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Evaluation and Influence of Aggregate Particle Shape and Form

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1.00 INTRODUCTION

In 1956, B. Mather presented a literature review and a discussion on the measurement and the influence of particle shape in aggregates for construction purposes. Since then, important research has been done in this field, and some new information may be added.

The aim of this paper is to summarize the results of the research on aggregate particle shape and form in order to form a basis on which these results can be discussed. It is the hope that suitable methods of measurement can be found by which the significance of aggregate shape and form can be determined; in existing literature or in future work.

To analyse the problem of the effects of particle shape and form on the properties of aggregate, the variables involved will have to be separated. Then some useful concepts must be developed from the simplifications which have be made. Lastly, each factor must be studied by itself, keeping the others constant as far as possible.

The definition of the term aggregate that shall be used in the present paper is: An aggregation of particles made or formed by nature or artificially from rocks. Onesize aggregate shall mean aggregate selected between two neighbouring sieves in a Tyler series. To describe the geometric characteristics of aggregate, four concepts are useful. Firstly, the size of the aggregate is of importance. If no other references are made, the sizes are given by the ASTM standard sieves (inches), or by the DIN sieves (mm). Secondly, the relationship between the dimensions of individual particles, or the mean dimensions in an aggregate is a property for which I will use the term shape. Three extremes of aggregate shapes are classified as flaky, elongated and cubical (equidimensional). The term sphericity is also commonly used in literature to mean shape. In literature on sedimentary petrography the term angularity or roundness is used to designate the degree of sharpness of the corners of the particles, and the term surface texture to designate the degree of roughness or smoothness of the particle surfaces. Although this distinction in some cases is justified, I feel that it will also make measurements of engineering properties unnecessarily complicated. Therefore I will use the term form for the property that measures the surface texture and angularity of aggregate.

The particle size parameters that shall be used in this study are the least dimension or thickness (a), the intermediate dimension or width (b) and the long dimension (c). There has been some discussion as to the definitions of these quantities because of the way different authors prefer to place the circumscribing box defining the coordinates. The most exact one is probably proposed by Heywood (1947). He says «the particle is assumed to be resting on a plane in the position of greatest stability. The width is defined as the distance between two parallel lines tangent to the projection of the particle on the plane, and placed so that the distance between them is as small as possible. The length is the distance between parallel lines tangent to the projection and perpendicular to the lines defining the width. The thickness is the distance between the two planes parallel to the plane of greatest stability, and tangent to the surface of the particle.» This is a sort of circumscribed box definition which probably has been a quite common concept of workers on particle shape, although it is impractical to use. Lees (1964 a) concludes that confusion over which directions through a particle should be measured in order to ascertain the long (c), the intermediate (b) and the short (a) diameters can be resolved by taking the actual longest axis as c, the axis determining the smallest circular (or square) aperture through which the particle could pass as b, and the axis determining the narrowest slot through which the particle could pass as a. By this definition, the long intermediate and short diameters are seldom at right angles to each other. (Rittenhouse 1943.) On the other hand a definition is obtained which is useful for practical work. This definition will therefore be used in the present paper with the restriction that only squared sieves should be used for definition of the width (b).

The scope of this paper is limited to the properties of sand fraction to the coarse aggregate fraction, although some useful information can be found in the literature on the properties of powders. Strictly only aggregate properties are discussed, but some useful information may also be drawn from studies on other granular materials, such as metal pieces.

The basic classification of aggregate is the sizing operation performed by means of sieves. The mechanism of this process has been studied by many authors (Markwick 1936, Krumbein and Pettijohn 1938, Rittenhouse 1943 a, Cadle 1955, Kiesskalt 1955, Dalla Valle 1959, Lees 1964 a and b, and Sahu 1965). It is agreed that the particles will tend to pass the sieve opening in the direction of their longest dimension. By use of squared sieve openings the intermediate dimension of the particles will tend to orient themselves parallel to the diagonal of the openings. In the limiting case, a thin stone flake with the intermediate dimension equal to this diagonal may pass the sieve. By trying thicker particles, one will find that, as the thickness increases, the intermediate dimension must decrease to make the particle pass. A sieving operation therefore sorts the particles according to a combination of cross-section and intermediate dimension in such a way that the largest particles in a fraction also are the most flaky. On the contrary, this does not imply that the smallest ones are the most cubical, since the longest dimension is not taken into consideration. As may be seen, it is only the least and the intermediate dimensions that play a part in the sieving operation.

Since the particles with largest widths in a fraction are larger than the nominal size of the sieve, it has been proposed that the diagonal $b\sqrt{2}$ should be preferred as an approximation for size classification. It has further been demonstrated that the particle form also plays a part in the sizing. Actual measurements performed by Lees (1964) disclosed that the ratio of the actual width of the aggregate used to the nominal size was 1,36 for crushed aggregate and 1,18 for gravel as opposed to the theoretical value $\sqrt{2}$.

The effect of particle shape on sifting will be minimized, but not eliminated if sieves with round openings are used, because the intermediate dimension then more frequently will be determined by the diameter of the opening.

The sifting of aggregates does not imply that the aggregates are sorted according to volume. By sorting aggregates in groups of rods, discs and equidimensionals, it has been found that the volume of rods averaged 1,6 over equidimensionals, and the latter averaged 1,5 the size of the disc's. (Lees 1964 b.) This has a consequence when calculating surface area, because the error when shape is neglected may be large.

En exact bulk method of sorting aggregate according to their size by means of sieves in all probability does not exist. The squared sieves have, however, been standardized for laboratory work throughout most countries for a long period of time. Since no important errors are made by using this approximation in most cases it is most practical to maintain the present definition of particle size, namely the opening of the squared sieves they pass and are retained on.

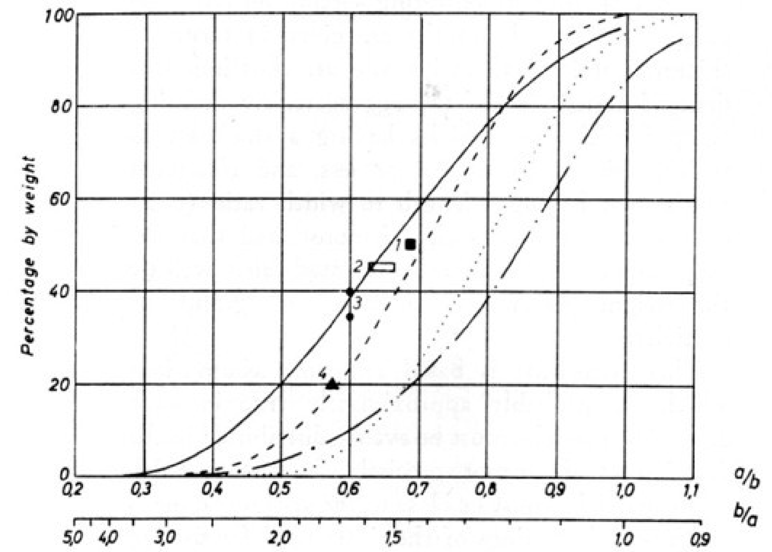

Fig. 1. A slotted sieve diagramm with some examples of the culumative flakiness distributions in some one-size aggregates. The marks indicate shape requirements for acceptance of road aggregate prescribed in some countries. 1 Scandinavian specifications, 2 Swiss specifications, 3 British Standard 812, and 4 German specifications (for «edelsplitt»). The German and Swiss specifications are given in terms of c/a, and the corresponding flakiness numbers are found from the correlation curve presented by Grønhaug (1964, fig. 2). The aggregate having the flakiness curve to the left is so rich in flaky particles that it only satisfies the British Standard 40 % flaky particle limit. The other aggregates, having flakiness curves passing to the right of the marks, satisfy the specifications in all countries.

2.00 PARTICLE SHAPE OF AGGREGATE

The term shape then is used pertaining to the dimensions of a particle. There is no widely recognized method of shape measurement as yet to indicate the amount of flaky or elongated particles in aggregate. In most countries, the common practice used to judge particle shape of aggregate seems to be visual inspection for abnormal contents of flaky or elongated pieces, since most standard specifications seem to agree that elongated or flaky particles affect the properties in a harmful way (fig. 1). If specifications for measuring the shape are given, these are in many cases too complicated and time-consuming so that most engineers feel reluctant to make the effort to accomplish them.

