A part of PROCEEDINGS OF THE AMERICAN CONCRETE INSTITUTE Vol. 38

JOURNAL
of the
AMERICAN CONCRETE INSTITUTE

Vol. 13 No. 1 7400 SECOND BOULEVARD, DETROIT, MICHIGAN September 1941

The Influence of Vibration, Consistency, and Grading of Aggregate Upon the Design of Concrete*

By G. W. HUTCHINSON†
Member American Concrete Institute

SYNOPSIS

Data in this paper supplement those previously published: "Concrete Aggregate Development on the Claytor Hydro Project." They are from the results of several investigations in the Claytor laboratory of factors affecting the design of concrete which could not be fully reconciled with existing theory. The more important indications:

1—That an optimum gradation exists for each aggregate or set of aggregates, when of given maximum size and combined with a given paste content, which provides maximum workability in concrete. Gradations of aggregate either finer or coarser than the optimum require additional mixing water in order to maintain equal workability.

2—To maintain a given consistency of concrete, a greater water content, per unit volume of concrete, is required as the paste content is increased.

3—The compressive strength and durability of concrete, especially in the mixtures sufficiently dry to require placement by vibration, are affected by the consistency of the concrete in a manner not definitely related to the water cement ratio except when the cement content is constant.

INTRODUCTION

In connection with concrete studies for the Claytor Dam, Pulaski County, Virginia,‡ numerous series of tests were made as a means to study the effects of different factors influencing the strength and other properties of the concrete. Some of these tests led to somewhat new conceptions of the parts played, even by such fundamental things as consistency and grading of aggregate. These roles became apparent in the endeavor to enhance, by any means possible, the quality of lean concrete of relatively dry consistencies of which large dams are built.

*Received by the Institute March 3, 1941.
†Concrete Technician for the Clayton Hydro Project.
‡G. W. Hutchinson: Concrete Aggregate Development on the Claytor Hydro Project. ACI JOURNAL, January 1940; *Proceedings* V. 36, p. 273.

They were perhaps emphasized by the rather unique properties of the artificial sand used—crushed dolomite reshaped by special milling to produce an unusual degree of workability, comparable to that of good natural sands. Some of these relations seem important enough to be taken into account in the design of concrete for major projects. In any case, they seem to disclose definite conditions under which there are occasional wide departures from the generally accepted water-cement ratio law.

If these deductions, together with the supporting evidence, as presented in this paper, are not fully accepted by those who care to study them, they at least suggest that well established notions regarding the internal structure of concrete will bear occasional re-examination from both the old and newer points of view.

OUTLINE OF TESTS

This discussion is based on five series of tests, the data of which are tabulated without unnecessary detail in Tables 1 to 5. The first four of these involve the same type and grading of coarse aggregate, but different types of fine aggregates.

Series X-1 (Table 1) constitutes a group of tests in which the cement ranged from 0.5 to 2.0 bbl. per cu. yd. A natural sand was used as fine aggregate. It was supplemented by additions of minus 100 mesh dolomite in such quantity that all mixes contained an amount of cement plus fine dolomite, equivalent to 2 bbl. of cement per cu. yd. on an absolute

TABLE 1—EFFECT OF CONSISTENCY AND WATER-CEMENT RATIO UPON THE COMPRESSIVE STRENGTH OF CONCRETE

SERIES X-1

Coarse Aggregate: Crushed dolomite, ⅜-¾ in.
Fine Aggregate: Natural sand B and crushed dolomite passing No. 100 sieve. Column 3 gives the amount of fine dolomite as the equivalent of bbl. of cement per cu. yd. on an absolute volume basis.
Test Specimens: 3 x 6 in. cylinders. Each value of strength is the average of five tests.

