Relationships of Concrete Strength to Maximum Size of Aggregate

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Data contradicting the long-accepted concept that concrete strength is benefited by using the largest maximum size of aggregate practicable have been derived from several studies made in the research laboratory sponsored jointly by the National Sand and Gravel Association and National Ready Mixed Concrete Association at the University of Maryland. These involved coarse aggregates of two types and gradings ranging from $\frac{3}{8}$- to $2\frac{1}{2}$-in. maximum size, with concrete tested for both flexural and compressive strengths.

In the first group of tests, maximum strengths in both flexure and compression were secured with coarse aggregate of about $\frac{3}{4}$-in. maximum size, strengths being lower for the $1\frac{1}{2}$- and $2\frac{1}{2}$-in. sizes. This was in spite of normal reductions in mixing water which caused the water-cement ratio to become less as size of aggregate increased.

The unexpected results of these first tests led to a somewhat more comprehensive investigation involving three percentages of sand with each of the four maximum sizes of one coarse aggregate. Strength tests in this case were made on 8-in. diameter cylinders and 8- by 8-in. beams in addition to the standard 6-in. sizes. The results supported the previous findings, with maximum strengths being secured for a maximum aggregate size of $\frac{3}{4}$-in. Although the larger specimens gave slightly lower strengths, the relationship between aggregate size and strength was the same as for the smaller specimens.

Still further tests, involving compressive strength only, were made using a wider range in sand contents (from 25 to 75 percent of total aggregate) for each of the same four maximum sizes. Again maximum strength was secured with the $\frac{3}{4}$-in. maximum size.

Additional confirmation that large sizes of coarse aggregate may reduce strength was secured in limited tests of concrete screened to remove large aggregate particles. In comparisons involving normal and air-entrained concretes of two different slumps, the portion of concrete passing a $\frac{3}{4}$-in. sieve tested about 7 percent stronger in compression and 15 percent stronger in flexure than the original concrete made with $1\frac{1}{2}$-in. maximum size coarse aggregate.

These tests suggest that, so far as strength is concerned, too much emphasis may have been placed on the desirability of using large sizes of aggregate. In spite of the lower mixing water requirement for large maximum sizes, strength may actually be less than for the intermediate or small sizes. Precisely why this should be so is not evident; probably it is related to the greater surface area for bond and cross-sectional area to resist shear available with the smaller sizes. Use of the smaller sizes has the added advantage of providing more easily placed concrete with less segregation and more reproducible strength tests.

• PROCEDURES FOR SELECTING concrete proportions are based largely on concepts which were developed 40 or more years ago. It is to the credit of the early researchers that there has been little occasion to check or modify these concepts despite changes in concrete technology brought about by such things as stronger cements, air entrainment, and use of drier mixes. For the most part, the problems of producing concrete with a proper balance between economy and performance are susceptible to solution from the same relationships today as were developed by the pioneers in the concrete field.

One danger in continuing to accept basic principles without reexamination is that over a period of years their application may be extended beyond the scope encompassed in their original development. For example, the water-ratio law states that, *for given materials* and workable mixtures, concrete strength in an inverse function of the ratio of water to cement. It has been assumed that the term "given materials" included aggregate from a given source irrespective of its maximum size or grading, although the original researches do not lend themselves to an accurate check of this premise. On the basis of this assumption, it has been generally considered that use of the largest size aggregate available and permissible will produce highest strengths for a given cement factor, inasmuch as mixing water requirement is reduced as size is increased.

By-product data available in reports of several investigations suggest that use of the larger aggregate sizes is not always advantageous to concrete strength. This is particularly true for flexural strength, as shown by Kellermann (*1*), Klieger (*2*), the Corps of Engineers Waterways Experiment Station (*3*), and Hubbard and Lewis (*4*). Researches at the laboratory of the National Sand and Gravel Association and National Ready Mixed Concrete Association at the University of Maryland showed some similarly contradictory effects of aggregate size, suggesting the need for a more thorough investigation. The result was the series of projects described in this report and conducted over the past three years.

SCOPE AND TEST METHODS

There were four groups of tests. The initial investigation, Series 155B, was a comparison among concretes made with two coarse aggregates, differing considerably in flexural-strength-producing properties, each used in four different maximum sizes $\frac{3}{8}$-, $\frac{3}{4}$-, $1\frac{1}{2}$-, and $2\frac{1}{2}$-in. Concrete proportions were selected by conventional methods to provide a cement factor of 6 sacks per cubic yard and a slump of 2 to 3 in. without air entrainment. Proportions of fine and coarse aggregate were made consistent with usual design criteria to produce a degree of workability suitable for placement in pavements. From each batch, one 6- by 12-in. cylinder and one 6- by 6- by 36-in. beam were molded, for standard compressive and flexural strength tests, respectively, at 28 days. Each beam provided two tests, using third-point loading on an 18-in. span. For each aggregate size and type, three batches were made on different days to provide reliable average results.

Two questions arose in connection with indications of the first group of tests. One was whether or not the sand contents used actually produced comparably workable mixes; the other had to do with the possibility that the 6-in. specimens might not have been large enough to give reliable strengths for the larger aggregate sizes. To get information on these possibilities, a more comprehensive investigation, Series 163A, was made with one of the same coarse aggregates used originally. Again the concrete was non-air-entraining with a design cement factor of 6 sacks per cubic yard and a slump of 2 to 3 in. The same four sizes and gradings of coarse aggregate were used, but this time three different sand contents were employed for each. They were selected to produce mixtures ranging from under-sanded to over-sanded. In addition to 6- by 12-in. cylinders and 6-

by 6- by 21-in. beams, 8- by 16-in. cylinders and 8- by 8- by 27-in. beams were molded from each batch. These were used for standard compressive and flexural strength tests at 28 days. Three batches were mixed on different days for each of the 12 test conditions.

In spite of the rather wide range of sand contents used in Series 163A, the data show that they did not always encompass the level required for maximum strength. This led to a third study, Series J-112, in which six different sand ratios, ranging from 25 to 75 percent of total aggregate, were used with each of the four coarse aggregate sizes. The coarse aggregate was the same as in the previous series, and concretes were again non-air-entraining with a design cement factor of 6 sacks per cubic yard. In this case, the slump was raised to 4 to 5 in. to check the possibility that compaction difficulties might have contributed to the unexpected strength indications of the earlier tests. Each of the 24 test conditions was represented by either four or five batches of concrete, from each of which three 6- by 12-in. cylinders were tested for 28-day compressive strength.

One additional group of tests, Series J-118, was made to secure limited data on the influence of the large aggregate particles *per se* on compressive and flexural strength. Both air-entraining and non-air-entraining concretes of 2- to 3-in. and 6- to 7-in. slumps were made with 1½-in. maximum size coarse aggregate. One-half of each batch of freshly mixed concrete was screened over a ¾-in. sieve and comparisons were made between strengths secured with the original concrete and the concrete after removal of the plus ¾-in. aggregate. Three batches were made on different days for each type of concrete. One 6- by 12-in. cylinder and one 6- by 6- by 21-in. beam were molded from each batch for compressive and flexural strength tests at 28 days. The molding of specimens from screened and unscreened concrete was performed simultaneously by two crews to avoid any effects of delay on measured strengths.

In general, procedures employed in mixing, handling and testing the concrete were the same for all groups of tests and were in accordance with applicable standards of the A.S.T.M. The same coarse aggregate gradings (Table 1) were used throughout. The aggregates were separated into individual sizes and recombined to the proper grading for each batch of concrete. The same fine aggregate, a well-graded siliceous sand with a fineness modulus of about 2.7, was used throughout. Within any one series, the sand was from the same lot. Also, for any one series, a given lot of cement, consisting of a blend of equal amounts of five brands, was used.

