HRB Special Report 109

Effects of Aggregate Size, Shape, and Surface Texture on Properties of Bituminous Mixtures

Highway Research Board

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Special Report 109

Effects of Aggregate Size, Shape, and Surface Texture on Properties of Bituminous Mixtures

Proceedings of a Conference Session Held
During the 47th Annual Meeting of the
Highway Research Board on
January 18, 1968

Subject Areas
31 Bituminous Materials and Mixes
32 Cement and Concrete
40 Maintenance, General

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Foreword

This Special Report contains the proceedings of a conference session held during the 47th Annual Meeting. The objective of the session was to develop current information based on the knowledge and practice of those who have either theoretical or practical backgrounds related to the design, construction, or performance of bituminous mixtures.

Informal presentations by a panel of four experts dealt with the effects of aggregate size, shape, and surface texture on selected properties of bituminous mixtures. Foster described the effect of fine aggregate on strength or stability. Monismith discussed the effects of several aggregate properties on stiffness and fatigue response. Britton brought out the effect of aggregate size on durability. Benson summarized a literature survey of the subject. The general discussion that followed these presentations was recorded and is included in this report. Two prepared discussions by Hargett and Kalcheff are also included. A formal paper, Packing Volume Concept for Aggregates, by Egons Tons and W. H. Goetz, was given at the session but was published earlier in Highway Research Record 236.

The scope of the mixture properties was purposely limited to stability, flexibility or stiffness, fatigue resistance, and durability; not included were other properties such as workability, permeability, or skid resistance. In some of the presentations, however, discussion of these characteristics could not be avoided.

This conference session was organized under the leadership of Frank R. Nichols, Jr., and was sponsored by the Committee on Characteristics of Aggregates and Fillers for Bituminous Construction.

—James M. Rice

Contents

Informal Presentations

Prepared Discussions

Dominant Effect of Fine Aggregate on Strength of Dense-Graded Asphalt Mixes

CHARLES R. FOSTER, National Asphalt Pavement Association

•IN TWO TEST SECTIONS at the U. S. Army Engineer Waterways Experiment Station (WES), tests were conducted on a sand-asphalt mix and on mixes made with two different coarse aggregates and the same fine aggregate used in the sand asphalt. Although the optimum asphalt content varied with the different mixes, all mixes at optimum showed essentially equal performance in resisting the stresses induced by traffic. These tests convincingly showed that the fine aggregate dominates the strength characteristics of dense-graded mixes. Although these tests were made years ago, it is believed that a review of the data is in order.

In the first section, the tires of the vehicles used were inflated to approximately 100 psi; in the second section, the tires were inflated to approximately 200 psi. Because the tests with 100-psi tires are more applicable to highway conditions and because these tests have been reported in detail (1, 2), only the data from the first section are reviewed.

The mixes were made with four aggregates and mineral filler. Gradation curves of the aggregates are shown in Figure 1 and descriptions of the aggregates are given in the following:

1. Crushed coarse aggregate—Crushed limestone from Dolcito Quarry Company, Birmingham, Alabama.
2. Uncrushed coarse aggregate—Washed, subrounded gravel, primarily chert, from St. Catherine Gravel Company, Natchez, Mississippi.
3. Sand—Washed siliceous sand from the St. Catherine Gravel Company, Natchez, Mississippi.
4. Fine sand—Siliceous sand from a Mississippi River bar near Vicksburg, Mississippi.
5. Filler—Commercial limestone dust from Dolcito Quarry Company, Birmingham, Alabama.

These aggregates were used, with 120 penetration asphalt cement, to produce a sand asphalt, an asphaltic concrete with crushed limestone, and an asphaltic concrete with uncrushed gravel. Three filler contents were used in each case; but because the performance was the same, only the mixes with intermediate filler content are used in this discussion. Figure 2 shows average gradation curves for the three mixes.

Figure 3 shows the gradation curves for the fraction passing the No. 10 sieve. Curves for mix 11 and mix 14 were computed from the curves shown in Figure 2 by increasing the percentage passing each sieve by the ratio required to result in 94 percent passing the No. 10 sieve, which was the percentage passing the No. 10 sieve in the sand-asphalt mix.

The tests at WES were designed primarily to develop procedures for designing mixes so that they would be capable of withstanding the stresses induced within the mix. Because asphalt mixes are weakest at high temperatures, the traffic was applied in the summer.

Each of the mixes was placed at a range of asphalt contents and subjected to traffic as described previously. Mixes placed at high asphalt content shoved out from under the path of the traffic and bulged up on the sides, thus providing evidence of plastic deformation, which in turn is lack of adequate strength to resist the stresses induced by traffic. Mixes placed at low asphalt content showed no plastic deformation or lack of strength but tended to ravel under traffic. Mixes at optimum asphalt content showed no plastic deformation or raveling, thus indicating adequate strength to resist the stresses

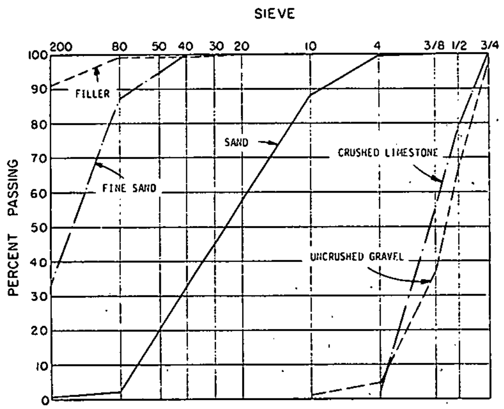

Figure 1.

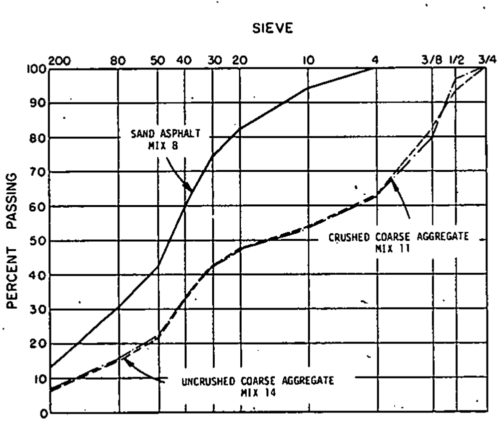

Figure 2.

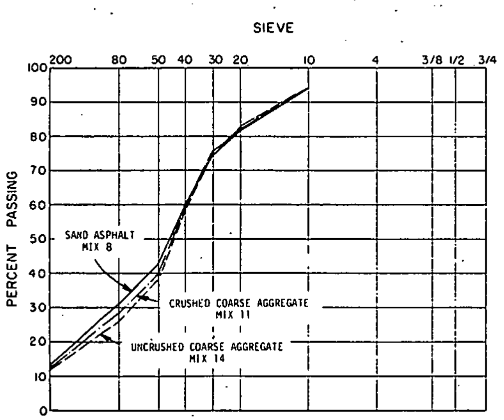

Figure 3.

induced by traffic. The optimum-content mixes that contained coarse aggregate showed no better performance than that of the sand asphalt, and the mix containing crushed coarse aggregate showed no better performance than that of the mix containing uncrushed aggregate. In these tests, the fine aggregate controlled the capacity of the mix to resist the stresses induced within the mix. Observations of the performance of pavements since then support the conclusion that the true capacity of dense-graded mixes to resist traffic-induced stresses is controlled by the characteristics of the fine aggregate.

A feature clearly reported in the WES data, but apparently often overlooked, is that the Marshall stability number did not rate mixes on their capability to withstand stresses induced within the mix. A test section is not needed for this purpose. A simple look at the curve of Marshall stability versus asphalt content shows that it peaks at optimum. This means that the Marshall stability number obtained for a lean mix, which has ample capacity to resist stress, will be the same as that obtained for a rich mix, which will shove out from under the traffic.

An asphalt mix must also be capable of spreading the stresses so that the underlying layer is not overstressed. The WES tests did not include the variables necessary to establish the effect of aggregate type on this feature. The tests did show, however, that asphalt over high-quality base courses need have very few stress-distributing qualities. In addition, there was a trend for higher stability mixes to be better stress distributors, although the effect of stability was not as pronounced as the effect of thickness. Stress-distributing capability is related to the modulus of elasticity at low strains. There have been no controlled traffic tests with the necessary variables to evaluate the effect of aggregate type on stress-distributing capabilities. The author's judgment plus observations of pavements on highways are that a mix with coarse aggregate would normally have stress-distributing capabilities better than those of a fine mix, and a mix with crushed coarse aggregate would have capabilities better than those of a mix with uncrushed aggregates. These differences would not, however, be large.

