.

3. Continued mixing also resulted in significant aggregate breakdown. Although the major portion of aggregate breakdown was obtained within the initial mixing period, continued mixing produced additional degradation of the aggregate. This degradation of aggregate increased with increase in continued mixing time. The major part of aggregate breakdown occurred within its sand fraction.

4. Air entrainment reduced somewhat the shrinkage characteristics of the concretes. Reduction in water-cement ratio by use of air entrainment was primarily responsible for the reduction in shrinkage.

5. Beneficiation of Livermore Valley coarse aggregate by heavy-liquid separation improved the quality of the aggregate with respect to its effect on the shrinkage and cracking characteristics of the concrete. This beneficiation was accomplished by removal of material of specific gravity less than 2.60.

Results of laboratory tests, as herein reported, should only be analyzed on a comparative basis. The relatively small laboratory specimens cannot duplicate the properties of concretes in a full-scale structure. Such laboratory tests, however, are essential to establish certain limits for various concrete properties.

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The casting of specimens and the collection of data were supervised by Dr. A. El-Erian, a visiting scholar from Egypt. Messrs. H. C. Ko and S. C. Chang, graduate students in Civil Engineering, carried out the various phases of this project. Mr. Yuzo Akatsuka, also a graduate student in Civil Engineering, was responsible for the shrinkage and crack-resistance studies.

Faculty investigators were Professors David Pirtz and Milos Polivka.

TABLE 1--CHEMICAL ANALYSIS OF SANTA CRUZ TYPE II CEMENT

Oxide Composition	Percent
SiO_2	23.4
Al_2O_3	3.9
Fe_2O_3	3.7
CaO	64.2
MgO	1.6
Alkalies as Na_2O	0.5
SO_3	2.0
Ignition loss	0.8
Compound Composition	
C_3S	46
C_2S	33
C_3A	4
C_4AF	11

TABLE 2—PHYSICAL PROPERTIES OF AGGREGATES

Sieve Size	Cumulative Percent Passing													
	Fair Oaks			Livermore Valley				Beneficiated Livermore[c]		Niles Valley			Watsonville		
	Sand[a]	No. 4 to 3/4 in	3/4 to 1 1/2 in.	Blend Sand[b]	Sand	No. 4 to 3/4 in	3/4 to 1 1/2 in.	No. 4 to 3/4 in	3/4 to 1 1/2 in.	Sand	No. 4 to 3/4 in	3/4 to 1 1/2 in.	Sand[d]	No. 4 to 3/4 in	3/4 to 1 1/2 in.
1 1/2 in	—	—	93	—	—	—	95	—	97	—	—	98	—	—	100
1	—	100	27	—	—	100	36	100	41	—	100	52	—	100	56
3/4	—	99	9	—	—	96	4	93	9	—	95	3	—	99	5
1/2	—	64	3	—	—	69	0	44	0	—	59	1	—	77	2
3/8	—	41	1	—	—	30	—	17	—	100	21	0	100	40	0
No. 4	100	2	0	100	100	0	—	0	—	96	1	—	95	4	—
8	96	0	—	99	85	—	—	—	—	77	0	—	76	0	—
16	63	—	—	98	56	—	—	—	—	57	—	—	67	—	—
30	33	—	—	93	32	—	—	—	—	37	—	—	45	—	—
50	19	—	—	33	14	—	—	—	—	17	—	—	20	—	—
100	4	—	—	7	5	—	—	—	—	5	—	—	4	—	—
Fineness Modulus	2.85	6.58	7.97	1.72	3.08	6.74	8.01	6.90	7.94	3.11	6.83	7.99	2.93	6.57	7.95
Specific Gravity	2.64	2.79	2.79	2.60	2.64	2.68	2.71	2.70	2.72	2.61	2.67	2.66	2.60	2.89	2.92
Absorption Capacity, %	0.8	0.9	0.8	0.9	1.9	1.3	1.2	1.1	1.0	1.0	1.7	1.5	0.9	1.0	0.8
Sand Equivalent	92	—	—	69	74	—	—	—	—	63	—	—	89	—	—
Cleanness Value	—	97	97	—	—	86	84	—	—	—	86	71	—	94	90

a—Prattco sand

b—Felton sand

c—Beneficiated by heavy-media separation to remove material of specific gravity lower than 2.60.

d—Olympia sand.

TABLE 2

TABLE 3--CONCRETE MIX PROPORTIONS

1½-in. maximum size aggregate
Santa Cruz Type II cement
Nominal slump 4 inches

Material	Quantities of Materials, lb per cu. yd.			
	Fair Oaks	Livermore Valley	Niles Valley	Watsonville
Cement	541	541	541	541
Water	265	280	280	270
Sand	1320	1111	1271	1244
Blend Sand	--	160	--	--
No. 4 to 3/4-in.	1030	814	814	827
3/4 to 1 1/2-in.	1040	1219	1219	1264

TABLE 4--PROPERTIES OF CONCRETES

1½-in. maximum size aggregate
Cement content 5 3/4 scy; Santa Cruz Type II cement
Slump 4 inches

Concrete	Aggregate	S/A Ratio, by weight	W/C, gal/sk	Air Content, percent	Compressive Strength, psi[a]	
					7 da	28 da
Plain	Fair Oaks	0.39	5.53	1.1	3090	4690
	Livermore	0.39	5.83	1.0	2260	4070
	Beneficiated Livermore	0.38	5.68	1.0	2540	4450
	Niles	0.39	5.71	0.9	2150	4110
	Watsonville	0.37	5.65	0.9	2740	4630
Air-Entrained[b]	Fair Oaks	0.36	4.92	4.7	2660	4290
	Livermore	0.36	5.22	4.4	2250	3780
	Watsonville	0.34	5.06	4.2	2550	4140

a - Average of three 6 by 12-in. cylinders; standard curing

b - Air-entraining admixture Darex

TABLE 5--SHRINKAGE OF CONCRETES

$1\frac{1}{2}$-in. maximum size aggregate
Cement content 5-3/4 scy; Santa Cruz Type II cement
Slump 4 inches

Concrete	Aggregate	Continued[b] Mixing and Retempering, hours	W/C, gal/sk	Shrinkage, millionths[a]						
				Moist-curing for 7 days then drying at 50% R.H. and 70°F, days						
				1	3	7	21	42	60	90
Plain	Fair Oaks	0	5.53	75	120	155	220	290	325	385
	Livermore	0	5.83	110	170	240	400	590	710	820
		3/4	6.12	90	150	240	410	595	715	825
		1 1/2	6.34	95	150	260	460	675	790	895
		3	7.05	120	220	290	515	740	860	955
	Beneficiated Livermore	0	5.68	85	120	175	325	490	575	665
	Niles	0	5.71	95	150	250	420	640	760	890
		3/4	5.90	115	165	255	470	690	805	925
		1 1/2	6.17	110	195	275	490	705	835	960
		3	6.62	140	220	325	580	820	950	1090
	Watsonville	0	5.65	45	60	85	160	240	290	360
		3/4	5.83	40	65	100	195	275	325	390
		1 1/2	5.87	40	60	110	200	285	335	390
		3	6.44	65	85	120	220	310	370	425
Air-Entrained	Fair Oaks	0	4.92	65	90	120	190	265	310	350
	Livermore		5.22	100	150	210	360	515	610	600
	Watsonville		5.06	35	50	80	160	240	285	340

a - Average of two 4 7/8-in by 6 by 16-in. concrete bars
b - After initial mixing for 4 minutes at normal speed (17 rpm), mixing continued at slow speed (5rpm) for period indicated.