Since the effect of particle shape on properties of aggregates is not well known, most agencies feel free to ignore the problem or to leave it to the construction engineer to judge the aggregate in this respect. On the other hand, since the effects are poorly investigated, little can be said as to the extent to which flaky or elongated particles are unsuitable, suitable or permissible in an aggregate for a certain construction job.

2.10 Measurement of particle shape

The most common classification used is probably that of Zingg (1935). He proposed to classify particles by the ratios a/b and b/c in four groups; cubical, elongated, flaky and elongated and flaky, the limiting values being 2/3.

The visual inspection commonly used is considerably improved if some standard is given by which the shapes of different aggregates can be compared. The British Road Research Laboratory has investigated the extent to which different observers were able to assess particle shape by visual inspection. (Shergold and Manning 1953.) It was concluded that 28 observers, familiar with road aggregate use and testing, «agreed considerably» as to which of 17 samples of ½″ aggregate had the poorest shape. There was «general agreement» between the opinions of the observers and the results of the British Standard flakiness and elongation tests. If, however, a handy method of particle shape measurement exists, there is no need for visual inspection. On the other hand, if no such standard exists, good results from visual inspection cannot be expected.

A large amount of work has been done to develop efficient methods of measuring aggregate particle shape. The proposed methods fall into two main groups, namely, the «in bulk» measuring methods, and methods that require handling of each individual particle. By defining the dimensions of the particles properly, there will be no difficulty involved, for instance measuring each of the particles by calipers. This is of course a cumbersome and time-consuming task that in all probability will not cope with the practical advantages obtained from such measurements. More simplified methods have therefore been proposed.

2.11. Methods based on measurement of individual particles.

The method that has been used most widely by sedimentary geologists (Krumbein and Sloss 1963) is that developed by Wadell (1933). His particle shape parameter involved the expression:

$$\frac{\textit{Surface area of particle}}{\textit{Surface area of sphere of same volume}}$$

Because it was impossible to measure the surface area of a particle, Wadell simplified the notation by introducing an «operating sphericity» defined as:

$$\sqrt[3]{\frac{\textit{volume of particle}}{\textit{volume of circumscribing sphere}}}$$

The volume is measured by water displacement, while the diameter of the circumscribing sphere is found by measuring the «maximum intercept» through the particle. Because this involves some work for each particle in a sample, the method has received little attention by researchers on the properties of aggregates for building purposes. For practical reasons, these researchers have mainly concentrated upon developing more rapid and handy methods. None the less, the studies by sedimentary geologists on single particles have made an important contribution to make clear the concepts of aggregate properties to be measured.

The most obvious way of evaluating particle shape, the caliper method, has been developed into a useful tool by the Corps of Engineers (1948) and Schulze (1953). Schulze developed a proportional caliper by which the length (c) of a particle could be measured. Another slit of the caliper was then automatically set at ⅓ of this dimension. The particles could therefore be sorted into a «pass group» (c/a less than 3) and a «nonpass group» (c/a larger than 3). The Corps of Engineers' caliper works by the same principle, except for the fact that it can be set for other ratios (Corps of Engineers, U.S. Army, Waterways Exp. St. 1949). In Finland, the same axial ratio is used to classify the shape of aggregate, but for the fact that a «mätlåda» (measurement box) is employed in the sorting operation. First the thickness is measured by placing the particle in contact with the walls of a box, the bottom of which is covered with graphic paper. The particle is then placed with the longest axis (c) perpendicular to the thickness (a) axis, and with one end of it at the coordinate corresponding to its thickness and zero length. The particles exceeding a linear curve corresponding to $c/a = 2{,}5$ are classified as elongated. (Kauranne 1963.) By these methods a point on the distribution curve of the c/a ratios is found.

2.12. Gauge and sieve methods.

An improvement in developing a ready and quick method was made by Markwick (1936) in specifying the widths of onesize aggregate by their mean sieve size. To determine the thickness and length parameters, two gauges were designed, a flake sorter and a length sorter. The flake sorter consists of a tray with slits of increasing widths ($\sqrt{2}$ ratio) in the bottom of it, while the length sorter has a row of pegs placed at increasing distances ($\sqrt{2}$ ratio) from one end to the other. By these, onesize aggregate particles (with constant mean sieve size-width) could be sorted in 19 different shape groups, and a flake or a length distribution curve could be drawn for each aggregate. This is not needed for most purposes, however. Just one point, on each of these curves is usually determined, thus necessitating sorting on only one gauge opening. The results are given in terms of thickness and length ratios, and are thus independent of actual size of the aggregate. By defining flaky particles as particles having a thickness to width ratio (a/b) of 0,6 or less, and elongated particles as having a length to width ratio (c/b) of 1,8 or more, Markwick demonstrated that the shape distribution may be represented fairly well by the weight percentages of these two groups of particles.

This assessment is based on some assumptions which are probably approximately true in most cases. The particles must be evenly distributed in the fraction tested. Or more precisely, the average width of the particles must be close to the arithmetic mean of the rated openings of the sieves used for sorting the aggregate tested. There will always be a slight discrepancy, because the effective sieve opening of squared sieves is shown to be 1,2—1,3 times the nominal sieve sizes. (Lees 1964 a). Pursuing this reasoning, it must be assumed that the lengths or the thicknesses of the particles must also be evenly distributed in the shape groups. Since the shape measurement method is developed to compare shape properties of different aggregates, accurate information on the shape of each individual particle is not required. (Shergold 1965.) If this were the case, bulk methods could not be used for shape assessment.

A further simplification of shape assessment was made at The State Road Institute of Sweden by also developing slotted sieves for coarse aggregate (von Matern and Hjelmér, 1943). The method is also based on the mean (squared) sieve size for assessment of the width of the onesize aggregate. The thickness is found by sifting the onesize aggregate on sieves with rectangular openings. The rectangular openings have constant lengths, while the widths of the sieve openings increase from one sieve to the next by a factor of $\sqrt{2}$, in accordance with normal sieve series (fig. 2). Such sieves have had some application in studies made in the USA,

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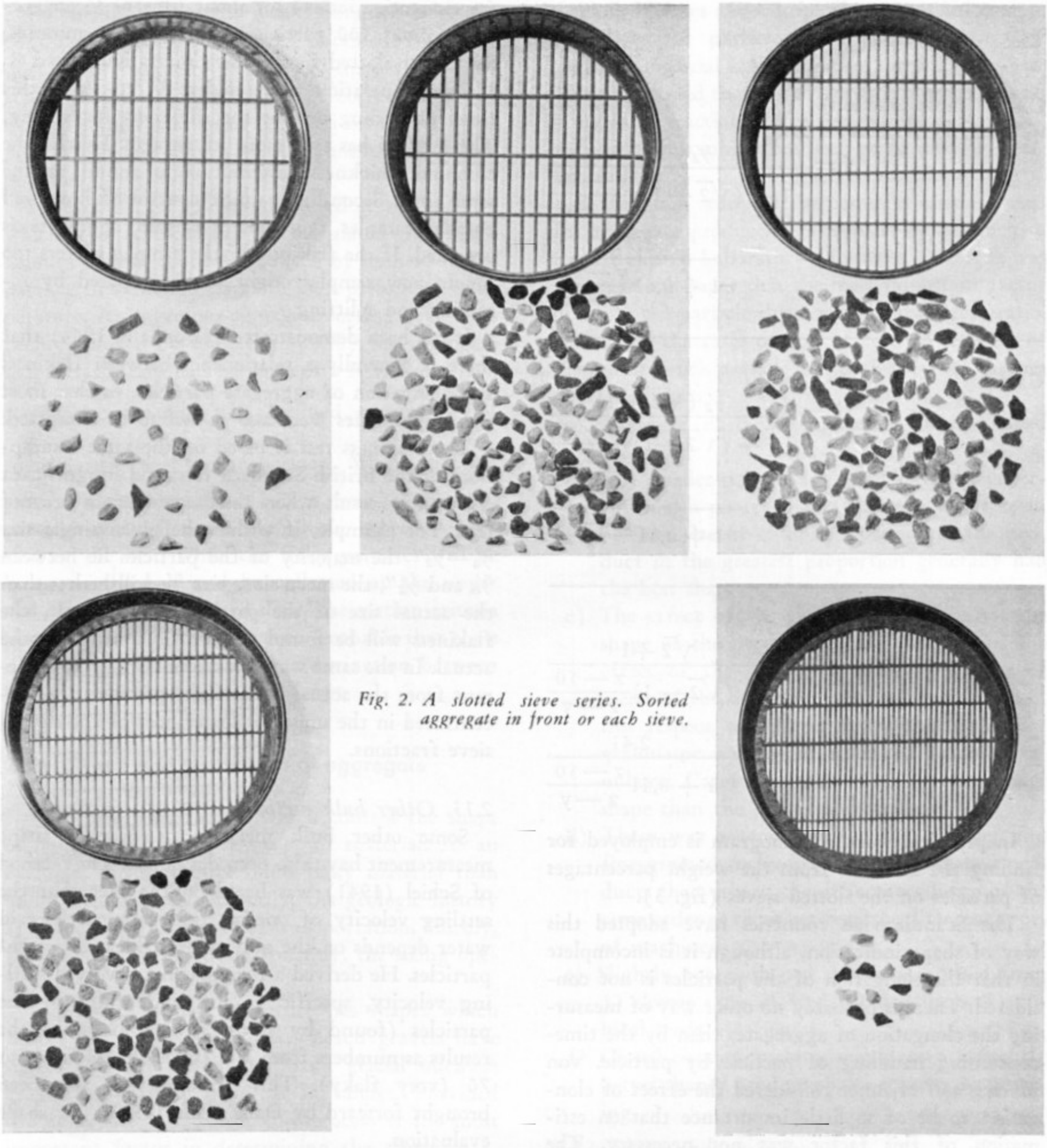

