THE EFFECT OF AGGREGATE ON THE STRENGTH OF CONCRETE

by

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SYNOPSIS

The strength of concrete is a function of several variables. This paper discusses the effect of aggregate alone. Major stress is given on coarse aggregates and consequent compressive strength, though, occasional references are made to fine aggregates and the flexural and tensile strengths of concrete. The discussion shows that though aggregate occupies the major volume in concrete mass, yet only a few properties have a significant effect on its strength--shape, size, compressive strength, surface texture and gradation being some of them. Little work has been done to establish quantitative relationships between the aggregate characteristics and their respective concrete strengths and only general remarks can be made by co-relating the different results. This field of concrete technology has largely remained unexplored.

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INTRODUCTION

Aggregate is an inert material used as a filler in cement concrete. As it generally occupies 66 to 78 percent of the concrete volume (Fig. 1), its quality and proportions affect the design of concrete, the chief requirements for which are that it should be (1) workable, when freshly mixed, (2) strong and durable when hardened, and (3) economical, consistent with the acceptable quality.

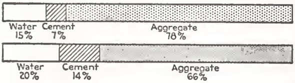

Fig. 1. Range in proportions of materials usually used in concrete. Upper bar represents lean mix of stiff consistency with large aggregate. Lower bar represents rich mix of wet consistency with small aggregate.

The three principal functions of aggregate are (1) to provide cheap filler in the concrete bulk (2) to provide mass of particles suitable for resisting the action of applied loads, abration, the percolation of moisture, and weathering action, and (3) to reduce volume changes resulting from the setting and hardening process and from moisture changes in the cement-water paste.

Strength of concrete is its ability to resist force; with regard to concrete it is taken as the unit force (stress) required to cause rupture. This may be caused by applied tensile stress (failure in cohesion), by applied shearing (sliding) stress, or by compressive (crushing) stress. Aggregate, being its chief component, contributes considerably towards its strength. It is therefore necessary that this aggregate should have hardness, toughness, soundness, strength and cleanliness. For that matter, weak, friable or laminated aggregate particles are undesirable. Aggregates containing natural shale or shaly, soft and porous particles, and certain types of cherts should be specially avoided, since they have poor resistance to weathering.

The most commonly used aggregates are sand, gravel, crushed stone and air-cooled blast-furnace slag. They produce normal-weight concrete, i.e., concrete weighing from about 140 to 160 lbs per cubic foot. Expanded shale, clay, slate, and slag are used as aggregates to produce structural lightweight concrete weighing about 85 to 115 lbs per cubic foot. Cinders, pumice, scoria, perlite, vermiculite and diatomite are used to produce insulating concretes weighing about 20 to 70 lbs per cubic foot. Aggregates like baryte, limonite, magnetite, ilmenite, iron and steel particles are used for producing heavyweight concretes.

The normal weight aggregates should meet the requirements of standard specifications which limit the permissible amounts of deleterious substances and cover requirements for gradation, abrasion, resistance, and soundness.

GENERAL CLASSIFICATIONS

Aggregates may be generally classified according to (1) source, (2) physical and chemical composition, (3) mode of preparation, and (4) size. This classification helps in becoming familiar with types of aggregates only; however, their acceptance for the purpose of the job shall depend upon the specific information regarding their quality.

(1) Source:

With reference to source, aggregate may be (a) natural or (b) artificial.

(a) Natural rocks may be subdivided into three groups in accordance with their geological origin: (i) igneous rocks, (ii) sedimentary rocks, and (iii) metamorphic rocks. Igneous rocks are formed by the more or less rapid cooling of molten material from inside of the earth; sedimentary, consolidated from particles of decayed rocks which have been deposited from streams of water; and metamorphic, either sedimentary or igneous which have undergone change due to pressure or heat or both. (4) Natural aggregates like sands and gravels are the product of weathering and the action of running water. Sands and crushed stones are also obtained by crushing and screening the quarried natural rock. Natural aggregates may be derived from any or all of the above described geological groups; however, not all members of these groups make satisfactory aggregates for concrete.

(b) Artificial aggregates are normally produced for a particular purpose, such as, for example, burned clay aggregates for making lightweight concrete. Other instances of artificial aggregates are industrial by-products like blast furnace slag and cinders. Steel rivet punchings are used for making heavyweight concrete.

(2) Physical and Chemical Composition:

(a) Based upon physical structure rocks may be divided into stratified and unstratified ones. The structure of unstratified rocks is, for the most part, an aggregate of crystalline grains firmly adhering together. Granite, trap and basalt are examples of this class. Unstratified rocks may be subdivided according to the physical structure:

(i) Compact crystalline structure, e.g. marble.
(ii) Slaty structure, e.g. clay.
(iii) Granular crystalline structure, e.g. sandstone.
(iv) Compact granular structure, e.g. limestone.
(v) Porous granular structure, e.g. minute shells cemented together.
(vi) Conglomerate (fragments of one stone embedded in the mass of another). (6)

(b) Based upon chemical nature, rocks are divided into the following three groups:

(i) Siliceous stones, in which silica is the main chemical constituent. Familiar examples of this class are granite, basalt and sandstone.
(ii) Argillaceous stones, in which alumina is the important constituent. An example of this type is slate.
(iii) Calcareous stones, in which lime carbonate is the predominating constituent. Examples of this class are marble and limestone. (6)

(3) Mode of Preparation:

Mode of preparation will mostly depend upon the type of the work for which the rock is needed. In its natural form, the aggregate obtained from river beds may be smooth and rounded, whereas the aggregate obtained by quarrying will rarely be smooth. Smooth and rounded surfaced aggregate lacks bond property and they will tend to make the aggregate less strong. For that matter, even pit-run aggregates are also used. However, for more important jobs, quarrying may be necessary. This will involve the use of crushers and subsequent screening for the purpose of specific gradations. The aggregate may also be cleaned and washed.

(4) Size:

Based upon size, the aggregate is divided into two groups, (a) coarse aggregate (b) fine aggregate or sand. Aggregate smaller than about 1/4 inch in diameter is classified as fine. There are available several sizes of coarse aggregate, e.g., 1/4 to 3/4 inches, 3/4 to 1-1/2 inches, 1-1/2 to 2-1/2 inches, etc. Similarly, two or three grades of sand are also available.

Irrespective of the classification the principal qualifications of the aggregate are that they be clean, hard, sound and durable and that the sizes of particles shall be graded within stated limits.

CHARACTERISTICS OF AGGREGATES AND THEIR EFFECT ON THE STRENGTH OF CONCRETE

The subject of strength of concrete is a complex matter, as it depends upon several variables. All the three constituents, namely, portland cement, aggregates and water contribute to this complexity by their respective qualities and quantities. In the pages to follow, the effects of aggregate characteristics alone are considered. The characteristics to be discussed are given below:

Resistance to surface abrasion
Resistance to freezing and thawing
Specific gravity
Bulk unit weight
Compressive strength
Size
Moisture absorption
Chemical stability
Shape and texture
Gradation

Resistance to Surface Abrasion

Resistance to surface abrasion measures the degree of hardness and is often used as a general index of aggregate quality.

