Effects of Aggregate Size, Shape, and Surface Texture on the Properties of Bituminous Mixtures—A Literature Survey

FRED J. BENSON, Texas A&M University

•THIS SURVEY of the literature on bituminous paving mixtures was done in 1965 and 1967 for the purpose of evaluating the function of the aggregate in the mixture; the 1965 survey was concerned with natural aggregates, and the 1967 survey with crushed aggregates.

This paper brings together the findings and opinions found in the literature, published principally during the past 40 years, concerning the effects of aggregate size, shape, and surface texture on the properties of bituminous mixtures. Where there are major differences of opinion, an attempt is made to present all important points of view. This survey also indicates the changes that have occurred in opinions on the effects under study. Even though nothing new is presented, it is hoped that the survey will stimulate new thinking and lead to a better understanding of bituminous mixtures.

This literature review is not exhaustive and no claim is made for its completeness. The effect of the variables under study on field production, including the operations of mixing, placing, and compaction, is not well covered in the literature studied.

AGGREGATE SIZE AND GRADATION

Aggregate size is considered to include maximum size, size range, and gradation. The earliest bituminous mixtures used the finer aggregate sizes and are generally referred to as sheet mixtures. When small amounts of coarser aggregates were added to the fine aggregate-bitumen mixture, the mixtures were known as stone-filled sheet mixtures. Balanced mixtures of coarse and fine aggregate are referred to as dense-graded mixtures or bituminous concretes, fine-graded for maximum-size aggregate of ½ in. (¾ in.) or less, and coarse-graded for larger maximum sizes. Mixtures in which the coarse aggregate predominates and in which fines are insufficient to fill the coarse aggregate voids are referred to as open-graded bituminous concrete mixtures. It seems evident that the characteristics of these mixtures will be a function of the characteristics of the predominant aggregate.

Much has been written on aggregate grading and its effect on the characteristics of bituminous mixtures. The subject has been studied extensively in this century. Opinions and conclusions, however, are certainly not completely consistent.

With regard to dense-graded mixtures, Francis Hveem (1) writes as follows:

> When the first oil mix roads in California were built in 1926 it was generally regarded as something new. . . . Detailed studies have been made, including among other things the effect of grading. In 1929 there were oil mix sections ranging from good to poor. When a series of samples taken from good and bad sections was analyzed it was found that some of the most unconventional and irregular curves were identified with the most successful roads and in several failures, the gradings complied quite nicely with Fuller's curve. We could not escape the conclusion that a satisfactory bituminous surface could be constructed almost without regard to aggregate gradation if the bitumen content were adjusted for the particular aggregate and gradation. . . .Gradation is important for workability, reduced permeability, economy. . . .as the stability is also influenced by cohesion, any reduction in fines tends to reduce cohesion and influence permeability. The best grading for any particular mixture can only be that which utilizes the available aggregates to give as many of the desired properties as possible.

J. R. Benson (2) is of the opinion that for bituminous mixtures "when optimum quantities and consistencies of bitumen are used, the flexibility will vary with aggregate structure. If the aggregate structure is weak, a low resistance to deformation will ensue, while too great a stability in the aggregate structure may result in brittleness and low resistance to impact." Benson further states, "In uniformly graded aggregates, particles are of uniformly decreasing size, coarse to fine to dust. Such aggregate structures have fairly uniform stress distribution. This type of grading is of special importance in the utilization of smooth, round aggregate such as alluvial sand and gravel. Careful grading control can yield high stability from aggregates possessing little stability."

Steele (3) classes gradings for bituminous mixtures as (a) open-graded, including materials ranging from a specified maximum to a specified minimum size, provided that such minimum size shall be retained, with specified tolerances, on a No. 4 sieve; (b) intermediate gradings including certain aggregate combinations with a substantial percentage passing the No. 4 sieve but with insufficient minus No. 10 material to qualify for the dense-graded classification; and (c) dense-graded having any specified maximum size with a continuous, and reasonably uniform, representation of particle sizes down to and including dust. Steele believes that a wide range of gradings is suitable for use in producing dense-graded mixtures.

Reagal (4), from his experience in Missouri, found a tendency for bituminous surfaces to rub and shove when constructed from aggregates having "humps" in their gradation curves. In comparison, McNaughton (5) believes that "there is a fairly wide band of tolerance through which the grading curve can shift without changing appreciably the fundamental characteristics of the mix as regards bitumen requirements, density and stability. ... I do not... say that mixtures of maximum density are necessary or even desirable."

Hveem and Vallerga (6), in discussing relationships between density and stability of bituminous mixtures, comment as follows: "Therefore, recognizing that interparticle friction is the major property that contributes to stability, it must be recognized that this property is largely independent of the contact area between particles. In paving mixtures this accounts for the fact that aggregate gradation has little predictable influence and adequate stability may be developed in mixtures composed of a wide variety of particle size combinations."