Fig. 2. A slotted sieve series. Sorted aggregate in front or each sieve.

(Coghill 1928), England (Markwick 1936) and the Netherlands (Nellensteyn 1936).

By sifting onesize aggregate on such sieves, the weight percentage on each sieve is found and a grading curve may be drawn. The mean thickness of the aggregate is obtained by finding the slit width corresponding to the 50 %-abscissa. The «flakiness» was defined as the ratio b/a. This ratio can more easily be found from graphs of the normal grading (b) curve and the slotted sieve (a) curve drawn on the same semilogarithmic graph paper. Defining flakiness by f = b/a, log f = log b-log a, the flakiness will be equal to the horizontal distance between the curves at the 50%-abscissa. This is an approximation because it must be remembered that an even distribution is not represented by a straight line in a logarithmic scale. The flakiness can also be found from a set of expression, assuming even distribution (Grønhaug 1964). Defining weight percent aggregate retained on slotted sieve $a\sqrt{2}$ as x, the combined weight percentages retained on slotted sieves $a\sqrt{2}$ and a as y and the combined weight percentages on the slotted sieves $a\sqrt{2}$, a and $\frac{1}{2}\, a\sqrt{2}$ as z, the flakiness is found to be:

Case 1 (most common)
$0 \leqq x \leqq 50\ \%, y \geqq 50\ \%,$

$$f = \frac{\frac{1}{2}\sqrt{2} + 1}{1 + (\sqrt{2} - 1)\frac{y - 50}{y - x}}$$

$$\text{or} \quad f = \frac{1{,}71}{1 + 0{,}41\frac{y - 50}{y - x}}$$

Case 2 $\quad x \geqq 50\ \%$

$$f = \frac{\frac{1}{2}(\sqrt{2} + 1)}{1 + (\sqrt{2} - 1)\frac{x - 50}{x}}$$

$$\text{or} \quad f = \frac{1{,}21}{1 + 0{,}41\frac{x - 50}{x}}$$

Case 3 $\quad y \leqq 50\ \%, z \geqq 50\ \%$

$$f = \frac{\sqrt{2} + 1}{1 + (\sqrt{2} - 1)\frac{z - 50}{z - y}}$$

$$\text{or} \quad f = \frac{2{,}41}{1 + 0{,}41\frac{z - 50}{z - y}}$$

In practical work a nomogram is employed for finding the flakiness from the weight percentages of particles on the slotted sieves (fig. 3).

The Scandinavian countries have adopted this way of shape indication, although it is incomplete in that the elongation of the particles is not considered. There is probably no other way of measuring the elongation of aggregates than by the time-consuming handling of particle by particle. von Matern and Hjelmér considered the effect of elongation to be of so little importance that en estimation of this factor was not necessary. The method can of course be completed by prescribing a length measuring procedure, for instance, the British Standard method (Markwick 1936); but calculating the mean length of a sample by measuring each particle in a gauge box is almost as quick. The bottom of the box must then be provided with a length scale. Each particle must be lying on its most stable face, and be kept in contact with two of the walls of the box so that the long direction of the particle is parallel to the scale. (Grønhaug 1964.)

The time involved in these operations is the main factor when selecting the method to use for shape evaluation. To determine the flakiness index (or elongation index) for about 2 lbs. of ½" aggregate (about 500 particles) takes 20—30 minutes. By use of slotted sieves, this process is reduced to a sifting operation that requires ⅓ to ⅙ of this time, depending on the specifications for sifting. The method has two more advantages. Firstly, the complete thickness distribution is found at the same time. Secondly, a quick control of how well parallel samples represent a certain aggregate is obtained. If the flakiness of the samples differs too much, new samples ought to be prepared by remixing and splitting.

It has been demonstrated (Grønhaug 1964) that there is generally a relationship between flakiness and elongation of aggregate particles, in that most flaky aggregates were also shown to be elongated.

The flakiness test is based on the same assumptions as the British Standard test, and insignificant errors may result when these assumptions are not true. For example, if within the given single size ¾—½" the majority of the particles lie between ⅝ and ½", the mean sieve size ⅝ will be less than the actual size of the particles. As a result, the flakiness will be found to be a little less than the actual. In the same way, the flakiness may be different from the actual if the flaky particles are concentrated in the upper or lower part of the slotted sieve fractions.

2.13. Other bulk methods.

Some other bulk methods of particle shape measurement have also been developed. The method of Schiel (1941) was based on the fact that the settling velocity of onesize aggregate particles in water depends on the gravity and thickness of the particles. He derived a formula that involved settling velocity, specific gravity and width of the particles (found by sieving), and expressed the results as numbers from 100 (good shape) to about 70 (very flaky). This principle has also been brought forward by Dalla Valle (1943) for shape evaluation.

The settling velocity is probably a function of particle form. It must be expected that the rougher the particle surface, the lower the settling velocity-and vice versa. This influence must be found before the method can be found suitable for shape assessment. Probably the method is not suitable for a distinction between shape and form properties.

Methods proposed by Rothfuchs (1931), Feret (1937, 1938), Pickel (1937), Pickel and Rothfuchs (1938) and Stern (1937) involve the number of onesize particles that can be held in i specified volume or weight. This method has been investigated by The State Road Institute, Sweden. (von Matern and Hjelmér 1943.) They demonstrated

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quite strikingly that the results obtained were not consistent with the flakiness obtained from the slotted sieve test, nor with visual inspection. They stated that the method might be correct provided that only the thickness of the particles varied. Since both width and length vary, erroneous results are obtained.

Heywood (1933) has discussed a method by which the surface area is calculated from the amount of wax coating produced by immersing the particle in a molten paraffin at a prescribed temperature. An ingenious aggregate sorting device has been employed by Dunagan (1940) for aggregate shape classification. The aggregate is fed onto a 6 feet long conveyor belt inclined arcsin $\left(\frac{30 \text{ in}}{6 \text{ in}}\right)$ to arcsin $\left(\frac{36 \text{ in}}{6 \text{ in}}\right)$ to the horizon. When the belt runs at a speed of about 160 ft./min. the cubical particles will roll down against the moving direction of the belt, while the flaky particles will be lying on the belt and be collected at the upper end of it. By varying the slope, the sorting criteria may be changed. It is, however, probable that these methods also fail in making a distinction between particle shape and form.

2.20 Shape and production of aggregate

2.21. Shape and crushing.

There are four factors which control the shape of aggregate. Firstly, the type of material. As an example, shists produce more flaky material than homogeneous rocks. Secondly, the geologic history as to the length and way of transportation. Thirdly, the type of crushing, and fourthly, the sizing operation.

