AGGREGATE GRADING AND THE INTERNAL STRUCTURE OF CONCRETE

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It is shown that there are many gradings for concrete aggregate that can be considered as optimum for one purpose or another. In addition to the behavior of the concrete in the fresh as well as in the hardened state, visual inspection of the internal structure of concrete reveals whether the grading used is close enough to the desired optimum. A method, adopted from a procedure used in petrography, is presented for such evaluation of the structure of concrete. This is based on the measurement of the intercepts of mortar layers among coarse aggregate particles in the finished concrete. Various kinds of concretes are analyzed by this method. The results indicate that there exists a needed minimum value for the average mortar layer intercept below which the workability of the concrete is inadequate; this needed minimum mortar intercept is dependent on several factors such as the method of compaction and the grading of the sand; and the minimum value seems to be independent of the particle shape of the coarse aggregate. The effect of the particle shape of coarse aggregate on the grading optimum is also discussed. Based on this, two methods for measuring the angularity of the particles are recommended. Finally, internal structures of concretes made with continuous gradings and comparable gap gradings are contrasted.

•THE term optimum grading is used in this paper to represent a grading that can provide the optimum of a given concrete property under a set of circumstances, including specified, reasonable amounts of cement and water. Economical considerations will be excluded because they vary drastically from location to location. Neither is there space in this paper to discuss the various methods for checking whether a grading is optimum without trial mixtures (ideal sieve curve, optimum fineness modulus, maximum denseness, etc.); these subjects have been treated thoroughly in a recent book by Powers (1). Rather, the internal structure of the hardened concrete will be discussed here in connection with the grading of the aggregate used. Nevertheless, two comments seem appropriate to resolve certain misconceptions about optimum gradings:

1. It is unrealistic to expect that there is any single grading that can optimize all or most concrete properties simultaneously. Although it is a common feature of all optimum gradings that they provide good workability under the given circumstances, there are numerous optimum gradings. For one thing, gradings that are optimum for one concrete property, say, the strength of concrete, may not be, and usually are not, optimum for another concrete property, such as impermeability. Second, the optimum of a grading for, say, the concrete strength is also influenced by the method of consolidation, the type of aggregate, and the amount of cement to be used. Third, different particle-size distributions, under otherwise identical conditions, can have practically identical concrete-making properties; i.e., they can produce the same optimum of the concrete property in question.

2. There is no single grading for fine aggregate that can provide an optimum combined grading, in any sense of the term optimum, with every coarse aggregate. Fine aggregates complying with accepted grading specifications, such as ASTM Designation C 33, can make good concretes with conventional coarse aggregates. However, combined with unusual coarse aggregates, in gap gradings for instance, the same fine aggre-

gates can be less than optimum. The effects of using a finer sand on the properties of concrete can usually be compensated for by using a smaller proportion of it (1, 2). In other words, the optimum grading, as well as the optimum quantity of a sand in concrete aggregate, depends on the grading, the type of coarse aggregate used, and other factors. The same is true in a reverse sense for the optimum grading of the coarse aggregate.

The amount of a given fine aggregate and the amount of a given coarse aggregate are well balanced in an optimum grading, but the nature of this balance is dependent on numerous factors. In the remainder of the paper, an attempt will be made to give a sense of this balance to the reader using photographs of well-graded concrete aggregates and internal structures of concretes made with such aggregates. The discussion is restricted to the most common case when the concrete strength is to be optimized.

RELATION BETWEEN AGGREGATE GRADING AND INTERNAL STRUCTURE OF THE CONCRETE

A simple petrographic method is also recommended in the paper for the numerical evaluation of the macrostructure of hardened concrete. Although there is a considerable amount of literature on the petrographic examination of concrete, especially on the microscopic determination of its air void content, no published systematic treatment has been found concerning the relation between the macrostructure of hardened concrete and the grading of the aggregate used. Thus, it is hoped that this paper, as a first step, will induce further research in this neglected area.