Gradation is an important factor in controlling the degradation of bituminous mixtures. Moavenzadeh and Goetz (7) concluded from a study of degradation: "Gradation of the mixture is the most important factor controlling degradation. As the gradation becomes denser, degradation decreases. ... from a degradation point of view, dense graded mixtures offer the best use of local aggregates with high Los Angeles values."

McLeod (8), in summarizing important fundamentals to be considered in the selection of aggregates, writes as follows with regard to aggregate size and gradation:

(1) For the best stability, a harsh crushed stone with some gradation, to be mixed with just sufficient asphalt to give high compaction.

(2) For impermeability, a uniformly graded aggregate with a sufficient quantity of fine sand, fine sand being considered more important in this respect than filler dust.

(3) For non-skid, a large quantity of the maximum size aggregate within the size limits used.

(4) For workability and freedom from segregation, a uniformly graded aggregate.

Stanton and Hveem (9), in discussing the same points, concluded that although stability may be affected by percentage of certain sizes it is unpredictably affected by changes in grading. Permeability of mixtures is dependent to a large extent on the percentage of material in the 30, 50, and 100 mesh sizes. Permeability is a matter of pore size rather than void volume. Workability is most affected by the quantity and grading of coarse aggregate. Finally, critical mixtures (those very sensitive to bitumen content) are associated with high percentages of fines.

Henderson (10) believes that, for construction of fine-graded bituminous concrete, no hard and fast rules can be laid down. Sands previously considered too coarse or too fine are being used successfully. He also pointed out that coarse aggregate bituminous concrete, where little or no gradation control of the aggregate was attempted, has performed well for 20 years.

Griffith and Kallas (11), from a study of crushed and uncrushed coarse and fine aggregates, found that the relative proportions of coarse and fine aggregate for maximum stability is a function of the angularity and surface texture of both coarse and fine aggregate fractions.

Warden and Hudson (12) report the results of a rather extensive study of the gradation of natural sand gravel aggregates. A basic gradation for ¾ in. maximum-size asphaltic concrete was developed by averaging the idea of the U. S. Corps of Engineers, Hveem, Nijboer, and Vokac to establish the following ideal gradation:

Passing ¾ in. sieve	100 percent
Passing ½ in. sieve	95 percent
Passing No. 4 sieve	66 percent
Passing No. 80 sieve	12 percent
Passing No. 200 sieve	6 percent

Varied aggregate gradings were then produced by (a) varying the percentage retained on the No. 4 sieve, (b) varying the gradation of the No. 4-No. 200 material by changing percentages passing the No. 20 sieve, and (c) varying the quantity passing the No. 200 sieve. The conclusions reached were as follows:

1. Satisfactory ¾ in. maximum-size sand gravel mixtures for bituminous pavements can be produced with reasonable asphalt content and 25 to 55 percent of total aggregate retained on the No. 4 sieve.

2. With a constant quantity of 34 percent retained on the No. 4 sieve and 6 percent passing the No. 200 sieve, maximum stability (Marshall stability) occurred at 30 percent of total aggregate passing the No. 20 sieve but satisfactory results were obtained for 20 to 50 percent passing the No. 20 sieve. Amounts above 35 percent increased the asphalt demand.

3. With 34 percent retained on the No. 4 sieve and 38 percent passing the No. 20 sieve, the percentage passing the No. 200 sieve was varied from 0 to 10 percent using limestone dust for filler. The Marshall stability increased as the filler content increased; the practical range of material passing the No. 1200 sieve was found to be 2 to 8 percent.

Warden and Hudson also studied natural aggregate containing little or no coarse material. They experimented with Central Kansas pit sand utilizing 100 percent passing the No. 4 sieve and 42 to 100 percent passing the No. 20 sieve. As the percentage passing the No. 20 sieve increased from 42 to 100 percent, the Marshall stability dropped from 920 to 490 lb and the optimum asphalt content increased from 5.5 to 9.2 percent.

Puzinauskas (22), in a study of the effect of particle shape on particle alignment during compaction of dense-graded mixtures, concluded that particle alignment tends to increase with increasing size of aggregate particles. The smallest orientation of particles was found for mixtures of sand or sheet asphalt.

Campen et al (13), in a review of factors affecting the proper asphalt content for bituminous paving mixtures, indicate that the gradation of the aggregate and the surface area of the aggregate are important factors in fixing the asphalt requirement. Surface area is a function of aggregate size and size range. The larger the aggregate size, the smaller is the surface area for a given weight or volume of aggregate. In dense-graded aggregates, the major portion of the surface area occurs in the fine aggregate fraction. These principles are generally accepted in the design procedures and specifications for bituminous mixtures. Sand-asphalt mixtures commonly require 10 percent or more by weight of asphalt cement, whereas 5 percent by weight might be quite suitable for a dense-graded asphaltic concrete of 1 in. maximum size.