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Influence of Shape, Size, and Surface Texture on the Stiffness and Fatigue Response of Asphalt Mixtures

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•THE PURPOSE of this paper is to briefly summarize the results of research related to the influence of shape, size (including size distribution), and surface texture of aggregates on the stiffness and fatigue response of asphalt paving mixtures. Because mixture stiffness influences the fatigue behavior of asphaltic concrete, a brief discussion of stiffness is presented first. Data are then given to illustrate the effects of aggregate characteristics on the fatigue response of asphalt paving mixtures.

MIXTURE STIFFNESS

Stiffness as used herein denotes the relationship between stress and strain, both as a function of the time of loading and temperature.

$$S(t,\ T) = \frac{\sigma}{\epsilon} \tag{1}$$

where

$S(t, T)$ = mixture stiffness at a particular time and temperature, psi or kg per sq cm; and

σ, ϵ = axial stress and strain respectively.

This definition corresponds to that suggested originally by Van der Poel (1).

The dependence of stiffness on time of loading is shown in Figure 1. At short loading times, the stiffness approaches a constant value and, in effect, is analogous to a modulus of elasticity. As the time of loading increases, the stiffness decreases. Over the range in times and temperatures encountered in pavements, the stiffness of asphalt mixtures may vary from about 4×10^6 psi (at cold temperatures and short loading times) to about 1×10^3 psi (at high temperatures and long loading times). From a fatigue standpoint, stiffness is important because it will influence the stresses and strains developed in the asphaltic concrete under loading and, as will be seen subsequently, these stresses or strains appear to be the damage determinant for fatigue.

Both the asphalt and aggregate have an influence on mixture stiffness. The harder the asphalt is, the stiffer the mixture will be, particularly at higher temperatures and slower rates of loading (2). In addition, there appears to be an optimum asphalt content for maximum mixture stiffness. This is illustrated by the data shown in Figure 2. At first, stiffness increases as asphalt content increases and then decreases with further increases in the amount of asphalt.

In the case of aggregate, available data indicate that the surface texture of aggregates may have little influence on stiffness, provided that mixtures are compared at their design asphalt contents. This is illustrated by the data given in Table 1 (3). Stiffness measurements (in flexure) are compared for two aggregates, one a rough-textured material and the other a smooth-textured material, with the same gradation. When the stiffnesses of the mixes are compared at the same void content, they are essentially the same.

The data given in Table 1 were obtained for mixtures that had been prepared at their design asphalt contents, which were based on the State of California method of mix

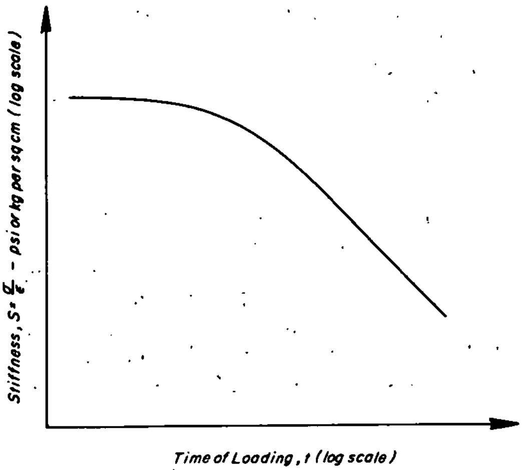

Figure 1. Influence of time of loading on stiffness of an asphalt paving mixture.

design (3). For the rough-textured material, the design asphalt content is considerably higher than it is for the smooth-textured material. Thus texture does not appear to have an effect on stiffness when comparisons are made at the respective design asphalt contents. However, the mix made with the smooth-textured material at the same asphalt content as that for the rough-textured material (in this case 5.9 percent) would be considerably less stiff than the mix made with the rough-textured material. Accordingly, under these circumstances, surface texture would appear to have a significant influence.

The size distribution of the aggregate also appears to have an influence on mixture stiffness; a dense-graded aggregate produces a mixture stiffer

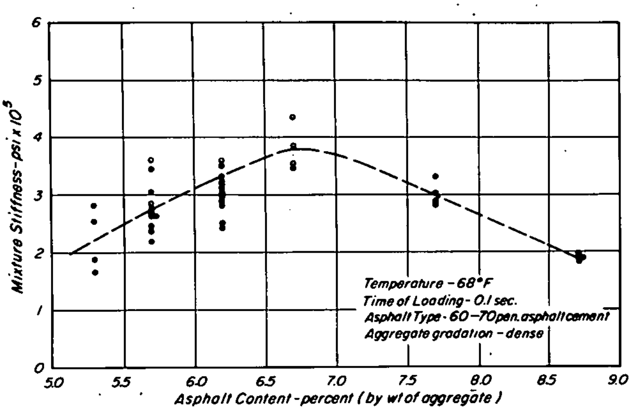

Figure 2. Influence of asphalt content on flexural stiffness of asphalt concrete.

TABLE 1

DYNAMIC STIFFNESS MEASUREMENTS

Aggregate	Asphalt Grade	Percentage Asphalt Content by Aggregate Weight	40 F		75 F	
			Percentage Air Voids	Dynamic Stiffness[a] (psi)	Percentage Air Voids	Dynamic Stiffness[a] (psi)
Watsonville (rough-textured, angular)	85-100	5.9	3.0	65.5×10^4	3.7	10.6×10^4
			3.6	52.6×10^4	4.6	7.7×10^4
			4.5	46.7×10^4	5.1	7.3×10^4
Watsonville (rough-textured, angular)	40-50	5.9	1.8	114×10^4	3.5	24.9×10^4
			3.4	65.9×10^4	3.9	25.9×10^4
			3.5	52.2×10^4	3.9	30.0×10^4
Cache Creek (smooth-textured, rounded)	85-100	4.5	3.6	52.2×10^4	3.2	14.7×10^4
			4.0	47.5×10^4	4.0	14.3×10^4

[a]Dynamic flexural stiffness: time of loading, 0.1 sec; stress, 100 psi.

than that produced by an open-graded material. In general, one can conclude that both texture and size distribution influence mixture stiffness. For a particular hardness of asphalt and asphalt content, mixture stiffness is increased as an aggregate rougher in texture is used and as the aggregate grading is changed from open to dense.

FATIGUE RESPONSE

To indicate the influence of aggregate characteristics on the fatigue behavior of asphalt mixtures requires a consideration of the methods used for determining fatigue response. In addition, because certain conflicting conclusions might be drawn with respect to desirable mixture characteristics, the method for determining fatigue response in the laboratory must be related to the performance of the mix under load on the pavement structure. Accordingly, in this section, a brief discussion of mode of laboratory loading for fatigue testing and the applicability of the various modes of loading to field response will be presented so that the available data on mixture response may be viewed within a reasonable framework.

Mode of Loading

Mode of loading is used to describe how stress and strain levels are permitted to vary during fatigue loading. If the nominal stress or load is maintained at a constant level throughout the life of the specimen, testing is of the controlled-stress or controlled-load mode. If the nominal strain or deflection is maintained at a constant level, testing is of the controlled-strain or controlled-deflection mode. Both modes of loading are shown schematically in Figure 3. By performing tests in either mode

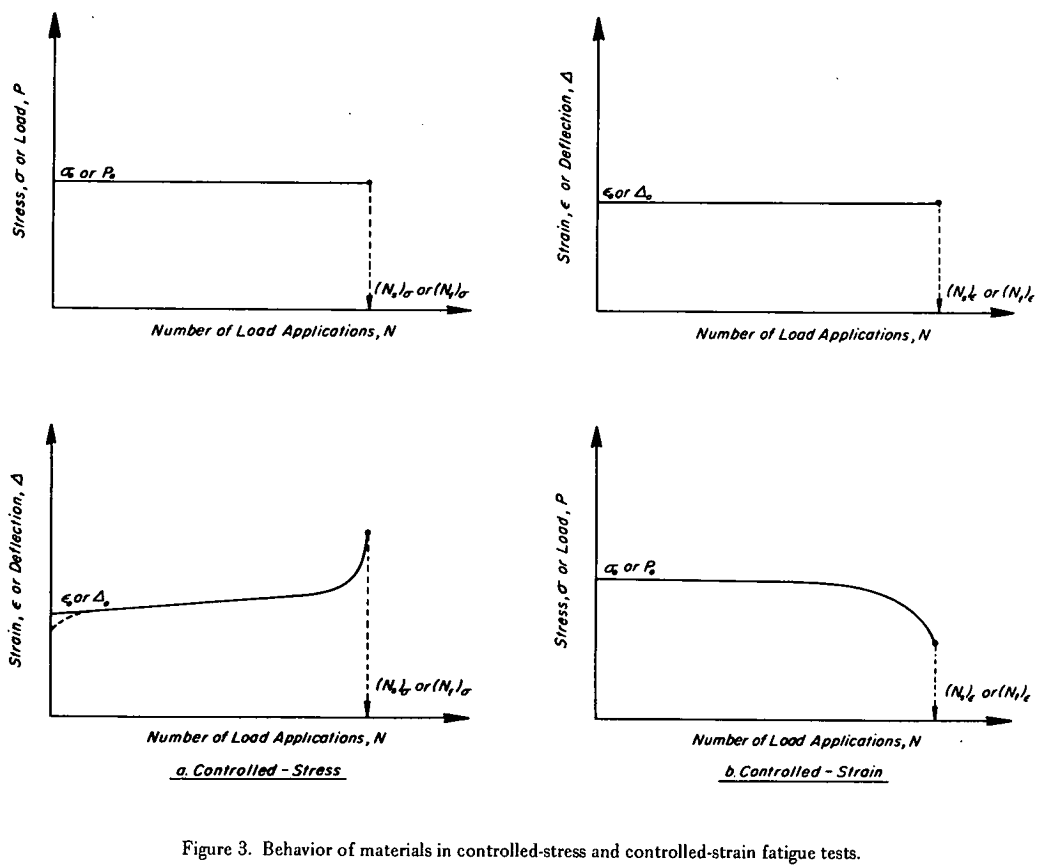

Figure 3. Behavior of materials in controlled-stress and controlled-strain fatigue tests.