For Series 155B and J-112, concrete was mixed in a small tilting mixer of 1.0-cu ft capacity. Because of the greater number of specimens in Series 163A and J-118, batches for these groups were mixed in a 3½S tilting mixer. In all cases, the mixing time was 6 min.

All concretes were tested for slump and for unit weight. Air contents were calculated gravimetrically from the unit weights.

DISCUSSION OF TEST RESULTS

Series 155B

Table 2 summarizes the data from Series 155B. Figure 1 shows the relationships of maximum aggregate size to mixing water requirement and strength of the concrete. For both coarse aggregates, there was the expected reduction in water requirement as maximum size was increased. The over-all difference between maximum sizes of ⅜ and 2½ in. was about

TABLE 1

COARSE AGGREGATE GRADINGS USED IN CONCRETE

Sieve Size	Percent Passing			
	⅜-In.	¾-In.	1½-In.	2½-In.
2½ in.	—	—	—	100
2 in.	—	—	—	85
1½ in.	—	—	100	70
1 in.	—	—	72	50
¾ in.	—	100	55	38
½ in.	—	63	35	24
⅜ in.	100	39	22	15
No. 4	0	0	0	0

TABLE 2

CHARACTERISTICS OF FRESH CONCRETE AND RESULTS OF STRENGTH TESTS (SERIES 155B)[1]

Aggregate					Water (gal)				28-Day Strength (psi)		Coeff. of Var.[6] (%)	
Max. Size (in.)	Sand (%)[2]	Fineness Mod.	b/b_0[3]	Cement (s/cy)	Per Cu Yd	Per Sack	Slump (in.)	Air (%)	Comp.[4]	Flex.[5]	Comp.	Flex.
(*a*) COARSE AGGREGATE SOURCE A												
⅜	47.0	4.42	0.58	5.93	39.9	6.74	2.7	2.3	5215	629	1.5	2.1
¾	37.4	5.14	0.68	5.96	35.7	5.98	2.7	1.5	5790	651	2.5	4.8
1½	30.2	5.85	0.77	6.00	32.1	5.35	2.5	0.8	5705	656	0.8	3.8
2½	23.3	6.57	0.82	6.01	29.9	4.98	2.1	0.1	4560	620	1.7	8.1
(*b*) COARSE AGGREGATE SOURCE B												
⅜	53.2	4.22	0.58	5.92	42.2	7.13	2.4	3.0	5045	698	2.0	2.5
¾	43.5	4.89	0.68	5.93	38.3	6.46	2.5	1.8	5660	756	0.9	2.0
1½	33.8	5.68	0.77	5.97	35.1	5.88	2.2	0.7	5780	771	4.5	2.7
2½	29.4	6.27	0.82	5.97	32.8	5.48	2.4	0.3	4630	752	19.0	6.2

[1] Each value is average for three batches mixed on different days.

[2] Percentage of total aggregate.

[3] Equivalent to dry-rodded volume of coarse aggregate per unit volume of concrete.

[4] Average for three 6- by 12-in. cylinders.

[5] Average for six tests of 6- by 6-in. beams (two breaks from 36-in. long beam from each batch).

[6] Coefficients of variation of strength tests: for compression, $v = \frac{100}{\bar{x}}\sqrt{\frac{\Sigma(x-\bar{x})^2}{3}}$; for flexure, $v = \frac{100}{\bar{x}}\sqrt{\frac{2\Sigma(x-\bar{x})^2}{3}}$; in which x is the individual strength test result and $\bar{x}$ is the average strength. The factor of 2 in the flexure calculation makes the values for compression and flexure comparable, because each batch was represented by two flexure tests but only one compression test.

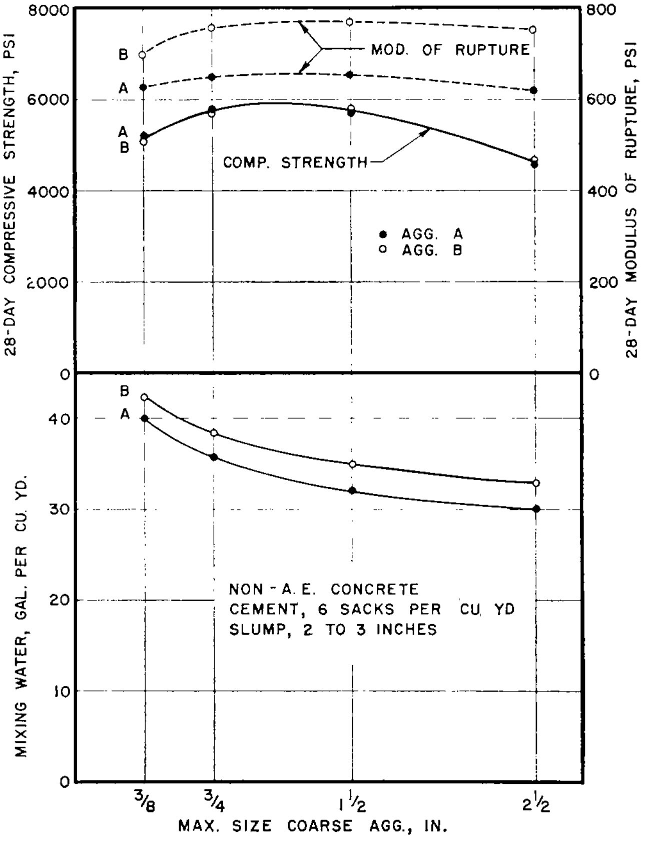

Figure 1. Effect of size of coarse aggregate on strength and mixing water requirement of concrete group 2 (Series 155B).

10 gal per cu yd, which checks well with accepted design criteria.

In spite of reductions in water-cement ratio brought about by the decreased mixing water demand, strength did not improve consistently as maximum aggregate size became greater. For both coarse aggregates, compressive strength was greatest for maximum sizes of ¾ and 1½ in., but was considerably less for 2½ in. In the case of flexural strength, the curves are very flat but show no improvement for sizes above ¾ in.

Series 163A

As mentioned earlier, Series 163A was intended to check on the possibility that the unexpected indications of Series 155B might have been due either to excessively low sand contents or to the use of too small strength test specimens for the largest size aggregate. The data are presented in Table 3 and are shown graphically in Figures 2, 3, and 4.

Figure 2 shows the relationship of sand content to mixing water requirement and strength for each of the four different maximum sizes of coarse aggregate. As would be expected, the water demand increased as sand content was increased for any given size of aggregate. Also, at any given sand content, mixing water increased as coarse aggregate size decreased, demonstrating that water requirement is a function of the over-all fineness of the solid ingredients.