Weak particles tend to lower the strength of concrete although they must be present in appreciable quantity before there is a noticeable effect on compressive strength. The effect is marked upon flexural or tensile strength. The cement paste in concrete has little resistance to abrasive conditions, hence, abrasive resistance of concrete is a function of the wear resistance of aggregate. From that standpoint, soft particles in aggregate may be objectionable, where the concrete surface is to be subject to wear or abrasion. (5)

The most common method of testing for abrasion resistance is the Los Angeles rattler method (ASTM C131). In this test, a specified quantity of aggregate is placed in a steel drum that is rotated; the percentage of material worn away during the test is then determined. The results of various tests using this equipment indicated that the Los Angeles abrasion values for the aggregates investigated agreed with their service behavior in concrete. Also, these tests showed that the lower the percentage of wear, the higher the strength of concrete in flexure and compression. (5, 7)

Resistance to Freezing and Thawing

Most destructive of the natural forces of weathering is freezing and thawing action; as such, when the aggregates are used in exposed concrete, the resistance to freezing and thawing is an important property.

Water expands when it freezes. The resistance of the aggregates to freezing and thawing is therefore directly related to its porosity and absorption. The aggregate which absorbs so much water that it cannot accommodate on its freezing will ultimately disintegrate due to increased pressure. To withstand such repeated cycles of freezing and thawing indicates the degree of soundness of aggregate.

Aggregates which are saturated when used are vulnerable to failure; however, the failure is dependent upon the critical size. This critical size is dependent upon the physical and structural properties of the aggregate like permeability, porosity and tensile strength. The normal size is good enough when the material is fine-grained and has comparatively lower permeability. On the other hand for coarse grained materials, the critical size may be so large that it is of no consequence, even though the absorption may be high. When potentially vulnerable aggregates are dry in state when used in concrete subjected to drying periodically, the failure may not occur as the aggregates may never get sufficiently saturated. (7) In general, the frost resistance of concrete is primarily dependent upon the amount of freezable water within concrete, air void characteristics and size of aggregate. Tests indicate that the resistance to frost action increases as the size of aggregate decreases.

Volume changes in aggregate due to freezing and thawing may have a varied effect on the strength of concrete. This will depend upon the range and the degree of deterioration. The localized pitting will be detrimental to the appearance of the structure, whereas deep seated cracks may bring down the strength of the concrete to such an extent as to cause the failure of the structure.

Specific Gravity

The specific gravity of the aggregate is the ratio of its unit weight to the unit weight of water. In the British system, the specific gravity is obtained by dividing the unit weight of aggregate by 62.4, the unit weight of water; whereas in the metric system the unit weight of the aggregate itself is the specific gravity, as the unit weight of water is unity.

For the purpose of concrete mix design, bulk specific gravity is more useful as it takes into account the voids normally present. Bulk specific gravity may be defined as the ratio of the weight in air of a given volume of material (including all voids) to the weight in air of an equal volume of distilled water. The measurements are taken at a standard temperature of 68° F. (5)

ASTM C127 and C128 give the test methods to determine the specific gravities for coarse and fine aggregates respectively. For the purpose of computations, the specific gravities of saturated surface dry aggregates are used. (7)

The bulk specific gravities of commonly used aggregates fall between 2.5 to 2.9, the average being around 2.65. There are, however, some satisfactory aggregates which do not fall in this range of specific gravity. Table 1 (5) gives a few types of aggregates.

Bulk specific gravity for lightweight aggregates generally varies between 1.0 to 2.4. It increases with the reduction in aggregate size.

Strong materials, in general, make strong concretes. From that standpoint, aggregates with higher specific gravities are more suitable as they have more strength in compression. A reference to Table 2 (4) will indicate the same. The table also shows the higher strengths in tension, shear and flexure with higher specific gravities.

Unit Weight

The weight of an aggregate contained in a measure of unit volume is

TABLE 1 . SPECIFIC GRAVITIES OF VARIOUS TYPES OF STONE USED FOR AGGREGATES

Material	Bulk specific gravity	
	Average	Range
Sandstone	2.50	2.0–2.6
Sand and gravel*	2.65	2.5–2.8
Limestone	2.65	2.6–2.7
Granite	2.65	2.6–2.7
Trap rock	2.90	2.7–3.0

*** Sands and gravels are usually a mixture of several kinds of rock materials, so the specific gravity will depend upon the preponderant type.**

TABLE 2.—PROPERTIES OF THE BUILDING STONES OF BAVARIA

(Bauschinger's *Communications*, Vol. 10, 1884)

Strengths given in Pounds per Square Inch.

Kind of Stone.	Specific gravity.	Weight per Cubic Foot.	Cross-bending.		Compressive Strength.			Tensile Strength.	Shearing Strength.	
			Modulus of Elasticity.	Modulus of Rupture.	Perpendicular to Bed.	Parallel to Bed.	Parallel to Bed after 25 Freezings.		Perpendicular to Bed.	Parallel to Bed.
Granite	2.65	165.4	2,986,000	1365	10,200	18,010	21,470	610	1370	142
Granite	2.66	166	1,621,000	1194	10,200	20,030	20,480	683	1450	853
Triassic limestone	2.48	154.8	6,420,000	882	8,130	8,320	6,810	583	555	384
Jurassic limestone	2.23	139.2	....	....	11,110	7,410	12,290	448	739	540
(marble)	2.08	129.8	4,906,000	462	4,664	8,760	3,313	213	498	299
Oölitic limestone	2.72	169.7	....	1792	19,340	20,620	18,770	010	1470	1138
Tuffa stone	1.80	112.3	....	469	1,105	2,545	2,076	227	227	213
Variegated sandstone	2.06	128.5	426,600	469	7,420	6,010	6,730	107	560	355
Variegated sandstone	2.20	137.3	867,400	718	0,040	7,790	7,910	199	512	313
Variegated sandstone	2.28	142.3	1,340,000	1109	12,930	13,410	11,520	576	010	540
Variegated sandstone	2.00	124.8	341,300	341	6,160	6,100	4,877	128	455	427
Carboniferous sandstone	2.30	137.3	910,000	483	7,636	8,390	5,986	341	640	284
Carboniferous limestone	2.23	139.1	334,200	441	6,684	6,670	5,000	213	583	469
Slaty sandstone	1.82	113.6	512,000	249	3,071	2,247	2,161	98	370	242
Slaty sandstone	1.02	119.8	270,200	135	3,029	2,659	4,252	67	242	185
Green sandstone	2.15	134.2	583,000	156	4,707	4,308	4,038	94	341	327
Cretaceous sandstone	2.60	162.3	568,800	507	13,510	14,500	......	327	668	370
Cretaceous sandstone	2.73	170.4	2,687,000	067	28,860	17,490	......	512	995	768
Quartz conglomerate	2.20	142.9	1,763,000	654	5,546	4,408	3,270	242		

defined as unit weight or specific weight and is normally given in pounds per cubic foot. Usually the term bulk unit weight is used to indicate the volume occupied by bulk aggregate and voids. (7) This definition indirectly refers to porosity which is the ratio of the volume of voids to the entire volume of solid mass of stone and voids. Hence, unit weight = 1 - porosity. (4)