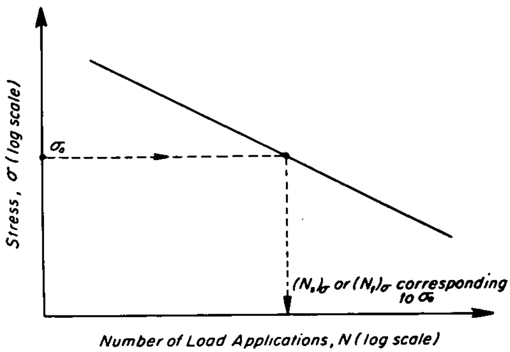

Figure 4. Stress versus load applications in controlled-stress tests.

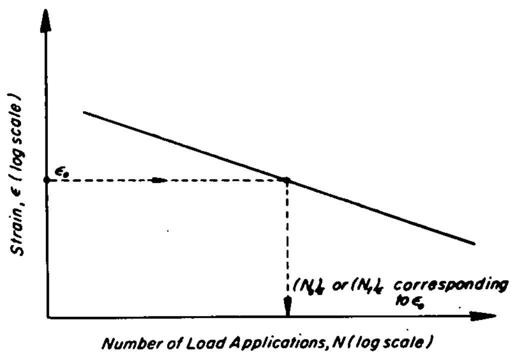

Figure 5. Strain versus load applications in controlled-strain tests.

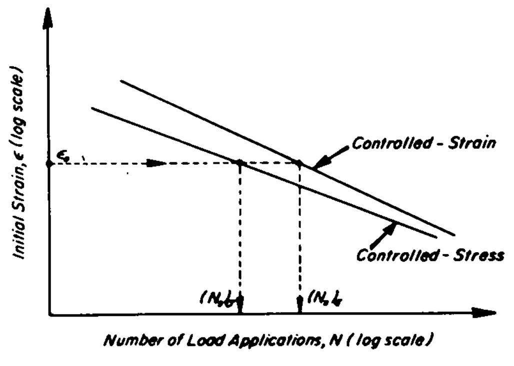

Figure 6. Initial strain versus load applications in controlled-stress and controlled-strain tests.

of loading at different stress or strain levels, one may obtain fatigue diagrams such as those shown in Figures 4, 5, and 6.

Interpretation of the results of these tests may lead to some conflicting conclusions. For example, in controlled-strain tests, mixture stiffness, for a particular combination of asphalt and aggregate, appears to influence the strain versus cycles-to-failure relationship in that the stiffer the mix, the shorter the fatigue life at a particular strain level. On the other hand, in controlled-stress tests, the higher the stiffness, the longer is the fatigue life at a particular stress level (3).

These tests merely represent limits of a range in possible modes of loading. In actuality, neither of the tests may be strictly applicable to define the performance of an asphalt mixture as it exists in the field. One may, however, choose one of the methods for a particular situation as a practical expedient until such time as a better definition of the problem can be obtained. Some guides for selection are presented in the following section.

Applicability of Various Types of Fatigue Tests

An indication of the applicability of the various fatigue tests was obtained by performing an analysis of a series of three-layer elastic systems in which the thickness and stiffness of the asphaltic concrete layer were varied to assess the influence of these variables on the computed stresses and strains on the asphaltic concrete layer (3). Because results of fatigue tests are usually presented in terms of stress or strain, the analysis should thus assist in determining the applicability of a specific mode of loading.

In these analyses, the structural section consisted of a layer of asphaltic concrete varying in thickness from 1 to 9 in. and an untreated base varying from 25 to 17 in. In all analyses, the total thickness was maintained at 26 in. Results of the analyses are shown in Figures 7 and 8, which also show the modular values for the various components of the structural sections.

Figure 7 shows that, regardless of the stiffness of the asphaltic concrete (for the range in moduli investigated), the tensile strains on the underside of the asphaltic

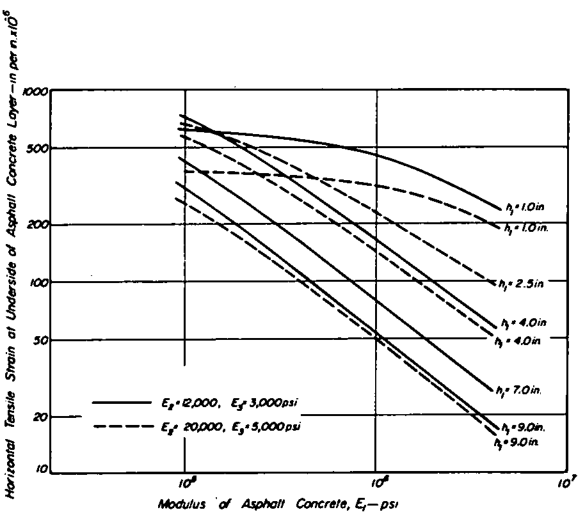

Figure 7. Influence of stiffness of asphaltic concrete, layer thickness, and modulus of base and subgrade on tensile strain on the underside of the asphaltic concrete layer (thick pavement section).

concrete of the 1-in. thick surfacing are essentially constant. On the other hand, for the thicker asphaltic concrete layers, the tensile strain is reduced markedly as the stiffness of the asphaltic concrete is increased. This would imply that for thin surface layers, regardless of the stiffness of the asphaltic concrete, its performance is governed primarily by the underlying materials. In thicker layers, however, the asphaltic concrete will begin to contribute more to the behavior of the section and exert more influence on the strains to which it is subjected. Thus it would appear that controlled-strain tests would be useful to define the performance of mixtures used in comparatively thin layers of asphaltic concrete, layers approximately 2 in. or less in thickness.

Figure 8 shows that, for thin layers of asphaltic concrete, the tensile stress at the underside of the layer changes quite markedly with change in layer stiffness. As the thickness of the layer increases, however, the change in stress with layer stiffness is less marked, e.g., approximately a factor of 2 for the 9-in. thick layer with a change in stiffness by a factor of 40. Because the change in strain is much larger than this, by at least a factor of 10, it appears that a test reflecting mixture stiffness advantageously would be more appropriate to represent the fatigue behavior of asphaltic concrete. For these conditions, it can be inferred that the controlled stress would thus be more representative.

Because a true controlled-stress condition may never be reached in practice (4), it is difficult to precisely define a minimum pavement thickness for which the results of controlled-stress tests would seem appropriate. It is suggested, however, that a 6-in. thick layer of asphaltic concrete be considered, at least at this time (1968), as the lower limit. Although the two types of fatigue tests, noted in the preceding, give an indication of desirable mixture characteristics, recent information (5) suggests that controlled-stress tests will provide a conservative estimate of fatigue response for any mixture regardless of the thickness of the asphaltic concrete.

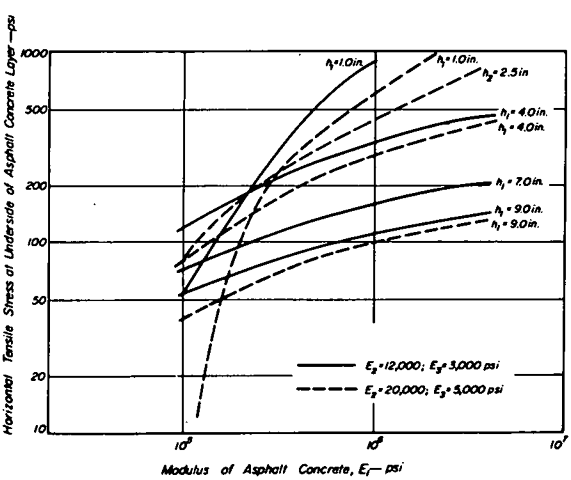

Figure 8. Influence of stiffness of asphaltic concrete, layer thickness, and modulus of base and subgrade on tensile stress on the underside of the asphaltic concrete layer (thick pavement section).