Figure 1 shows the internal structure of an air-entrained gravel concrete through a cut surface. The continuous grading used is shown as curve 1 in Figure 2. The fineness modulus of this grading is 5.7. The cement content of the concrete is 570 lb/cu yd (340 kg/m^3) of portland cement and 170 lb/cu yd (100 kg/m^3) of fly ash. The water-cement ratio is 0.50 by weight, and the air content is about 3 percent. The unit weight of the fresh concrete was 146 lb/cu ft (2,340 kg/m^3), and the slump was about 1 in. (2.5 cm). This concrete had a compressive strength of 5,960 psi (420 kg/cm^2) and a flexural strength of 525 psi (37 kg/cm^2) at the age of 28 days.

The high strength values indicate that this concrete, and thus the grading, too, is good. It is a good grading but not quite optimum. The behavior of this fresh concrete in the laboratory, especially during the compaction by rodding performed according to ASTM Designation C 192-68, indicated that there was a slight excess in the amount of mortar. This observation is supplemented by the fact that the optimum fineness modulus of the aggregate recommended for the maximum strength of the particular mixture is approximately 6.2 (3, 4).

Figure 1 shows that the concrete aggregate used is well graded: The matrix is a dense mortar in which a number of coarse particles are embedded in a random manner, although perhaps a few more gravel pieces could have been placed in it without overcrowding the internal structure. This evaluation is of course highly subjective and only qualitative. An attempt to make this approach numerical is presented as follows.

MORTAR-INTERCEPT METHOD

For a simple numerical analysis of the internal macrostructure of hardened concrete, the intercepts of mortar layers between coarse aggregate particles in a cut, plain concrete surface can be utilized. The coarser the overall grading, the smaller these intercepts become along with the actual thicknesses of the coatings of mortar surrounding the coarse aggregate particles. The mortar intercepts can be measured with the linear traverse method, which is similar to the procedure used in petrography or as described in ASTM Designation C 457 for the air content determination in the hardened concrete, except that there is no need for a microscope in this case. That is, a random cut is taken through the concrete, a regular grid is randomly placed thereon, and linear intercepts are measured along the lines of the grid with the lengths as intercepts in mortar among coarse aggregate particles. These measured intercepts can be summed and averaged, the result of which is a number called "average mortar intercept."

Some difficulty has been encountered during the preliminary intercept measurements in distinguishing between fine and coarse aggregate particles. As a result, it was decided that any aggregate particle having a cut surface larger than $^5/_{32}$ in. (4.0 mm) in diameter be accepted as coarse aggregate because the probability is extremely low that all the particles in any given cut will be intersected in the equatorial plane and that all these will have the grid line crossing the particle at the diameter. It also follows that the average mortar intercept is always greater than the average mortar layer between the closest points of two neighboring coarse aggregate particles in the finished concrete.

The linear traverse method can provide the proportion of the cement paste or that of the mortar in the concrete with a fair accuracy (5, 6). It is also conceivable to obtain the equivalent of an aggregate sieve analysis or the specific surface of the aggregate from linear traverse measurements. But the mathematical difficulties are formidable even for a spherical aggregate. If the aggregate is assumed cuboidal, the situation becomes more complex because lines passing through a cube can be longer or shorter than the cube side. Irregular shapes or mixed shapes present even more difficult problems; thus, the reliability of such grading analysis is highly questionable (7). An advantage of the mortar-intercept method is that it is free from these difficulties.