It is evident from the upper portions of Figure 2 that size of specimen had no effect on the relationships between ag-

TABLE 3

EFFECT OF MAXIMUM SIZE OF COARSE AGGREGATE ON STRENGTH OF CONCRETE (SERIES 163A)[1]

								28-Day Strength[4] (psi)			
Aggregate				Water (gal)				Compression		Flexure	
Sand (%)[2]	Fineness Mod.	b/b_0[3]	Cement (s/cy)	Per Cu Yd	Per Sack	Slump (in.)	Air (%)	6 × 12 Cyl.	8 × 16 Cyl.	6 × 6 Beams	8 × 8 Beams
(*a*) ⅜-In. Maximum Size Coarse Aggregate											
50.6	4.35	0.53	6.09	39.3	6.45	2.5	1.9	5600 (3.3)	5465 (2.0)	621 (3.6)	617 (5.3)
59.8	4.05	0.42	6.03	41.7	6.91	2.6	3.0	4950 (1.8)	4760 (1.0)	567 (3.2)	547 (1.6)
69.0	3.75	0.32	5.94	43.1	7.25	1.7	3.9	4360 (0.4)	4200 (2.9)	576 (4.4)	528 (5.5)
(*b*) ¾-In. Maximum Size Coarse Aggregate											
31.3	5.40	0.76	6.13	33.5	5.46	2.3	0.2	6265 (3.8)	6165 (2.8)	633 (4.5)	632 (8.4)
39.0	5.10	0.66	6.05	34.5	5.70	2.6	1.6	6150 (1.3)	5935 (0.8)	615 (7.3)	614 (5.6)
46.8	4.80	0.57	6.04	35.6	5.89	2.4	1.9	5900 (2.5)	5660 (3.3)	613 (4.8)	601 (5.3)
(*c*) 1½-In. Maximum Size Coarse Aggregate											
26.9	6.02	0.82	6.09	31.2	5.13	1.8	—0.6	5835 (4.0)	5740 (1.4)	606 (1.6)	617 (6.6)
33.6	5.72	0.73	6.05	31.9	5.27	2.6	0.4	5955 (2.6)	5810 (2.3)	625 (3.3)	605 (3.6)
40.3	5.42	0.65	6.02	33.3	5.53	2.4	1.2	5960 (1.5)	5655 (3.0)	629 (2.4)	590 (2.6)
(*d*) 2½-In. Maximum Size Coarse Aggregate											
24.2	6.55	0.82	6.07	29.9	4.92	2.3	—0.8	4465 (5.0)	4635 (3.7)	601 (7.6)	593 (6.4)
30.2	6.25	0.74	6.03	30.4	5.04	2.5	0.1	5480 (14.7)	5275 (3.1)	586 (7.0)	580 (2.3)
36.2	5.95	0.67	6.01	31.6	5.25	2.4	0.6	5640 (6.2)	5425 (3.4)	640 (11.1)	591 (7.3)

[1] All concrete made with coarse aggregate from Source A. Each value is average for three batches mixed on different days.

[2] Percentage of total aggregate.

[3] Equivalent to dry-rodded volume of coarse aggregate per unit volume of concrete.

[4] Values in parentheses are coefficients of variation of strength tests; $v = \frac{100}{\bar{x}} \sqrt{\frac{\Sigma(x-\bar{x})^2}{3}}$ where x is the individual strength and $\bar{x}$ is the average strength for three tests of given condition.

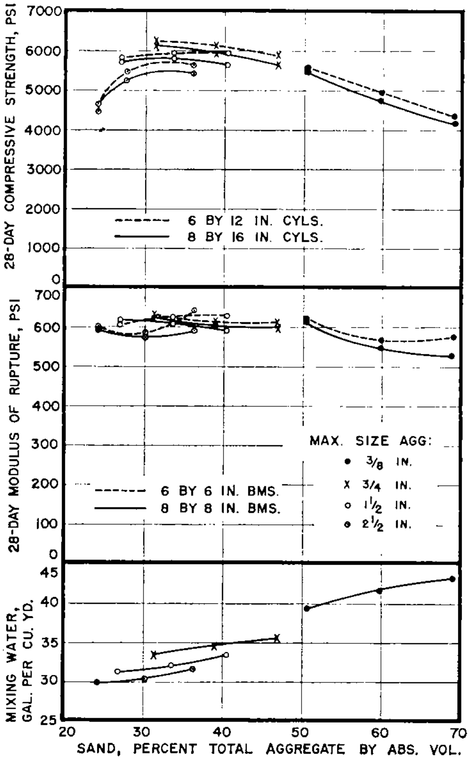

Figure 2. Effect of aggregate size on water requirement and strength of concrete (Series 163A).

gregate size or sand content and measured strength. Although the larger specimens gave consistently lower strength in both compression and flexure, the curves are essentially parallel for the 6-in. and 8-in. sizes.

The curves confirm the indications of Series 155B that increasing maximum size of coarse aggregate above about $\frac{3}{4}$ in. produces no strength advantage and may actually cause reduction. In compression, consistently higher strengths were secured for the $\frac{3}{4}$-in. aggregate than for either the larger or smaller sizes. In flexure, the results are less clear-cut but suggest that strengths for the largest sizes can be matched by sizes down to a maximum of $\frac{3}{4}$ in. and probably even $\frac{3}{8}$ in.

In Figure 3, the data from Series 163A have been replotted in terms of the fineness modulus of total aggregate. In this way, the different aggregate sizes can be compared on a common basis. For example, the water requirement relationship produces a single curve for all maximum sizes, indicating that required mixing water is a function of the over-all fineness of the combined aggregate when cement factor is constant. (Or, because cement is constant, water demand is shown to be a function of the fineness modulus of the solid ingredients.) (*5*)

In the upper portions of Figure 3, strength curves for the different aggregate sizes have been shown separately, but it appears that the relationships of strength to fineness modulus do conform reasonably well to single curves for each specimen size. However, as shown in Figure 6, if greatly over-sanded mixes or very harsh, unworkable mixes had been used, it would be expected that the curves for individual aggregate sizes would break away from the general relationship. In any event, the curves again demonstrate that strengths obtainable with an intermediate maximum aggregate size of about $\frac{3}{4}$ in. are as good or better than with either larger or smaller sizes.

Figure 4 shows water-ratio *vs* strength relationships for Series 163A. Of chief interest here is the fact that a common relationship is not secured for the different maximum aggregate sizes. Although the curves do not all encompass a common abscissa, it appears from their shape and location that strength for a given water-cement ratio becomes progressively higher as maximum aggregate size decreases. In other words, the large sizes of coarse aggregate tend to reduce measured strength. Whether or not the actual measured concrete strength is reduced will depend on whether the reduction in water-cement ratio accompanying the use of the larger sizes is enough to offset the effect of size itself.

Figure 4 again suggests the possibility that the ranges in sand contents did not produce comparable workability for all of the coarse aggregate sizes. For the $1\frac{1}{2}$- and $2\frac{1}{2}$-in. aggregates, the water-ratio curves tend to indicate lower strengths in some cases as water-cement ratio was re-

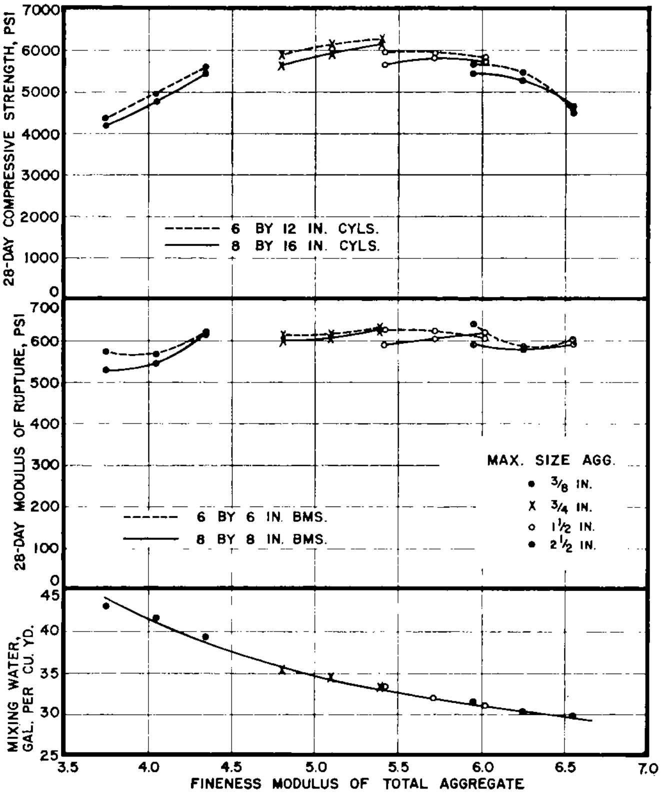

Figure 3. Relationships of fineness modulus to water requirement and strength of concrete (Series 163A).

duced. The likelihood that this anomalous behavior indicated poor workability for the lower sand contents (which corresponded to the lower water-cement ratios) led to a third group of tests.