Aggregate formed in nature has shapes which reflect the formation process. Beach gravels have shapes that are different from glacial outwash gravels or gravelly materials in taluses. Provided the aggregate is crushed, this process is the most important factor in determining the shape.

The influence of crushing on the shape of the product has been studied by many authors. It was first observed by Gaudin (1926) by visual inspection that when a material was crushed in rolls, there was a definite change in the average shape with size. The largest aggregate particles were found to be flaky, the medium sizes appeared to have equidimensional shapes, while the still smaller sizes had a marked tendency to have flaky, elongated shapes. Aggregates crushed in jaws obtained a similar shape pattern, while aggregates crushed in rod or ball mills were scarce in flaky particles in the coarse range sizes.

Analogus and more exact data were given by Coghill, Holmes and Campbell (1928). Using slotted sieves for particle shape classification, they studied a material crushed in disc and rolls crushers. They concluded that the size of maximum flakiness is a certain fraction of the size of feed. Since then, a study on this subject has been performed by Røsslein (1941).

A thorough study of the common crushers used for aggregate production was made by The British Road Research Laboratory (Shergold 1959). It was shown in the paper that the most important factor deciding the particle shape was the reduction ratio, defined as the ratio of size of feed to the size of the crushed rock particle in question. It was further concluded that:

a) A larger sized feed gave a poorer shaped product.
b) The smaller sizes in any given product generally had a poorer shape than the larger sizes, but the size of chippings present in the product in the greatest proportion generally had the best shape.
c) The effect of the type of granulator on the shape of the product was not as great as the effect of the reduction ratio. The order of merit of the different types of granulators in this respect was 1) impact breaker, 2) jaw granulator, 3) crushing rolls and 4) cone granulator. Careful handbreaking gave no better shape than the jaw granulator.
d) There was a tendency for the stronger and fine-grained rocks to give poorer shaped products than others, the differences being of the same order as those between the different types of machines.
e) Slightly poorer-shaped products resulted from 1) slower rates of feed, 2) dry feeds, 3) cubical feeds.
f) Closed-circuit crushing would give a slightly better-shaped product than open-circuit crushing.

2.22. Shape and screening.

The particle shape of aggregate will also be affected by the type of screen used for sizing. The upper portion of aggregates sieved on screens with rectangular openings will be flaky, as opposed to the smaller portion. This fact will be less pronounced provided squared sieve cloths are used. By using sieves with round openings, the flaky particles will be evenly distributed in the size series. As a corollary, it is therefore possible to transfer the flaky particles to a neighbouring fraction or remove them by use of different types of sieves. Such operations have been employed to remove shale from coal or aggregate (Banning and Lamb 1944).

2.30 Influence of particle shape on properties of aggregates

2.31. Shape and testing for durability.

Data obtained from durability testing of aggregates show that a close relationship exists between this property and the shape of the samples tested. This fact is found to hold true for aggregate impact tests, aggregate crushing tests and for Los Angeles tests.

The fact is well illustrated if impact test results of homogeneous rock aggregates are plotted against the flakiness of the different samples. It will appear that there is a linear increase in aggregate impact value with increasing flakiness (Selmer-Olsen 1949, Grønhaug 1964, Ramsey 1965, Höbeda 1966). The impact value of the tough rocks seem to be less affected by shape than the hard, brittle ones. This is demonstrated by the steeper slope of the impact value/flakiness curve for granites as compared to rocks of the basalt-gabbro family. (Fig. 4.) That this relationship holds true for aggregate crushing test results was demonstrated by Croeser (Knight 1953). By mixing cubical and flaky particles in various proportions for test samples, he observed that there was a serious decrease in crushing resistance caused by the presence of flaky particles.

The Los Angeles test results are less sensible to particle shape than the test results described above. (Selmer Olsen 1949). Recent data presented by Höbeda (1966) show that if the flakiness of homogeneous samples of rock aggregate is increased from 1,0 (cubical particles) to 1,4 (a normal value), the Los Angeles test result increased from 30 to 36. This must be due to the fact that this test is more of an abrasion test than the other two mentioned above.

The way the samples are prepared will also affect the impact test results. Provided the samples of different flakiness are prepared by mixing slotted sieve fractions, the impact value will be less sensitive to flakiness than if the samples are produced by recrushing. (Grønhaug 1964.) This is illustrated by figs. 4 and 5. The explanation for this must be that, in addition to obtain a better form and shape by recrushing, the less durable particles will be reduced in size by this process, and thus will be removed from the sample to be tested.

2.32. Shape and voids content.

The amount of voids in a granular material is influenced by the degree of packing. For smooth spheres, several types of packing are possible, each with a proper voids space. The closest theoretical packing of spheres appear to give a void percentage of 26 %. By changing the particles from spheres to discs or ovaloides, the voids ratio will be changed.

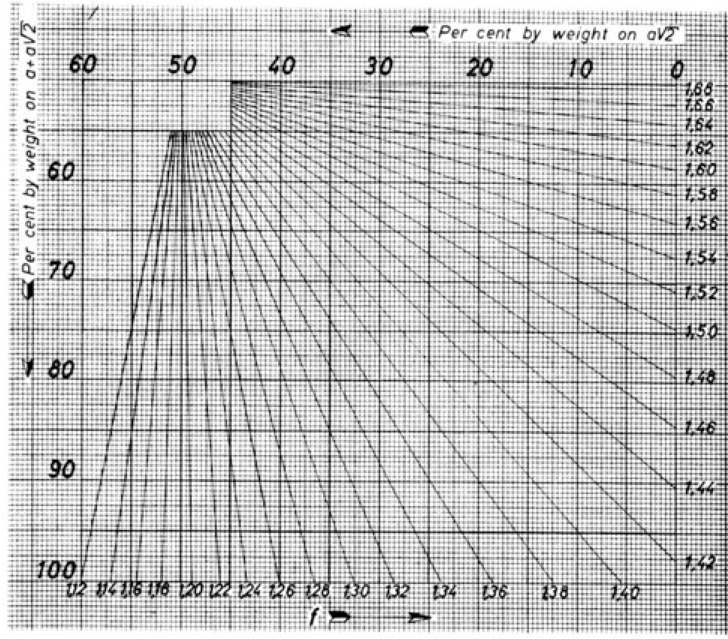
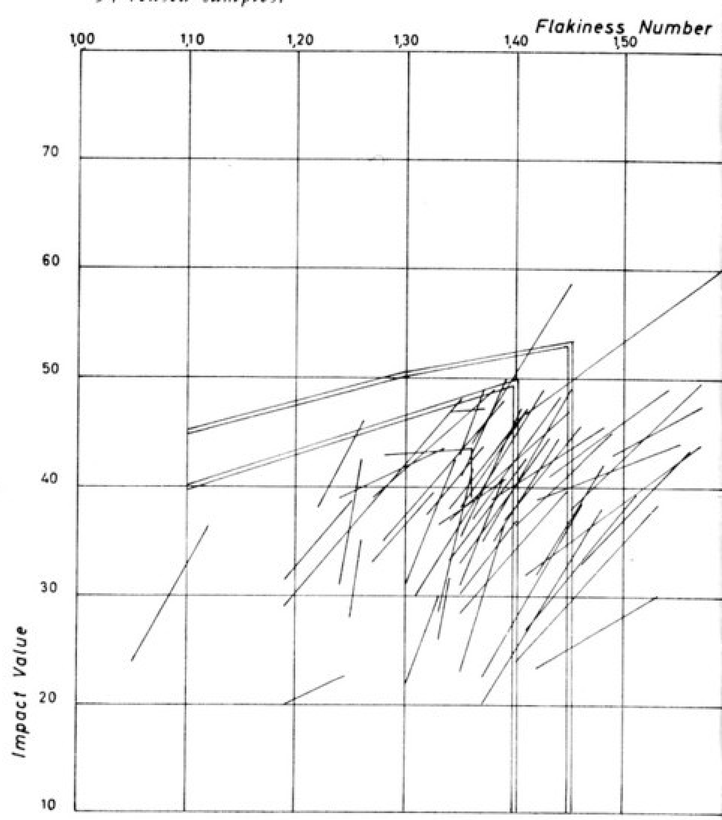


Fig. 3. Nomogram for determining the flakiness from the weight percentage of aggregates on slotted sieves $a\sqrt{2}$ and $(a + a\sqrt{2})$. (Dugstad 1962.)