Vallerga (14) believes that "Brittleness (or inflexibility) of asphaltic paving mixtures is a function of asphalt content, aggregate grading, and, in particular, the final condition of the asphalt in the pavement."

The effect of gradation on the proper asphalt content is well illustrated by experiments conducted by Williams and Gregg (15) on paving mixtures made from a relatively soft crushed sandstone. Analysis was made on the basis of a gradation modulus defined as the sum of percentages passing the 1 in., ¾ in., ½ in., ⅜ in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves. The optimum asphalt content, determined by the Marshall method, varied from 6.3 percent at a gradation modulus of 280 to 9.8 percent at a gradation modulus of 670.

Some of the earliest work on gradation for maximum density was carried on from 1901 to 1906 by Fuller and Thompson (16) in connection with their studies of the best aggregate proportions for portland cement concrete. Some of the pertinent conclusions follow:

1. The largest stone makes the densest concrete. Concrete made with graded stone having a maximum diameter of 2½ in. is noticeably denser than that with a 1-in. diameter stone.
2. Under similar conditions a denser concrete is given with round material, like gravel, than with broken stone. A denser concrete also is produced with sand than with screenings of grains of similar size.
3. The best mixture of cement and aggregate has a mechanical analysis curve (percentage by weight smaller than given diameters, y, versus diameter of particle, x, in natural scale) resembling a parabola, which is a combination of a curve approaching an ellipse for the sand portion and a tangent straight line for the stone portion. The ellipse runs from 7 percent passing the No. 200 sieve to a diameter of one-tenth of the diameter of the maximum size of stone, the stone from this point being uniformly graded.
4. The ideal mechanical analysis curve is slightly different for different materials. The form of the best analysis curve is, however, the same for all sizes of the same stone; thus the best curve for different maximum sizes may be described by an equation in which the maximum diameter is the only variable. The equation of the elliptical portion of the curve is $(y - 7)^2 = (b^2/a^2)\cdot(2ax - x^2)$ where a and b are to be determined for the particular material.

The principles stated by Fuller and his maximum density gradations have been widely used for many years for all types of paving mixtures containing combinations of coarse and fine aggregate. The starting point for the ellipse can be varied from that suggested by Fuller.

In 1943 Nijboer (17) studied aggregate gradations plotted on a log-log gradation chart with percentage passing plotted against the sieve opening in microns. The gradation used in the study plotted as straight lines on the log-log scale. Regardless of whether an angular crushed stone or rounded gravel was used, the gradation with minimum voids plotted as a straight line with a slope of 0.45.

Goode and Lufsey (18) extended the work of Nijboer to develop a general procedure for maximum density curves. They showed that, with the assumption that maximum density gradings will have a 0.45 slope on the log-log scale, the equation for the gradation curve is as follows:

$$P = 100\ (S/M)\ 0.45$$

$$\text{Log } B = 2 - 0.45 \log M$$

where

P = percentage passing the particular sieve;
S = size of sieve opening for the particular sieve in microns;
M = maximum size of aggregate in microns; and
B = intercept on percentage passing axis at 1 micron (log 0) on the sieve-opening axis.

The National Crushed Stone Association has used similar principles in its "square root gradation chart" for which the slope on the log-log scale is 0.5.

The preceding principles were used to develop the Public Roads Gradation Chart on which the vertical axis is used for percentage passing on a natural scale and the horizontal axis for the sieve size plotted in terms of the sieve opening, S, to the 0.45 power. Any gradation that plots as a straight line from zero to the maximum size on this chart will also plot as a straight line on a log-log chart and have a slope of 0.45.

The Goode and Lufsey studies indicated that a number of "tender mixtures" (those slow in developing sufficient stability to permit rolling) showed an upward hump in gradation curves on the Public Roads Gradation Chart at the No. 30 sieve indicating an excess of fine sand in relationship to total sand. Further studies of these mixtures showed that they had higher voids in the mineral aggregates and reduced Marshall stability as compared to gradations plotting as straight lines on the Chart.

In summary, the maximum size of aggregate is important with regard to the skid resistance of the pavement, the percentage asphalt needed in the mixture, and the workability and economy of the mixture. Aggregate gradation and size range influence the strength and stiffness characteristics of the mixture, permeability, asphalt content, economy, workability, and skid resistance.