TABLE 6--CRACKING CHARACTERISTICS OF CONCRETES

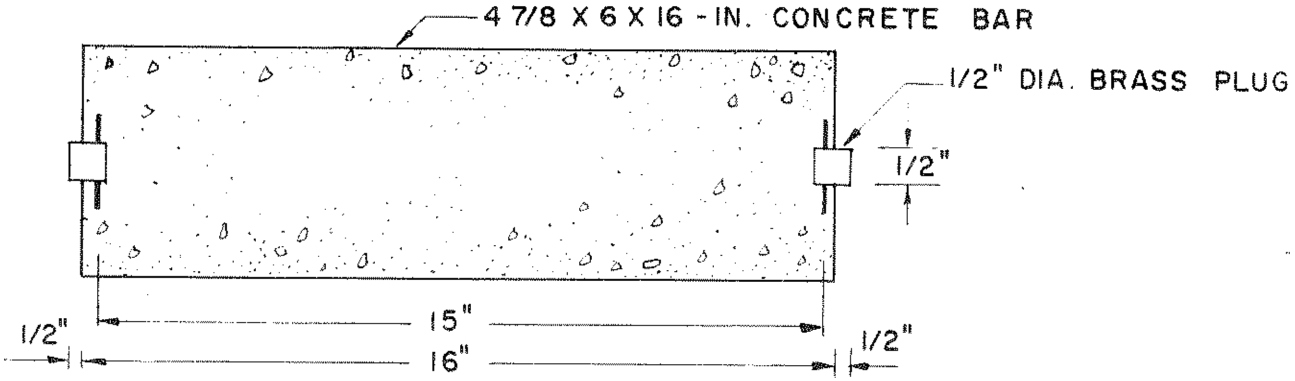
1½-in. maximum size aggregate
Cement content 5 3/4 scy; Santa Cruz Type II cement
Slump 4 inches

Concrete	Aggregate	Continued Mixing and Retempering, hours	W/C, gal/sk	Crack Formation[a]		Shrinkage, Millionths (at time of crack formation, or at 90 da)
				Days at 50% R.H.	Tensile stress, psi	
Plain	Fair Oaks	0	5.53	(90)[c]	(300)[c]	(385)[c]
	Livermore	0	5.83	13	220	305
		3/4	6.12	12	240	305
		1 1/2	6.34	13	265	355
		3	7.05	10	240	345
	Beneficiated Livermore	0	5.68	26	270	370
	Niles	0 0	5.71	13	230	320
		3/4	5.90	11	225	310
		1 1/2	6.17	10	267	325
		3	6.62	8	190	345
	Watsonville	0 0	5.65	(90)[c]	(265)[c]	(360)[c]
		3/4	5.83	(90)[c]	(295)[c]	(390)[c]
		1 1/2	5.87	(90)[c]	(285)[c]	(390)[c]
		3 3	6.44	(90)[c]	(290)[c]	(425)[c]
Air-Entrained	Fair Oaks	0	4.92	(90)[c]	(270)[c]	(350)[c]
	Livermore		5.22	28	315	415
	Watsonville		5.06	(90)[c]	(300)[c]	(340)[c]

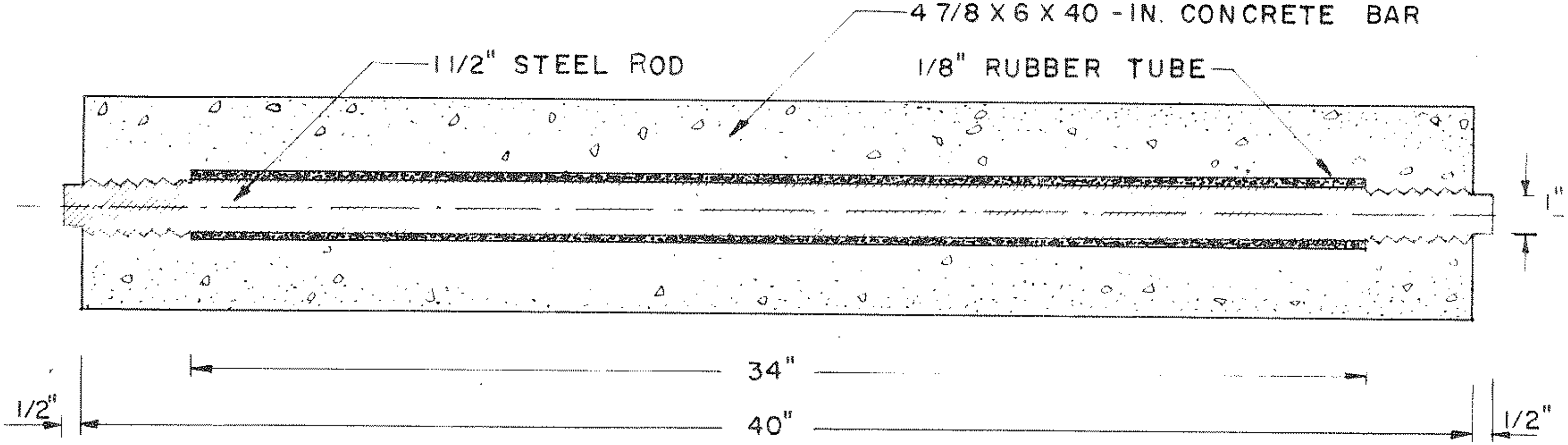
a - Average of two 4 7/8 by 6 by 40-in. restrained concrete bars, moist cured for 7 days

b - After initial mixing for 4 minutes at normal speed (17 rpm), mixing continued at slow speed (5 rpm) for period indicated.

c - No crack within 90 days of drying; values of tensile stress and shrinkage are for 90 days of drying.