Series J-112

In Series J-112, a wide range of sand contents (25 to 75 percent of total aggregate) was used with each of the four different maximum sizes to assure that maximum strengths and comparable degrees of workability would be secured. Strength tests were confined to compression. Average data are given in Table 4 and are shown graphically in Figures 5, 6 and 7.

Figure 5 is comparable to Figure 2 previously discussed, and provides the same general indications. Mixing water requirements were lower for the larger maximum sizes of coarse aggregate and increased as sand content increased. Differences in water demand among the different maximum sizes tended to disappear for the very high sand contents, suggesting that in these mixes the coarse aggregate represented a relatively few particles imbedded in mortar, hence its fineness had little effect on water requirement. As in the earlier tests, maximum strength was secured with a maximum size of about $\frac{3}{4}$ in., with lower strengths obtaining for both the larger and smaller sizes.

The relationships of water requirement and strength to fineness modulus of total aggregate are shown in Figure 6. In this case, the relationship of water demand to fineness modulus is not as good

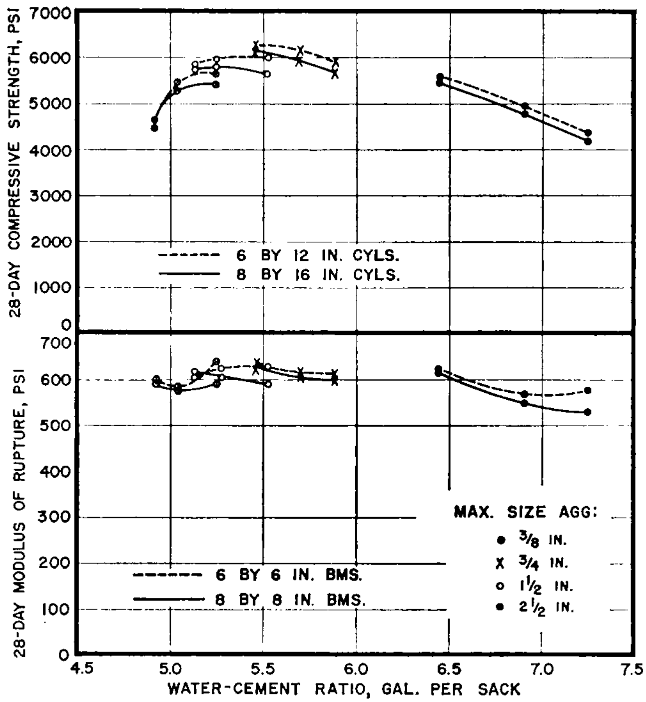

Figure 4. Relationships between water-cement ratio and strength of concrete (Series 163A).

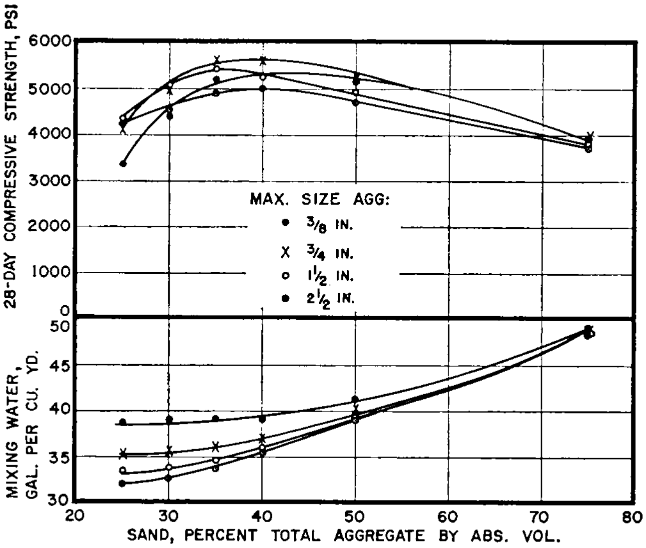

Figure 5. Effects of aggregate size on water requirement and strength of concrete (Series J-112).

TABLE 4

EFFECT OF MAXIMUM SIZE OF COARSE AGGREGATE ON COMPRESSIVE STRENGTH OF CONCRETE (SERIES J-112)[1]

Aggregate				Water (gal)					
Sand (%)[2]	Fineness Mod.	b/b_0[3]	Cement (s/cy)	Per Cu Yd	Per Sack	Slump (in.)	Air (%)	28-Day Comp. Str.[4] (psi)	Coeff. of Var.[5] (%)
			(*a*) ⅜-IN. MAXIMUM SIZE COARSE AGGREGATE						
25	5.16	0.84	5.98	38.6	6.45	7.1	0.3	3360	4.4
30	4.99	0.71	6.00	39.1	6.51	5.3	0.5	4370	5.0
35	4.82	0.72	5.99	39.1	6.52	3.7	0.7	5165	4.7
40	4.65	0.66	6.00	39.3	6.55	4.8	1.2	5305	2.4
50	4.32	0.53	5.96	41.2	6.91	5.1	2.4	5150	3.1
75	3.47	0.24	5.98	49.1	8.21	4.8	3.8	3930	3.1
			(*b*) ¾-IN. MAXIMUM SIZE COARSE AGGREGATE						
25	5.61	0.83	6.03	35.2	5.84	5.1	—0.3	4130	9.6
30	5.42	0.77	6.03	35.6	5.90	4.3	0.0	4990	5.9
35	5.22	0.70	6.01	36.2	6.01	4.5	0.7	5600	3.1
40	5.02	0.64	6.01	37.0	6.15	4.5	1.2	5580	2.1
50	4.63	0.52	6.00	40.3	6.72	5.2	1.9	5195	1.9
75	3.62	0.24	6.01	48.6	8.09	4.4	3.9	3980	2.7
			(*c*) 1½-IN. MAXIMUM SIZE COARSE AGGREGATE						
25	6.08	0.83	6.03	33.4	5.54	5.2	—0.3	4350	7.1
30	5.85	0.77	6.02	33.6	5.58	4.0	—0.1	5075	3.1
35	5.62	0.70	6.03	34.6	5.74	4.5	0.3	5425	3.1
40	5.39	0.64	6.02	36.0	5.98	4.7	0.8	5230	2.5
50	4.94	0.52	6.01	39.5	6.57	5.0	1.6	4915	2.0
75	3.78	0.23	5.99	48.4	8.08	4.8	3.8	3820	2.5
			(*d*) 2½-IN. MAXIMUM SIZE COARSE AGGREGATE						
25	6.47	0.80	6.05	32.0	5.28	5.3	—0.4	4230	6.0
30	6.22	0.74	6.04	32.7	5.42	4.4	—0.2	4545	5.9
35	5.96	0.67	6.04	33.7	5.58	4.4	0.2	4895	4.5
40	5.71	0.62	6.04	35.4	5.86	4.3	0.5	5000	5.4
50	5.21	0.49	6.00	39.1	6.51	4.8	1.3	4705	5.3
75	3.91	0.22	6.02	48.6	8.08	4.4	3.3	3735	3.1

[1] All concrete made with coarse aggregate from Source A. Each value is average for either four or five batches of concrete mixed on different days.