Mix	Cement bbl./ cu. yd.	Fine Dolomite	Slump (in.)	W/C by wt.)	Water gal./ cu. yd.	Compr. Str., psi.		
						7 Day	28 Day	90 Day
A	0.50	1.50	5½	1.72	39.1	469	651	830
B	0.75	1.25	5¾	1.17	39.7	743	1290	1550
C	1.00	1.00	6	0.91	40.9	1320	1970	2560
D	1.25	0.75	6	0.73	41.4	1630	2330	3480
DD	1.25	0.75	4	0.68	38.7	1900	3110	4400
DDD	1.25	0.75	2	0.63	35.7	2490	3990	5410
DDDD	1.25	0.75	0	0.53	30.1	3410	4490	6730
E	1.50	0.50	6	0.62	42.0	1970	3200	4290
F	1.75	0.25	6	0.54	42.6	2430	3890	5160
G	2.00	0.00	6	0.48	43.3	3220	4220	6040

TABLE 2—RELATION BETWEEN COMPRESSIVE STRENGTH OF CONCRETE AND FINENESS MODULUS OF AGGREGATE

SERIES X-7

Cement Content: 1.20 bbl. of cement per cu. yd. of concrete.
Water Cement Ratio: 0.62 by weight.
Aggregates: Stone sand A and four natural sands, B, C, D, E. Coarse aggregate: ⅜ to ¾ in. crushed dolomite.
Consistency: Stiff, suitable for vibrating.
Test Specimens: 3 x 6-in. cylinders. Each value of compressive strength in the table is the average of 10 tests. Age 28 days.

Aggregate Ratio, Fine : Coarse	Fine Aggregate Identification				
	A	B	C	D	E
	Compressive Strength, psi.				
3 : 7	2600	2280	2260	2190	2550
4 : 6	3460	2700	2710	2530	3130
5 : 5	4730	2940	3150	2700	3400
6 : 4	5840	2750	3040	2810	3300
7.5 : 2.5	5270	2620	1240	1460	765
	Fineness Modulus of Total Aggregate				
3 : 7	5.76	5.76	5.76	5.60	5.54
4 : 6	5.35	5.35	5.35	5.13	5.05
5 : 5	4.94	4.94	4.94	4.67	4.55
6 : 4	4.52	4.52	4.52	4.21	4.07
7.5 : 2.5	3.92	3.92	3.92	3.51	3.34

TABLE 3—VARIATION IN COMPRESSIVE STRENGTH AND PLACEABILITY OF CONCRETE WITH CHANGE IN AGGREGATE GRADING

SERIES X-7B

Cement Content: 1.20 bbl. of cement per cu. yd. of concrete.
Aggregate: Stone sand A, 0-4; Crushed dolomite ⅜-¾ in.
Stone sand F, 0-4; Crushed dolomite ⅜-¾ in.
Test Specimens: 3 x 6 in. cylinders. Each value in the table is the average of 6 tests. Age 28 days.

Sand A	Aggregate Ratio Fine : Coarse	Fineness Modulus	Placeability (Seconds)	Compressive Strength psi.	W/C (by wt.)
1-A *	3 : 7	5.76	16	1760	0.62
2-A	4 : 6	5.35	12	3780	0.62
3-A	4.5 : 5.5	5.14	10	4470	0.62
4-A	5 : 5	4.94	9	5440	0.62
5-A	5.5 : 4.5	4.73	9	5680	0.62
6-A	6.5 : 3.5	4.32	15	5610	0.62
7-A	7.5 : 2.5	3.92	20	5590	0.62
Sand F					
1-F	3 : 7	5.76	15	2100	0.69
2-F	4 : 6	5.35	13	3200	0.69
3-F	4.5 : 5.5	5.14	11	3730	0.69
4-F	5 : 5	4.94	11	4040	0.69
5-F	5.5 : 4.5	4.73	12	3960	0.69
6-F	6 : 4	4.52	15	4000	0.69
7-F	6.5 : 3.5	4.32	20	3760	0.69

*All specimens honey-combed about one-half of total vertical area.

volume basis. The test results obtained from this series indicate: (1) that even in fairly wet mixes, suitable for hand placing, the water required to maintain a given consistency is not constant, but increases with the cement content; (2) that strength depends not alone on water-cement ratio, but on consistency as well. Durability of these concretes is discussed in the Appendix.