The voids content will also be effected by changing the surface texture from smooth to various degrees of roughness.

Since particle form and shape often mix together, it is difficult to distinguish between the effect of each factor, and the result often arrived at appears

Fig. 4. The relationship of impact value to flakiness for 54 reused samples.



to be the combined effect of both. The State Road Institute of Sweden has found that while the flakiness of crushed aggregates used for surface treatment varied from 1,2 to 1,6, the voids content (DIN 2110) varied from 53 % to 58 % (von Matern and Hjelmér, 1943). Correspondingly the unit weight decreased as the flakiness of the aggregates increased.

Four rounded aggregates did not show this relationship, however, the voids space being constant while the flakiness was increased from 1,2 to 1,3.

2.33. Shape and degradation.

It may be deduced from the results of durability tests that flaky aggregates are more susceptible to degradation during construction and service than

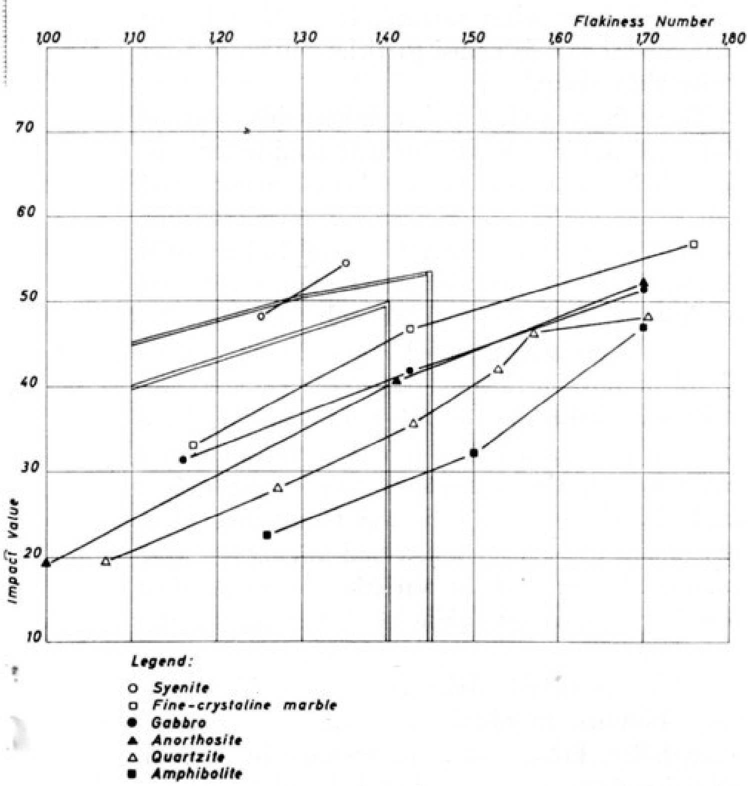


Fig. 5. The relationship of impact value to flakiness for crushed rock aggregates sorted on slotted sieves.

more cubical ones of the same rock composition. Three types of degradation may be distinguished, namely degradation during 1) handling 2) compaction and 3) service.

A thorough investigation of these types of degradation was made by The State Road Institute of Sweden. A test road was constructed with surface treatments of aggregates from 33 different sources, each stretch 10 m long. (von Matern and Hjelmér 1943.) The road vas inspected and samples of the surface treatment were tested prior to construction, after compaction, then after one week, 4 months, 8 months and 35 months. The original flakiness of the aggregates was compared to the flakiness of these samples. The average flakiness of 8 samples was found to decrease from 1,51 to 1,39 after handling and compaction, and then through 1,33, 1,32, 1,26 to 1,19 after 35 months of service. Fig. 6 shows the trend for 8 different materials. It was concluded that there was a tendency for the aggregates to obtain a flakiness of 1,3 to 1,1 during the service period. Aggregate that has an initial flakiness in this range may increase in flakiness, at least in the first couple of years.

The breakdown of aggregate particles under compaction and traffic has also been investigated by The British Road Research Laboratory. The data from this investigation confirmed that shape has an influence on aggregate degradation. (Shergold 1954.)

2.34. Shape and strength of aggregate or aggregate-binder mixes.

Data on the effect of particle shape on stability of aggregate masses appear to be very scarce in the literature. Some investigators have studied the stability of crushed aggregates and compared the results to the results from tests on natural, uncrushed gravels, or on mixes of crushed and uncrushed aggregates. Since crushed stone ordinarily is more flaky than natural gravels, some effects from this property should be expected in such tests. Any possible effect is, however, overshadowed by the more pronounced effect of the particle form. To evaluate the effect of shape on stability, the particle form must be held constant.

It is a fact that flaky aggregate particles have a greater surface area than cubical particles. (Markwick 1936.) Probably the particle to particle contact area is larger in flaky aggregate than it is in cubical. One might therefore expect more friction and, as a corollary, greater strength of flaky aggregate than of cubical. This is, however, opposed by the fact that voids content is less, and therefore the packing of the cubical particles is more perfect than with flaky particles.

The same statements are valid for stability data of aggregates incorporated in bitumen. Few investigations seem to have been reported on the effect of shape only on the stability of such mixes. Investigations by Croeser (Knight 1953) disclosed that aggregates of different shape made mixes that varied with respect to stability. The flaky material broke down excessively and gave rise to dense gradings and relatively high stability. The elongated material disintegrated less than the cubical material and so produced a less stable mix. Soveri (1964) found an increase of Marshall stability of about

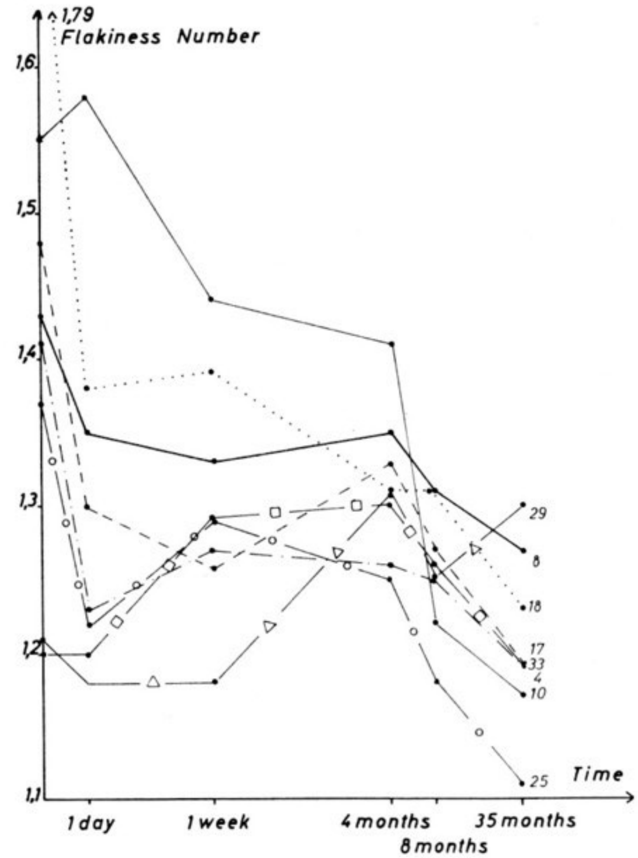


Fig. 6. The decrease of flakiness with time of surface treatment aggregates in service.

10 % to 20 % of flaky aggregate/bitumen mixes over equidimensional aggregate/bitumen mixes in the range of 4 % to 6 % bitumen. On the other hand Lees (1946) found little effect on Marshall stability by changing shape. From a degradational standpoint, flaky particles are detrimental because they tend to break down during compaction and so produce uncoated surfaces. The Marshall stabilities mixes of cubical and flaky and elongated aggregates with equal gradings and bitumen contents were investigated at the State Road Research Laboratory, Finland (Soveri 1964).

The stability of the cubical mix consisting of particles with c/a <2,5, varied from 8 % (6 % bitumen) to 15 % (4 % bitumen) higher than that of the flaky particle mix.