The percentage of voids between the particles in a given gross volume of aggregate can be computed by

$$\text{Percent voids} = \frac{(\text{Solid unit weight}) - (\text{Unit weight})}{(\text{Solid unit weight})} \times 100$$

$$= \frac{(62.4 \times \text{specific gravity}) - (\text{Unit weight})}{(62.4 \times \text{specific gravity})} \times 100 .$$

For a given specific gravity, the unit weight varies inversely as the percentage of voids; and better the gradation, lower will be the percentage of voids. (5)

Aggregates are usually selected on the basis of the density, preference being given to the materials of the higher density (percentage of solids). Since the dense volume is also dependent upon other considerations, such as, grading, shape and surface texture of particles, the unit weight (and void content) serve to indicate an approximate degree of grading. However, the grading which gives the maximum density, also produces harsh mixes (of poor workability); hence, density cannot be the only criterion to decide the type of aggregate. (5)

Besides the conditions mentioned above, the unit weight is affected by the compactness and the moisture content of the aggregate mass. The effect of all these is reflected in the wide range of unit weights. Table 3 indicates the same.

Keeping aside other factors, it is seen that density and strength go hand in hand. Concretes made with lower density aggregates have lower strengths. From a series of tests on approximately 115 natural sands the relation between density and the average compressive strength of 2 inch cubes of 1:3 mortar was established as compressive strength = 26,500 x Density - 15750. Also based upon the experiments conducted by Feret, "for all series of plastic mortars made with the same cement and of inert sands, the resistance to compression after the same kind of set under identical conditions is solely a function of the ratio $\frac{c}{c+v}$ or $\frac{c}{1-(c+s)}$, whatever may be the nature and size of sand the proportions of elements--sand, cement, and water--of which each is composed." He gave the following relationships for compressive strength: (8)

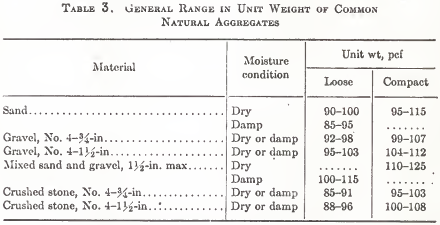

TABLE 3. GENERAL RANGE IN UNIT WEIGHT OF COMMON NATURAL AGGREGATES

Material	Moisture condition	Unit wt, pcf	
		Loose	Compact
Sand	Dry	90–100	95–115
	Damp	85–95	....
Gravel, No. 4–¾-in	Dry or damp	92–98	99–107
Gravel, No. 4–1½-in	Dry or damp	95–103	104–112
Mixed sand and gravel, 1½-in. max	Dry	....	110–125
	Damp	100–115	....
Crushed stone, No. 4–¾-in	Dry or damp	85–91	95–103
Crushed stone, No. 4–1½-in	Dry or damp	88–96	100–108

$$So = j \frac{c}{1-(c+s)} - 0.1$$

and

$$So = k(\frac{c}{1-s})$$

where

Sc = strength in compression

c = absolute volume of cement

s = absolute volume of sand

e = volume of water

v = volume of air voids

k and j = constants.

The above discussion indicates that as the voids decrease, unit weight and compressive strength increase. Thus, in general, higher the unit weight of aggregates, higher will be the compressive strength of concrete.

Compressive Strength

The compressive strength of the aggregate is the most useful mechanical property which is associated with the strength of concrete; however, concrete is sometimes tested for tensile and shear strengths also.

The compressive strength of the aggregate is its resistance to compressive forces.

Though, strong and hard aggregates are required for strong concretes, yet the strength of the aggregate is not the problem usually come across in making concrete. In the concrete, which is made of cement paste and aggregate, cement paste is comparatively weaker constituent; hence as long as the cement paste does not give way, the aggregate in general will hold its own. The relation for the compressive strength of the cement paste is given by Powers as $f'c = 34{,}000\ X^3$, where f'c is the compressive strength and X^3 is the gel space ratio. For the gel space ratio of unity, the theoretical maximum compressive strength of paste is 34,000 psi. In actual practice, however, concretes of 2,500 psi to 7,000 psi are made. Compared to this, Table 2 (4) shows that the aggregates of 7,000 psi and above compressive strength capacity are commonly available. (Incidently, this table also indicates that no definite relationship can be established among the compressive tensile and shear strengths of the aggregates.)

Kaplan designed an experiment to study the effect of different aggregate properties on the strengths of concrete. He says, ". . . the flexural strength of concrete is generally lower than the flexural strength of the corresponding mortar. This suggests that an upper limit to the flexural strength of concrete is generally set by the strength of the mortar and that the presence of coarse aggregate generally reduces the flexural strength of the concrete to below that of mortar. On the other hand, the compressive strength of concrete is usually greater than the compressive strength of its comparable mortar, which indicates that the mechanical interlocking of the coarse aggregate contributes to the ultimate strength of concrete when subjected to compressive loads." (16) Though, he has not been able to establish a relationship between the crushing strength of the aggregate and the compressive strength of the concrete, yet, he remarks that "the possibility should not, however, be excluded that aggregates having much lower strength than those used in this investigation may affect the strength of concrete."

The above discussion brings out the fact that though no definite relationship can be established between the compressive strengths of aggregate and the corresponding concrete, yet a broad statement can be made that within certain limits, stronger aggregates yield stronger concretes.

Size

Based on size the aggregates are devided into two groups: coarse and fine. Aggregate more than 1/4 inch in size is termed as coarse; and that smaller than 1/4 inch is known as fine or sand. There are available several size groups of coarse material, such as 1/4 to 3/4 inch, 3/4 to 1-1/2 inch, 1-1/2 to 2-1/2 inch and higher. Likewise two or three grades of sand are also available. This segregation of size is necessary for designing the concrete mix, as the mix proportions are always given in terms of cement:coarse aggregate: fine aggregate. The quantity of water is to be specified for each mix.