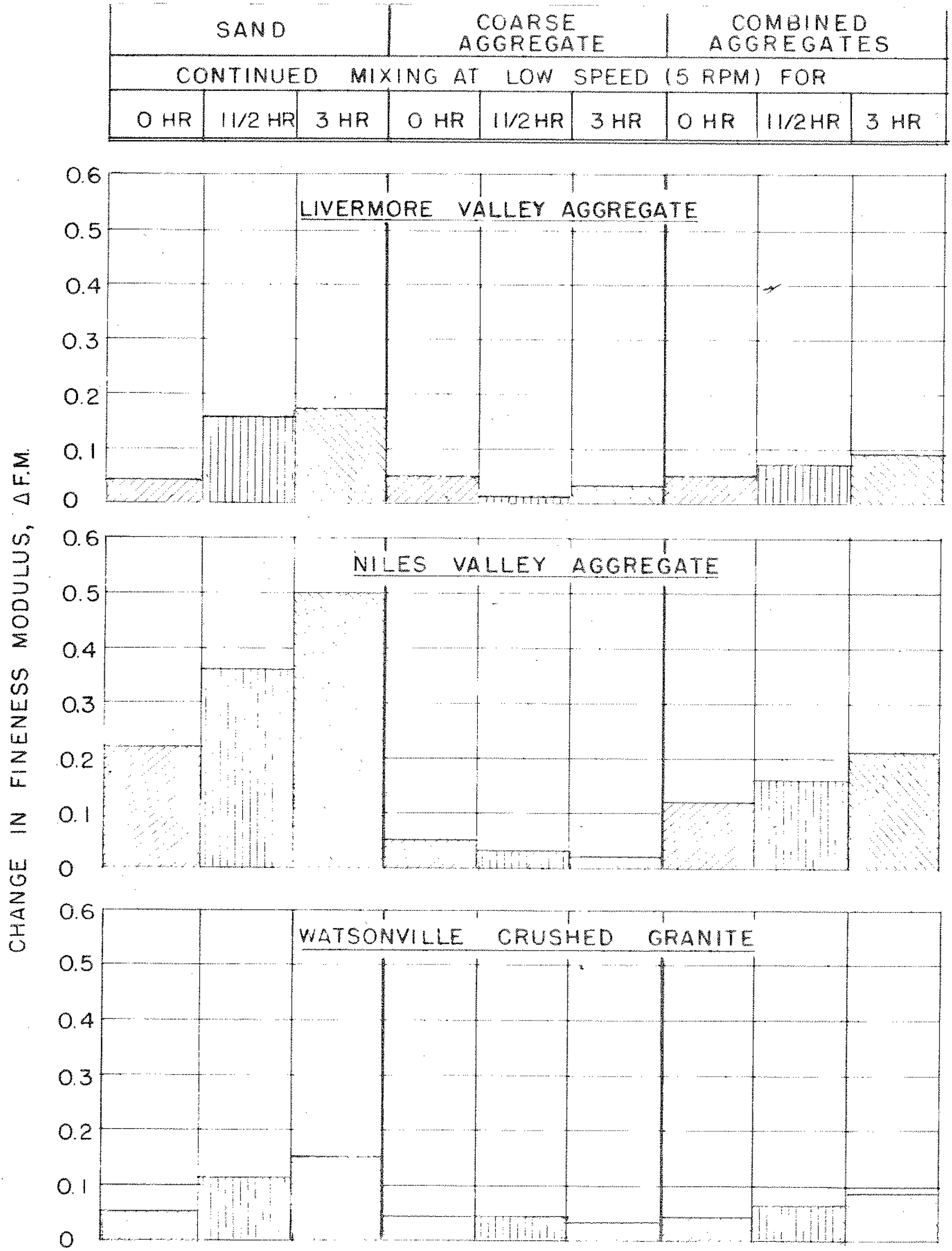


SHRINKAGE SPECIMEN



CRACK RESISTANCE SPECIMEN

FIG. 1 — SHRINKAGE AND CRACK RESISTANCE SPECIMENS



CONCRETE MIXED FOR 4 MINUTES AT NORMAL SPEED (17 RPM),
MIXING CONTINUED AT SLOW SPEED (5 RPM).

FIG. 2 — EFFECT OF CONTINUED MIXING ON GRADING OF AGGREGATES

Fig. 2

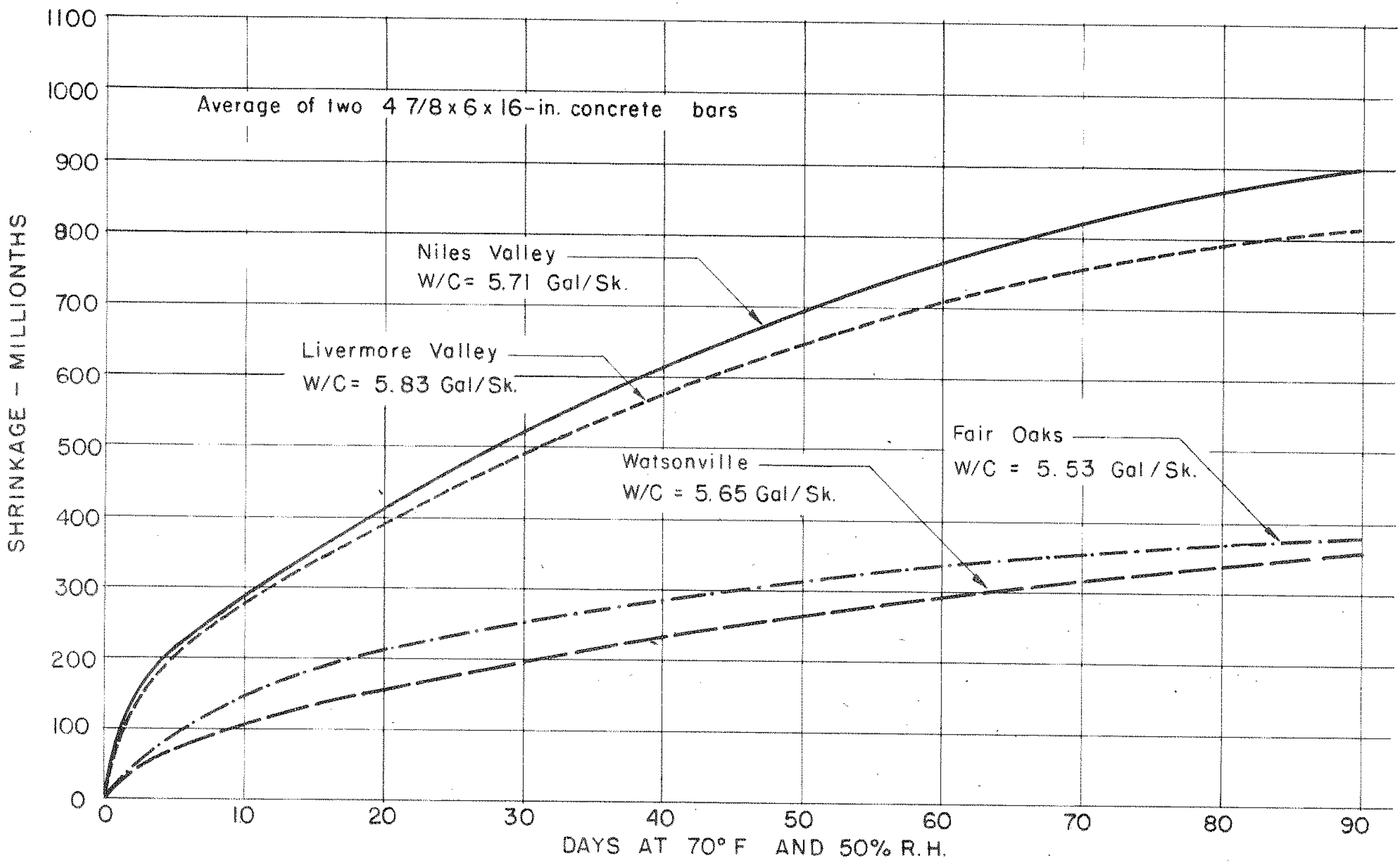


FIG. 3 — EFFECT OF TYPE OF AGGREGATE ON SHRINKAGE OF CONCRETE

5 3/4 Scy., Santa Cruz Type II Cement, 1 1/2-in. Maximum Size Aggregate, 4-in. Slump, Moist Cured for 7 Days