EFFECT OF AGGREGATE SHAPE

Aggregate shape is discussed in the literature primarily in terms of differences between natural aggregates (gravels and sands) and crushed aggregates (crushed gravel or crushed stone). There are substantial differences in the angularity of gravels depending on the source rock and the weathering process to which the gravel has been subjected. In a similar manner, the shape of crushed aggregates, both gravel and stone, is dependent on the fracture characteristics of the materials crushed and on the crushing process.

Herrin and Goetz (19) made a study of the effect of aggregate shape on the stability of bituminous mixes. The coarse aggregates used in the tests were a natural gravel; the same gravel 55 percent crushed, 70 percent crushed, and 100 percent crushed; a crushed limestone; and two artificial gravels produced from the crushed limestone by abrading it in the Los Angeles abrasion machine at 5,000 and 10,000 revolutions with the steel-ball charge not used. Fine aggregates were a natural rounded sand and crushed limestone sand. The filler used was portland cement. The aggregates were studied in dense-graded mixtures (68 percent fine aggregate), open-graded mixtures (39.7 percent fine aggregate), and one-size mixtures (0 percent fine aggregate). The asphalt content was held constant for a given grading and type of fine aggregate. The triaxial compression test was used to evaluate stability. The summary of results includes the following:

1. As the percentage of crushed gravel in the coarse aggregate fraction increased, strength varied with grading, becoming less as the grading became more dense; i.e., the increases were most important for strength in one-size mixtures and of little importance in dense-graded mixtures. This was true for both natural sand and crushed stone fine aggregates.

2. For the one-size grading, strength increased directly and substantially with increasing percentage of crushed gravel. The angle of internal friction increased; cohesion did not.

3. In open-graded mixtures, an increase in the percentage of crushed gravel from 0 to 55 percent produced a slight increase in strength; percentages of crushed gravel above 55 percent gave no further increase in strength. The angle of internal friction did not change for varying percentages of crushed gravel. Cohesion increased as the percentage of crushed gravel increased from 0 to 55 percent.

4. The strengths of dense-graded mixtures were not influenced by the percentage of crushed gravel. Neither the angle of internal friction nor cohesion was affected.

5. In all gradings (one-size, open, and dense) and with either type of fine aggregate, more strength was shown by crushed stone than by crushed gravel. The increased strength was primarily due to increased cohesion.

6. Regardless of the coarse aggregate used, the strengths of both dense- and open-graded mixtures increased substantially when the fine aggregate was changed from

rounded sand to crushed limestone. The increases caused by a change in fine aggregate were much larger than those caused by changes in the angularity of the coarse aggregate. Values of cohesion increased materially, but angles of internal friction did not.

7. The test results demonstrate that aggregate grading (dense, open, one-size) may be more of a determining factor on strength than aggregate shape over a wide range of aggregate gradings.

8. Greater strength was shown by the mixtures containing crushed stone coarse aggregate than by the same mixtures with any percentage of crushed gravel.

9. Artificial limestone gravels had strengths much lower than those of crushed limestones in one-size mixtures. The angle of internal friction was substantially lower for the artificial gravels. Cohesion changed very little.

Griffith and Kallas (20) studied the effect of various aggregate types on the aggregate voids characteristics of bituminous paving mixtures. Their studies included natural gravel, crushed limestone, crushed granite, and crushed trap rock. The results of their studies are included in the following:

1. The natural gravel mixtures developed aggregate voids lower than those developed by the crushed stone mixes through the grading range investigated.
2. The aggregate voids curves indicated that the coarse aggregate particle shape, whether the aggregates are crushed or uncrushed, has considerable influence on the aggregate voids, particularly when the coarse fractions make up more than 50 percent of the aggregate.
3. Less asphalt would normally be required by the natural gravel aggregate mixtures than by the crushed stone mixtures.
4. Aggregate voids are dependent on type and gradation of aggregate, asphalt content, and method of compaction.

Griffith and Kallas (11) also studied the influence of fine aggregates on asphaltic concrete paving mixtures. The laboratory investigation included combinations of natural and crushed coarse aggregates in combination with crushed New York trap rock and natural Maryland sand as fine aggregates. Marshall and Hveem test procedures were used. Some of the conclusions reached were as follows:

1. An increase in angularity increased Marshall and Hveem stability values of asphaltic concrete at optimum asphalt content.
2. Increased angularity of the fine aggregate fractions increased minimum void percentages.
3. Increased angularity of the fine aggregate fraction produced increased optimum asphalt contents.

Lottman and Goetz (21) studied the effect of crushed gravel fine aggregate on the strength of asphaltic surfacing mixtures. The laboratory studies included dense-graded asphaltic concrete and sand asphalt. In many cases an increase of as little as 25 percent crushed gravel in the fine aggregate produced a significant increase in strength.