APPLICATION OF THE MORTAR-INTERCEPT METHOD

The method of intercept, as described previously, was applied to the concrete section shown in Figure 1. The total length of the measured grid lines was about 25 in. The frequency distribution of these intercepts is given in Table 1. As can be seen, the average mortar intercept in this concrete is 0.148 in. (3.75 mm). Because there was a slight excess of mortar in this concrete, one could estimate that, under the given circumstances (that is, traditional gradings of the fine and coarse aggregate for a smooth and continuous combined particle-size distribution, medium cement content, etc.), an average mortar intercept of 0.14 in. (3.5 mm) still would have provided a workability that is suitable for compaction by standard hand-rodding. This would have been the grading that is usually considered as an optimum for the strength of this concrete. A series of similar analyses (8-11) of internal structures performed on photographs of various but comparable concretes resulted in the same needed minimum average for mortar intercepts. It is important also that this 0.14-in. value seems to be the needed minimum in these concretes, not only for gravel particles but for crushed coarse particles as well. That is, this criterion of workability seems independent of the particle shape. Thus, one can define the coarsest permissible gradings for the preceding concretes as those that provide a dense mortar and an average mortar layer intercept of 0.14 in. (3.5 mm) in the finished concrete. Any amount of mortar less than this minimum in a continuously graded concrete would not provide enough lubrication for the coarse aggregate particles for a workability that is adequate for hand compaction. This does not mean, however, that smaller mortar layer intercepts result always in an inadequate workability. For one thing, a reduction in workability caused by a moderate reduction in the mortar quantity can be overcome by intensive mechanical compaction, such as vibration. This is in accordance with the experience that coarser gradings can be used in the concrete when it is compacted by vibration (1). Second, less mortar can also do the job when its lubricating ability is improved. This can be done to a certain extent either by increasing the cement content or by using a finer sand.

An illustration of this latter statement is shown in Figure 3. This shows a cut surface of an air-entrained concrete made with beach sand and crushed reef shell as a coarse aggregate (11). The aggregate grading used is shown in Figure 2 as curve 2. The maximum particle size in the sand is $^3/_{128}$ in. (0.6 mm), and its fineness modulus is approximately 1.3. The fineness modulus of the complete grading is 4.95. The cement content of the concrete is 570 lb/cu yd (340 kg/m^3) of portland cement and 170 lb/cu yd (100 kg/m^3) of fly ash. The water-cement ratio is 0.69 by weight, and the air content is about 3 percent. The unit weight of the fresh concrete was 140 lb/cu ft (2,240 kg/m^3), and the slump was about 3.5 in. (9 cm). This concrete had a compressive strength of 2,830 psi (200 kg/cm^2), a flexural strength of 590 psi (42 kg/cm^2), and a splitting strength of 325 psi (23 kg/cm^2) at the age of 28 days.

A series of trial mixtures indicated that the use of 62 percent crushed reef shell as coarse aggregate is the maximum that still provides a reasonable workability with beach sand. Figure 3 indicates that attempts to insert more shell pieces would overcrowd the internal structure, causing interference among the particles.

The results of mortar-intercept measurements for this concrete are given in Table 1. The average intercept thickness among the shell particles is 0.120 in. (3.04 mm). When the beach sand in this concrete was substituted by a traditional, coarser sand in the same quantity, the workability of the concrete became poor. Thus, the reducibility of the permissible minimum average layer intercept of mortar from 0.14 in. (3.5 mm) in the previous concrete to 0.12 in. (3.0 mm) in this concrete is attributed to the fine grading of the beach sand used.

EFFECT OF PARTICLE SHAPE ON THE STRUCTURE OF CONCRETE

For the illustration of the effect of particle shape of coarse aggregate on the internal structure of concrete, crushed stone and gravel concretes were made with compositions similar to the composition of the reef shell concrete shown in Figure 3. The macrostructures of these concretes are shown in Figure 4. It can be easily seen that, despite the application of an identical grading (curve 2, Fig. 2), the distances between the coarse aggregate particles, particularly in the gravel concrete, are, by and large, greater than in the reef shell concrete. Mortar-intercept measurements given in Table 1 confirm this judgment numerically for these concretes. The average intercept of mortar layers in the crushed stone concrete shown in Figure 4 is 0.148 in. (3.75 mm), and that in the gravel concrete is 0.159 in. (403 mm), as compared to the 0.120-in. (3.04 mm) value in the reef shell concrete shown in Figure 3.