[2] Percentage of total aggregate.

[3] Equivalent to dry-rodded volume of coarse aggregate per unit volume of concrete.

[4] Average for either 12 or 15 6- by 12-in. cylinders (3 from each batch).

[5] $v = \frac{100}{\bar{x}}\sqrt{\frac{\Sigma(x-\bar{x})^2}{n}}$ where x is the individual strength, $\bar{x}$ is the average strength for given condition, and n is the number of cylinders for that condition (either 12 or 15).

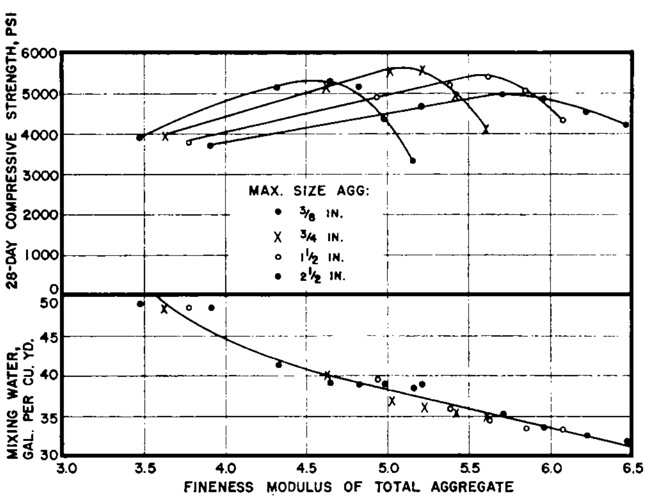

Figure 6. Relationships of fineness modulus to water requirement and strength of concrete (Series J-112).

as that shown in Figure 3 for Series 163A. Particularly at the high sand contents (low fineness moduli), there is a tendency for all maximum sizes to require the same amount of mixing water rather than to conform to the single-curve relationship of water to fineness modulus.

The upper portion of Figure 6 shows that the range in sand contents was sufficiently great to produce peak strengths for each maximum size of coarse aggregate. Points to the left of the peak for any one size represent mixes that were over-sanded, hence required additional water; those to the right represent mixes that were so harsh as to cause reduced strengths. It is of interest to compare the fineness moduli corresponding to maximum strengths in Figure 6 with recommended values used in selecting proportions (*5*), as follows:

Max. Size Coarse Agg. (in.)	Fineness Mod. of Agg.	
	Recommended	For Max. Str., Series J-112
⅜	4.1	4.4
¾	5.1	5.1
1½	5.7	5.6
2½	6.2	5.8

For the smallest size, the fineness modulus indicated as optimum in Series J-112 was higher than the recommended value. For the intermediate sizes, agreement is very good and, for the largest size, Series J-112 indicated a lower value. It appears, therefore, that current design criteria may result in over-sanding for mixes with small-size aggregate and under-sanding for the large sizes.

Figure 7 shows the water-ratio-strength relationships for Series J-112. These also support the earlier data, indicating progressively reduced strengths for a given water-cement ratio as coarse aggregate size is increased. The sharp drop in strength toward the left end of each curve reflects the lack of adequate workability for mixes with the lowest sand contents.

Series J-118

Additional limited data on the effects of large-size aggregate particles were secured in Series J-118, where comparisons were made between concrete with 1½-in. maximum size coarse aggregate and the same concrete after screening to remove the plus-¾-in. sizes. The average data are given in Table 5.

For these tests, companion concrete samples with and without the larger size aggregate particles both contained the same mortar and should be expected, therefore, to have similar strength properties except for the effects of the coarse aggregate. For all four classes of concrete — air-entraining and non-air-entraining, of high and low slump — strengths were improved by removing the plus-¾-in. particles. The increase averaged 7 percent in compression and 15 percent in flexure. These results are consistent with the experience of others (*7*) and demonstrate that the large particles actually do disrupt the continuity of the concrete and tend to reduce its strength.

Reproducibility of Strength Tests

Tables 2, 3, 4, and 5 give coefficients of variation for replicate strength tests of each type of concrete studied. These represent such small populations of data (from three to five batches of concrete for each condition) that, individually, they have little significance as to factors influencing reproducibility (*8*). Considered together, however, they provide some interesting indications.

Altogether in Series 155B, 163A, and J-112, there were 141 strength tests for each of the four maximum sizes of coarse aggregate. Averaging the coefficients of variation from Tables 2, 3 and 4 yields the following comparison on the relationship of aggregate size to reproducibility of strength tests:

Max. Size Coarse Agg. (in.)	Av. Coeff. of Var. of Strength Tests(%)
⅜	3.0
¾	3.9
1½	3.0
2½	6.5

The three smaller sizes produced comparable uniformity, but the largest size (2½-in.) gave more variable strengths.

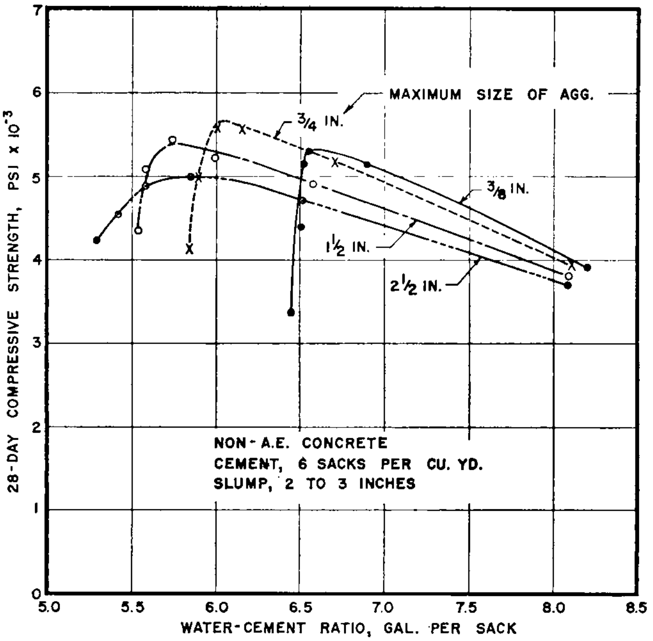

Figure 7. Relationship between water-cement ratio and concrete strength (Series J-112).

TABLE 5

EFFECTS OF REMOVAL OF LARGE AGGREGATE PARTICLES ON PROPERTIES OF CONCRETE (SERIES J-118)[1]

	Non Air-Ent. Conc.				Air-Ent. Conc.			
	2-3-In. Slump		5-6-In. Slump		2-3-In. Slump		5-6-In. Slump	
Item	As Mixed	Scr.	As Mixed	Scr.	As Mixed	Scr.	As Mixed	Scr.
Cement (sacks/cu yd)	5.52	7.11	5.56	7.34	5.45	7.04	5.48	7.11
Water (gal/cu yd)	32.7	42.1	33.7	44.5	28.8	37.2	31.3	40.3
Slump (in.)	2.8	6.2	5.2	8.4	3.1	4.6	4.9	7.6
Air (%)	1.0	1.2	0.7	0.9	5.4	7.1	5.3	6.6
28-Day strength (psi):								
Compressive	5145	5485	5040	5470	4535	4745	3990	4210
Flexural	575	667	554	668	556	623	541	596
Coeff. of var.[2] (%):								
Compression	1.7	0.7	3.4	3.1	4.2	6.5	5.5	3.6
Flexure	6.9	2.5	5.2	4.4	1.8	1.0	2.4	2.9
28-Day strength (%):								
Compressive	100	107	100	109	100	105	100	106
Flexural	100	116	100	121	100	112	100	110

[1] All concrete made with coarse aggregate from Source A. Each value is average for three batches mixed on different days. Concrete made with 1½-in. maximum size aggregate; half of batch screened to remove plus-¾-in. sizes before testing; remaining half tested as mixed.