Puzinauskas (22) studied the effect of aggregate structure on the properties of asphalt paving mixtures. The tests compared dense-graded asphaltic concrete mixtures containing angular aggregate consisting of South Carolina crushed granite as the coarse aggregate and fine aggregate and filler from Maryland crushed gravel with mixtures containing rounded aggregate consisting of Maryland natural gravel and sand and Mississippi loess filler. Cubical specimens were prepared and tested in compression. Results were evaluated in terms of the aggregate structure index defined as the ratio of the compressive strength of cubic specimens loaded parallel to the direction of compaction to that measured by loading in the direction perpendicular to compaction. The purposes of the studies were (a) to assess aggregate particle alignment in compacted mixtures, and (b) to evaluate the influence of such alignment on the mixture properties. Important conclusions reached are given in the following:

1. Visual observation and values larger than 1.00 for the structure index indicate that, regardless of type of aggregate or method of compaction, aggregate particles tend

to become axially aligned in a direction perpendicular to the direction of the compacting force.

2. Greater values of the structure index indicate that a more pronounced effect is produced by particle alignment in mixtures containing elongated or flattened particles than in mixtures containing rounded particles.

3. Test data indicate an appreciable degree of particle alignment for in-service pavements.

Shklarsky and Livneh (23) made a very extensive study of the differences between natural gravel and crushed stone coarse aggregates in combination with natural sand and crushed stone fine aggregates. The natural gravel consisted of chalk, flint, and cretaceous flint, and the natural sand was from the same source. Crushed limestone was used for the crushed coarse and fine aggregate. The mixtures were ¾ in. maximum-size in a single gradation suitable for binder course with 38 percent passing the No. 10 sieve. The variables studied were the Marshall stability and flow, angle of internal friction and cohesion as measured in triaxial shear, resistance to moving wheel loading, resistance to splitting, immersion-compression strengths, and permeability. With regard to types of materials, Shklarsky and Livneh reported as follows:

> The influence of the fine fraction at the gradation in question is decisive. This is reflected in all series: Marshall, triaxial shear, moving wheel load and immersion-compression. Replacement of the natural sand with crushed fines improves incomparably the properties of the product, increases its stability, reduces rutting, improves water resistance, reduces bitumen sensitivity, increases the void ratio and brings the mixture (with gravel coarse aggregate) to the quality level of one with crushed coarse and fine aggregate. On the other hand, replacement of the coarse material with crushed coarse aggregate entails no such decisive effect.

Wedding and Gaynor (24) studied the effect of aggregate particle shape in dense-graded asphaltic concrete with varying asphalt content, varying aggregate gradation, varying percentages of crushed particles in coarse aggregate, and varying types of fine aggregate including natural sand and crushed gravel sand. Comparisons were made on the basis of laboratory studies utilizing the Marshall procedure and including stability, flow, unit weight, voids in compacted mixture, voids in mineral aggregate and percentage of voids in the mineral aggregate filled with asphalt. Their summary and conclusions include the following:

> 1. Crushed gravel when used as a coarse aggregate for a mix causes a significant increase in the stability as compared to a similar mix containing natural gravel.
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> 2. When used in place of natural sand as fine aggregate, crushed gravel sand produces some increase in stability for mixes containing natural gravel as a coarse aggregate; however, it had relatively little effect on the stability of 100 percent crushed gravel mixtures.
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> 3. The use of crushed gravel sand in place of natural sand is about equal in effectively raising stability as the use of 25 percent crushed gravel in the coarse aggregate.
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> 4. The substitution of all crushed aggregate, crushed gravel sand and coarse aggregate for natural sand and gravel causes an increase in stability of about 45 percent.
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> 6. An increase in the amount of crushed particles in the total aggregate causes a slight decrease in the unit weight and slight increases in mineral aggregate voids and optimum asphalt content of the mix.
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> 7. The flow value was not materially affected by the amount of crushed material in the aggregate.

Field (25) studied the effect of the percentage of crushed particles in the coarse aggregate of bituminous paving mixtures. In his studies, aggregates from six sources graded from a ⅝ in. to No. 4 sieve were used consisting in each case of uncrushed gravel and the same gravel crushed. The fine aggregate was a well-graded, clean sand with particles that were fairly rounded. The percentage of crushed aggregate was varied from 0 to 100 percent in 10 percent increments in mixtures containing 40, 50, and 60 percent fine aggregate. Four degrees of angularity were studied for one aggregate. Asphalt contents were established to yield approximately 4 percent voids in the mixture. The Marshall procedure was used for producing and testing specimens. Field enumerates the following results:

1. Voids in the mixture (fixed) and voids in the mineral aggregate showed little variation with variations of the percentage of crushed coarse aggregate. Flow values were also not affected by the percentage of crushed coarse aggregate particles.