The behavior of these two concretes in the fresh state indicated also that there was an excess amount of mortar present, particularly in the gravel concrete.

Thus, the well-known rule-of-thumb, the more unfavorable is the particle shape of a concrete aggregate the finer the grading required for an adequate workability, can be explained using these photographs. Therefore, fewer coarse aggregate particles can be packed without interference into concrete when the particle shape is unfavorable, elongated for instance, than when the shape is spherical.

Incidentally, the reverse of this sequence of thoughts helps us select two promising approaches from the many available methods (12) for the numerical evaluation of particle shape. First, one can utilize the ratio of the actual specific surface of the aggregate particles in question to a hypothetical (minimum) specific surface, which is calculated using the premise that each particle in the sample keeps its volume but changes its shape into a sphere. The closer this surface ratio is to unity, the better the particle shape is for the workability of concrete. The second approach is the measurement of the denseness of packing of a one-sized fraction of the given aggregate under well-defined conditions. The denser the packing is, the more favorable the particle shape is. This latter principle was utilized in a test method developed by Shergold (13) for the measurement of the so-called angularity number of coarse aggregate particles. This angularity number (AN) is defined as

$$AN = \text{the percentage of voids among coarse aggregate particles} - 33$$

when the aggregate sample of a narrow size range is compacted in a prescribed manner in a specific container. The approximate angularity numbers for the reef shell, crushed stone, and gravel shown in Figures 3 and 4 are 30, 10, and 5 respectively. A test method on the same principle has been incorporated in the British standards (14).

It does not seem too difficult to establish the needed minimum amount of mortar as a function of the shape of the coarse aggregate particle when this shape is characterized by a properly selected number, such as the ones mentioned previously.

SUPPORTING EVIDENCE

The findings concerning the effects of the sand grading and the particle shape of the coarse aggregate on the grading optimum were obtained by the analysis of the internal

Figure 1. Concrete made with traditional sand and gravel according to curve 1 shown in Figure 2 (6).

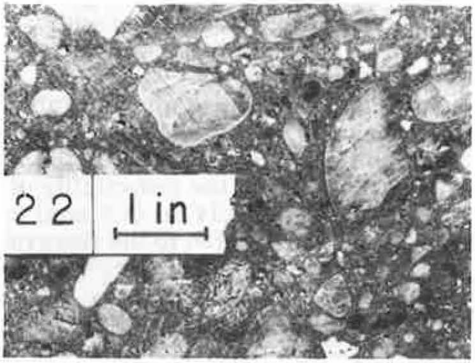


Figure 3. Concrete made with beach sand and crushed reef shell according to curve 2 shown in Figure 2 (7).

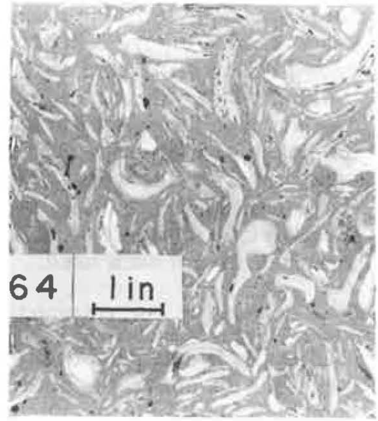


Figure 2. Gradings used in test concrete.

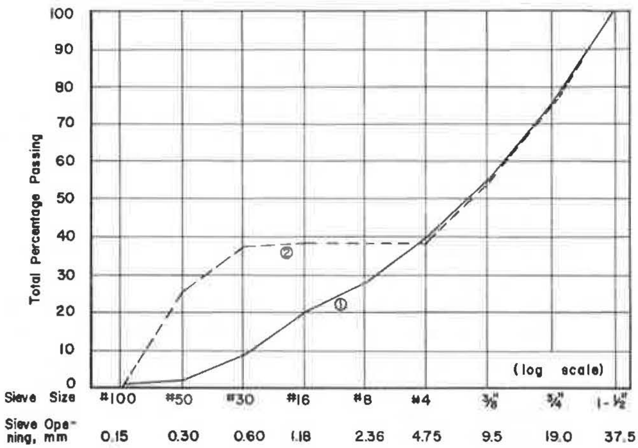


Figure 4. Crushed stone and gravel concretes.