Fig. 3

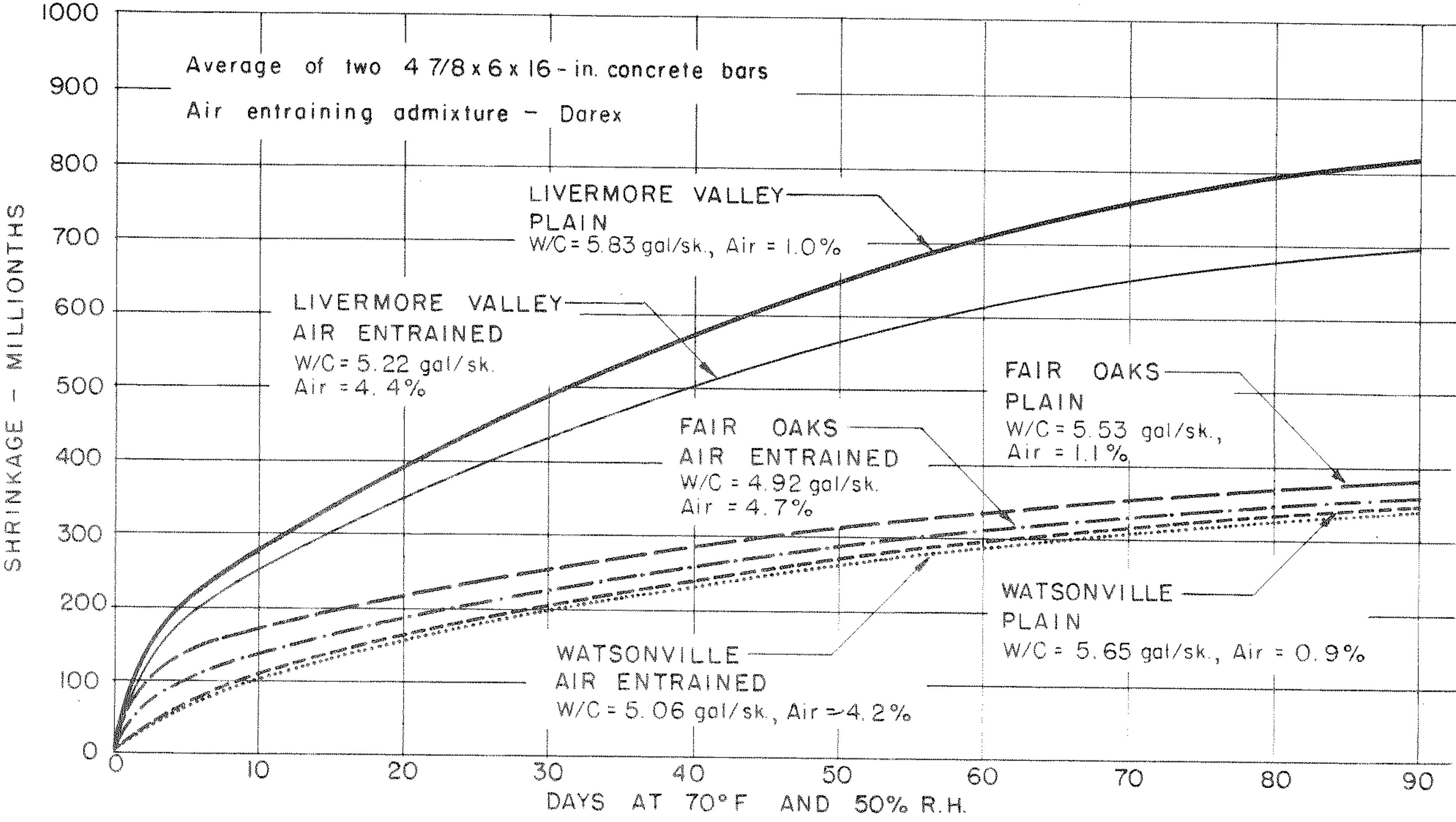
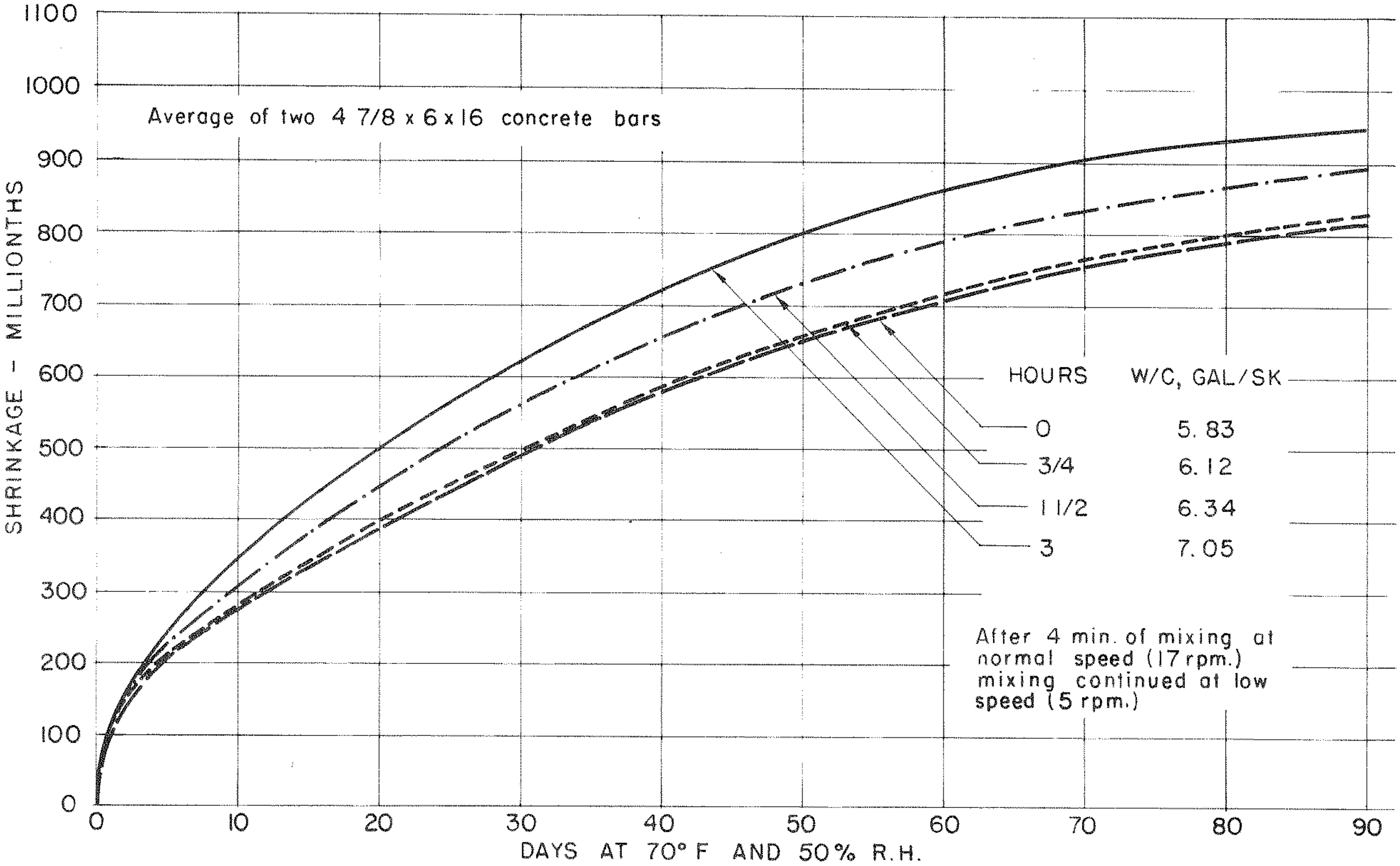


FIG. 4 - EFFECT OF AIR ENTRAINMENT ON SHRINKAGE OF CONCRETE

5 3/4 Scy., Santa Cruz Type II Cement, 1 1/2-in. Max. Size Aggregate,
4-in. Slump, Moist Cured for 7 Days