2. The Marshall stability changed little for 0 to 35 percent crushed particles, then increased substantially as the percentage of crushed particles was increased to 100 percent. The average stability was 55 percent higher for 100 percent crushed particles than for 35 percent crushed particles. Field concludes that specifications should require at least 60 percent crushed particles in the coarse aggregate.

3. The degree of angularity for mixes with 50 percent or more coarse aggregate significantly affected the voids in the mineral aggregate—the more angular the aggregate, the more open the mix. Flow values were not affected by degree of angularity. Crushed particles of maximum angularity gave 100 percent more stability than that given by uncrushed gravel.

W. H. Campen, commenting on Field's paper, emphasized that (a) the aggregates were deficient in fines and (b) the aggregates were all limestones and dolomites; thus, the principles may not apply for other types of aggregates.

Lefebvre (26) studied dense-graded asphaltic concrete mixtures utilizing (a) two coarse aggregates, a crushed gravel containing particles mostly cubical in shape, and a crushed trap rock with rather long and flat particles; (b) two fine aggregates, a natural bank sand with medium sharp grains, and screenings from crushed trap rock; (c) a fine, dense sand; (d) commercial limestone dust for filler; and (e) 85 to 100 penetration asphalt. The percentage proportions of coarse aggregate to fine aggregate used were in the mixtures 75 to 25, 50 to 50, 25 to 75, and 0 to 100. The 50-to-50 mixtures were repeated substituting 10 and 50 percent of fine, dense sand in the fine aggregate. The natural sand-crushed gravel mixtures were repeated with 6, 12, and 18 percent limestone dust. Lefebvre writes as follows:

> Although each of the fractions which make up the mineral aggregate has a considerable influence on the characteristics of a paving mixture, the fine aggregate as usually referred to can be considered as the most critical component. Its quantity and characteristics control to a large extent the percentage of voids in the total aggregate and affect also the stability as well as the amount of bitumen which can be incorporated. . . . The fine aggregate should be such that by its rough texture, angularity of particles and gradation, it will develop a high stability while maintaining a relatively high percentage of voids in the mineral aggregate at a bitumen content producing the required percentage of voids in the compacted mix.

Chapel (27) studied the use of siliceous gravels for coarse aggregate in pavements in Pennsylvania. Such gravels were first used in hot-plant mixtures in the 1930's with good results under a specification requiring 85 percent crushed with one crushed face, a maximum of 35 percent Los Angeles abrasion loss and a maximum of 10 percent loss after 5 cycles in the sodium sulfate soundness test. In the late 1930's, problems developed in pavements produced under this specification, and in 1940 new specifications required 90 percent crushed particles with two crushed faces. Later experimental pavements having 50 to 75 percent of particles with two crushed faces and 85 percent with one crushed surface proved equally satisfying. The crushing process produced considerable crushed material passing the No. 10 sieve and was considered to be very advantageous in the mixture, particularly for stability. Lee and Marwick (28) found that mixtures made with flaky particles offer resistance to deformation 50 percent greater than that offered by mixtures made with cubical stones under otherwise identical conditions.

Campen and Smith (29) carried on a series of experiments in which Platte River rounded sand was mixed with varying proportions of a river angular sand, crushed gravel sand, and crushed limestone sand. The sands were first used in various combinations in sheet asphalt mixtures. The study was then extended to stone-filled sheet asphalt and asphaltic concrete using weak and strong mortar from the sheet asphalt experiments and a series of coarse aggregates consisting of river rounded gravel, crushed quartzite, chats, crushed gravel, and crushed limestone. The Hubbard-Field test was used for the sheet asphalt studies and the Omaha Testing Laboratory bearing-index test for stone-filled sheet asphalt and asphaltic concrete. Campen and Smith found as follows:

1. The addition of 20 to 40 percent of sharp sand or crushed sands to the Platte River rounded sands resulted in increases of 200 to 300 percent in the Hubbard-Field stabilities with the crushed gravel and crushed quartzite sands being most effective.
2. For stone-filled sheet asphalt produced with strong mortar utilizing crushed sands, the increase in stability obtained by using crushed coarse aggregate as compared to natural rounded gravel was 20 to 70 percent at maximum stability.
3. For asphaltic concrete with a maximum size of ½ and ¾ in. built with strong mortar, the increase in stability obtained by using crushed aggregate as compared to natural rounded aggregate was 30 to 190 percent at maximum stability.
4. With angular aggregates, the asphalt content for satisfactory stability was much less critical than for rounded aggregates.