[2] $v = \frac{100}{\bar{x}}\sqrt{\frac{\Sigma(x-\bar{x})^2}{3}}$ where x is the individual strength and $\bar{x}$ is the average strength for the three tests.

This probably reflects the influence of size of specimen in relation to aggregate size, but does demonstrate that use of the larger aggregate sizes can be expected to reduce uniformity of tests and hence complicate the interpretation of results.

The data from Series 155B, 163A, and J-118, where both compression and flexure tests were made, show the former to be slightly more uniform than the latter. The average coefficient of variation for compressive strength tests was 3.5 percent, compared with 4.5 percent for flexural strength tests. Increasing the size of specimens produced only slight improvement in uniformity, as shown by the data from Series 163A. The average coefficient of variation for 6-in. specimens was 4.5 percent; for 8-in., 3.8 percent.

In Series J-112, coefficients of variation became progressively smaller as percent of sand in terms of total aggregate was increased, although differences among sand contents above 35 percent were too small to be significant. The average coefficients of variation were as follows:

Sand Cont. (% Tot. Agg.)	Av. Coeff. of Variation (%)
25	6.8
30	5.0
35	3.8
40	3.1
50	3.1
75	2.8

The screened concrete of Series J-118 produced slightly, but probably not significantly, more uniform strengths than the untreated concrete containing the larger coarse aggregate sizes. Average coefficients of variation were 3.9 and 3.1 percent for the untreated and screened concretes, respectively.

SUMMARY AND CONCLUSION

Principal indications of the tests were as follows:

1. The progressive reduction in mixing water requirement of concrete as maximum size of coarse aggregate increases was confirmed.

2. In spite of the normal water reductions, increasing maximum size of coarse aggregate above about $\frac{3}{4}$ in. did not improve either flexural or compressive strength. Considering all of the data, highest strengths were secured with a maximum size of $\frac{3}{4}$ in., slightly lower and about equal strengths with the $1\frac{1}{2}$- and $\frac{3}{8}$-in. sizes, and lowest strengths with the $2\frac{1}{2}$-in. maximum size.

3. Careful check tests demonstrated that the effects of aggregate size on strength were not caused by extraneous influences of specimen size or proportions of fine and coarse aggregate.

4. The same effects of aggregate size were observed for two coarse aggregates differing considerably in physical properties and flexural strength development.

5. Reproducibility of strength tests was poorer for $2\frac{1}{2}$-in. maximum size coarse aggregate than for smaller sizes; was poorer for flexural than for compressive strength; was very slightly poorer for 6-in. than for 8-in. specimens; became poorer as sand content of the concrete was reduced; and was very slightly improved by screening to remove the larger coarse aggregate sizes.

These investigations suggest that changes in maximum size of coarse aggregate involve two opposing influences on strength. As coarse aggregate size is increased, mixing water requirement is reduced, lowering the water-cement ratio and tending to improve strength. Apparently, at the same time, inclusion of the large aggregate particles is in itself detrimental to strength, probably because of reduced surface area for bond and reduced total cross-section of particles to resist shear. For increases in size up to about $\frac{3}{4}$ in. the effect of reduced water predominates and strength increases. Beyond this point the advantage of reduced water is more than offset by the large pieces of aggregate which, in themselves, cause strength reduction.

The advantages in strength test reproducibility for smaller aggregate sizes probably reflect the effect of ratio of specimen size to size of aggregate particles. Although the variability of tests for concrete with large-size aggregate is probably not significant in terms of uniformity in the structure, it would tend to complicate the interpretation of tests used to determine acceptability of concrete. Also, segregation is aggravated by use of large-size aggregate.

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DISCUSSION

J. E. GRAY, *Engineering Director, National Crushed Stone Association.* — It is assumed that the data given in this paper apply to pavement concrete, because the authors state: "Properties of fine and coarse aggregate were made consistent with usual design criteria to produce a degree of workability suitable for placement in pavements." The essential requirements for pavement concrete are durability, high flexural strength, and low volume change or shrinkage. Of the four series of tests reported, two were non-air-entraining concrete of paving consistency (1.7 to 2.6 in. slump), with compressive and flexural strength results; the third was non-air-entraining, high slump (4.3 to 7.1 in.), with compressive strength tests only; and the fourth was air-entrained concrete of paving consistency but compared the strength-making properties of 1½-in. maximum size aggregate having a cement factor of 5.5 sacks with ¾-in. maximum size aggregate having a cement factor of 7.1 sacks. The only flexural strength data submitted that are comparable involve two aggregates in 6-sack non-air-entraining concrete, as follows:

Aggregate A	Series 155B	Series 163A	Average
¾-in. max. size	651	633	642
1½-in. max. size	656	629	642
2½-in. max. size	620	640	630
Aggregate B			
¾-in. max. size	756	—	756
1½-in. max. size	771	—	771
2½-in. max. size	752	—	752

Thus, the authors' data show that for the two particular aggregates used, there is no significant reduction in flexural strength with the larger maximum sizes. Because the characteristics of the coarse aggregate have such a marked influence on the flexural strength of concrete, it has been advocated by many engineers that pavement concrete should be designed for a given flexural strength based on laboratory tests of the particular materials involved.

TABLE 6

CHARACTERISTICS OF NCSA TEST CONCRETE

Coarse Aggregate			
Maximum size	2 in.	1 in.	½ in.
Gradation:			
Total % passing 2½ in.	100	—	—
2 in.	98	—	—
1½ in.	75	100	—
1 in.	52	98	—
¾ in.	36	70	100
½ in.	20	42	95
⅜ in.	13	28	55
No. 4	2	5	8
No. 8	0	0	0
Sp. gravity, bulk, dry		2.96	
Absorption (%)		0.47	
b_0, sol. vol. coarse agg. per unit vol. coarse agg.	0.61	0.59	0.56
Fine Aggregate			
Fineness modulus		2.80	
Sp. gravity, bulk, dry		2.56	
Absorption (%)		1.85	
Mix Proportions and Test Results			
Coarse agg. max. size	2 in.	1 in.	½ in.
Cement factor (s/cy)	6.01	5.93	5.94
Water content (gal/cy)	31.9	34.1	37.0
Coarse aggregate (lb/cy)	2380	2065	1630
Fine aggregate (lb/cy)	915	1075	1365
Air content; (%)	4.5	6.3	6.7
Slump (in.)	2¼	2¾	2¼
Flex. str. 14-day av. (psi)	560	485	470
Comp. str. 28-day av. (psi)	4280	4240	3970
Coeff. therm. exp. (in./in./°F $\times 10^{-6}$)	3.1	3.4	3.4
Drying shrinkage[1] (%):			
2 weeks	0.019	0.024	0.029
4 weeks	0.024	0.032	0.041
8 weeks	0.029	0.039	0.050
12 weeks	0.032	0.046	0.058
16 weeks	0.036	0.049	0.064
24 weeks	0.038	0.055	0.073

[1] Exposure to air in laboratory after 14 days moist curing.