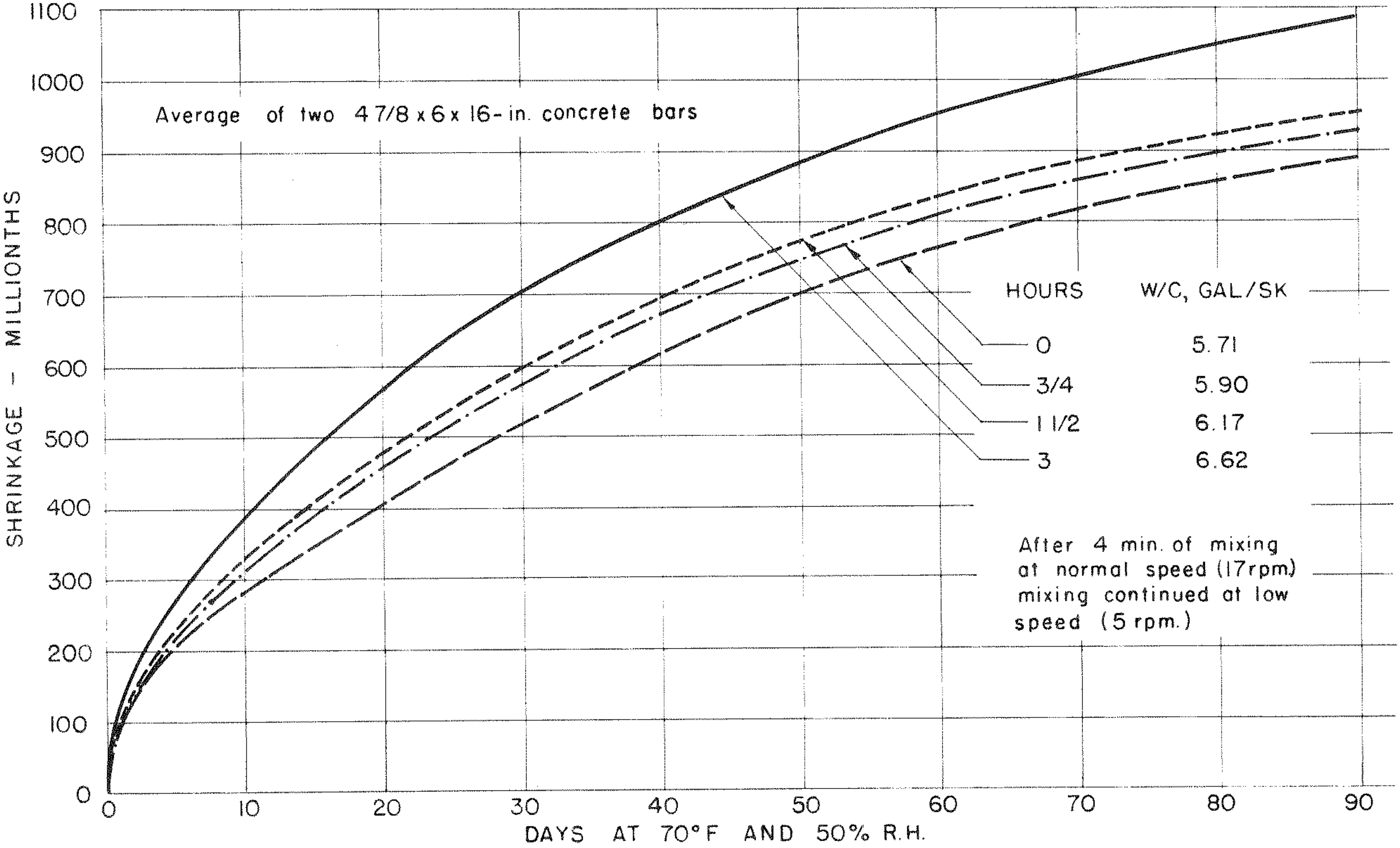
Average of two 4 7/8 x 6 x 16 concrete bars

After 4 min. of mixing at normal speed (17 rpm.) mixing continued at low speed (5 rpm.)

FIG. 5 — EFFECT OF CONTINUED MIXING AND RETEMPERING ON SHRINKAGE OF CONCRETE CONTAINING LIVERMORE VALLEY AGGREGATES

5 3/4 Scy., Santa Cruz Type II Cement, 1 1/2-in. Maximum Size Aggregate, 4-in. Slump, Moist Cured for 7 Days

Fig. 5



Average of two 4 7/8 x 6 x 16-in. concrete bars

After 4 min. of mixing at normal speed (17rpm) mixing continued at low speed (5 rpm.)

FIG. 6 — EFFECT OF CONTINUED MIXING AND RETEMPERING ON SHRINKAGE OF CONCRETE CONTAINING NILES VALLEY AGGREGATES

5 3/4 Scy., Santa Cruz Type II Cement, 1 1/2-in. Maximum Size Aggregate,
4-in. Slump, Moist Cured for 7 Days