There are differing opinions on the effects of flaky aggregate on the strength of concrete. A quite common belief is that the bulk strength is reduced by introducing flaky aggregate into the concrete (Blanks 1950, Gilkey 1943, Scholer 1931, Mercer 1952). Information pertaining to this is given by Gilkey (1927). He made concrete with — 1 1/2″ broken scraps of 1/8″ and 1/4″ plate glass. The concrete made with 1/8″ glass had lower strength than that made with 1/4″ glass, which in turn had lower strength than concrete made with round aggregate. Recently, however, it has been shown that a flaky aggregate may lead to higher tensile strength in concrete than that produced with cubical aggregate. (Orchard 1964.)

2.35. Shape and workability of aggregate-binder mixes.

The term workability is used to indicate the work required to obtain complete mixing of the constituents to be mixed. The more work required to obtain complete mixing, the lower the workability of the material — and vice versa. The aggregate will tend to orient itself in the direction that requires the least work, and since rolling, combined with sliding, has lower friction than sliding alone, this is the way the particles in the material tend to behave when worked. It is then obivous that cubical and elongated particles will move more easily than flaky.

There is a widespread opinion that flat or elongated particles in an aggregate tend to decrease workability and thus require more cement, sand and water to make useful concrete (Blanks 1950). A study of the movement of gravel bed material in water in canals may be pertinent to the effects of shape on workability (Lane and Carlson 1954). Flaky and elongated particles were much less inclined to move in flowing water than cubical. Particles with sphericity of 0,5 were found to have the same moving ability as cubical particles (sphericity 0,9) with almost three times their weight. In a study by Kaplan (1958) it was found that when the effects of both flakiness and angularity were considered, 20 % of the variation in workability was due to flakiness, while 59 % was due to angularity.

Analogous to this flaky aggregates will require more bitumen to obtain a reasonable degree of workability. From investigations done by Croeser (Knight 1953), it was concluded that the optimum binder content for the flaky material tested was 1,24 %, while the corresponding contents were 0,85 and 0,80 % for the cubical and the elongated respectively. The grading and high bitumen content led to a higher strength and stability of the mix.

2.36. Shape and anisotropy of pavements.

The effect of particle shape on the quality and finish of the concrete surface has been discussed (Walker 1930). It is claimed that flat particles have been observed to catch on to the finishing belt and be pulled out and dragged, thereby causing a torn surface hard to finish to a satisfactory smoothness. This effect was studied by the National Sand and Gravel Association (NSGA). (Goldbeck

1930.) It was stated that in mixes consisting of up to 10 % flaky particles, no such effect was observed.

It is also argued that there is a tendency for flat particles to work to the top of the mix and lie parallel to the surface, subsequently to be kicked out by traffic or to be popped out by weathering. Again there was no indication of this effect in the tests ran by the NSGA (Goldbeck 1930). It is, however, possible that such effects may occur in mixes with a higher content than 10 % of flat pieces, but this remains to be investigated.

During compaction of asphaltic wearing courses, the aggregate particles tend to align their longest axis perpendicular to the compactive force. This alignment may be very pronounced in mixtures made from elongated or flaky aggregates. Such alignment is found regardles of type of compaction, but it increases with an increase in binder viscosity, aggregate angularity and aggregate size (Puzinauskas 1964). It is found in test samples and in in-service pavements. Depending on the degree of alignment, the compressive strength of compacted aggregate/bitumen mixtures will be up to 2,6 times larger in the direction of the compaction force than in the directions perpendicular to this force.

2.37. Shape and coverage of surface treatment aggregates.

Since the sifting operation mainly sorts particles according to one dimension of the particles, there will be a wide distribution of projected areas of individual particles within a onesize aggregate. This may lead to difficulty in estimating the amount of aggregate required for a surface treatment.

McLeod (1960) has proposed a method based on the data obtained from the British Standard flakiness test. However, applying the slotted sieve curve to find the average least dimension gives a quicker and more exact method of finding the amount of aggregate required for the surface treatment. The volume is given by the expression: a x area to be covered. The average least dimension a is found directly on the slotted sieve curve at the 50 % abscissa.

3.00 FORM OF AGGREGATE PARTICLES

By surface texture, the sedimentary geologists mean the roughness or the smoothness of the faces of the particles. The degree of sharpness of the corners or edges of the particles is defined as the roundness of the particles. Since this definition requires particle by particle handling and measurement it is not convenient for aggregate testing. One may therefore apply texture, angularity or roundness to cover approximately the same concepts. The distinction between surface texture and roundness is justified in certain cases, such as for crushed fine-crystalline rocks (chert, obsidian) which may be angular, but smooth textured or as for porous or corroded gravel particles (pumice, limestone) which may be well rounded, but rough textured. The effects of these distinctions are probably not important with respect to the engineering properties of the aggregates, provided testing methods are designed taking both properties into account.

3.10 Evalution of aggregate particle form

The lack of recognized general definitions and methods of measurements of aggregate particle form is even more pronounced than was the case for particle shape. As a result, it is difficult to compare the conclusions arrived at in papers by different authors. A large amount of work has been done to develop significant methods to measure the form properties of aggregates. There are also methods based on handling of individual particles, and methods that measure bulk properties.

3.11. Evaluation by visual inspection.

Most investigators control particle form by controlling the amount of crushed and uncrushed particles in the aggregates tested, or they compare properties of crushed and uncrushed aggregate. This procedure is undersireable, firstly because the particle shape comes into play, and secondly because a standard of particle form is lacking. The form of natural gravels may vary within wide limits, and so may the form of crushed stone. In the extreme case, one investigator may use rounded aggregate for what another might term rough textured.

On the other hand, when a standard is developed, visual inspection can be a useful way of estimating particle form. Experiments done by the British Road Research Laboratory demonstrated that observers agreed to a considerable degree on the classification of form of single-sized aggregates. (Shergold 1953.)

Visual inspection has been reflected in many specifications on road materials. A common requirement is that a material for a certain purpose shall contain a minimum amount of crushed particles or a maximum amount of rounded particles. The Swedish specifications use for example the term «krossytegraden» (degree of crushed surfaces) to specify the percentage by weight of completely crushed particles divided by the percentage by weight of round particles. To obtain this number,

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the aggregate has to be sorted by hand and the fractions weighed. Difficulty is encountered when classifying partly crushed particles, since the classification only takes into consideration completely crushed or round particles. An additional classification instruction is given in that gravel reduced to ⅓ of its original size by crushing is considered as crushed.

A further development is to classify the particle form in the groups angular, subangular, subrounded, rounded and well rounded. The surfaces may also be classified as furrowed, grooved, scratched, ridged, pitted, dented, striated, frosted and etched. (Pettijohn 1949, Lees 1964 c.) Still the aggregate has to be sorted by hand.

3.12. *Radii of curvature measurements.*

More elaborate are the methods developed by Wentworth (1922, 1933) and Wadell (1932, 1933, 1935). By these methods the radii of curvature of the individual particles are measured. The particle is projected on a piece of paper, and the radius of curvature of the corners and edges are found. The roundness is then defined as the average radius of curvature of the particle image, divided by the radius of the largest possible inscribed circle, $\frac{\Sigma \frac{i}{R}}{N}$, N is the number of corners, R radius of largest inscribed circle, and i individual radii of corners.

An improvement was introduced by preparing a chart of standard shapes, making a more rapid estimation of sphericity possible (Rittenhouse 1943 b). A method based on measurement of radii of curvature by means of steel gauges was investigated by The British Road Research Laboratory. The results obtained were reported to be so variable that the method was abandoned (Shergold 1953). Another method that must be classified in this group, has recently been brought forward by Mackey (1965). It is based on the measurement of the departure of the particles from a perfect ellipsoid.

3.13. *Measurements by sifting.*

The surface roughness and the angularity or roundness influence the tendency for the particles to pass sieves. By using only one type of sieve, this effect probably will not be particularly evident. If, however, a onesize fraction sifted on sieves with squared openings are resifted on sieves of the same nominal size, but with round openings, new fractions will be sorted out according to the form of the aggregate particles. The method of form evaluation developed by Schiel (1948) is based on this fact. He proposed to use the differences between the percentages passed by squared- and roundholed sieves as a measure of particle form.

The method has been investigated by the Road Research Laboratory, Great Britain. It was found that the method was too sensitive to the particle size distribution within the onesize aggregate to be recommended for general practice. (Shergold 1953.)