Strength is only one characteristic of concrete that affects pavement performance. Drying shrinkage is of importance in that it has a pronounced effect on the frequency of cracking and slab warping or curling. Hveem and Tremper (*9*) state: "The integrity and smoothness of the pavement can be prolonged if the characteristic shrinkage of concrete can be reduced." Surely, any change in the properties of concrete that would increase shrinkage can only be viewed with alarm. A reduction in the maximum size of aggregate increases the amount of shrinkage and therefore is detrimental to pavement performance. A preliminary series of tests made in the laboratories of the National Crushed Stone Association lends confirming data to the effect of maximum size of aggregate on drying shrinkage. Moreover, these data show, for the particular coarse aggregate used, no reduction but rather an increase in flexural strength with the largest maximum size aggregate. The concrete was proportioned in accordance with *NCSA Bulletin No. 11*, Revised, for a constant cement factor, slump, and workability with three maximum sizes of trap rock coarse aggregate, Potomac River sand of 2.80 fineness modulus, and Darex as the air-entraining agent. The data on the aggregates and the concrete are given in Table 6.

These data on drying shrinkage are most pertinent, for they apply to air-entrained concrete and confirm the work of other investigators (*10*) whose work was with non-air-entraining concrete. They show that drying shrinkage of 2-in. and $\frac{3}{4}$-in. (by interpolation) maximum size aggregate may be 0.038 and 0.064 percent, respectively, which is a 69 percent increase in shrinkage due to the smaller aggregate.

On the basis of all the data presented, there appears to be no sound basis for advocating small maximum sizes of aggregate for pavement concrete.

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D. W. LEWIS, *Chief Engineer, National Slag Association.* — The comprehensive study reported in this paper demonstrates that some of the ideas developed many years ago regarding concrete strengths may not always be correct when applied to present-day concrete mixes. The data reported amply justify the authors' conclusion that for their test conditions increases in maximum size of coarse aggregate above about $\frac{3}{4}$ in. did not result in increased flexural or compressive strength.

However Mr. Gray reports data showing higher strengths for the larger size of aggregate particularly in flexure. Both the data reported by the authors and those contained in Mr. Gray's discussion are based on a single test age — and therefore a single general strength level of the concrete.

Data on the effect of aggregate size on concrete strengths obtained in the National Slag Association Research Laboratory were reported by Lewis and Hubbard (*4*). These data included test results at ages of 7, 14, 28, 90, and 365 days, and led to the conclusion that: "Variations in maximum size of the slag coarse aggregate from $\frac{3}{4}$ in. to 2 in. in 6-sack mixes had no marked effect on the strength in either compression or flexure." Mixes used were comparable in cement content and slump with those of Messrs. Walker, Bloem, and Gaynor, and Mr. Gray, and were made with air-entraining cement.

Study of the data obtained for the blast furnace slag mixes indicates that the optimum size of aggregate for maximum strength was not a constant, but varied with the age at time of tests. Tests conducted at early ages correspond to those reported by Mr. Gray, and show the larger size of aggregate to pro-

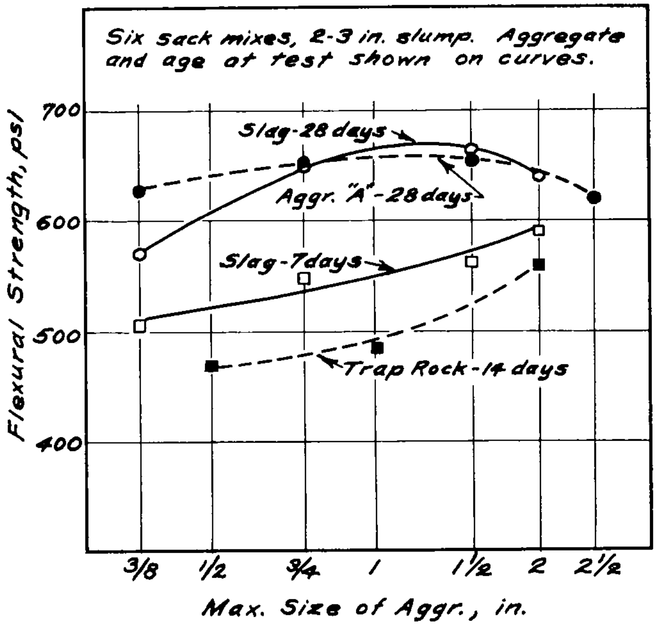

Figure 8. Effect of aggregate size on flexural strength of concrete for different aggregates and test ages.

duce the stronger concrete. At later test ages — and, of course, higher concrete strengths — the best results were obtained with smaller top sizes of coarse aggregate.

These comparisons for flexural strength are shown in Figure 8, where the 7- and 28-day tests with slag are plotted along with Mr. Gray's data on the trap rock concrete and that of the authors for aggregate A in Series 155B. Data on flexural strengths of the slag concrete shown here are based on mixes made with various sizes of aggregate on the same day rather than on over-all averages reported in the original paper. When tested at 7 days age, the slag concrete showed the same trends as the trap rock concrete. Tested at the age of 28 days, strengths and curve shape were comparable to those of aggregate A.

In compressive strength tests, which were less variable than flexure results, the trend of decreasing optimum size of aggregate with increased curing time is even more marked. Figure 9 shows the data for compressive strength of the blast furnace slag concrete at 7 and 28 days and 1 year, again compared to the curves for the trap rock and aggregate A concretes. Although not shown, the test results for 14 and 90 days fall between the other curves indicating a continuous change. In compression, the 2-in. top size slag aggregate had the highest strength at 7 and 14 days; the $1\frac{1}{2}$-in. aggregate was highest at 28 and 90 days; and after 1 year of curing the highest strength was produced by the $\frac{3}{4}$-in. top size.

These results suggest that there is no one answer to the question: "What top

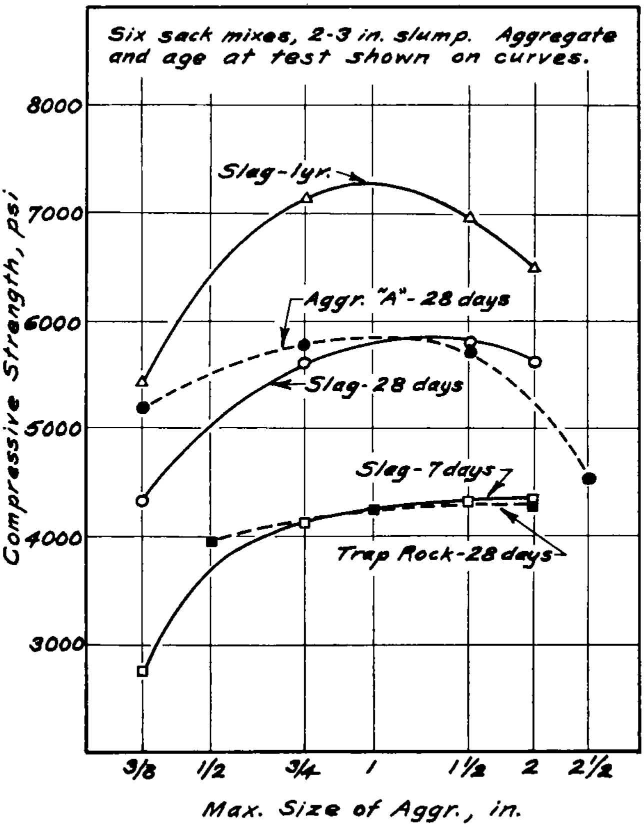

Figure 9. Effect of aggregate size on compressive strength of concrete for various aggregates and test ages.

size of aggregate will produce the best strength for a given combination of cement and aggregate?" With the lower concrete strengths, large sizes of aggregate would appear to be advantageous; at higher strength levels the smaller sizes of aggregate seem to be best.