In general, concrete made of larger maximum size aggregate is more economical. However, size has a bearing on the cement requirement, water cement ratio and eventually on strength. Fig. 2 (5) shows the effect of size on the cement requirement and density. It can be seen that there is marked effect on both the cement requirement and density upto about 2-1/2 inch. Similiarly, the water cement ratio is also smaller for the concretes of same strength but larger maximum size of aggregate. There is a general relationship between the water cement ratio and the compressive strength. Fig. 3 (10) indicates that higher compressive strength is obtained at lower water cement ratio. Hence, it can logically be inferred that as the size of aggregate in the mix increases, the water cement ratio decreases and consequently the strength of the concrete increases. In a way, this has been the basis of mix design for a considerable time; however, the recent work done in this branch of concrete technology puts certain limitations and indicates this conclusion is only partially correct. (3) An experiment was conducted with 56 combinations of aggregates obtained from various parts of the United States and also from Great Britain, and among other things relationships among aggregate size,

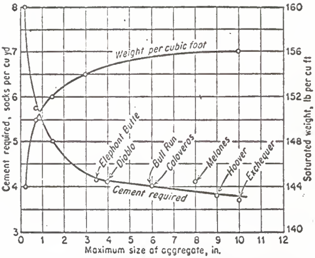

FIG. 2. Effect of size of aggregate upon cement requirement and unit weight of concrete of given water-cement ratio and consistency. Water-cement ratio = 6.5 gal per sack of cement. Slump 3 to 5 in. (*Portland Cement Association.*)

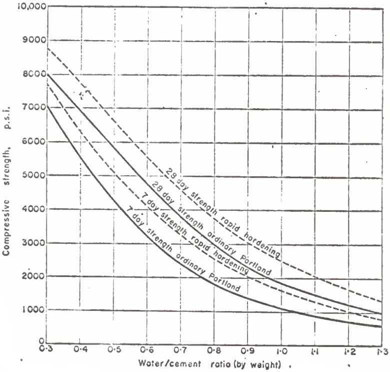

Fig. 3. W/c ratio strength curve.

water requirement and strength of concrete were studied. The results are represented in Fig. 4 (3). The lower part of the diagram shows the mixing water requirement for both large size and small size aggregates. On the average, mixing water for 1-1/2 inch aggregate was about 2-1/2 gallons per cubic yard less than that for 3/4 inch. The upper part of the diagram indicates that this advantage in reduced water ratio was sufficient to give stronger concrete in larger aggregate size but leaner 5-sack mix. In the richer 7-sack mix concrete, smaller maximum size produced the higher compressive strength, even though the water cement ratio for it was higher. Approximately each increase of 1 gallon per cubic yard in required mixing water resulted in 250 psi reduction in compressive strength. Curves in Fig. 5 (3) bring out one more point of interest. It is seen that for a given water cement ratio, somewhat higher strength is obtained from the 3/4 inch than from the 1-1/2 inch maximum size aggregate. In compression, additional strength to the tune of 300 to 400 psi is obtained. (The same is true for flexure, advantage being about 50 psi.)

Another point that was noted with respect to water requirement was that the detrimental effect on strength due to increase in size from 3/4 inch to 1-1/2 inch could be offset by the reduction of approximately 2-1/2 gallons per cubic yard. In general, the magnitude of water reduction was greater than 2-1/2 gallons in the case of 5-sack concrete which resulted in higher strength with increase in maximum size. On the other hand, in the case of 7-sack concrete, water reduction was comparatively less than this 2-1/2 gallons, with the result that the net effect was a reduction in strength.

In Table 4 (1) are given the results of some earlier work. The results vividly bring out the fact that the compressive strength of concrete increases to some limit with the increasing size of aggregate, and then it decreases.

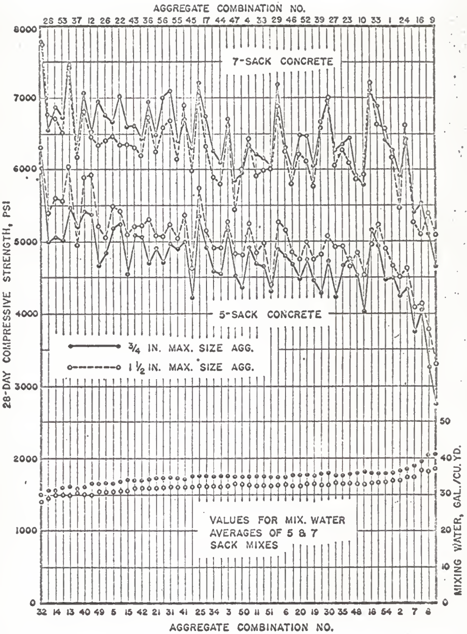

Fig. 4.—Compressive strengths for aggregate combinations in order of increasing mixing water requirements (Series 178)

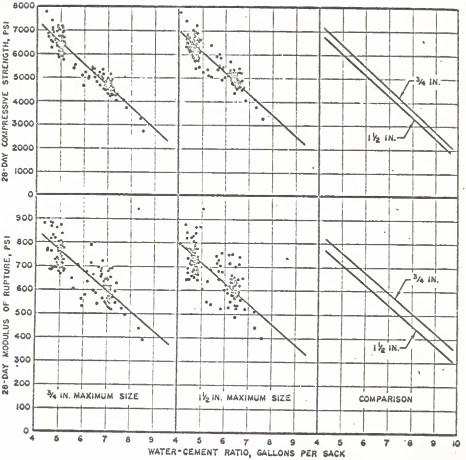

Fig.5. —Water-cement ratio strength relationships (Series 178)

TABLE 4.—RESULTS OF STRENGTH TESTS, SERIES 173*

Design cement, sacks per cu yd	Maximum size aggregate, in.	Compressive strength of 6 x 12-in. cylinders, psi			Modulus of rupture of 6 x 6-in. beams, psi			tensile strength, psi (splitting)	
		7 days	28 days	91 days	7 days	28 days	91 days	28 days	91 days
Group 1—Non-air-entrained concrete									
4	⅜	1545	2320	2440	319	431	428	340	346
	¾	1875	2780	3000	351	491	483	389	409
	1½	1990	2910	3300	409	444	501	411	404
	2½	2010	2920	3015	362	494	498	426	408
6	⅜	3800	5035	5365	553	615	624	504	527
	¾	4025	5090	5740	598	658	633	528	517
	1½	3950	4915	5275	574	606	625	510	528
	2½	3725	4675	5195	523	624	617	517	526
8	⅜	4740	5950	6640	713	783	799	531	569
	¾	4680	5665	6455	692	771	802	485	547
	1½	4570	5545	6105	668	776	812	516	549
	2½	4350	5100	5970	662	718	773	515	544
Group 2—Air-entrained concrete									
4	⅜	1530	2365	2560	296	405	416	330	341
	¾	2125	3010	3300	370	472	495	403	408
	1½	2195	3110	3310	377	459	476	402	425
	2½	2145	2955	3140	357	464	483	365	403
6	⅜	3920	5115	5555	581	639	628	536	539
	¾	3715	4670	5235	573	624	611	502	490
	1½	3660	4680	5055	574	616	614	496	498
	2½	3710	4465	4555	566	568	608	494	505
8	⅜	4710	5700	6465	668	775	759	538	556
	¾	4110	4960	5595	649	573	710	469	471
	1½	3835	4700	5245	610	700	691	454	504
	2½	3845	4610	4980	630	664	684	442	497

*Each value average for tests of specimens from three batches mixed on different days.