Controlled-Stress Tests

The infleunce of aggregate surface texture on fatigue resistance is shown in Figure 9 (6). As long as there is sufficient asphalt in the mixture for the particular aggregate, rough-textured materials tend to perform better than smooth-textured materials for identical asphalt contents. This effect is probably caused in part by increased stiffness associated with the rough-textured materials.

Comparisons made of fatigue response at constant stiffness, as noted before, would show in all probability that the mixture containing rough-textured material has an asphalt content higher than that of the mixture containing the smooth-textured material. Under these circumstances, the mixture containing the rough-textured aggregate would show a longer fatigue life because the strain in the asphalt (7), defined as

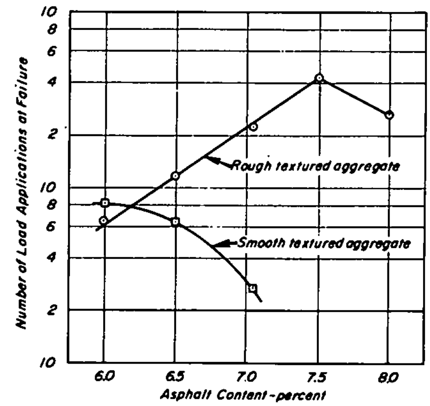

Figure 9. Asphalt content versus number of load applications at failure for two aggregate types.

$$\epsilon_B = \frac{\epsilon}{B_V} \tag{2}$$

where ϵ_B = asphalt strain, ϵ = mixture strain, and B_V = volume concentration of asphalt, would be less than that in the mix containing the smooth aggregate.

Limited data are also available concerning the influence of aggregate gradation on fatigue response. Figures 10 and 11 show data obtained from tests on two mixtures: one containing a dense-graded aggregate and the other an open-graded material (3). For comparable asphalt contents, longer service lives are exhibited by the dense-graded mixtures than by the open-graded mixtures. This is caused in part by the increased stiffness associated with the dense-graded mixture and in part by its lower void content.

The influence of fines content (percentage passing the No. 200 sieve) is illustrated by data presented by Pell (7). His data, shown in Figure 12 for a mix in which the asphalt content was maintained constant at 6 percent but the mineral filler was varied from 0 to 17 percent passing the No. 200 sieve, illustrate that as the fines content is increased the fatigue life at a particular stress level is improved. However, with further increase in filler content beyond a certain level (in this mix, 9 percent), the fatigue life was again reduced, probably because of insufficient asphalt for the amount of fines present.

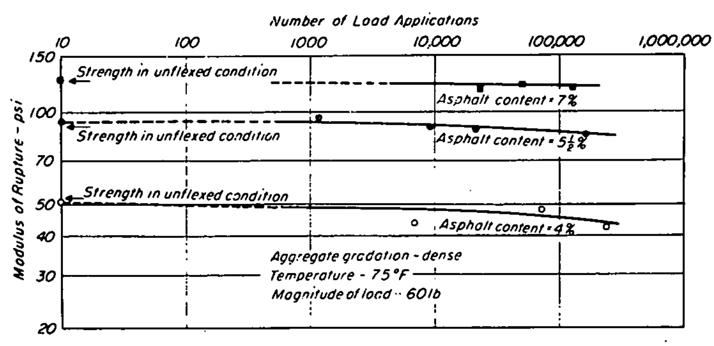

Figure 10. Effect of asphalt content on the behavior of dense-graded mixtures subjected to repeated load applications.

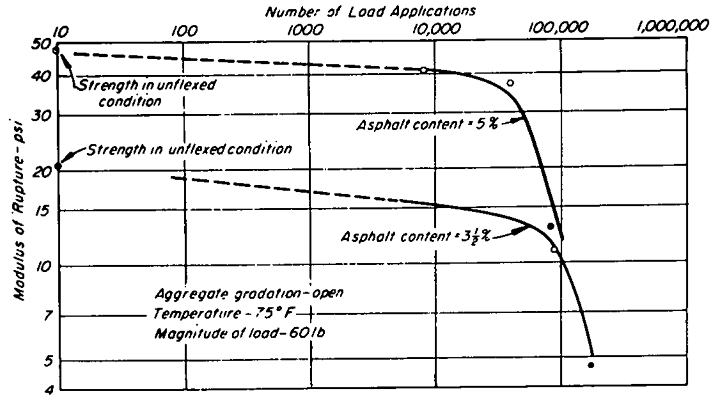

Figure 11. Effect of asphalt content on the behavior of open-graded mixtures subjected to repeated load applications.

Controlled-Strain Tests

Limited data concerning the influence of aggregate type in fatigue behavior in controlled-strain tests are shown in Figure 13 (3). The Watsonville material is a rough-textured granite, whereas the Cache Creek material is a smooth, rounded gravel (Table 1). Both types of aggregate, however, have the same gradation, and both mixtures were designed according to the State of California mix design procedure. The asphalt content was 5.9 percent for the mixture containing the granite and 4.5 percent for the mixture with the gravel. Because both mixtures had essentially the same stiffness characteristics (Table 1), stiffness cannot be used to explain the difference in response as shown in Figure 13.

In this instance, the difference is no doubt caused by the increased asphalt content associated with the Watsonville material, which in turn resulted in a reduced strain in the asphalt (Eq. 2). It is interesting to conjecture, however, that, had both mixtures been tested at the 5.9 percent asphalt content, in all probability the mixture containing the rounded material would have produced superior performance because of its reduced stiffness as compared with the granite. Although no published data are available, it appears that more open-graded aggregates (less than 3 percent passing the No. 200 sieve) tend to perform better in controlled-strain tests than more densely graded materials, provided that comparisons are made at comparable asphalt contents. Such differences can be explained by differences in mixture stiffness, with less stiff mixtures produced by the more open-graded materials than by those that were dense-graded.

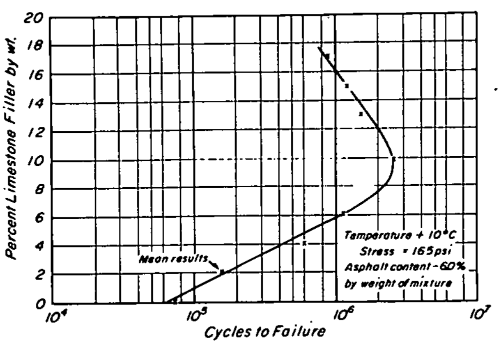

Figure 12. Influence of filler content on fatigue response of asphaltic concrete.

SUMMARY

The data presented in this paper indicate that aggregate characteristics affect both stiffness and the fatigue response of asphalt paving mixtures. In addition, it has been demonstrated that stiffness and fatigue response are interrelated.

For thick pavement sections, it appears desirable to utilize rough-textured materials with dense gradations and to produce well-compacted mixtures because all of these factors tend to increase mixture stiffness. On the other hand, in thin pavement sections, it appears that more open-

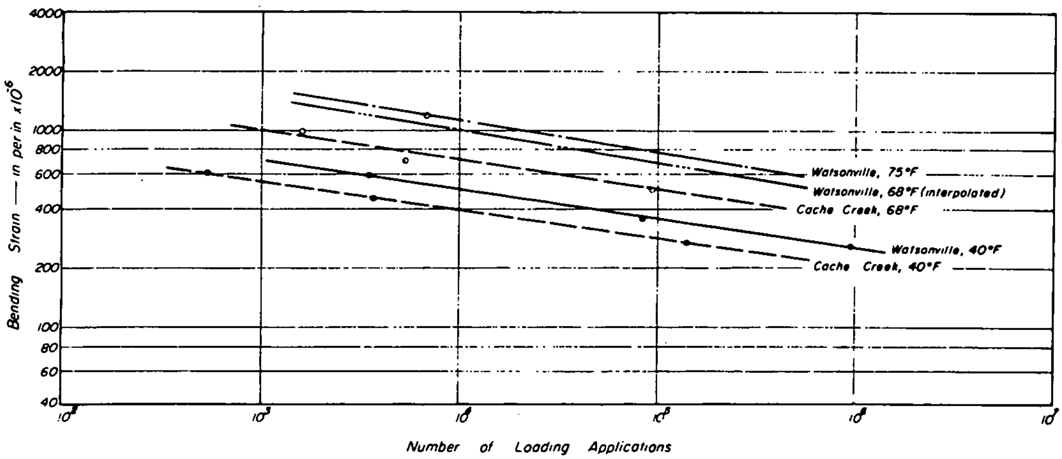

Figure 13. Comparison of controlled-strain amplitude fatigue test results for specimens containing Watsonville granite and Cache Creek gravel.

graded aggregates should be utilized because flexibility is increased somewhat with reduction in fines content (minus No. 200 material). In thin sections, the effect of surface texture is not so apparent because of conflicting demands for load-carrying ability (stability). At comparable asphalt contents, mixtures produced with smooth-textured materials may be more desirable because they produce less stiff mixtures. However, if stability is not adequate for the loading conditions, then the rough-textured material appears more desirable.