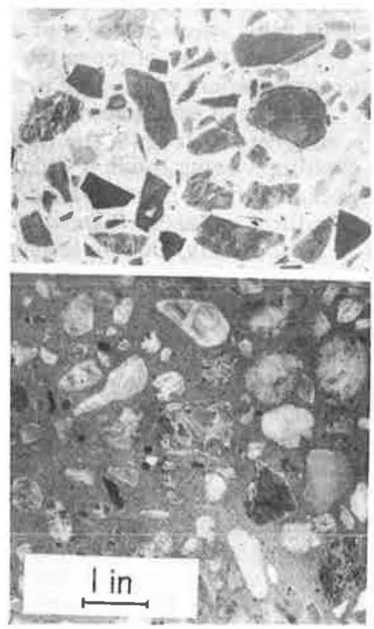


Table 1. Frequency distributions of intercepts of mortar layers.

Concrete Presented In	Aggregate		Intercept of the Mortar Layers Among Coarse Particles (in.)						Total Number of Intercepts	Average Mortar Intercept (in.)
	Grading	Type	0 to 0.1	0.1 to 0.2	0.2 to 0.3	0.3 to 0.4	0.4 to 0.5	0.5 to 0.6		
Figure 1	Curve 1, Figure 2	Sand and gravel	20	20	9	3	-	1	53	0.148
Figure 3	Curve 2, Figure 2	Beach sand and crushed shell	37	37	8	2	-	-	84	0.120
Figure 4 (upper)	Curve 2, Figure 2	Beach sand and crushed stone	20	30	8	4	1	-	63	0.148
Figure 4 (lower)	Curve 2, Figure 2	Beach sand and gravel	17	22	11	4	1	-	55	0.159

structure of the hardened concrete. Because this writer has been unable to find other numerical analyses published concerning the relation between the grading and the internal structure of concrete, a direct comparison with results by other authorities was impossible. It is still encouraging, however, that published data on optimum gradings based on differing approaches are in line with the findings presented in this paper. Reference is made here to (a) the suggested modification for various particle shapes of the optimum values of the fineness modulus that are valid for rounded gravel aggregate (15); (b) the recommended b/b_0 values, as a function of the sand grading, for the needed amount of coarse aggregate in proportioning concrete (16); and (c) the determination of the optimum amount of coarse aggregate in concrete as recommended by Hughes (17).

CONTINUOUS GRADING VERSUS GAP GRADING

The internal structure of concrete depends not only on the coarseness of the grading and on the particle shape of the aggregate but also on the details of the employed particle-size distribution. This is shown in Figure 5, which is a portion of a larger investigation (18). Here, three non-air-entrained concretes of differing but identically coarse gradings and of otherwise identical compositions are presented. The cement contents are 520 lb/cu yd (310 kg/m^3), and the water-cement ratios are 0.62 by weight. Concrete 10 was made with a continuous grading (C_1), concrete 15 with a one-gap grading (O_1), and concrete 18 with a two-gap grading (T_1). Details of the particle-size distributions are shown in Figure 6. These three gradings were set up so that the three important characteristics of coarseness, namely, the maximum particle size, the fineness modulus, and the calculated specific surface of the aggregate, were kept practically constant despite the obvious differences in the particle-size distributions.

The differences in the internal structures shown in Figure 5 are quite obvious. Especially the concrete made with the grading of one large gap (O_1) appears different; the grading seems coarser (which is actually not true), and excessive mortar seems to be present (which is true). This latter fact again supports the statement that a thinner average mortar layer is acceptable when a finer sand is used. Mortar intercepts were not measured on these three concretes because the available cut surfaces were too small to make such meaningful measurements. For the sake of comparison, the fractured surfaces of these concretes are shown in Figure 7, as obtained by the compression test of 3- by 6-in. (7.5- by 15-cm) cylinders. The three graded aggregates are shown in Figure 8.