This table suggests that that limit can be placed at 3/4 inch size. The compressive strength can also be associated with the percentage of cement content in the mix and the time; higher strengths being obtained with the increase in percentage of cement content and with the passage of time. This is in agreement with the results obtained later and discussed at length earlier. The results of Table 4 also furnish information about the strength in rupture and tension. Here the dividing line appears to fall on 3/8 inch size; strengths in general decreasing with the increase in size of aggregate. The results are, however, not very consistant as compared to results obtained for compressive strength. All other conditions being the same, the air-entrained concrete is found to be stronger than the corresponding non-air-entrained one.

The discussion shows that reduced strengths are obtained for large maximum size, even though water cement ratio is smaller. "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 smaller sizes has the added advantage of providing more evenly placed concrete with less segregation and more reproducible strength tests." (11)

Brief conclusions of the discussion are as follows:

1. Though 3/4 inch size aggregate appeared to be the optimum size for obtaining the maximum strength of concrete, (11) yet, in general, the optimum size will vary according to aggregate types, cement factors, test ages and probably other conditions.

2. Increasing size from 3/4 inch to 1-1/2 inch results in reduction of water requirement, but has an offsetting detrimental effect on the strength of concrete. (3, 12) For increases in size upto 3/4 inch the effect of reduced water predominates and strength increases. (3)

3. In the leaner concretes of lower strengths, the reduction of water

offsets the detrimental effects of the larger size. The result is higher strength with larger sizes. By the same token, in rich mixes, the effect of size will dominate, lower sizes, producing higher strengths. (3)

4. Air-entrained concrete has higher strength than the corresponding non-air-entrained one. The air-entrained concretes show relatively greater strength reduction for the larger sizes in spite of their lower strength level.

5. Age has relatively small effect on the size-strength relationship. (1)

6. A realistic appraisal of the data brings home the point that the general relationships are of limited significance since individual aggregates vary many times more in strength development characteristics than the moderate differences attributable to usual changes in maximum size. (3)

Moisture Absorption

An aggregate particle's internal structure is made up of solid matter and voids. The voids may or may not contain moisture. Based on the moisture conditions, the aggregate may be obtained as follows:

(a) Oven dry; when it contains neither external or internal water. Water is usually driven off by heating the aggregate at 100°to 110°C. The aggregate is in fully absorbant condition.

(b) Air dry; the particles are dry at the curface, but contain some internal moisture. Thus, the aggregate is partially absorbant.

(c) Saturated surface dry; an ideal condition in which aggregate has no free or surface water, but all the internal voids are fully saturated. In this condition, the aggregate neither absorbs water from the concrete paste nor contributes to it.

(d) Damp or wet; the aggregate is fully saturated and in addition contains free or surface moisture. In this condition the aggregate contributes water to the cement mix. (5, 7)

All the above four conditions are represented in Fig. 6 (5).

The total internal moisture content of an aggregate in the saturated surface dry condition may be termed as "absorption capacity," although it is sometimes referred to simply as the "absorption." The amount of water required to bring an aggregate from the air dry condition to the saturated dry condition is termed as the "effective absorption."

While designing the mix, the aggregates are supposed to be in saturated surface-dry condition. Depending upon the conditions of aggregate, necessary provision is to be made in the water-cement ratio; extra water to be added if the aggregates are in air-dry conditions, or vice versa. Table 5 gives the approximate amounts of free water and absorption for commonly used aggregates.(4)

Moisture content of aggregates has an indirect effect on the strength of the concrete which will be reflected if the initial moisture condition of the aggregates is ignored. The result will either be extra wet or stiff mix, depending upon the fact that the aggregates are damp or air-dry. Extra water in concrete will promote segregation and bleeding, thus contributing hetrogeneous pockets within the mass. The resulting product is a weak concrete. From that standpoint it may appear that the other condition of air-dry aggregates is better; however, these aggregates will absorb the water from the mix and render it unworkable and stiff and the concrete will lose its plasticity.

Thus, this discussion brings forward the need of knowing the initial condition of aggregate moisture for the purpose of correcting the water-cement ratio. Ignoring this aspect of design will result in the making of weak concretes; on the other hand, concretes of required strengths can be made, once, along with other precautions this part of the design is also taken care of.

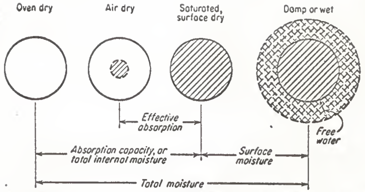

Fig. 6. States of moisture in aggregate. Heavy circle represents the aggregate; crosshatching represents moisture.

TABLE 5.–USEFUL DATA FOR DESIGNING CONCRETE MIXES (*Continued*)

APPROXIMATE AMOUNTS OF FREE WATER IN AGGREGATES[a]

Very wet sand	6 to 8 per cent by weight
Wet sand	4 per cent by weight
Moist sand	2 per cent by weight
Moist gravel or crushed stone	1½ per cent by weight

[a] The amount of free water carried increases with the fineness of the aggregate.

APPROXIMATE ABSORPTION OF AIR DRY AGGREGATES

Ordinary sand	0.5 to 1 per cent by weight
Gravel and crushed limestone	0.5 to 1.5 per cent by weight
Trap rock and granite	0.3 to 0.5 per cent by weight
Porous sandstone	7.0 per cent by weight

Chemical Stability

The bond between the aggregate and the matrix has a considerable influence on the strength and durability of concrete. In the case of failure, when the breaks are observed through the aggregate, it is the evidence of good bond; and when the break occurs around the aggregate, a poor bond is indicated. One of the factors which contribute towards a weak bond and ultimate deterioration is the chemical reaction between the aggregate and the matrix. (13)

Among other constituents present in the cement are alkalies which may range from 0.4 to 1.3 percent. When aggregate have opaline silica, chalcedony, zeolite, rhyolite, etc., as mineral constituents, they react with the alkalies present in the cement. The probable reactions that take place between opaline silica and alkali are such as follows:

$$4SiO_2 + 2NaOH = Na_2SiO_4O_9 + H_2O \quad (1)$$

$$SiO_2 + 2NaOH = Na_2SiO_3 + H_2O \quad (2)$$

The osmotic pressure hypothesis has been put forward to explain this situation. When the reaction takes place, alkali-silicate formed on the surface of an aggregate particle tends to draw solution from the cement paste and forms a pocket of liquid within the body of concrete and exerts a hydrostatic pressure against the confining paste. Since these alkali-silicates form in the space originally occupied by silica from which they were formed, and as the resulting silicates occupy more volume than that occupied by silica alone, they tend to exert pressure against the confining paste which would be augmented by the hydrostatic pressure. These pressures cause abnormal expansions which sometimes take place even after two years after placing the concrete. (14, 5)

Although many kinds of aggregates contain small amounts of undesirable reactive materials, yet it is not known how much of such materials must be present to produce an undesirable reaction with alkalies in cement. On the other hand it has been seen that cements containing more than 6 percent alkalies are liable to give adverse reactions and undesirable expansions. (5, 13) Fig. 7 gives the relationship between age and degree of expansion with cements of different alkali-contents.