The results discussed here provide some indication for the design of thicker sections of asphaltic concrete, that is, sections containing asphaltic concrete bases. The resistance of such sections to repetitive loading (fatigue) will be improved, it appears, by using as much asphalt as possible rather than by producing mixtures that tend to be lean as is current practice in some areas. Figure 2 shows, for example, that the increased asphalt content results in increased mixture stiffness (up to a point beyond that required for optimum stability), which in turn results in improved performance.

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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 $(y - 7)^2 = (b^2/a^2)(2ax - x^2)$ 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 $^3/_4$ 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.
>
> 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.
>
> 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.
>
> 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.
>
> * * * * * * * *
>
> 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.
>
> 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 $^5/_8$ 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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Effects of Aggregate Size, Shape, and Surface Texture on the Durability of Bituminous Mixtures

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•VIRGINIA has been using bituminous mixtures as its major construction and maintenance material for more than 30 years, having started with liquefier-type "cold" mixes. The varying terrain ranging from the Atlantic coastal plain through the Piedmont area to the Appalachian Mountains offers quite a variety of aggregates including sand, gravel, granite, trap rock, dolomite, and limestone. In the interest of economy, every effort has been made to use locally available aggregates in bituminous mixes. With the emphasis on skid resistance during the past 10 to 12 years, it has been necessary to import aggregates for the wearing course in some areas of the state, but the thickness of these courses has been held to the practical minimum.

This discussion of the effect of aggregate size, shape, and surface texture on the durability of bituminous mixtures is based on a review of the maintenance records of the Virginia Department of Highways. For design and estimating purposes, we usually use an average life of 10 years for surfaces of bituminous pavements, realizing, of course, that many factors influence the life span of any specific treatment. In the western area of the state where limestone is prevalent, many pavements exceed 10 years in service. However, it has been necessary to place on major routes a safe, skid-resistant wearing surface incorporating silica sand, slag screenings, or similar nonpolishing aggregate after from 2 to 5 years. Now the design provides for a nonskid wearing surface as a part of the original application.

These skid-resistant surfaces are laid down in thin applications of approximately 30 lb per sq yd, and they frequently have to be replaced in 3 to 6 years depending on the volume of heavy truck traffic. We believe, however, that, other factors being equal, the coarse aggregate mix, 1 in. down, will wear longer than the sand or fine-aggregate mix. Aggregate mixes do not tend to wear away as rapidly as the fine mixes, particularly silica sand. The sand treatment will, in the process of wearing, continually present a sharp angular particle face for tire contact.

The durability of these sand mixes can vary greatly, depending on the aggregate source. For example, one bituminous concrete producer has a plant located adjacent to a sand and gravel supplier from whom he obtains crushed sand produced as the supplier crushes gravel. This crushed sand was used on US-1 in a sand-asphalt mixture that did not require resurfacing for 13 years, whereas similar mixes from other suppliers under similar traffic conditions required resurfacing from 3 to 7 years. This sand showed equally good performance in other places where it was used. Isolated local sand deposits produce mixes that give comparable performance, but these are the exception rather than the rule.

In localities where nonpolishing coarse aggregate is economically available, bituminous concrete surface mixtures are now used with a maximum-size coarse aggregate of either ¾ or ⅜ in. The local sand mixes may allow aggregates up to ⅜ in. top size; however, most of the mixes are manufactured from aggregates with 75 to 100 percent passing the No. 4 screen. The deslicking mix, which is applied at approximately 30 lb per sq yd, has from 95 to 100 percent passing the No. 8 screen and may have as much as 95 percent passing the No. 30 screen.

It seems, therefore, that the local sand mixes wear away the fastest, but they always provide a skid-resistant surface. The "weardown" in some cases is sufficient for the driver to notice an elevation difference immediately adjacent to the pavement marking. The very fine deslicking mixes wear down less rapidly than do the local sand mixes, and the coarse aggregate mixes give the greatest length of service. These are general statements, however. The durability of any particular bituminous mixture is dependent on many factors, such as characteristics of the aggregate, mix design, plant procedures, application procedures, temperature and atmospheric conditions, and traffic types and volumes. Chances of securing a long-wearing pavement are greatly enhanced if the best aggregate available is used.

In addition to durability, economic factors must also be considered, and durability may be sacrificed for economy. For example, two applications of a cheap mixture may cost less and last longer than one application of an expensive mix. This was the consideration for the eastern shore of Virginia where there is an abundance of sand, but where it is impossible to secure mixes with adequate stability in accordance with normal standards. Even when used in limited proportions, 25 percent or less, the sand caused troubles with control and subsequent pavement failures. A review of traffic weights and volumes on secondary roads led the Virginia Highway Research Council to consider a design for this type of service. Utilizing this local material with a small amount of mineral filler and strict controls on asphalt content, the Council produced a bituminous mixture that costs 25 percent less than mixtures manufactured from commercial materials and provides comparable service on all but major routes. Certainly, in this case, particle shape has a great effect on service and durability, but durability can be related to traffic types and volumes. It is not enough to be limited to standard mixes, that is unless there are unlimited funds, and certainly operational people are not in this position.

In closing, it is appropriate to acknowledge the value of research to the operating divisions of the Virginia Department of Highways. The Virginia Highway Research Council developed the deslicking mixes and pioneered in the use of local materials and local sands for particular applications. It has currently recommended that changes be made in gradation of base mixtures to provide greater durability and is developing statistical specifications that the Department hopes to adopt shortly.

Effects of Size, Surface Texture, and Shape of Aggregate Particles on the Properties of Bituminous Mixtures

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•THE THREE basic strength properties of bituminous concrete consist of the cohesive strength of the bituminous material, the frictional resistance between the aggregate particles, and the interlocking resistance that is introduced in the compacted structure of the aggregate combination. Two of the basic strength properties, not including cohesive strength, are profoundly affected by the size, surface texture, and shape of the aggregate particles that are used in the bituminous mixture. The following brief commentary relates the effects of size, surface texture, and shape of aggregate particles to the properties of bituminous mixtures.

SIZE OF PARTICLES

The term "size of particles" must be qualified for a discussion of the effects of particle size on the properties of bituminous mixtures. Bituminous mixtures are actually affected by the maximum size of particles, minimum size of particles, and the gradation of the particle sizes within the size limits. Therefore, particle size must be discussed in terms of size limits as well as in terms of the gradation of the various sizes included in the bituminous mixture. Particle size discussed in terms of gradation and gradation limits affects the amount of asphalt required for the mix, workability, density, stability, and the performance characteristics of the pavement. A large percentage of coarse particles will produce a harsh mix that complicates laydown or construction operations. Aggregate combinations that are poorly graded (skip-graded) have a high voids ratio, require a large percentage of asphalt, and normally produce low stability mixes. Fine-grained mixes are workable, but they lack the stability that is developed in a well-graded aggregate combination. The large surface area of particles that is present in fine-grained mixes may present a problem of selective absorption of the asphalt. This condition may lead to early hardening or aging of the pavement.

SURFACE TEXTURE

The frictional resistance that is developed between aggregate particles depends on the surface texture of the particles. Therefore, surface texture has a profound effect on the stability of the bituminous mixture. This property of the aggregate is reflected in the angle of internal friction. Laboratory tests conducted by the author indicate that frictional resistance is responsible for about 50 percent of the shearing resistance that is developed in a dense-graded bituminous mixture. Bituminous mixes containing friction-textured aggregates reflect a significant decrease in workability and an increase in stability.

SHAPE OF PARTICLES

The shape of the aggregate particles affects the interlocking resistance that is developed in the bituminous mixture. However, the aggregate particles must be well graded in order to develop a keying action between individual particles. Laboratory tests conducted by the author indicate that about 25 percent of the shearing resistance in a dense-graded mix is developed in the form of interlocking resistance. The shape of the aggregate particles may also affect voids and workability.

SUMMARY

The two basic strength properties that reflect significant effects of the size, surface texture, and shape of aggregate particles are frictional resistance and interlocking resistance. These two basic strength properties hold promise for the development of additional shearing resistance (or stability). The effects of size, surface texture, and shape of aggregate particles are not reflected in the cohesive strength of a bituminous mixture. It is the author's opinion that the inherent material properties of asphaltic binders preclude the development of major increases in shearing resistance in the form of cohesion. In fact, the strength component developed in the form of cohesion is subject to deterioration or a strength loss because of aging and the thermoplastic properties of the asphalt binder.