Series X-7 (Table 2) involves tests of concrete made with different sands at vibrating consistency. The cement content and water cement ratio remained constant. A group of tests was made for each sand with a progressive change in the ratio of fine to coarse aggregate. Comparison of compressive strengths with fineness modulus of aggregate show: (1) that the strengths vary widely with change in grading of the aggregate even when the W/C is constant; (2) that the maximum strengths occur at relatively low values of fineness modulus.

Series X-7B (Table 3) is similar to Series X-7, except that the tests are confined to two stone sands, one the specially milled sand and one coming direct from the primary stone crusher, the latter having many flat and elongated particles. These concretes made with each sand were of the same cement content and W/C, and of stiff but generally placeable consistency with the vibrator. Placeability* was measured by a special device for indicating the relative workability of mixtures having zero or near zero slump. These tests show markedly the increase in compressive strength with decreasing fineness modulus and they show that strength is near the maximum at maximum placeability.

Series X-12 (Table 4) shows compressive strength-fineness modulus relations for the reshaped dolomite aggregate at 3 different cement contents and water-cement ratios, all at vibrating consistency. In all groups, maximum placeability corresponds nearly to maximum strength, regardless of cement content, and in all cases the highest strengths are associated with what would ordinarily be regarded as over-sanded mixtures.

The fifth series of tests (Table 5) is a study of the placeability of different concretes of vibrating consistency, of constant cement content and W/C, as the ratio of fine to coarse aggregate varied progressively. The tests indicate that particle shape and surface characteristics of the fine aggregate have considerable effect on workability in concrete of this type.

MATERIALS

Sufficient normal cement to complete each investigation was secured in advance and properly stored. Coarse aggregate was crushed dolomite

*Description published in A.S.T.M. Bulletin, August, 1939.

TABLE 4—RELATION OF PLACEABILITY AND STRENGTH OF CONCRETE TO FINENESS MODULUS IN MIXTURES OF DIFFERENT CEMENT CONTENT

SERIES X-12

Cement content as indicated. Water-Cement Ratio constant for any given cement content.
Aggregate: Stone sand A, 0-4; Crushed dolomite, ⅜-¾ in.
Consistency: Stiff, suitable for vibrating.
Test Specimens: 3 x 6 in. cylinders. Age 28 days. Each value in the table is the average of 5 tests.

	Aggregate Ratio Fine : Coarse	Fineness Modulus	Placeability (Seconds)	Compressive Strength psi.	W/C (by wt.)
Cement Content: 0.95 bbl. per cu. yd.					
AS-1	3 : 7	5.76	45		0.83
2	4 : 6	5.35	12	2440	0.83
3	5 : 5	4.94	8	3190	0.83
4	6 : 4	4.52	7	3550	0.83
5	7 : 3	4.11	11	3630	0.83
Cement Content: 1.25 bbl. per cu. yd.					
BS-1*	3 : 7	5.76	15	2140	0.62
2	4 : 6	5.35	9	4270	0.62
3	5 : 5	4.94	6	4920	0.62
4	6 : 4	4.52	7	5220	0.62
5	7 : 3	4.11	10	5230	0.62
Cement Content: 1.75 bbl. per cu. yd.					
CS-1	3 : 7	5.76	15	5240	0.46
2	4 : 6	5.35	11	7040	0.46
3	5 : 5	4.94	8	7810	0.46
4	6 : 4	4.52	13	7850	0.46
5	7 : 3	4.11	20	8080	0.46

*All specimens honey-combed about one-half of total vertical area.

TABLE 5—EFFECT OF TYPE AND GRADING OF FINE AGGREGATE ON PLACEABILITY (WORKABILITY) OF CONCRETE

Cement Content: 1.00 bbl. pr cu. yd. of concrete.
Water-Cement Ratio: 0.70 by weight.
Coarse Aggregate: Crushed dolomite, ⅜-1½ in.