Fig.6

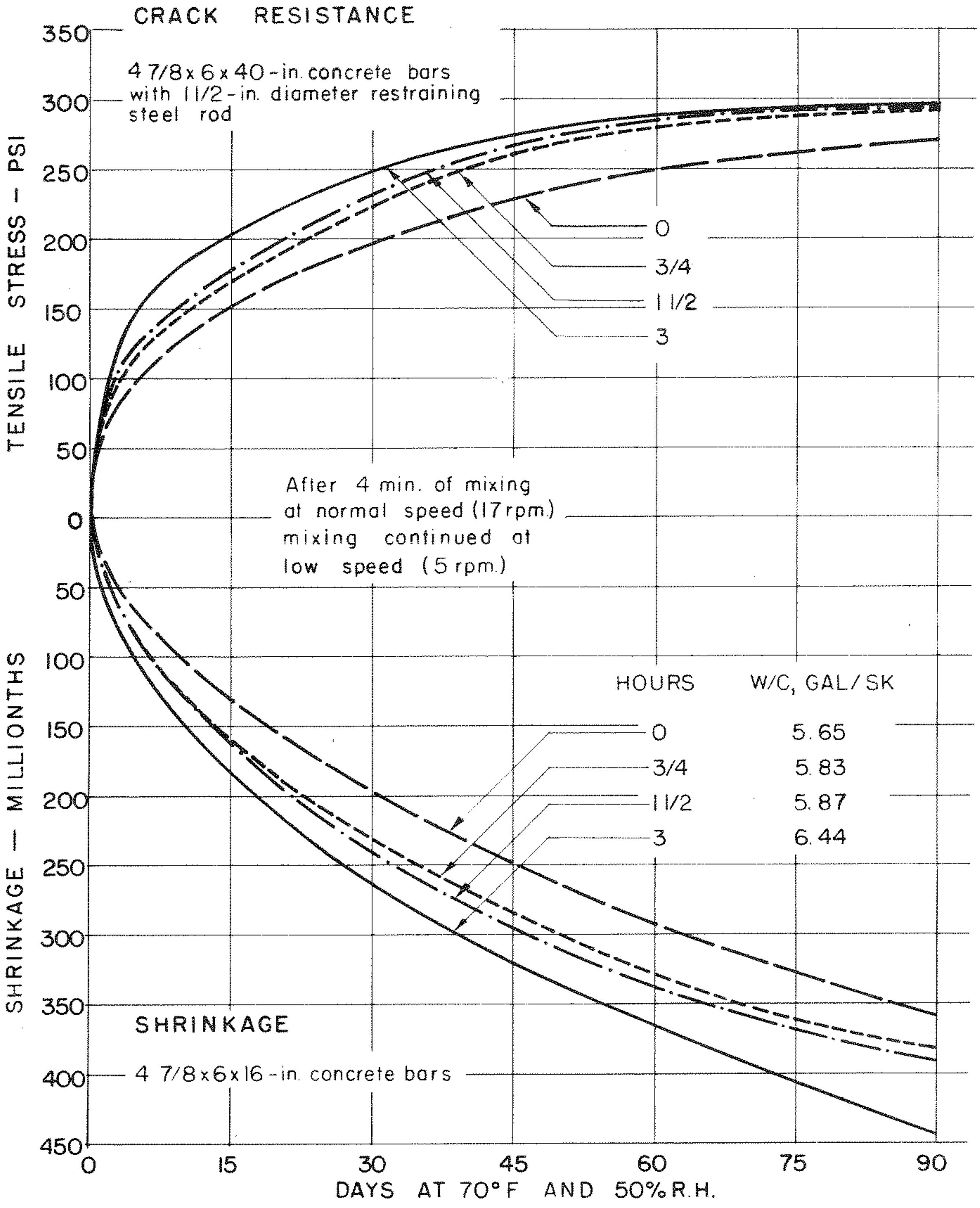


FIG. 7 — EFFECT OF CONTINUED MIXING AND RETEMPERING ON SHRINKAGE AND CRACK RESISTANCE OF CONCRETE CONTAINING WATSONVILLE CRUSHED GRANITE

5 3/4 Scy., Santa Cruz Type II Cement, 1 1/2-in. Maximum Size Aggregate, 4-in. Slump, Moist Cured for 7 Days

Fig. 7

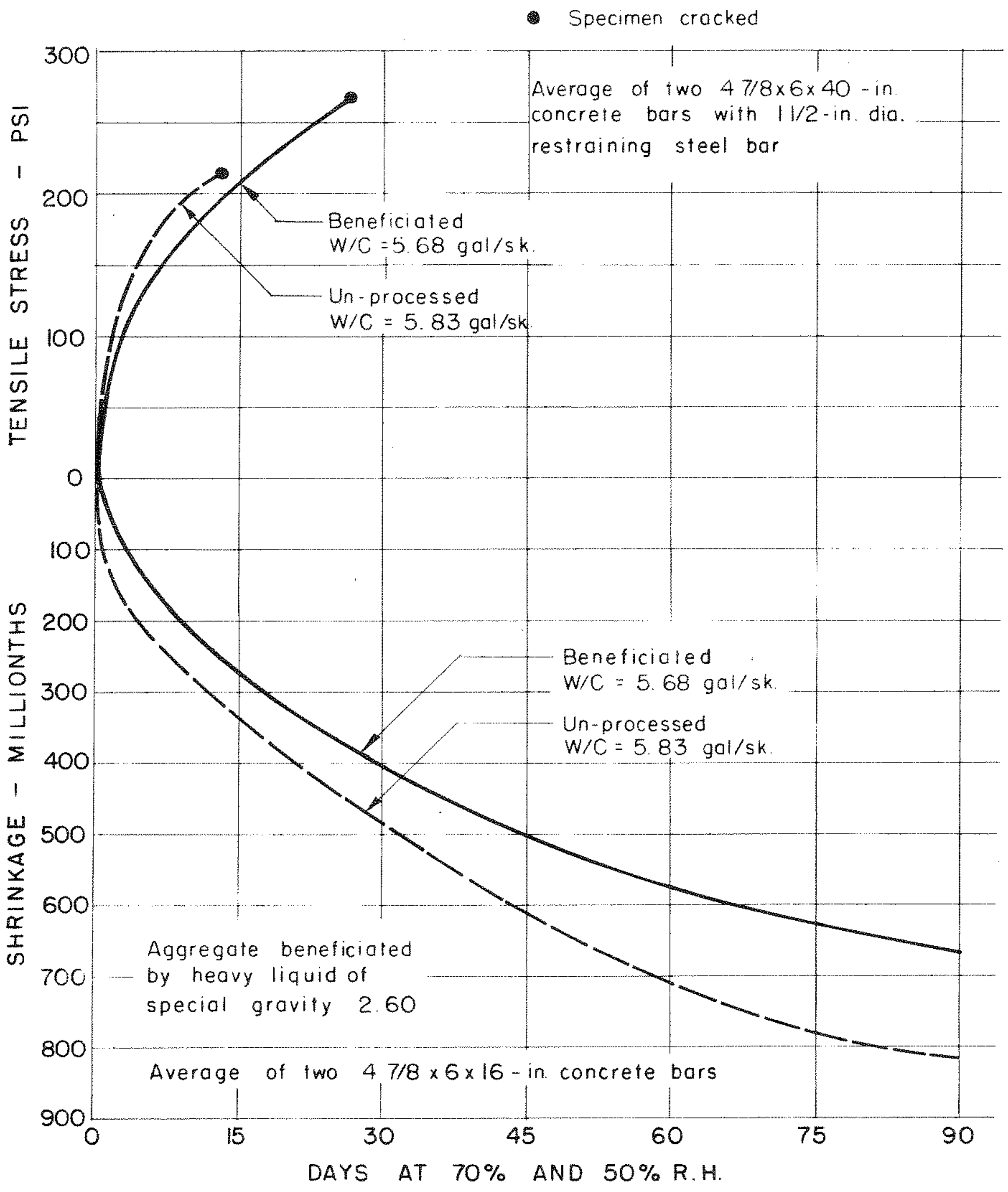


FIG. 8 — EFFECT OF BENEFICIATION OF LIVERMORE VALLEY AGGREGATE ON SHRINKAGE AND CRACK RESISTANCE OF CONCRETE

5 3/4 Scy., Santa Cruz Type II Cement, 1 1/2-in. Maximum Size Aggregate, 4-in. Slump, Moist Cured for 7 Days