Chemical reaction between cement and aggregate results into expansion and development of surface cracks and decline in concrete strength. The osmotic pressure exceeds the tensile strength of concrete, (osmotic pressure is sometimes 550 psi) causes the formation of cracks, which are sufficiently extensive to account for the increase in volume and decline in strength. (15)

With some aggregates, over a long period of time, slight interaction may occur between cement paste and aggregates at particle surfaces. This action is sometimes beneficial as it improves the bond and strength in general. The extent of such reactions appears to be very small. (5)

Shape and Texture

Angularity or roundness describe shape; likewise, the degree of roughness or smoothness gives the idea about texture.

Workability of concrete mix is affected if very flat and elongated aggregate particles are present in appreciable amount. Water-cement ratio is then increased to improve the workability which in turn affects the strength. Flat pieces tend to affect durability also if they are so oriented as to promote the accumulation of water underneath their bottom surfaces. Though specific quantitative limits can not be given for the use of flat and

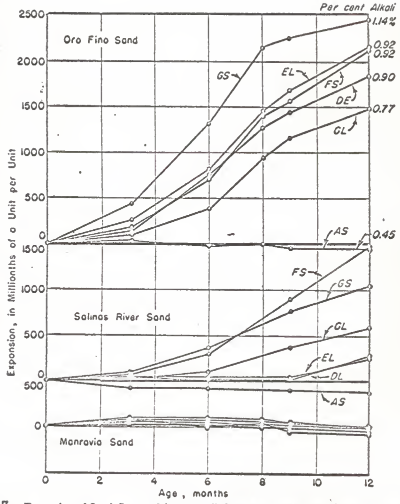

FIG. 7. —Expansion of Sand-Cement Mortars as Influenced by the Type of Sand and the Alkali Content of the Cement. (From Stanton (2).)

elongated particles, yet roughly 10 to 15 percent of such shaped particles can be accepted in the aggregate. (5) Concrete with rounded aggregate requires comparatively less water-cement ratio than the corresponding one with crushed rock, but the bond between the cement paste and the aggregate in the hardened mass being less in the former than in the later, the strength is correspondingly reduced. (10)

Kaplan (16) designed an experiment to study the effect of coarse aggregate characteristics on the strength of concrete. Tables 6 and 7 (16) furnish the information about the types and the properties of the aggregate used. He explains the terms used by him as follows:

Flakiness index: It is measured by expressing the total weight of different size fractions of the aggregate, passing specified thickness gages, as a percentage of the total weight of the sample tested. The width of the thickness gages is 0.6 times the mean size of the aggregate.

Elongation index: The same as flakiness index, except that length gages equal to 1.8 times the mean sieve size of the aggregate are used.

Aggregate crushing value: This is obtained by subjecting a stipulated quantity of the 1/2 inch to 3/8 inch fraction of the coarse aggregate to a specified compressive bond. The weight of aggregate passing a No. 7 British Standard (No. 8 Tyler) sieve is then expressed as a percentage of the total. This percentage is the aggregate crushing value.

Surface texture: This involves embedding a particle of aggregate in a synthetic resin and obtaining thin sections of the aggregate surrounded by the resin. The interface between stone and resin is magnified 125 times on a projection microscope and traced. The length of the profile is measured and compared with the length of an uneveness line drawn as a series of chords. The difference between the two lengths is taken as a measure of the roughness

TABLE 6.—TYPE, SOURCE, AND CONDITION OF THE COARSE AGGREGATES USED

Aggregate identification	Type	Source in United Kingdom	Condition
A	Quartzite gravel	Bridport	Natural
B	Quartzite gravel	Bridport	Crushed with a low reduction ratio from 1½-in. single size gravel
C	Flint gravel	Chertsey	Natural
D	Flint gravel	Chertsey	Crushed with a low reduction ratio from 1½-in. single size gravel for the ¾-in. to ⅜-in. fraction and from ¾-in. single size gravel for the ⅜-in. to $\frac{3}{16}$-in. fraction
E	Flint gravel	Chertsey	Crushed with a high reduction ratio from 2-in. to 3-in. size natural gravel
F	Limestone gravel	Lancashire	Natural
G	Limestone gravel	Lancashire	Crushed with a low reduction ratio from 1½-in. single size gravel
H	Basalt	Blodwell	Crushed with a low reduction ratio from 1½-in. single size
J	Basalt	Blodwell	Crushed with a high reduction ratio from 3-in. to 4-in. size
K	Granite	Penryn	Crushed with a low reduction ratio from 1½-in. single size
L	Granite	Mountsorrel	Crushed with a low reduction ratio from 1½-in. single size
M	Trachyte	Downhead	Crushed with a low reduction ratio from 1½-in. single size
N	Limestone	Somerset	Quarried and crushed by supplier

TABLE 7.—PROPERTIES OF THE AGGREGATES

Aggregate	Shape			Strength					Elastic properties					
	Average flakiness index	Average elongation index	Angularity No.	Crushing, psi	Flexural, psi	Indirect tensile, psi	Crushing value	Impact value	Dynamic modulus × 10^{-6} psi	Pulse velocity, ft per sec	Poisson's ratio	Surface texture (roughness factor)	Absorptive capacity, percent	Specific gravity
A	8	24	1	—	—	—	8	15	8.6	16,370	0.15	4.4	0.5	2.51
B	27	35	5	—	—	—	16	20	8.6	16,370	0.15	5.3	0.4	2.52
C	28	33	6	—	—	—	16	22	8.0	16,640	0.24	2.5	1.0	2.52
D	22	27	8	—	—	—	20	23	8.0	16,640	0.24	2.2	0.3	2.55
E	34	42	9	—	—	—	20	28	8.0	16,640	0.24	2.2	0.1	2.58
F	7	13	2	22,900	2720	1100	18	24	10.7	21,100	0.33	9.4	0.9	2.61
G	22	33	6	22,900	2720	1100	23	23	10.7	21,100	0.33	7.5	0.8	2.62
H	31	42	9	44,500	6490	2210	11	11	10.9	19,830	0.29	13.1	0.6	2.64
J	34	44	10	44,500	6490	2210	14	14	10.9	19,830	0.29	12.2	0.5	2.64
K	9	18	9	22,950	900	920	29	33	3.3	12,780	0.36	16.6	0.3	2.62
L	23	30	8	35,800	3650	1690	19	21	10.2	18,050	0.27	8.8	0.2	2.61
M	25	43	10	41,400	5060	2400	12	11	10.5	19,330	0.30	11.6	0.2	2.71
N	26	33	7	26,700	2270	1230	20	20	11.3	21,080	0.31	10.0	0.4	2.66

or surface texture of the aggregate.