Aggregate Ratio, Fine : Coarse	Fine Aggregate Identification				
	A	B	C	D	E
	Seconds Required for Maximum Compaction				
3 : 7	25	18	26	18	15
3.5 : 6.5	15	8	16	9	11
4 : 6	11	5	10	8	10
4.5 : 5.5	9		14	13	13
5 : 5	9	5			
6 : 4	8	6			
7 : 3	16				
	Fineness Modulus of Total Aggregate				
3 : 7	6.11	6.11	6.11	5.95	5.89
3.5 : 6.5	5.88	5.88	5.88	5.70	5.62
4 : 6	5.65	5.65	5.65	5.44	5.35
4.5 : 5.5	5.42		5.42	5.18	5.08
5 : 5	5.19	5.19			
6 : 4	4.70	4.70			
7 : 3	4.27				

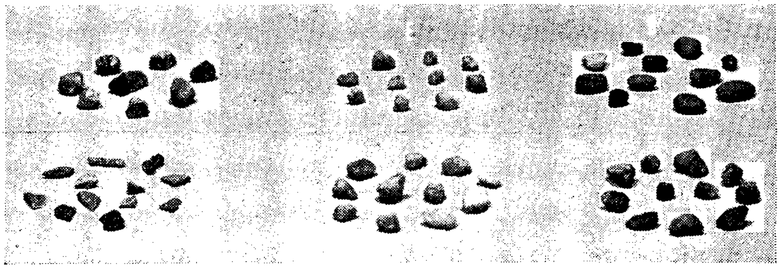

Fig. 1—Particle shape and surface characteristics of fine aggregate.

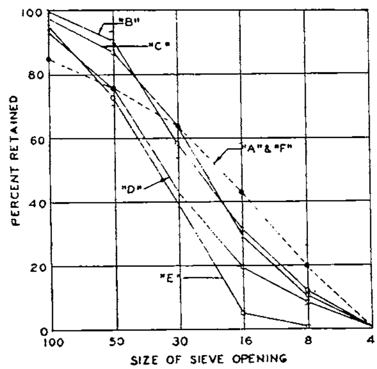

Fig. 2—Grading curves of fine aggregates

screened to pass a ¾-in. and to be retained on a ⅜ in.-opening. This was used for all series reported herein, except for the placeability studies summarized in Table 5, in which the size range was ⅜ to 1½ in.

The fine aggregates, with the exception of those used in series X-7 (Table 2) were separated into three sizes, 0-50, 50-16, 16-4, and then recombined in definite proportions for each investigation. The character of the different sands is shown in Fig. 1—typical particles of each, A and F being the dolomitic sands (prepared and unprepared, respectively), B and C relatively coarse natural sands, and D and E relatively fine natural sands. The gradation is shown in Fig. 2, in which attention may be called to the relatively limited amount of 16-50 material in the dolomitic sands, and to the relatively high fraction (about 17 per cent) passing the No. 100 sieve.

CASTING OF SPECIMENS

All concrete batches were mixed by hand, sufficient for making from four to seven 3 x 6-in. cylinders. Those of approximately 2-in. slump or less were cast by vibration. Each set of specimens, in the latter case, was cast at one time as the molds rested on a vibrating table. When casting specimens by vibration, the concrete was placed in the molds by means of a large spoon, filling about one-fifth each time. No additional concrete was added until the matrix of that previously placed was flushed to the surface. The specimens for each complete set, or each investigation, were made at one time by continuous operation. They were covered by a wet cloth and stored at room temperature until the next day, and were then removed to damp closet storage until time for test. Leadite caps (top and bottom) were used when testing all specimens.

The deficiency in fine aggregate of two stone sand mixtures (1-A, Table 3, and BS-1, Table 4) did not permit satisfactory compaction.* The result was that about one-half the vertical surface was honey-combed in each of the specimens. All others were sufficiently workable to permit proper compaction by the method used.

DISCUSSION OF RESULTS

In this discussion the order in which the tabular data are presented will be adhered to as nearly as possible. Inter-comparisons of data from two or more series are shown by a number of diagrams, one or two of which depend upon data omitted from this report for the sake of brevity.

The effect of consistency on compressive strength of concrete

Table 1 contains the summarized data of a series of tests which indicate that consistency varies with change in cement content of similar mixtures and that strength is dependent on consistency apart from water cement ratio, even in concretes suitable for hand placing. As stated in the outline, seven concretes were included which varied in cement content from 0.5 to 2.0 bbl. of cement per cu. yd. Fine and coarse aggregates were constant throughout, but minus 100 mesh dolomite was added in such quantity as to keep the cement plus dolomite at the equivalent of 2.0 bbl. of cement per cu. yd. on an absolute volume basis. In the seven concretes (specimens placed by hand rodding) the slump was kept as nearly as possible at 6 in.