A general remark seems appropriate for closing. The photographs of gap-graded and continuously graded concretes presented in this paper, and elsewhere in the literature, prove that the internal structure of concrete does not resemble at all the picture that is proposed by advocates of the maximum denseness principle, i.e., a structure that consists of symmetrically arranged, contacting circles of identical d diameter, representing the coarse aggregate particles, where the remaining holes are filled first with circles of identical 0.15-d diameter and then with subsequently smaller circles. In actuality, the coarse aggregate particles are distributed in a random manner in the mortar. This is true even in the case of concretes where the aggregate was carefully blended to obtain gradings of maximum denseness (19). Thus, it is little wonder that none of the "ideal gradings" derived mathematically from this unrealistic picture of maximum denseness in the aggregates has been proved optimum from the standpoint of concrete technology.

CONCLUSIONS

The various optimum gradings have the common feature that they provide a dense mortar in which coarse aggregate particles are embedded in appropriate quantity. The coarser the grading, the closer the coarse aggregate particles are packed in the concrete. This evaluation of the aggregate grading from the structure of concrete can be made numerical by measuring the intercepts of mortar layers among coarse aggregate particles in a cut surface of the finished concrete. The results of such analyses indicate that, for the strength of traditional concretes (that is, usual gradings of the fine and

Figure 5. Concretes made with gradings of identical coarseness according to curves shown in Figure 6 (11).

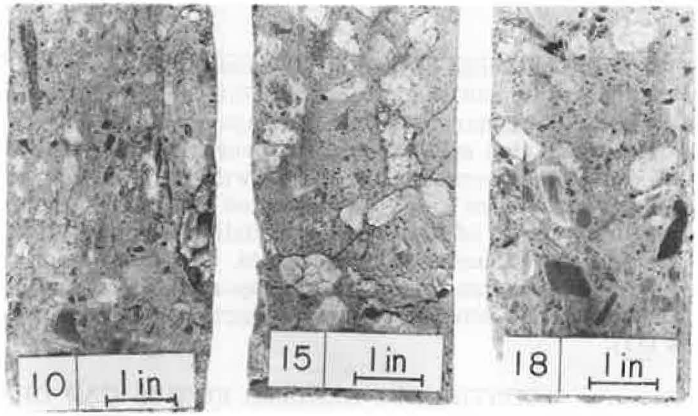


Figure 6. Gradings having the same maximum size, fineness modulus, and specific surface values (11).

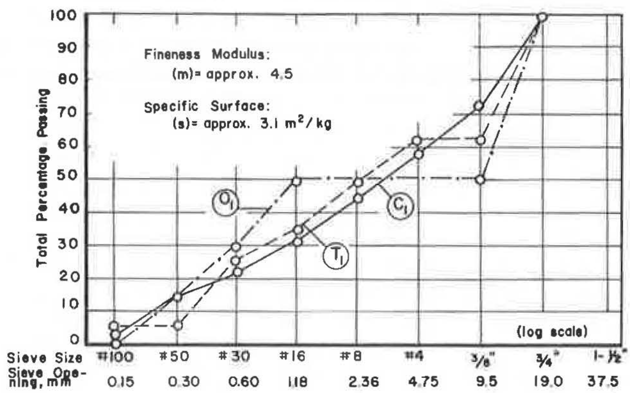


Figure 7. Fractured surfaces of the concretes shown in Figure 5 (11).