Fig. 8

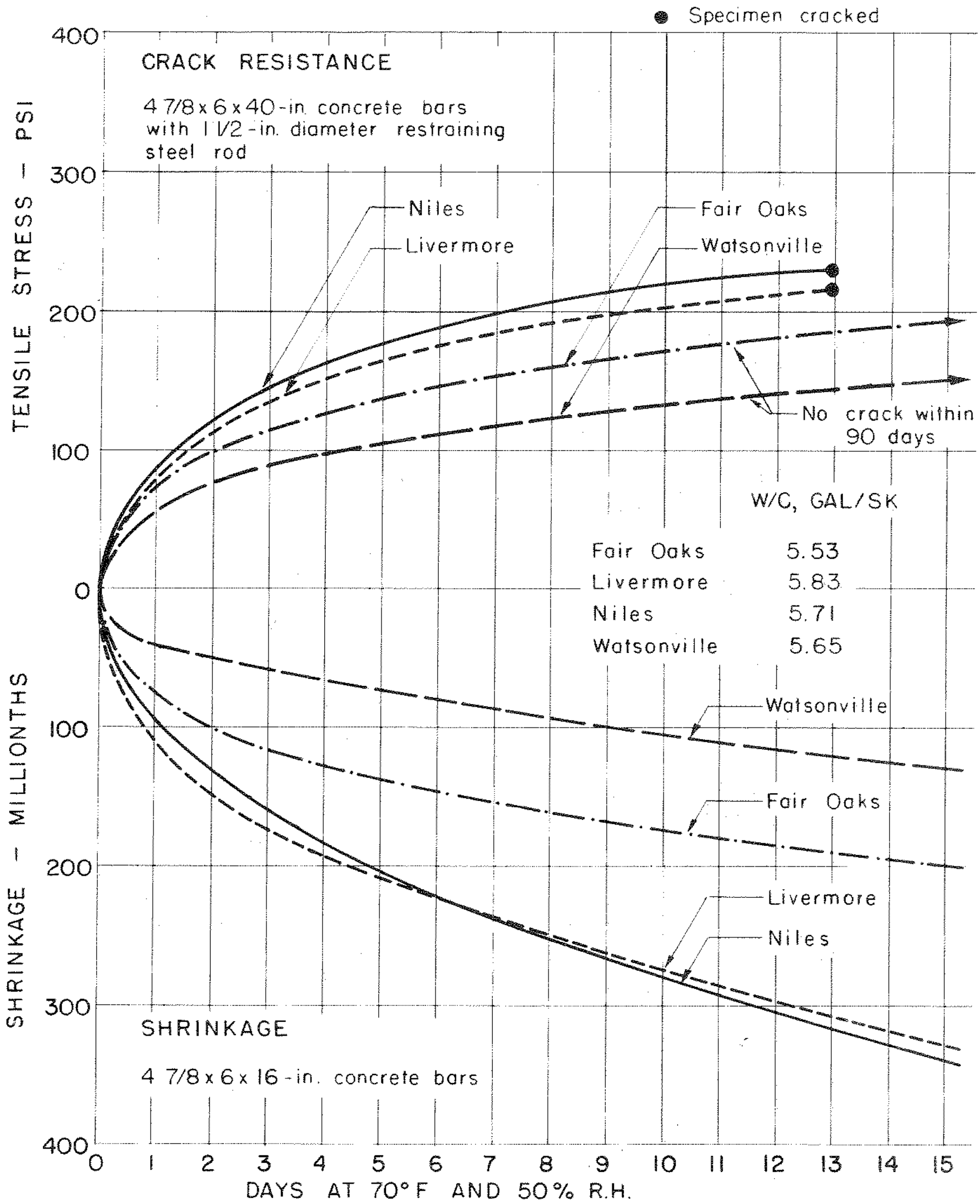


FIG. 9 — EFFECT OF AGGREGATE ON SHRINKAGE AND CRACK RESISTANCE OF CONCRETE

5 3/4 Scy. Santa Cruz Type II Cement; 1 1/2-in. Maximum Size Aggregate; Slump 4-in., Moist Cured for 7 Days

Fig. 9

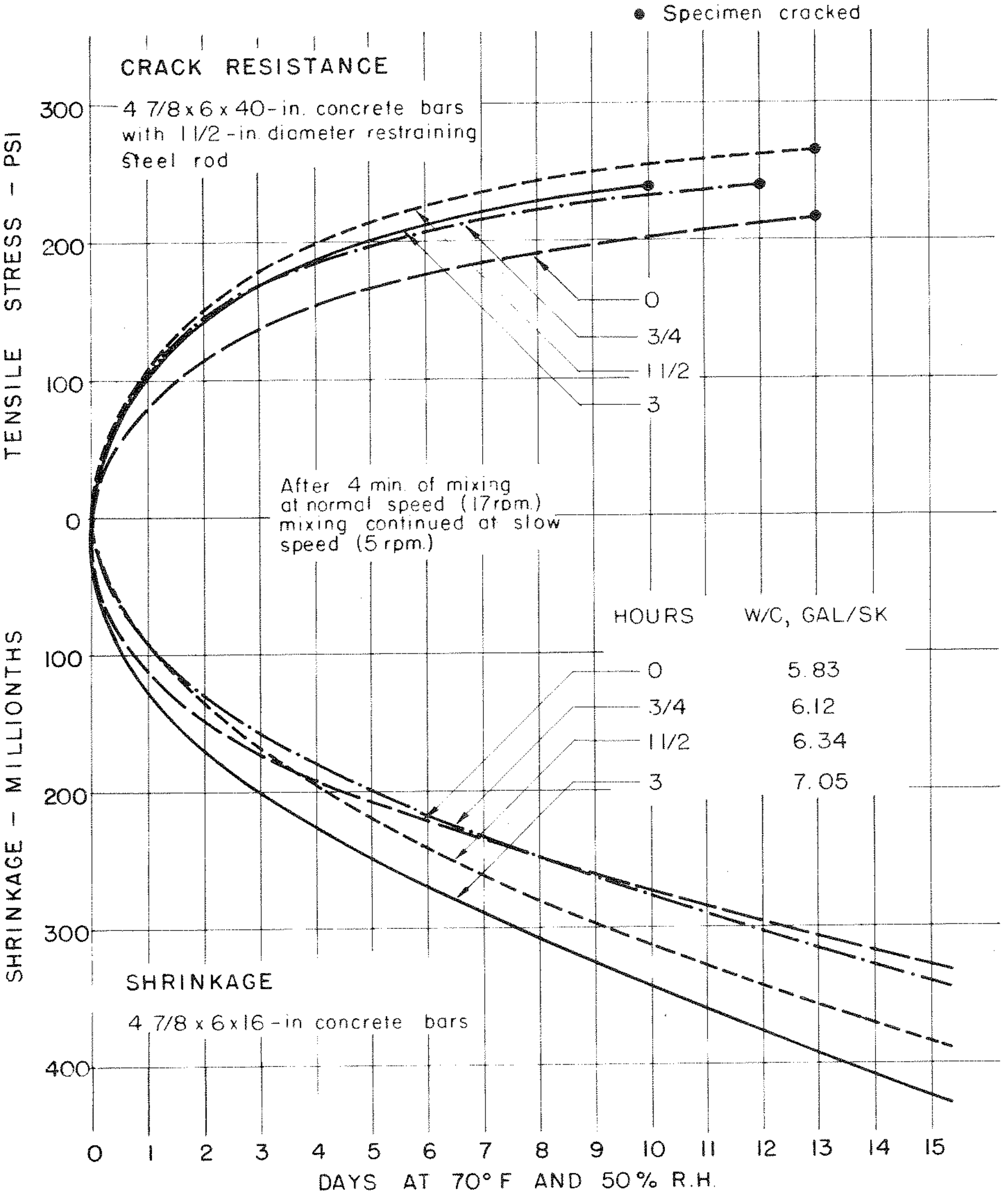


FIG. 10 — EFFECT OF CONTINUED MIXING AND RETEMPERING ON SHRINKAGE AND CRACK RESISTANCE OF CONCRETE CONTAINING LIVERMORE VALLEY AGGREGATE

5 3/4 Scy., Santa Cruz Type II Cement, 1 1/2-in. Maximum Size Aggregate, 4-in. Slump, Moist Cured for 7 Days