Three additional concretes were also included as a variation of Group D, all containing 1.25 bbl. of cement per cu. yd., but gaged to 4-, 2- and 0-in. slump, respectively. The reduced water content in this group permitted a comparison of compressive strengths of concretes having the same W/C but different consistencies.

The 3-months compressive strengths from Table 1 are plotted against the total water content of the concretes in Fig. 3. The strengths of the

*The relative workability of these mixtures could be determined without difficulty. The frequency of the vibrator attached to the workability device was 8000 per minute with the vibratory action being transmitted laterally. The vibrating table upon which the compressive test specimens were cast operated at a lower frequency of 3600 per minute, and the vibratory action was transmitted in a vertical direction.

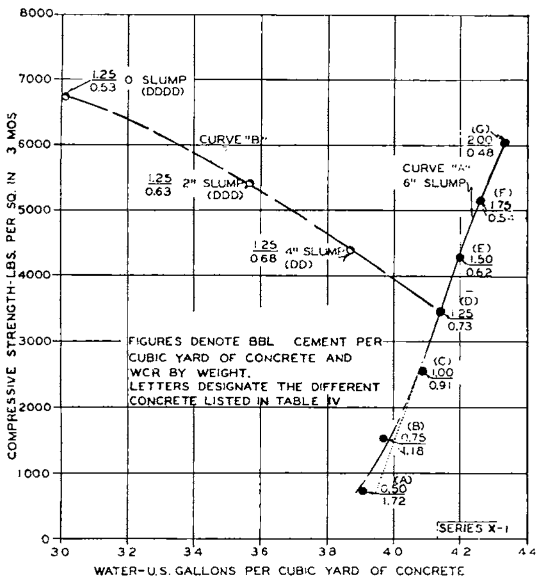

Fig. 3 — Relation between compressive strength of concrete and water content, water - cement ratio and consistency.

6-in. slump concretes lie in the full curve, which is so nearly s straight line that one might be justified in making a slight correction (as shown by the dotted line) to compensate for the lower slumps of the two weakest mixtures, A and B. In the same manner, the strengths of the D groups are plotted on the dash line.

Curve A of Fig. 3 is significant in showing that change in the cement content with the minus 100 mesh aggregate compensation requires a change in water content if equal consistency is to be maintained. This is contrary to the commonly accepted view that slump and total water per unit volume remain constant under these conditions. The change in water content for constant consistency, while slight for small changes in cement content, is nevertheless proportional to the quantity of cement in the mix and amounts to over 10 per cent for the range covered in this series. In the case of the mixtures shown by Curve A, Fig. 3, the additional water required to maintain the given slump was directly proportional to the increase in cement content (and decrease in the minus 100 dolomitic aggregate). The mixtures in the series shown by Fig. 8, however, indicate the mixture containing the intermediate cement content (1.25 bbl. per cu. yd.) as having the lowest water content for a given placeability. A greater amount of water was necessary for equal placeability as the mixture became either leaner or richer in cement.

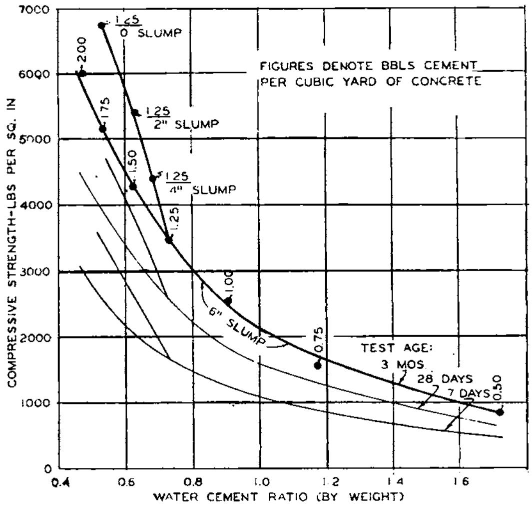

Fig. 4 — Relation between compressive strength of concrete and water - cement ratio, cement content and consistency.