Research on Bituminous Concrete Properties With Large-Sized Aggregates of Different Particle Shape

I. V. KALCHEFF, National Crushed Stone Association

•A REVIEW of the literature reveals that, with the exception of some surface courses where the maximum size of the aggregate has been limited to about ½ in., the merits of different aggregates in bituminous mixtures have not been thoroughly explored. The technical literature contains little information relative to properties of hot-mixed asphaltic concrete with larger sizes of aggregates, and no single criterion has been established for such mixtures.

The National Crushed Stone Association (NCSA) staff undertook the task of developing a method of test by which mixtures with large-sized aggregates could be evaluated. This research is an attempt to demonstrate the merits of some aggregates with respect to others and assist the engineers and interested agencies in selecting the best-suited materials and developing the most economical designs.

The first step in this program was to adopt a procedure for preparation of specimens of uniform composition and such a size that could be conveniently handled yet accommodate at least a 1½-in. maximum-sized aggregate. Following this, two typical commercial aggregates, a crushed limestone and a washed gravel, were used in the preparation of specimens at three gradations having nominal sizes of ½, 1, and 1½ in. Each gradation of each material was then tested triaxially at several confining pressures and at two different temperatures. The 1-in. stone mix was also tested at different asphalt contents, and tests are under way to evaluate the effect of the asphalt variability for the remaining mixtures. The results, as available up to now, support the hypothesis that angular aggregates are preferable.

TEST PROCEDURE

For the purpose of studying the effects of different variables on the physical properties of bituminous mixtures, the triaxial method of test used by the Texas Highway Department (1) for soil-aggregate combinations, as well as for dense-graded aggregates, was adopted with some modification. The basic change was close control of temperature during mixing, compaction, and testing.

After considerable experimentation, a combination of drop-hammer compaction and mechanical vibration was selected. The procedure chosen produced densities and void contents similar to the Marshall method as compared with the ½-in. mix. All specimens in this investigation were fabricated in an identical manner, and the method of investigation is described in the following.

Specimens were prepared in 6-in. diameter, split cylindrical molds and compacted in four 2-in. lifts. Seventy-five blows from a 10-lb circular face mechanical hammer, through a free-fall drop of 18 in., were used per lift. The 8-in. specimen, while still in the mold, was placed in the oven to regain any lost heat and then vibrated for 1 minute under a surcharge of 85 lb using a vibrating table (2).

After extraction from the mold, the specimens were measured for density using ASTM Designation D 1075 and were prepared for triaxial compression evaluation at the desired temperature. The triaxial testing was performed using a constant rate of deformation (0.15 in./min). The load was recorded manually at increments of 0.01 in. deformation, and the stress-strain curves were established. Each specimen was tested at a constant, but different, lateral pressure. Lateral pressures of 0, 5, 10, 15, and 20 psi were normally employed.

MATERIALS

The materials used in this investigation were supplied from commercial sources. The crushed stone was from a commercial limestone deposit and had a bulk specific gravity of 2.72 and Los Angeles abrasion loss of 19 percent. The crushed stone screenings were processed to achieve a relatively good particle shape with a void content of 52 percent (3).

The washed siliceous gravel was from a typical natural deposit. It had about 1½ to 2 percent heavy ferruginous impurities. These were very carefully removed from the specific gravity samples, but some were included with the material from which specimens were prepared and may have influenced the air-void computations somewhat. The clean siliceous gravel had a specific gravity of 2.63 and Los Angeles abrasion loss of 37 percent. This gravel was not processed by crushing, yet it contained a large number of subangular or chipped pieces and could be described as follows:

Sieve Sizes (in.)	Percent Rounded Particles	Percent Fractured Particles	
		One Face	Two or More Faces
1½ to 1 in.	16	15	69
1 to ¾ in.	12	23	65
¾ to ½ in.	21	31	48
½ to ⅜ in.	25	30	45

The fine natural aggregate was a river siliceous sand with well-rounded particles, 48.5 percent voids (3), and specific gravity of 2.60. None of the minus-100 mesh from this material was used, but rather a limestone filler with 80 percent passing the 200 mesh was substituted. The asphalt cement was supplied by the American Oil Company and was of 85-100 pen. paving grade. The Saybolt Furol viscosity of this asphalt was quoted by the manufacturer as being 156 sec at 275 F, and 71 sec at 310 F.

PROPORTIONING AND AGGREGATE COMBINATIONS

The proportioning of the aggregates was based on the midgrading of ASTM Specification D 1663 for hot-mixed, hot-laid asphaltic concrete. For closer control over uniformity in specimen preparation, each was weighed cumulatively from sized materials in accordance with the distribution given in Table 1. Selection of the asphalt requirement was based on the U.S. Army Corps of Engineers void criteria (4, p. 17), using the Rice method of maximum specific gravity (5), because the commonly used Marshall design (6) does not apply to

TABLE 1
AGGREGATE COMPOSITION OF ASPHALTIC PAVING MIXTURES

Gradation[a]	Mix B	Mix C	Mix E
Sieve size			
1½ in.	100		
1 in.	80[b]	100	
¾ in.	70	85[b]	100
½ in.	61[b]	70	95
⅜ in.	54[b]	62[b]	85[b]
No. 4	38	42	58
No. 8	25	30	40
No. 16	19[b]	23[b]	30[b]
No. 30	14[b]	16[b]	20[b]
No. 50	9	10	12
No. 100	4[b]	5[b]	7[b]
No. 200	3	4	5.5

[a]The materials were combined to the midpoint of ASTM Specification D 1663.
[b]The marked figures were obtained through extrapolation.

TABLE 2
SUMMARY OF TRIAXIAL TEST RESULTS FOR CRUSHED STONE MIX C AT DIFFERENT ASPHALT CONTENTS TESTED AT 140 F

Category	Percent Asphalt		
	4.0	4.4	4.8
Properties of compacted specimens			
Bulk specific gravity	2.427	2.449	2.466
Unit weight, pcf	151.1	152.4	153.5
Air voids, percent	5.0	3.6	2.4
VMA, percent	14.2	13.8	13.5
Voids filled, percent	65.0	73.0	83.0
Maximum normal strength[a], psi, at lateral pressure of			
0 psi	90.0	82.0	97.0
5 psi	135.0	127.0	–
10 psi	180.0	167.0	160.0
15 psi	222.0	–	200.0
20 psi	240.0	247.0	265.0
Deformation, percent strain, at maximum normal strength, lateral pressure of			
0 psi	1.1	0.7	1.1
5 psi	1.4	1.4	–
10 psi	1.8	1.7	2.0
15 psi	1.9	–	2.2
20 psi	2.1	2.4	2.6

[a]Triaxial strength tests (deformation of 0.15 in./min).

TABLE 3

SUMMARY OF TRIAXIAL TEST RESULTS WITH DIFFERENT AGGREGATES IN MIX C ASPHALTIC CONCRETES TESTED AT 140 F

Category	Materials Combination			
	Stone[a] Stone[b]	Stone[a] River Sand[b]	Gravel[a] Stone[b]	Gravel[a] River Sand[b]
Properties of compacted specimens				
Asphalt, percent	4.4	4.2	4.2	4.0
Bulk specific gravity	2.449	2.426	2.432	2.403
Unit weight, pcf	152.4	151.0	151.4	149.6
Air voids, percent	3.6	4.6	2.5	3.0
VMA, percent	13.8	13.2	12.3	11.7
Voids filled, percent	73.0	65.0	80.0	74.0
Maximum normal strength[c], psi, at lateral pressure of				
0 psi	82.0	62.0	50.0	35.0
5 psi	127.0	104.0	97.0	72.0
10 psi	167.0	145.0	130.0	102.0
15 psi	–	197.0	–	140.0
20 psi	247.0	–	202.0	167.0
Deformation, percent strain, at maximum normal strength, lateral pressure of				
0 psi	0.7	0.9	0.9	0.7
5 psi	1.4	1.1	1.2	1.0
10 psi	1.7	1.1	1.1	1.2
15 psi	–	1.7	–	1.5
20 psi	2.4	–	1.8	1.7

[a]Coarse aggregate (+No. 8).
[b]Fine aggregate (–No. 8).
[c]Triaxial strength tests (deformation of 0.15 in./min).

mixtures with large-sized aggregate. A limited correlation for the ½-in. mix indicated that the selected method of specimen preparation yielded slightly greater densities than the 50-blow Marshall method.