3.14. *Percentage voids as a measure of particle form.*

Since rough-textured and angular aggregate particles obviously require more space than smooth-textured and round particles of the same weight or volume, it might be expected that it should be possible to use this property as a means of form evaluation. This fact has been conceived a long time ago (King 1899), and a method of particle form measurement based on this principle was investigated almost 40 years ago (Lamar 1928). A method applied for stone sand was proposed by Goldbeck (1951).

The most thorough study on this subject is probably that of The Road Research Laboratory, Great Britain. After a study of the literature, a couple of methods were selected for further investigation (Shergold 1953). It was concluded that the percent voids method was the most significant way of indicating the degree of angularity of aggregate. Since the most important factors affecting the percentage voids besides particle form is the grading and compaction, the method is applicable only to onesize aggregates compacted in a standard way. After 720 tests, it was concluded that the personal factor was the cause of the greater part of the variability of the results. By improving the compaction method, a satisfactory degree of reproduceability was obtained.

Since the most rounded of the gravels tested had a voids content of 33 %, the degree of angularity was proposed to be measured by the amount by which the voids content of an aggregate exceeded 33 %. This means that the angularity number varies from 0 for a very well rounded gravel to 9 for freshly crushed rock. Investigations by Townsend and Madill (1964) demonstrated that there was good relationship between the angularity number and the percentage of crushed stone in a crushed stone/gravel mix. They also found a relationship of angularity number and permeability of water through the material. As the angularity of the base course increases, there is a decrease in the permeability of the material. This effect has been developed to particle form measurement methods by Carman (1938), Schiel (1948) and Shacklock and Walker (1958).

The angularity number is, however, sensible to differences in particle shape. Shergold (1953) found that the percentage voids in crushed aggregate increased by 1,3 %, when the amount of flaky particles was increased from 20 to 40 %. In natural gravels he found correspondingly an increase of 0,9 %. The influence of shape on percentage voids in aggregate in loose condition (DIN 2110) has been investigated by the State Road Institute, Sweden (von Matern and Hjelmér, 1943). In different crushed stone aggregates used for a test road, the flakiness varied from 1,25 to 1,65. The mean voids varied by about 5 % over this range. It is improbable that normal compaction could reduce this difference to about 1,3 % without changing the shape and grading of the one-size material considerably.

The relationship has been further investigated by Höbeda (1966), applying the method proposed by Shergold. He found that samples made of granite with a flakiness of 2,0 had 5 % higher percentage voids than samples with a flakiness of 1,0. The relationship is, however, found to be very complex. If for example a sample of flakiness 1,4 is made by mixing aggregates with flakiness 1,0 and 2,0, the percentage voids for this material will be higher than that retained on the 1,4 flake sorter (slotted sieve). Contrary to this is a mix of 1,42 and 1,0 flakiness aggregate demonstrated to have a percentage voids content 2—3 % less than the cubical sample of 1,0 flakiness. Höbeda therefore concludes that the densest possible packing is not produced by isolating equidimensional particles. To obtain the denses possible packing, some content of more flaky particles is required.

It was further demonstrated that by applying mylonitic quartzite instead of granite, the voids content was reduced 3—5 % compared to the granite aggregate in the same shape group. This is obvious due to the differences of surface textures of the aggregates, the mylonitic quartzite having a relative high percentage of tectonic polished surfaces.

A percentage voids method which takes into account the rate of compaction and the particle size in addition to the total percentage voids at some standard compaction is proposed by Huang (1962). The expression for the «particle index» was intended to take into account all form and shape characteristics of aggregate. As stated earlier, these factors ought to be studied separately to evaluate their effect on aggregate properties.

As a conclusion it may be said that the percentage voids method probably is the most significant of the methods investigated to indicate particle form. Since it is sensitive to differences in particle shape, this factor will have to be taken into account when the results obtained from the test are appraised.

3.15. *Measurement by angle of repose.*

Most engineering properties of aggregates are probably dependent on the frictional conditions in the aggregate mass. This factor should therefore be one of the most important to be measured. Besides size and gradation, this property is probably controlled by the particle form, and to some extent by particle shape. Particle shape mainly determines the area of contact and the form determines the degree of interlock in the aggregate. The frictional properties of the total mass must be controlled by the contact area, the surface roughness and the interlock. The most theoretically correct way of measuring the form properties therefore must be to measure a property related to friction.

In fact, a couple of methods have been proposed based on measuring the frictional forces in aggregate. The disadvantage of these methods is the fact that for the present they are only convenient for powders, sand and fine aggregate, because research has so far been restricted to that particle range.

The angle of repose was used for particle form assessment in a study by Morris (1959), on the influence of particle form on the strength of 1/8″ aggregate. Since no numerical control on the shape of the aggregate was effected, the results obtained were the combined effects of particle shape and form. From the description of the preparation of the samples, it appears that it was principally the particle form that was varied.

The angle of repose was studied in some initial experiments. It was found that the angle of repose of a heap of particles falling onto a level surface from an orifice above, varied by as much as 8 degrees around the same pile. To obtain more consistent results, a wooden box, $18 \times 4 \times 1$ in^3 was made. The box was filled with fine aggregates, and vibrated at the critical frequency to maximum density. By elevation of one end of the box at a specified constant speed, the aggregate was brought to collapse, at an angle determined by the type of material under test. This angle, which was easily measured, was found to be consistent for any specified type of material. The numerical data obtained was termed dense angle of repose. Uniformly worn river gravel, and aggregate polished in the Los Angeles machine for several days appeared to have the lowest values of angle of repose, while crushed, rough-textured aggregate had the highest.

3.16. *The orifice flow test.*

The static method of form assessment has also a

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dynamic counterpart. The test proposed by Rex and Peck (1956) is based on the principle that smooth-textured, rounded sand particles offer less resistance to free flow than do rough-textured angular particles. The test is applicable to dry, one-sized sand that is made to flow through a circular orifice. The sand is placed in a jar with diameter of 2⅞″. The jar has a coneshaped transition towards the orifice that inclines 30 degrees to the vertical axis of the jar. The time is taken from the instant the stopper in the orifice is removed until the sample of 500 g has passed through the orifice. The rate of flow is then determined in terms of seconds per 100 cm^3.

It was demonstrated that for +30 —20 mesh sand the size of the orifice diameter was not critical in respect to the ability to differentiate between sands. It was recommended that ⅜″ diameter should be used because the error in reading the time of flow was a convenient compromise between reading accuracy and time consumed. The rate of flow was found to vary from 13 sec/100 cm^3 for well rounded standard Ottawa sand, to 20 sec/100 cm^3 for crushed sand. Investigations by Bloem and Gaynor (1963) indicated good correlation between the dry-loose voids content and the orifice test.

3.20 Influence of aggregate particle form on properties of aggregate

3.21. Form and testing for durability.

It is a well-known fact that the aggregate form influences the amount of degradation during testing for durability. This can be demonstrated by testing rounded and angular aggregate of the same petrographic composition in the Los Angeles machine. The rounded, smooth-surfaced material is always found to have the lesser amount of breakdown (Woolf 1953), and increasing the revolutions of the Los Angeles machine from 500 to 1000 does not increase the breakdown by more than 50 %, provided the steel shot is omitted (Aughenbaugh 1963). It is highly probable that the polishing and grinding action during the first revolutions must be the main factor responsible for the lesser amount of degradation during the last. This effect is always pronounced in aggregate impact tests, the breakdown being from 10 to 30 % higher for crushed particles than for rounded.

3.22. Form and degradation.

Very little work has been done in which aggregate of controlled form have been subjected to degradational forces. However, investigations have been carried out from which at least some qualitative information on the subject may be obtained. These investigations compare the properties of gravels to those of crushed stone.

From investigations on the degradation of surface-treatment aggregates, Shelbourne (1940) found that 1,3 times as much degradation occurred in rolling crushed gravels than in rolling natural gravels. This seems to be too relative a statement, because it should not be difficult to find a gravel that was crushed to a larger extent than the crushed gravel used for the investigation. Shelbourne stated, however, that the crushed gravel he employed had a higher percentage of hard particles than the uncrushed. Since the crushed gravels still degraded more during the same compactive effort, Shelbourne interpreted this finding as an indication that particle form influenced the amount of breakdown. The same view has been brought forward by other investigators (Macnaughton 1937, Vallerga et al. 1956, Ekse and Morris 1959).