The seeming inconsistency between these two series is clearly explained by Dunagan.*

Curve A in Fig. 3 shows that for constant slump, the strength is an inverse function of the water cement ratio, but Curve B shows that when cement content is constant and slump is reduced, the strengths increase above that indicated by the water cement ratio, and therefore the strength must depend to some extent upon consistency or relative water content.

The discrepancy is seen more easily in Fig. 4, in which the data are plotted in the conventional method — strength vs. W/C. There it is seen that a compressive strength of 5000 psi. at 3 months is obtained with 1.25 bbl. of cement per cu. yd. at approximately 3-in. slump (W/C = 0.65), or with 1.7 bbl. of cement per cu. yd. at 6-in. slump (W/C = 0.54). Similar differences occur in the strength relations at 7 and 28 days. It is obvious that greater economy will result in the use of drier consistencies and placement by vibration than with wetter consistencies by hand methods, and that the factor governing strength is not water-cement ratio alone. A leaner mixture, at a higher water-cement ratio, produces a compressive strength equal to that of a richer mixture at a lower water-cement ratio.

Effect of grading of aggregate on compressive strength of concrete at vibrating consistency

Data from Table 2 are plotted in Fig. 5 — compressive strength vs. fineness modulus of aggregate. The concretes were made with five

*W. M. Dunagan: The Application of Some of the Newer Concepts to the Design of Concrete Mixes. ACI Journal, June, 1940; *Proceedings* V. 36. See (b) The validity of the Slater-Lyse rule, p. 667.

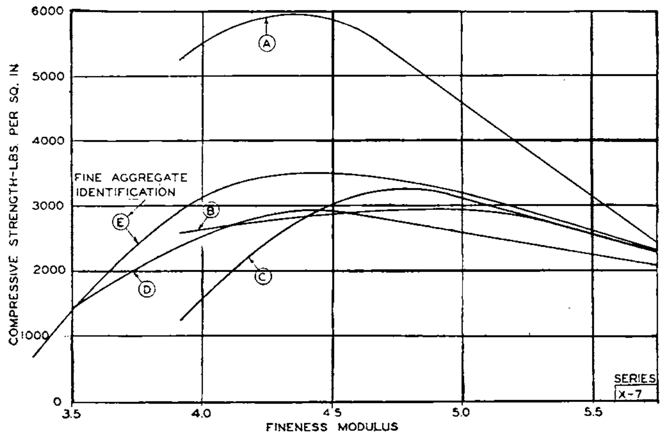

Fig. 5—Relation between strength of concrete containing different fine aggregates and fineness modulus of total aggregate; cement content and water-cement ratio constant

different sands used in varying proportions with the coarse aggregate, and all mixtures were of the same cement content and water-cement ratio. Each value of strength in Table 2 was obtained from the average of 10 specimens. The curves in Fig. 5 indicate that considerable variation in the strength of vibrated concrete can exist as the result of changes in type and gradation of aggregate. The outstanding quality of sand A is shown, but for a more complete and fair comparison, some adjustment would have to be made on the basis of comparative workability—not possible by present accepted tests in this type of concrete.

Relation between placeability of stiff concretes and character of aggregate

The introduction of a method for measuring the relative placeability of low or no slump concretes opens up new possibilities in design and control. Table 3 summarizes the data of a series of concretes, in which two types of stone sand were used, one being the re-shaped sand A, and the other sand F, composed of relatively sharp and elongated particles from the primary crusher. Grading of the total aggregate was changed as before, by changing the ratio of fine to coarse, and the placeability was determined by the method previously referred to under "Outline of Tests." The same cement content was used throughout, but a higher water ratio was required for sand F than for sand A to give about the same optimum placeability. The results are plotted in Fig. 6. Both placeability, which is indicated as the time in seconds required for maximum compaction, and compressive strength, are plotted against fineness modulus of aggregate. Maximum placeability is reached at the lowest points on the dot-dash curves. It is seen that the compressive strength falls off rapidly for gradations coarser than that giving maximum placeability.