Expectations regarding the new design procedure were rewarded. This first series of testing has been most encouraging, and it is hoped that this new method for bituminous concrete design will find wide acceptance because it is applicable to mixtures having maximum aggregate sizes up to and including 1½ in.

TEST RESULTS AND DISCUSSION

The triaxial strength results were fairly reproducible, although individual test results might vary at times by more than 5 percent because of the large-sized aggregate and the many problems associated with the preparation of a homogeneous specimen. The effect of asphalt variability on mix properties can be observed from a series of triaxial test results (Table 2). As might be expected, the air voids of the mix were affected. Surprisingly, however, the strength tests were not significantly different. A mixture with a 1-in. nominal-sized crushed stone did not lose its stability with void contents less than 3 percent.

Another series of tests (Table 3) sheds some light on the controversial subject of angularity versus strength. For this purpose, mixtures with all stone, stone coarse aggregate with river sand fines, gravel coarse aggregate with stone fines, and gravel coarse aggregate with river sand fines were compared. The gradations in all cases were identical to Mix C (1 in. top size) as given in Table 1. The resulting strengths shown in Figure 1 clearly demonstrate that the crushed stone contributes to the strength of a bituminous concrete when used in the coarse or fine portion of the mix. The best combination undoubtedly is the mix having all crushed particles. The data also indicate that the angularity in the particles of the coarse aggregate (material retained on the No. 8 screen) is more effective than the angularity of the particles of the fine aggregate. This is in slight disagreement with the work of Herrin and Goetz (7), who used double-plunger static compaction on the specimens having a gradation of ½ in. nominal size. The mix investigated by NCSA was of the 1-in. nominal size that had 70 percent coarse aggregate.

A complete series of tests on the effects of aggregate particle size is given in Tables 4 and 5 and shown in Figure 2, where at least

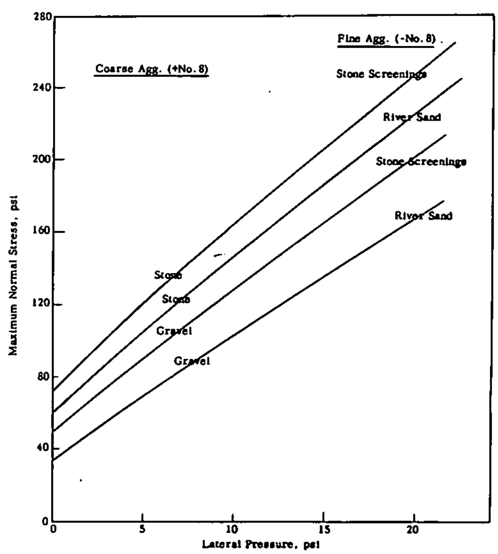

Figure 1. Effect of aggregate particle shape on triaxial compressive strength of asphaltic concrete (1 in. maximum-sized aggregate tested at 140 F).

TABLE 4

SUMMARY OF TRIAXIAL TEST RESULTS FOR STONE AND GRAVEL ASPHALTIC CONCRETE MIXTURES TESTED AT 140 F

Category	Stone			Gravel		
	Mix B	Mix C	Mix E	Mix B	Mix C	Mix E
Properties of compacted specimens						
Asphalt, percent	3.9	4.0	5.2	3.8	4.0	5.0
Bulk specific gravity	2.430	2.427	2.420	2:392	2.403	2.378
Unit weight, pcf	151.3	151.1	150.6	148.9	149.6	148.0
Air voids, percent	4.9	5.0	3.4	3.8	3.0	2.8
VMA, percent	14.0	14.2	15.5	11.9	11.7	13.4
Voids filled, percent	65.0	65.0	79.0	68.0	74.0	79.0
Maximum normal strength[a], psi, at lateral pressure of						
0 psi	80.0	90.0	92.0	35.0	35.0	30.0
5 psi	125.0	135.0	142.0	67.0	72.0	60.0
10 psi	173.0	180.0	174.0	98.0	102.0	94.0
15 psi	215.0	222.0	226.0	134.0	140.0	130.0
20 psi	248.0	240.0	256.0	165.0	167.0	150.0
Deformation, percent strain, at maximum normal strength, lateral pressure of						
0 psi	1.1	1.1	1.1	0.8	0.7	0.8
5 psi	1.3	1.4	1.2	1.2	1.0	1.1
10 psi	2.3	1.8	1.9	1.3	1.2	1.6
15 psi	2.2	1.9	2.4	1.4	1.5	1.7
20 psi	2.3	2.1	2.3	1.6	1.7	2.0

[a]Triaxial strength tests (deformation of 0.15 in./min).

TABLE 5

SUMMARY OF TRIAXIAL TEST RESULTS FOR STONE AND GRAVEL ASPHALTIC CONCRETE MIXTURES TESTED AT 72 F

Category	Stone			Gravel		
	Mix B	Mix C	Mix E	Mix B	Mix C	Mix E
Properties of compacted specimens						
Asphalt, percent	4.2	4.2	5.2	3.8	3.8	5.0
Bulk specific gravity	2.443	2.442	2.429	2.401	2.386	2.372
Unit weight, pcf	152.0	152.0	151.1	149.4	148.5	147.6
Air voids, percent	4.0	4.2	3.0	3.0	3.7	2.9
VMA, percent	13.8	13.8	15.5	11.6	12.1	13.6
Voids filled, percent	71.0	70.0	81.0	74.0	70.0	78.0
Maximum normal strength[a], psi, at lateral pressure of						
0 psi	250.0	270.0	290.0	251.0	245.0	210.0
5 psi	260.0	312.0	302.0	262.0	248.0	226.0
10 psi	270.0	298.0	336.0	280.0	255.0	250.0
15 psi	305.0	327.0	356.0	305.0	295.0	270.0
20 psi	365.0	344.0	386.0	307.0	305.0	286.0
Deformation, percent strain, at maximum normal strength, lateral pressure of						
0 psi	1.1	1.2	1.3	1.1	0.9	1.3
5 psi	1.6	1.1	1.4	0.9	1.0	1.5
10 psi	1.2	1.3	1.4	1.1	1.0	1.5
15 psi	1.6	1.2	1.8	1.3	1.0	1.8
20 psi	1.3	1.7	2.3	1.3	1.0	1.9

[a]Triaxial strength tests (deformation of 0.15 in./min).

TABLE 6

TRIAXIAL STRENGTH RATIO OF STONE TO GRAVEL MIXES, PERCENT

Lateral Pressure (psi)	Test Temperature 140 F			Test Temperature 72 F		
	Mix B	Mix C	Mix E	Mix B	Mix C	Mix E
0	228	257	307	100	110	138
5	186	188	237	99	126	134
10	176	176	185	96	117	134
15	160	159	174	100	111	132
20	150	144	171	119	113	135

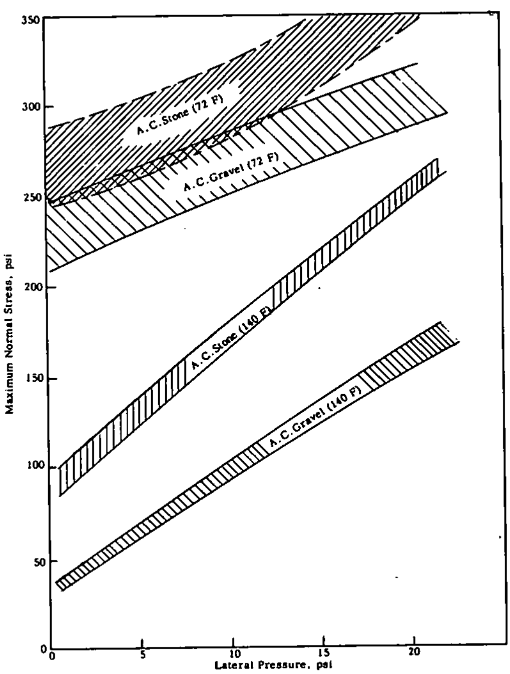

Figure 2. Triaxial compressive strength of asphaltic concrete crushed stone, gravel, and river sand.

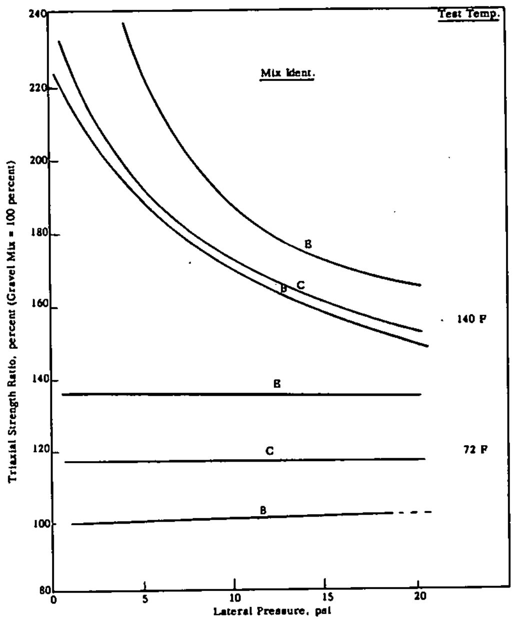

Figure 3. Triaxial strength comparison of asphaltic concrete with crushed stone and gravel.

half of the mixes were repeated. A general conclusion from these tests is that no appreciable contribution to the strength is made by increasing the maximum size of the aggregate, but, looked at from another point of view, it may be said that, as the maximum size is increased, equally strong mixes can be developed using somewhat less asphalt.