Angularity No. is measured according to the following formula given by Shergold: (10)

$f_a = 3\ f_{h/20} + 1.0$, where

f_a = Angularity number,

$f_h = Vo - 33$

V_0 = Voids in the compacted aggregate. (10)

The three mixes which Kaplan used for the experiment had the cement-aggregate ratio (by weight) of 1:3.08 (mix No. 1), 1:7.53 (mix No.2) and 1:10.25 (mix No. 3) and the water-cement ratio (by weight) of 0.35, 0.60 and 0.85 respectively. Tables 8, 9 and 10 give the results obtained by him. Statistical study shows the correlation between the angularity of aggregates and the flexural and compressive strengths of concrete. Likewise significant correlation is found between the surface texture of the aggregates and the flexural and compressive strengths of concrete. It is further noted that flexural strength is also affected by the elasticity of the aggregate.

In general both shape and the surface texture influence the compressive strength; surface texture being the predominating factor between the two characteristics. A logical explanation as to why rougher surface texture of the aggregate results into increased concrete strength may be that it provides greater adhesive force between the cement matrix and the aggregate. Likewise angularity provides the aggregate with more surface area than does the rounded one. Thus, adhesive force between angular aggregate and the cement matrix is more than for a rounded aggregate.

The flexural strength of the concrete is affected by coarse aggregate;

TABLE 8.—FLEXURAL STRENGTH OF THE CONCRETE, PSI

Aggregate	Mix I			Mix II			Mix III		
	7 days	28 days	91 days	7 days	28 days	91 days	7 days	28 days	91 days
A	670	775	840	435	530	560	280	365	445
B	750	855	975	495	630	705	280	420	500
C	650	755	740	445	605	590	335	425	475
D	735	825	845	525	650	675	300	415	525
E	—	870	870	—	660	710	—	385	415
F	760	825	835	520	655	690	315	430	450
G	775	950	950	535	695	760	320	480	550
H	805	1000	960	535	740	770	350	480	555
J	830	1060	1045	540	725	840	335	490	560
K	685	820	940	470	575	635	290	390	455
L	775	940	955	515	695	755	335	470	520
M	755	970	1015	540	695	820	315	445	515
N	850	975	1060	555	795	805	330	480	540

TABLE 9.—COMPRESSIVE STRENGTH OF THE CONCRETE, PSI

Aggregate	Mix I			Mix II			Mix III		
	7 days	28 days	91 days	7 days	28 days	91 days	7 days	28 days	91 days
A	7780	9770	10360	3770	5910	6880	1880	3140	4010
B	8080	10500	11640	4100	6240	7380	2140	3330	4140
C	8160	9520	10020	4460	6660	7470	2260	3610	4420
D	8100	9960	10850	4360	6700	7800	2140	3540	4340
E	—	9990	10420	—	5480	6920	—	2840	3530
F	8040	10180	11170	4420	6660	7690	2170	3370	4360
G	8720	10160	11440	4300	6440	7450	2230	3520	4360
H	8440	11130	11280	4550	6910	8050	2420	3660	4570
J	8670	10950	11770	4490	6600	7850	2420	3600	4420
K	8290	10620	11270	4020	6100	7290	2150	3310	4130
L	8940	11240	12430	4460	6720	8020	2280	3820	4650
M	8680	11460	12240	3850	6150	7450	2180	3260	4180
N	8140	10410	11460	4250	6500	7500	2170	3340	4070

TABLE 10.—FLEXURAL AND COMPRESSIVE STRENGTH OF THE MORTAR IN THE CONCRETE AFTER 91 DAYS

Property	Mix I	Mix II	Mix III
Flexural strength, psi	1130	795	525
Compressive strength, psi	11090	5920	3380

strength of the mortar is greater than the corresponding strength of concrete with coarse aggregate. On the other hand, concrete compressive strength is generally greater than that of the mortar; the presence of coarse aggregate therefore contributes to the ultimate compressive strength of concrete.

Bloem and Gaynor studied the effects of coarse aggregate shape and texture as indicated by void content and adopted the indirect approach by observing the relationship to concrete mixing water requirement. (3) In general the mixing water requirement increased as coarse aggregate void content increased. They conclude by saying, "Coarse aggregates void content does not relate directly to concrete strength but probably, as a measure of differences in particle shape and texture, does provide an indication of mixing water requirement." Elsewhere they remark that "each percentage increase in coarse aggregate voids will produce an average reduction in compressive strength of about 125 psi and in flexural strength of about 15 psi."

The above discussion does not give a quantitative conclusion but a general remark can be made that aggregate with rougher texture and angular shape (within limits) will contribute towards increasing the compressive and flexural strength of the concrete.

Gradation

Gradation of aggregates refers to particle size distribution and is normally determined by a sieve analysis. The standard sieves commonly used for this purpose are numbers 4, 8, 16, 30, 50 and 100 for fine aggregates and 6 inch, 3 inch, 1½ inch, 3/4 inch, 3/8 inch, and No. 4 for the coarse aggregates. These numbers refer to the number of square openings per inch.

During processing at the quarry, aggregates are screened into various sizes. The amount present of material of different sizes expressed as the cumulative percentage of material passing the various sieve sizes, starting with the largest and finishing with the smallest. The grading curve is then plotted by plotting the cumulative percentage retained on the sieves. The grading of aggregates is a major factor determining segregation, bleeding, handling, workability and strength characteristics of the concrete.

There is no universal ideal grading curve for aggregates to obtain the satisfactory concrete. Fig. 8 (2) shows the limits specified in specification for aggregates, within which a grading must lie to obtain a satisfactory concrete, but these depend upon the shape, surface, texture, type of aggregate and the amount of flaky or elongated material. (10)

Fig. 9 (17) shows the variation of compressive strength of concrete with the voids in it. As the number of voids goes on decreasing, the strength goes on increasing. For those aggregates that give the minimum voids, the magnitude of the voids in the concrete is extremely small. Though this grading of aggregate results theoretically in high strength concretes, yet the mixes so obtained are very harsh ones and it becomes very difficult to place so as to make homogeneous concrete free from air spaces unless they were most carefully mixed, placed and tamped. In field work the ordinary methods of placing and tamping such mixtures would result in uneven concrete, with many voids at several places, and consequent loss of homogenity and strength. (17)

Depending upon the required workability, the proportion of sand varies with the water content of the paste. For any fine and coarse aggregates used in combination with a given cement paste, there is a definite percentage of sand--called optimum--which, for a particular workability requires the least quantity of cement paste. Any variation from optimum will require larger quantity of cement paste, otherwise the mix will be either too harsh or too

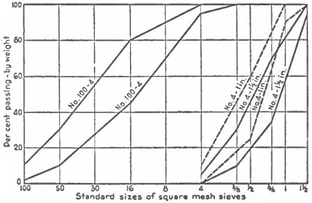

Fig. 8. Curves indicate the limits specified in *Tentative Specifications for Concrete Aggregate* (ASTM C33) for fine aggregate and for two sizes of coarse aggregate.