Moyer and Shupe (30), in a study of the skid resistance of bituminous pavement surfaces, found that the friction values for rounded aggregate were about 25 percent lower than those for angular aggregates in wet pavement tests. Stephens and Goetz (31) also found that the shape of the aggregate particle affects the skid resistance of a fine bituminous mix. Comparison of relative resistance values for round and angular shapes of the same material reveals an initial superiority for the angular aggregate. However, long-term skid resistance depended on the polishing characteristics of the aggregates.

In summary, the literature indicates that the shape of the aggregate has appreciable effect on the physical properties of the mixture, on the proper asphalt content, and on the voids relationship. The generally accepted principle that the shape of the coarse aggregate is critical with regard to properties of graded mixtures seems to apply only to open-graded mixtures. The literature indicates that the characteristics of the fine aggregate fraction are dominant for down-graded mixtures. Aggregate shape is also quite important in its effect on skid resistance.

EFFECT OF SURFACE TEXTURE

Griffith and Kallas (11) found that increased roughness of surface texture of fine aggregates increased Marshall and Hveem stability values for asphaltic concrete at optimum asphalt. They also found that increased roughness of surface texture of the fine aggregate fractions increased the minimum percentage of voids in the mineral aggregate and increased the optimum asphalt content.

Campen and Smith (13) found that more asphalt is required by rough-textured aggregates than by rounded smooth-faced ones. The increased asphalt is required to overcome loss of workability and to fill pits and crevices.

Hveem (32) writes, "High frictional resistance is obtained by selecting aggregates having a sandpaper-like surface texture, and with the quantity of asphalt maintained definitely below the total void volume."

Winterkorn (33) believes that the resistance to stripping of bitumen and aggregate is dependent, among other things, on the surface and physical character of the aggregate.

Lefebvre (26) considers that the first requisite for a satisfactory paving mixture of the dense-graded type is the use of a moderately high percentage of fine aggregate containing a small percentage of fine sand. The fine aggregate should be such that by its rough surface texture, angularity of particles, and gradation it will develop high stability while maintaining a relatively high percentage of voids in the mineral aggregate.

Vallerga (14) is of the opinion that the strength of an asphaltic paving mixture depends primarily on the frictional resistance between aggregate particles and that it is, therefore, essential to have well-graded, rough-surfaced aggregate of good quality.

Neppe (34) writes that the "stability of road aggregates depends primarily on internal friction and mechanical arrangement of interlocking of individual particles of the mass, which are greatly affected by the degree of compaction, particle slope or angularity and surface texture in addition to grading."

Ryan (35), in discussing aggregates for bituminous plant mixtures, writes as follows: "It is a generally accepted fact that to obtain desirable stability and density in an asphalt pavement, a well graded interlocking coarse aggregate should be used. ... Particle shape and surface characteristics are just as important in the fine aggregate, even down to the minus 200 mesh or flow size as in the coarse aggregate...."

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REFERENCES

1. Hveem, F. N. Gradation of Mineral Aggregates for Dense Graded Bituminous Mixtures. Proc. AAPT, Vol. 12, 1940, pp. 315-330.
2. Benson, J. R. The Grading of Aggregates for Bituminous Construction. ASTM Symposium on Mineral Aggregates, 1948, pp. 117-133.
3. Steele, D. J. Mineral Aggregates for Asphalt Highway Surfaces. Proc. 12th Nat. Asphalt Conf., 1939, pp. 97-103.
4. Reagal, F. V. Factors Governing the Selection of Aggregates: Practice in Missouri. Proc. 13th Nat. Asphalt Conf., 1940, pp. 181-186.
5. McNaughton, M. F. Discussion of paper by W. H. Campen. Proc. AAPT, Vol. 12, 1940, pp. 309-314.
6. Hveem, F. N., and Vallerga, B. A. Density versus Stability. Proc. AAPT, Vol. 21, 1952, pp. 237-254.
7. Moavenzadeh, F., and Goetz, W. H. Aggregate Degradation in Bituminous Mixtures. Highway Research Record 24, 1963, pp. 106-137.
8. McLeod, N. W. Review of Design of Subgrades and of Base Courses and Selection of Aggregates. Proc. Nat. Bituminous Conf., 1937, pp. 75-80.
9. Stanton, T. E., Jr., and Hveem, F. N. Role of the Laboratory in Preliminary Investigation and Control of Materials for Low Cost Bituminous Pavements. HRB Proc., Vol. 14, Part II, 1935, pp. 14-54.
10. Henderson, G. H. Application of Present Knowledge in the Construction and Maintenance of Bituminous Macadam and Bituminous Concrete. HRB Proc., Vol. 8, 1929, pp. 184-187.
11. Griffith, J. M., and Kallas, B. F. Influence of Fine Aggregates on Asphaltic Concrete Paving Mixtures. HRB Proc., Vol. 37, 1958, pp. 219-255.
12. Warden, W. B., and Hudson, S. B. Hot Mixed Black Base Construction Using Natural Aggregate. Proc. AAPT, Vol. 30, 1961, pp. 291-312.
13. Campen, W. H., Smith, J. R., Erickson, L. G., and Mertz, L. R. Factors that Control Asphalt Requirements of Bituminous Paving Mixtures and a Method for Determining the Proper Asphalt Content. Proc. AAPT, Vol. 32, 1963, pp. 530-544.
14. Vallerga, B. A. On Asphalt Pavement Performance. Proc. AAPT, Vol. 24, 1955, pp. 79-99.
15. Williams, E. G., and Gregg, L. E. Evaluation of Sandstone as an Aggregate in Plant Mix Bituminous Pavements. Proc. AAPT, Vol. 22, 1953, pp. 92-106.
16. Fuller, W. B., and Thompson, S. E. The Laws of Proportioning Concrete. Trans. ASCE, Vol. 59, 1907, pp. 67-143.
17. Nijboer, L. W. Plasticity as a Factor in the Design of Road Carpets. Amsterdam Laboratory of the N. V. De Bataafsche Petroleum Maatschappij (Royal Dutch Shell Group), Elsevier Publishing Company, Inc.
18. Goode, J. F., and Lufsey, L. A. A New Graphical Chart for Evaluating Aggregate Gradations. Proc. AAPT, Vol. 31, 1962, pp. 176-192.
19. Herrin, Moreland, and Goetz, W. H. Effect of Aggregate Shape on Stability of Bituminous Mixes. HRB Proc., Vol. 33, 1954, pp. 293-308.