It seems probable that for any given combination of cement and aggregate similar trends might be found if a wide range of strengths were covered by the tests. The strength level at which a given aggregate size would show the highest strength, however, should not be expected to be the same for different combinations of materials. As shown in Figure 9, for example, the $\frac{3}{4}$-in. size was "optimum" for aggregate A at compressive strengths less than 6,000 psi, whereas the $\frac{3}{4}$-in. blast furnace slag showed higher strength than the $1\frac{1}{2}$-in. size only when concrete strengths around 7,000 psi were attained.

The optimum size of aggregate may be dependent on the relative strength of the cement paste, strength in bond, and strength of the aggregate particles. For a given aggregate, changes in maximum size would affect the surface area for bond and, in some cases, the strength of the particles. Variations in amount of mixing water, type of curing, and age at time of test affect both the strength of the cement paste itself and the strength in bond — but not necessarily to the same extent. Many variables are apparently involved, including characteristics of the cements and aggregates themselves. The effects of these variables on the relationship of aggregate size to concrete strength is certainly worthy of further study.

From a practical standpoint, concrete strength variations with aggregate size shown by these studies are believed to be of minor importance, provided a reasonable range of sizes is considered, such as $\frac{3}{4}$ to $1\frac{1}{2}$, or 1 to 2 in. Other factors, such as durability and shrinkage, should also be investigated. Even when all factors are evaluated and considered it may well be that "optimum" size of the aggregate will be different for different combinations of materials or conditions of use.

Stanton Walker, Delmar L. Bloem, and **Richard D. Gaynor,** *Closure.* — The authors appreciate the opportunity afforded by the discussions of Messrs. Gray and Lewis to reaffirm and emphasize what was said in the paper, which presents convincing evidence that, for the conditions of test, "increasing the maximum size of coarse aggregate above about $\frac{3}{4}$ in. did not improve either the flexural or compressive strength."

To the extent that the "conditions of test" have any bearing on the results, it is probably the strength level that is most significant. As Mr. Lewis suggests, the conclusion concerning effect of maximum size might not have been supported by strength tests at a lower level. This is a factor which is being investigated. However, it should be emphasized that the strengths obtained are consistent with highway construction practices. Further, the cement factor of 6 sacks per cubic yard and the slump of 2 to 3 in. used in major portions of the investigation are also typical of highway practice.

The concrete containing 5.5 and 7.1 sacks of cement per cubic yard, to which Mr. Gray refers, applies only to a small group of tests, covering only four conditions, which was not a part of the major investigation. It was for the purpose of comparing the strength of concrete as mixed with that of the portion finer than $\frac{3}{4}$-in. screened from it, with the resulting wide disparity in cement factor and slump. The 4.3 to 7.1-in. slump concrete, which Mr. Gray would seem to imply represented poor control, was the "conclusion clinching" last portion of the major investigation.

Fine aggregate percentages ranging from 25 to 75 were used to definitely assure that the optimum fine-coarse aggregate ratio was bracketed. A slump of about 4 to 5 in. was used to assure that compaction difficulties were not influencing results. Slumps did not depart significantly from the 4 to 5 in. except in a single case; with $\frac{3}{8}$-in. maximum size coarse aggregate and only 25 percent sand, the concrete was so coarse and nonworkable that it would not hold together and a slump of 7.1 inches was measured, it being pretty much independent of water content.

The nine values of strength quoted by Mr. Gray from the original paper as "the only flexural strength data comparable" were selected from 32 average values in Series 155B and 163A. The tests for $\frac{3}{8}$-in. maximum size were not quoted. For Series 163A, no consideration was given to the highly significant tests of 8- by 8-in. beams. These showed (selecting, as Mr. Gray did, the fine-coarse aggregate ratio giving highest strengths): 617 psi for $\frac{3}{8}$ in.; 632 psi for $\frac{3}{4}$ in.; 617 psi for $1\frac{1}{2}$ in.; and 593 psi for $2\frac{1}{2}$ in.

Had comparisons been made using the intermediate values and, also, the lowest values, which seems equally as valid as using the highest, further support would have been found for the conclusion that increasing the maximum size within the limits under discussion does not improve either the flexural or compressive strength. Also, it seems that Mr. Gray should have given weight to the highly significant compressive strength data, which included tests of 8- by 16-in. as well as the standard 6- by 12-in. cylinders.

Mr. Gray presents data on three classes of concrete tested in the laboratories of the National Crushed Stone Association and proportioned in accordance with *NCSA Bulletin No. 11*. These were 6-sack concretes for maximum sizes of aggregate of 2, 1, and $\frac{1}{2}$ in. Some question as to comparability of these concretes is presented by the differing air contents — ranging from 4.5 percent for the 2-in. material to 6.3 percent for the 1-in., and 6.7 for the $\frac{1}{2}$-in. These differences in air content are enough to have a significant effect on the strength comparisons. Further, it seems likely that in these relatively under-sanded mixtures the entrained air may have had a disproportionate effect on the strength for the different sizes. At any rate, one cannot consider these few tests, with only one sand content for each maximum size and differing air contents, as adequate evidence to deny the findings concerning strength.

Mr. Gray attaches a great deal of importance to differences in volume changes. No such data were secured in the authors' investigations. It is agreed that this phase should be investigated.

Not enough is known about the significance of volume changes to evaluate the data reported by Mr. Gray. The range in thermal coefficients of 3.1×10^{-6} in. per in. per deg F for the 2-in. maximum size to 3.4 for both the 1-in. and $\frac{1}{2}$-in. sizes is small and may be less than the reproducibility of the test results. The wide ranges in shrinkage shown for the three classes of concrete were something of a surprise, especially since increases in water over that required for 2-in. aggregate were only 7 percent for the 1-in. and 16 percent for $\frac{1}{2}$-in. size. Carlson (*10*) says that for each 1 percent increase in the quantity of mixing water, the shrinkage is increased about 2 percent. This is to be contrasted with increases in shrinkage, after 24 weeks drying, of 45 and 93 percent, respectively, reported by Mr. Gray.

That the amount of coarse aggregate has a significant effect in reducing drying shrinkage, independently of water content, has been well demonstrated. Carlson says: "But under practical conditions, a large reduction in shrinkage is obtained for larger maximum sizes of aggragate, both because of the lower water contents that can be used and because the larger aggregate sizes encourage cracking between particles." It should be of interest to know what effect this encouragement of cracking between particles has on the durability of concrete.

Gaynor, in a Master's thesis (University of Maryland), compared the drying shrinkage of concretes in which the absolute volume of coarse aggregate constituted 25 and 45 percent of the volume of concrete. Four coarse aggregates were used. The water ratio and the ratio of fine aggregate to cement were constant. The drying shrinkage of concrete containing 45 percent of coarse aggregate was found to be about two-thirds of that containing 25 percent of coarse aggregate.

In his oral discussion, Mr. Gray expressed the hope that the authors would not expect their conclusions to be applicable to concrete pavement construction. In response, they assured him that they most certainly did, and suggested that the advantages of greater homogeneity, greater ease of placement, and the better wearing characteristics of the concrete might very well more than compensate for any doubtful detriment due to greater drying shrinkage.