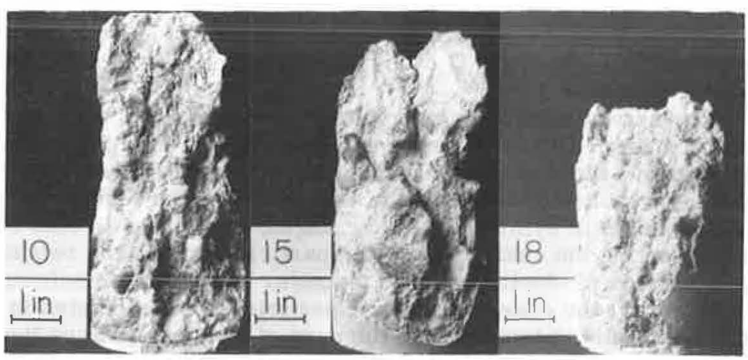
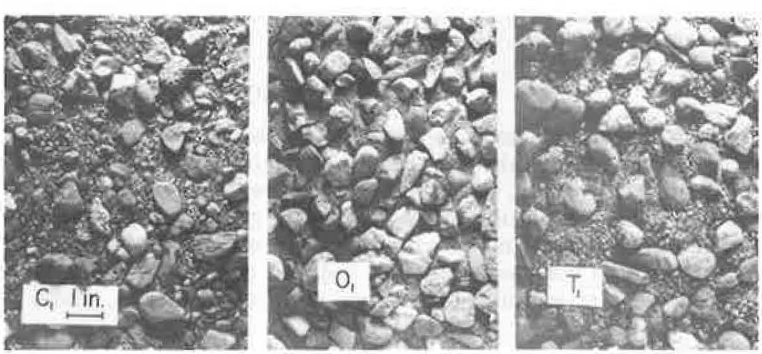


Figure 8. Appearance of continuous gradings shown in Figures 5 through 7.



coarse aggregates for a smooth and continuous combined particle-size distribution, medium cement content, etc.), the coarsest permissible gradings for compaction by hand-rodding are those that provide an average mortar layer intercept of 0.14 in. (3.5 mm). Under other circumstances, however, this mortar quantity can be reduced. For instance, when a very fine sand was used in the concrete, 0.12-in. (3.0-mm) average mortar layer intercept still provided a reasonable workability.

The needed minimum average intercept of mortar layers does not seem to be affected by the shape of the coarse aggregate particles. The primary effect of the particle shape on the grading optimum is that fewer coarse aggregate particles can be packed without interference in concrete when the particle shape is unfavorable than when it is spherical. This observation supports the test method developed by Shergold for the measurement of the angularity number of coarse aggregates.

These considerations seem valid both for continuous and for gap gradings even though the usual lack of the middle-sized particles in a gap grading may change the appearance of the internal structure of concrete; the gap grading may seem coarser than it actually is, and excessive mortar may be present in the concrete.

ACKNOWLEDGMENT

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DISCUSSION

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The interesting photograph (Fig. 3) of a slice through a sample of concrete using reef shell as coarse aggregate reveals a structure that is unfamiliar to many students of concrete. A study of this photograph suggests quite strongly that the structure represents not only one in which the coarse aggregate particles are flat and elongated but also one in which there is a quite pronounced preferred orientation of these particles, specifically an orientation in which they have their minimum dimension generally in the plane of the slice. For many purposes, when dealing with the structure of a substance consisting of non-equidimensional particles in a matrix, when the question of preferred orientation exists, it is useful to examine slices cut in three mutually perpendicular planes or, at least, in planes both parallel and perpendicular to the direction of the influence that may have been at work to induce a preferred orientation. This discussion invites the author to comment as to whether he has prepared or can prepare slices of this concrete in a plane or planes perpendicular to the one illustrated and to comment on what they do or might reveal as it relates to the matters discussed in the paper.

AUTHOR'S CLOSURE

The experiments presented in the paper were conducted years ago, so there is no possibility of producing the cuts recommended by Mather, no matter how instructional they would be. Still, it is useful that he points out the importance of the preferred orientation of aggregate particles because this is one of the primary sources of the anistropy of concrete. Although it is a practically important property, many of us "students of concrete" are more than willing to neglect it.