20. Griffith, J. M., and Kallas, B. F. Aggregate Voids Characteristics in Asphalt Paving Mixes. HRB Proc., Vol. 36, 1957, pp. 382-387.
21. Lottman, R. R., and Goetz, W. H. Effect of Crushed Gravel Fine Aggregate on the Strength of Asphaltic Surfacing Mixtures. Nat. Sand and Gravel Assn., Washington, D. C., Circular 63, 1956.
22. Puzinauskas, V. P. Influence of Mineral Aggregate Structure on Properties of Asphalt Paving Mixtures. Highway Research Record 51, 1964, pp. 1-15.
23. Shklarsky, E., and Livneh, M. The Use of Gravels for Bituminous Paving Mixtures. Proc. AAPT, Vol. 33, 1964, pp. 584-610.
24. Wedding, P. A., and Gaynor, R. D. The Effects of Using Gravel as the Coarse and Fine Aggregate in Dense Graded Bituminous Mixtures. Proc. AAPT, Vol. 30, 1961, pp. 469-488.
25. Field, Frederick. The Importance of Percent Crushed in Coarse Aggregate as Applied to Bituminous Pavements. Proc. AAPT, Vol. 27, 1958, pp. 294-320.
26. Lefebvre, J. Recent Investigations of Design of Asphalt Paving Mixtures. Proc. AAPT, Vol. 26, 1957, pp. 297-309.
27. Chapel, K. F. The Use of Sand and Gravel in Bituminous Mixtures. Proc. AAPT, Vol. 25, 1956, pp. 392-397.
28. Lee, A. R., and Marwick, H. D. The Mechanical Properties of Bituminous Surfacing Materials Under Constant Stress. Jour. Society of Chemical Industry, London, Vol. 56, 1937, p. 146T.
29. Campen, W. H., and Smith, J. R. A Study of the Role of Angular Aggregates in the Development of Stability in Bituminous Mixtures. Proc. AAPT, Vol. 17, 1948, pp. 114-135.
30. Moyer, R. A., and Shupe, J. W. Roughness and Skid Resistance Measurements of Pavements in California. HRB Bull. 37, 1951, pp. 1-35.
31. Stephens, J. E., and Goetz, W. H. Designing Fine Bituminous Mixtures for High Skid Resistance. HRB Proc., Vol. 39, 1960, pp. 173-190.
32. Hveem, F. N. Some Basic Factors and Their Effect on the Design of Bituminous Mixtures. Proc. Nat. Bituminous Conf., 1937, pp. 220-228.
33. Winterkorn, H. F. Progress in Research on the Adhesion Between Mineral Fractions and Bituminous Materials. Proc. Montana Nat. Bituminous Conf., 1938, pp. 136-143.
34. Neppe, S. L. Mechanical Stability of Bituminous Mixtures: A Summary of Literature. Proc. AAPT, Vol. 22, 1953, pp. 383-427.
35. Ryan, A. E. Discussion of Plant Mixes. Crushed Stone Jour., Vol. 29, No. 1, March 1954, pp. 20-24.