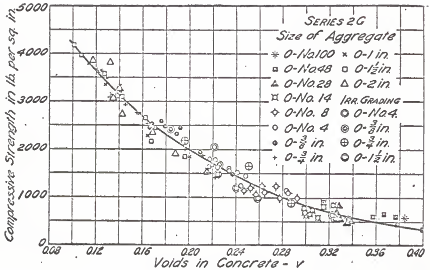

FIG 9. VOIDS AND COMPRESSIVE STRENGTH OF CONCRETE, SERIES 2G

stiff. As seen earlier, ultimate effect on strength shall be reflected.

Grading of individual aggregates also affects the proportions of fine to coarse aggregates. If the grading of coarse aggregate of given size is varied and the proportion of fine aggregate is accordingly adjusted to obtain the necessary workability, the cement requirement will not be appreciably affected. However, if the proportions of fine aggregate are kept constant, variations in coarse aggregate gradings will effect in variations in the cement requirement. Table 11 (2) shows the variations in cement requirements when a constant water-cement ratio was maintained as the optimum amount of sand was used. Whereas the changes were made in the grading of the coarse aggregate. If a constant cement factor is used, the optimum amount of sand will need the least quantity of water for a given workability, and hence will produce the best concrete. (It has earlier been stated that with other factors maintained constant, higher strength in concrete is obtained at the lower water-cement ratio.) (3, 6)

TABLE 11—EFFECT OF GRADATION OF COARSE AGGREGATE ON CEMENT REQUIREMENT

Grading of coarse aggregate (per cent by weight)			Optimum* amount of sand	Cement required at per cent of sand indicated—sacks per cu. yd.	
No. 4-⅜ in.	⅜-¾ in.	¾-1½ in.	Per cent	Optimum	35 per cent
35.0	00.0	65.0	40	5.4	5.7
30.0	17.5	52.5	41	5.4	5.8
25.0	30.0	45.0	41	5.4	6.2
20.0	48.0	32.0	41	5.4	6.0
00.0	40.0	60.0	46	5.4	7.0

*Amount giving best workability with aggregates used. Water content 6.3 gal. per sack of cement.

It is seen that the cement requirement is not much affected whether fine sand or coarse sand is used provided the optimum amount of sand is used. In general the percentage of sand should be less when it is fine than when it is coarse. Use of very fine sand is undesirable; combined with coarse aggregate it often produces a mix in which segregation can easily result. There is also possibility of bleeding and consequent loss of strength. The finer the sand, the more likely it is made up predominantly of one or two sizes. As such, coarsely graded sands are more desirable. This, however, does imply the presence of sufficient quantity of fine particles for producing the required workability. Specifications of the American Society of Testing Materials allow 10 to 30 percent of material passing 50-mesh sieve.

A grading of sand in which one or two particle sizes predominate should be avoided; such a sand requires a large amount of cement water paste. In general very fine and very coarse sands are both undesirable. The coarse sand results in hardness and segregation; and fine sand requires a large amount of water to produce the required workability, which once again tends to segregate. The net result is loss of strength. (5, 7)

Grading of coarse aggregate may vary appreciably without affecting the cement requirement for a given water-cement ratio and workability, provided optimum proportion of sand is used. This is true for a given maximum size. However, for given water-cement ratio, the amount of cement required decreases as the maximum size of aggregate increases. (7) Upto some maximum size of aggregate, say 3/4 inch, the compressive strength also increases with the diminishing water-cement ratio. In other words, the effect of the maximum size of the aggregate on the efficiency of cement can be measured also in terms of the amount of water required with a fixed amount of cement to produce concrete of a given slump and the effect this has on the compressive strength. The maximum of aggregate that can be used generally depends upon the size and shape of concrete members and the amount and distribution of reinforcing steel. In general the maximum size of aggregate should not exceed:

a. one-fifth the minimum dimension of non-reinforced members,

b. three-fourths the clear spacing between reinforcing bars or between reinforcing bars and forms, or,

c. one-third the depth of non-reinforced slabs on ground. (2, 7)

It is seen that the effect of gradation is constantly varying, depending upon the cement and water content. Its effect is more important with lean mixes of high workability and is less important with mixes containing sound aggregates. (10)

In general, optimum gradings producing maximum density consistent with good workability will give maximum compressive strength with minimum cement requirement.

CONCLUSION

This paper has discussed the aggregate characteristics and their effect on the strength of concrete.

The aggregate is a filler material in the concrete mass and is relatively cheap; but unless the appropriate material is used, this cheap material may turn out to be quite an expensive proposition in the long run. Some of its properties like gradation and chemical stability may have a marked effect on the immediate or ultimate strength. Also a lot of economy can be effected by a careful and judicious use of aggregate.

Probably, because aggregate is cheap and in general far stronger than the cement paste, it has not been investigated so thoroughly with respect to its effect on the strength of concrete. Only recently the effect of size on strength has been studied and it was seen that the smaller the maximum size of coarse aggregate, the greater the concrete strength. A more thorough investigation needs to be done to relate strength of concrete with aggregate characteristics like shape, texture, gradation, moisture absorption and compressive strength.

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THE EFFECT OF AGGREGATE ON THE STRENGTH OF CONCRETE

by

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AN ABSTRACT OF A MASTER'S REPORT

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The purpose of this report is to discuss the effect of aggregate on the strength of concrete. Aggregate, both coarse as well as fine, is chemically inert material added into cement paste as a filler material to increase its volume. The chief requirements of aggregates are that they be hard, tough, clean, strong and well graded.

Aggregates with high unit weight give comparatively denser concretes; and the denser concretes have higher compressive strength.

Moisture content is mainly dependent upon the voids in the aggregate mass (aggregate may have surface moisture as well). This study helps in assigning the correct water-cement ratio which will, otherwise, affect the strength adversely.

When water freezes, it expands. This expansion can cause a high pressure which may be sufficient to disintegrate the strongest concrete. Hence, aggregates with low water content, absorption, and low permeability will give stronger concretes. The size or the thickness of the body also has an effect on freezing. Concretes containing small entrained air, stand freezing better.

The strength of concrete is the function of the bond between aggregate and matrix, as the crushing strength of aggregate is usually much more than the strength of concrete made with them. However, it can not be said that the concretes made with less strong aggregates will not result into weak concretes.

For a given water-cement ratio upto some limit, the strength increases with the increasing size of aggregate; then it reduces. Optimum size for this purpose is 3/4 inch size aggregate.

Alkali-aggregate reaction can be sometimes so pronounced as to affect the strength of the structure to the extent as to cause concern. Chemical reaction causes expansion and cracks. With reactive aggregates, the alkali-content of cement should not exceed 6 percent.

Compared to rounded, smooth aggregates, the rough, crushed and angular aggregates impart more strength to concrete. However, the quantity of angular aggregates should be kept within 15 percent to avoid the unworkable concretes.

Judicious gradation of aggregates will not only give economical mixes by requiring less cement, but also give stronger concretes due to lower water cement ratios.

Only general remarks can be given when discussing the role of aggregates with respect to strength of concrete, as very little work has been done to establish quantitative relationships between each characteristic and strength. This field of concrete technology needs to be explored as yet.