Fig. 10

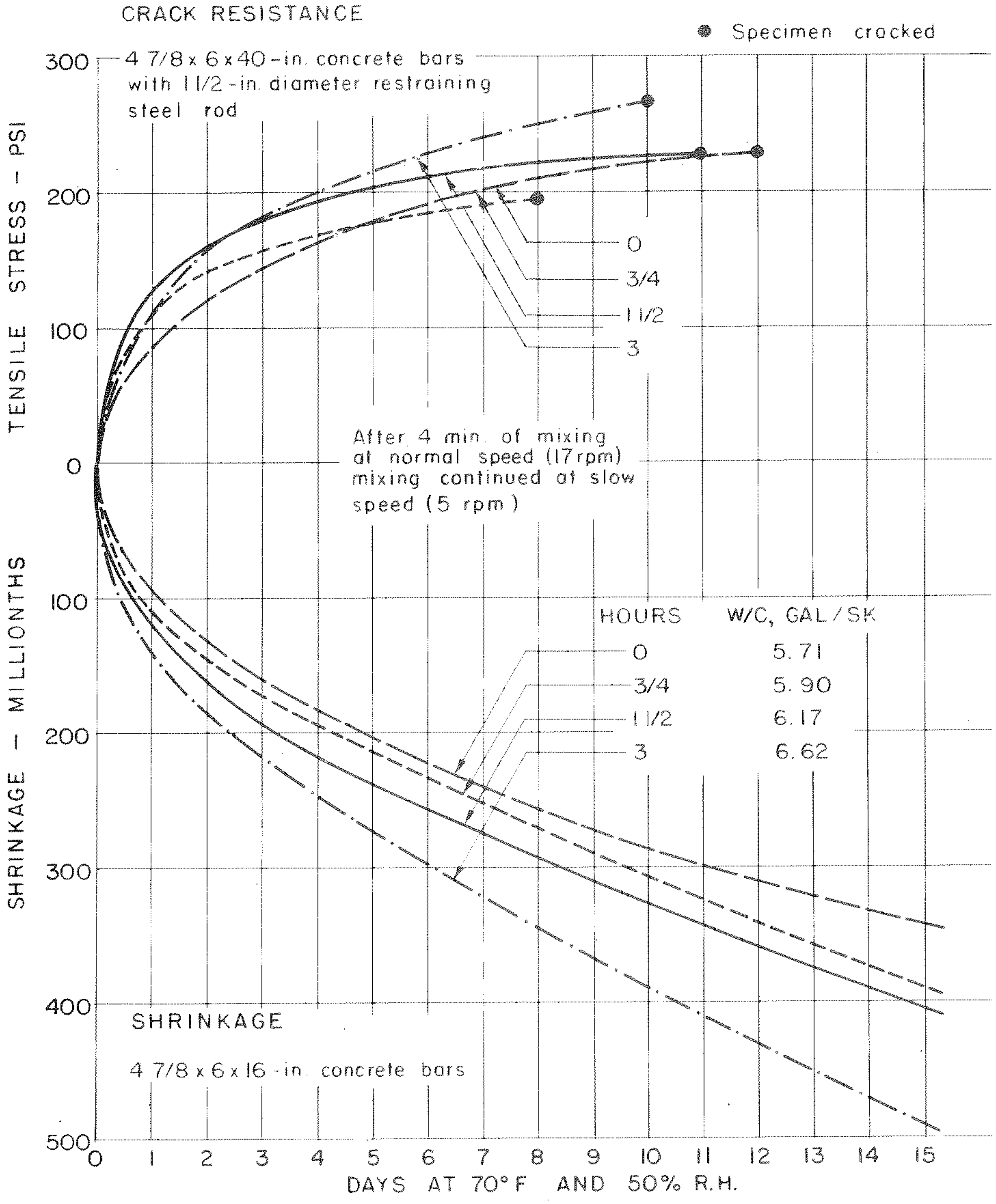


FIG. 11 — EFFECT OF CONTINUED MIXING AND RETEMPERING ON SHRINKAGE AND CRACK RESISTANCE OF CONCRETE CONTAINING NILES VALLEY AGGREGATE

5 3/4 Scy, Santa Cruz Type II Cement, 1 1/2-in. Max. Size Aggregate, 4-in. Slump, Moist Cured for 7 Days

Fig. 11

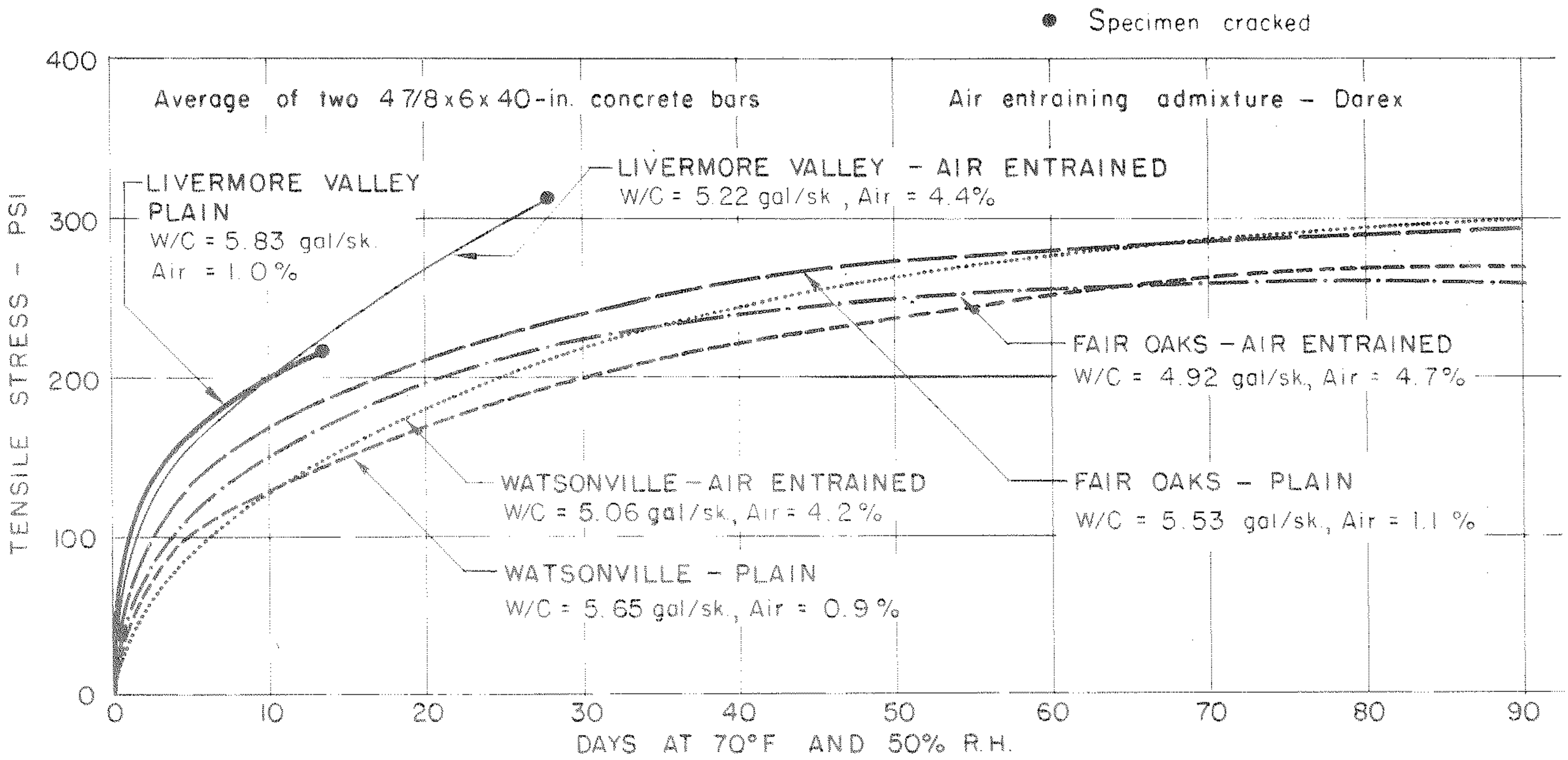


FIG. 12 — EFFECT OF AIR ENTRAINMENT ON CRACK RESISTANCE OF CONCRETE

5 3/4 Scy., Santa Cruz Type II Cement, 1 1/2-in. Maximum Size Aggregate, 4-in. Slump, Moist Cured for 7 Days

Fig. 12