3.23. Form and the workability of aggregate-binder mixes.

As discussed previously, a rough-textured and angular aggregate has a higher voids content and a higher interparticle friction than a well rounded, smooth aggregate. As a corollary, more effort is needed to work the rough-textured than the smooth-textured aggregate. By adding binder (paste of flowing viscous material), which acts as a lubricant, a reduction in the interparticle friction in the aggregate mass results. Since the pits and grooves in the surface of the aggregate particles have to be filled by paste until satisfactory workability is obtained, rough aggregates demand a thicker layer of paste than the smooth aggregates in order to lubricate the movement of the mass to a certain degree of workability.

Since the quality of the finished product is dependent on the efficiency of the mixing operation, and since this operation is limited by the equipment employed, paste is usually added to obtain a satisfactory degree of workability. The workability therefore determines the amount of binder to be used, and, since this constituent is the most expensive of the materials employed, the economics of the materials. In the mixing of concrete, water is often added, instead of paste to improve workability. This leads to concrete of poorer quality. A water/cement ratio of 0,25 is required to wet the cement. Additional water may be regarded as available to make concrete workable. Little work has been done to evaluate more exactly the effect of particle form on workability, although this qualitative relationship and its economic consequences are well-known from practical work. The reason for this is probably to be found in the fact that a recognized significant and handy method of measuring the particle form is lacking.

Nevertheless Blanks (1952) reports a case where two aggregates were used, one angular and one rounded. The angular aggregate required 1,7 sacks of cement and 80 lbs of water more per. cu. yd. of concrete than the rounded. Yet it had a lower quality because of its higher water content. Blanks stated that the cost of the extra cement used would more than pay for an abrading operation to improve the workability of the angular aggregate.

Bloem and Gaynor (1963) found that mortar flow correlated very well (r = 0,9) to the dry-loose voids content of concrete sands, and the time of flow in the orifice test.

3.24. *Form and strength of concrete.*

Rough-textured, angular aggregate has a larger surface area and more grain interlock than smooth-textured, rounded aggregate. Since the strength of glued matter is proportional to the glued area, it would be reasonable to expect that angular, rough-textured aggregate would have a higher strength than smooth, rounded ones. This effect has been studied by Goldbeck (1939), who reported results of tests on aggregate particles imbedded in concrete. The particles were shaped to 1 in. square area, then embedded in cement briquettes and tested for bond strength in tension. As may be expected, the rough particles appeared to have considerably higher bond strengths than the smooth ones. The largest difference was found in samples which were cured 28 days in water, then 28 days in air. A strength of 260—300 lbs/sq. in. was found for rough particles as compared to 40—45 psi for smooth particles. The results for samples cured 28 days in water were 215—350 psi and 120—195 psi respectively. The Corps of Engineers have reported that samples made of 5,5 bag/cu. yd. cement and 1½ in. maximum size rough aggregate had a flexural strength of 670 lbs/sq. in as compared to 595 lbs/sq. in for smooth aggregates (Mather 1956).

As for the compressive strength the higher water demand is the most important factor involved, and a compressive strength of 4850 lbs/sq in was found for the smooth aggregate as compared to 4125 psi for the rough. The effect of the higher water content will therefore completely overshadow an expected, possible effect of the higher contact area of paste/aggregate provided by the rough aggregate. Evidence of this is demonstrated by the tests run by The National Sand and Gravel Association, investigating the effects of aggregate properties on the strength of concrete. Particle shape in that study was controlled by the orifice test. (Bloem and Gaynor 1963.)

Dempsey (1958) stated that concrete samples made from smooth or even highly polished aggregate had low shrinkage, good durability and satisfactory strength as compared to samples made of rough, manufactured sands. The highest strength mix was made, however, from the most rough-textured sand combined with a high cement content and a low water content.

3.25. *Form and stability of pavements.*

The stability of pavements may be defined as the ability of wearing surfaces and base courses to resist permanent deformations caused by moving loads. Some laboratory work has been done on this subject, but there is very little data available from field investigations. Since the days of MacAdams, it has been a recognized fact that crushed stone make more stable pavements than natural gravels. Actual measurements of the stress distribution under base courses have proved that crushed aggregate bases distribute the loads over a much larger area than gravel bases. (Herner 1955.) Some investigations have been performed on mixes of crushed and uncrushed aggregate. The stability or strength is most often evaluated by means of triaxial testing of a prepared specimen.

From a series of tests performed at Purdue University on bitumen-aggregate mixtures, Herrin and Goetz (1954) were able to conclude that:

1. the stability of onesize gradings was materially increased by increasing the ratio of crushed gravel to natural gravel.
2. open and dense gradings were not significantly influenced by this ratio.
3. in all gradings investigated, the stability was increased by adding crushed stone.
4. the greatest effect on stability was obtained when natural sand was replaced by angular manufactured sand.

These findings are substantiated by the works of Lottman and Goetz (1956) and Lees (1964 b).

The stability of bitumen-sand mixes has been studied by Schmidt and Schütter (1958). They employed sands of different origin for their experiments, and used the Hubbard-Field method for evaluating the stability. The particle shape was controlled by the orifice test method, and precautions were taken to minimize the effect of change of bitumen content on stability. The stability was found to increase with an increase in the orifice flow value. The increase was especially rapid for sand mixes with flow values increasing over 20 sec/100 cm³. This means that the most pronounced effect of adding rough-textured sands to

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natural sands is obtained for mixes with less than 50 % well rounded sands.

Contrary to this Lottman and Goetz (1956) found that a content of only 25 % crusher dust fines substituted for fine sand aggregates produced a significant increase in stability of asphaltic concrete mixtures. Increases of crusher dust fines above 75 % had little influence on stability.

It has also been found that the stability of mixes of round particles is about the same as for angular, flaky aggregate mixes (Soveri 1964), provided the same grading and bitumen content is used. For low bitumen contents (4 %), however, the stability of the flaky aggregate mix is a little higher than that for the round aggregate mix.

It has been found that during compaction (rolling) of aggregate layers, displacement of the particles takes place. Aughenbaugh (1963) found that the greatest amount of particle movement occurs at the top of the section, and there is a gradual decrease in such movement towards the bottom. He estimated the individual particles to be moved «much more» than «several inches». However, as the density increases, this movement probably comes to a stop after a certain amount of roller passes.

The resistance to such movement or the stability of base courses made from gravel, crushed aggregate, or mixes of these, have been investigated by some investigators (Chen 1948, Hennes 1952, Vallerga et al. 1956, Holz and Gibbs 1957, Morris 1959, Huang et al. 1964, Townsend and Madill 1964). Most of these researchers, using mixes of crushed and natural aggregate to control particle form, and vacuum triaxial testing of the samples, obtained significant effects of particle form on strength. Chen (1948) found that the angle of friction increased with increasing angularity of the particles, while Vallerga et al. concluded that «the angle of internal friction appeared» to increase considerably «if the angularity of the particles was increased by crushing». Hennes (1952), on the other hand found little effect of particle form on stability of the aggregate tested.

Morris (1959) tested samples of sand that varied with respect to surface texture, for strength, and employed the «dense angle of repose» for form assessment. He found that the particle form was responsible for up to 40 % variation of the yield strength. The tangent of the dense angle of repose was found to be related to the yield strength by a parabolic function. The maximum yield strength was found for samples with tangent of angle of repose of about 1,22. This result seems to be somewhat confusing, since the strength decreases with roughness for very rough-surfaced aggregate, reaching values as low as those obtained for well rounded materials in the extreme case. Thus, the samples of rough-surfaced pumice had large dense angles of repose, but not a higher yield strength than perfectly rounded and smooth material.

Huang (1964) found a linear relationship between his «particle index» and the maximum principal stress difference in testing various soil-coarse aggregate mixes. The strength of such mixes could therefore be changed by changing the particle index of the material. Townsend and Madill (1964) obtained significant increases in stability of dense aggregate mixes by increasing the angularity number of the coarse aggregate.

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ASTM: American Standards for Testing and Materials.
STP: Special Technical Publication.
HRB: Highway Research Board.

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