A comparison of the strengths of the stone and gravel mixes is given in Table 6 and shown in Figure 3. The tests at 140 F show that the stone mixes developed strengths much greater than those of mixes containing gravel, but the strength ratio is not constant and decreases as the confining pressure increases. The difference in strength at 72 F was not as great, but was approximately constant and approximately as follows:

Mix B (1½ in.)—stone and gravel equal
Mix C (1 in.)—stone better by 15 percent
Mix E (½ in.)—stone better by 34 percent

CONCLUSIONS

The present status of our research into the merits of different aggregates in hot-mixed, hot-laid asphaltic concrete may be summarized as follows:

1. A method of test has been developed to realistically evaluate bituminous mixtures with large-sized aggregates up to and including those having a 1½-in. maximum size.
2. A small variation in the asphalt content of mixtures with large-sized crushed stone aggregates does not detrimentally affect the strength.
3. Equally stable mixes with less asphalt can be prepared as the aggregate size is increased.
4. Crushed stone asphaltic concrete mixtures, when tested at 140 F and lower lateral pressures, are almost twice as strong as those prepared with natural materials, but the difference is not as great at higher confining pressures or lower temperatures.

5. Although testing at 140 F may not be justified for base course mixes, tests at some intermediate temperature, such as 100 to 110 F, should provide an indication of the beneficial effect of the crushed stone aggregates.

6. Angular aggregates contribute to the strength properties of asphaltic concrete either in the coarse or fine portion of the mix. The best results were achieved with crushed aggregates throughout the mix.

These conclusions are based on tests using the method as described. Although these aggregates are judged to be typical, the results and ratios developed may not necessarily be applicable to all aggregates.

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General Discussion

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G. Y. Sebastyan

I would like to make just a short comment on some of the work we are doing. We are concerned with asphaltic concrete surfaces for high-intensity and high-density aircraft traffic. One of the strength parameters, of course, is the mechanically induced angularity or crushed-face content. At present we specify 60 percent crushed face to achieve what we feel is necessary. Some other organizations specify 90 percent and two crushed faces, some others 100 percent and one crushed face. In our work across the country it costs us millions of dollars to provide the 60 percent and one crushed face. Questions are asked, Why use 60 percent? Why not use something else? Why use crushed face at all? In order to answer these questions, we have been performing during the last few years triaxial compression tests on 6 by 12 in. samples of the granular materials meeting the Department of Transport standard specification gradations. It is a controlled strain test, about 0.1 percent strain per minute. Our results at present show that, if there is a high confining pressure, there is no significant difference in strength among 0 percent crushed, 90 percent crushed, and 100 percent crushed gravel or crushed limestone. We can find significant differences in strength at the level of deformation expected in the airport pavement structure (0.05 to 0.15 in.) at low confining pressures in the range of 5 psi. That is the only case where we could demonstrate a significant difference in strength.

James M. Rice

Does anyone want to speak in defense of crushed faces?

C. L. Monismith

Did I understand that this is without asphalt?

G. Y. Sebastyan

This is without asphalt.

Charles R. Foster

I will speak in defense of crushed faces. I think that, without a doubt, crushed faces have a better record of sticking to asphalt, or asphalt sticking to crushed faces, than uncrushed faces. From a durability standpoint on surface course mixes, crushed faces may be justified even if they show no strength advantage.

W. J. Kari

The crushed faces that show importance at low confining pressures would be important in the compaction of the asphaltic concrete mix when the mix is hot. We do notice a difference in the rolling and construction characteristics of the mix depending on the gradation and also on particle roughness.

James M. Rice

This is a very important aspect that we have not touched on very much so far. Would anyone else want to comment on the effect of these various aggregate properties on the matter of workability and placement?

Bob M. Gallaway

In his prepared discussion, Mr. Hargett states: "The two basic strength properties that reflect significant effects of the size, surface texture, and shape of aggregate particles are frictional resistance and interlocking resistance. These two basic strength properties hold promise for the development of additional shearing resistance (or stability). The effects of size, surface texture, and shape of aggregate particles are not reflected in the cohesive strength of a bituminous mixture. It is the author's opinion that the inherent material properties of asphaltic binders preclude the development of major increases in shearing resistance in the form of cohesion. In fact, the strength component developed in the form of cohesion is subject to deterioration or a strength loss because of aging and the thermoplastic properties of the asphalt binder." Mr. Hargett also indicated that about 50 percent of the strength of the mix is a function of the surface texture of the aggregate and about 25 percent of the grading and size distribution.

William H. Goetz

I think that in this area you have to be very careful in making such categorical statements. In his paper, Mr. Tons stated that you cannot even categorize these aggregates; you cannot say you are using the same size aggregate when the shape changes. Aggregate size is determined by sieve size, and our studies show quite definitely that the same sieve size does not give the same size distribution. In addition, the same compactive effort to compact these different aggregates with different shapes will result in a different structural arrangement. Because something different is measured from this, is particle shape the influencing factor? Furthermore, if you use aggregates of different shapes and size them all the same, use the same methods of compaction and compactive effort, and use the same asphalt content so that you provide equal treatment, the resulting mixes will show quite different results as far as cohesion is concerned. We have cohesion results, evaluated from a triaxial test, that are a direct contradiction in their categorical aspects to the statements that were just made.

James M. Rice

I am glad you brought that out, because I am a little disturbed that this packing-volume concept may disrupt our previous thinking about some of these effects and variables. Maybe we have to go back and look at all this knowledge that Dean Benson has summarized.

Egons Tons

May I add to what Professor Goetz has said? Maybe we have been overly enthusiastic about the friction between rough surfaces and smooth surfaces. If you take two marbles, clean them off with benzene, and rub them together, you will find that there is friction between them. If you roughen these marbles and rub them together again applying the same force, you will find about the same amount of friction between them as when they were smooth. One roughness is on a macro level, and the other is on a micro level. You can polish the surfaces down to the molecular "roughness" level and still have friction between the marbles on a molecular level. If you compare mixes containing particles with different shapes, angularity, and roughness, you may get the impression that friction is an important variable. But if you isolate friction, you may find that there is not a great deal of difference from rock to rock. In fact, in our laboratory vibratory compaction using dry rocks, as well as in gravity pouring of the aggregate in a container, we found that the friction is about the same in all the three aggregates and in all the three sizes used in the experiment. If the friction had been different for different rocks, we would not have gotten the same bulk volumes.

C. L. Monismith

To state categorically that a certain percentage of the stability of a mix is contributed by each of these factors is not, at least in my viewpoint, a correct way of looking at this. I would presume that contribution of each will vary depending on the particular materials with which you are concerned. With respect to the effect of surface texture, this characteristic has a considerable effect on the resistance to deformation of asphalt mixtures. Mr. Sebastyan's remarks are probably quite applicable for uncoated materials. As soon as asphalt is added, however, the effect of surface texture on the resistance to deformation becomes significant. This is evidenced, for example, if one examines the results of the stabilometer test, which measures the resistance to deformation of a mix. Rather than being a failure test, the stabilometer provides a measure of the stress versus deformation characteristics of asphalt-coated aggregates. In effect, the test measures stability by determining the resistance to deformation at a comparatively small amount of strain. With asphalt present in the aggregate, the effects of surface texture become very, very pronounced. To state categorically, however, that shape or texture contributes a certain percentage would appear inappropriate. This is, I think, a characteristic that is a function of a particular aggregate. Hence, I would agree with Professor Goetz in this regard.

James M. Rice

Mr. Wissa, who has recently done some work that may be applicable to this subject, has offered to present a very brief summary of his work.

Anwar Wissa

We must not forget that the volume characteristics during the shearing process can be considerably influenced by grain size, density of aggregate, and so on, and therefore can alter the measured (apparent) frictional and cohesive behavior. This volume change tendency can have an influence on the strength during the shearing process. For example, let us consider a dense-packed system. If you keep it at a constant volume (let us even forget about asphalt) and try to shear it, the only way it can fail is by breaking the aggregate. Obviously, in asphaltic concrete this should not occur. However, the asphalt does tend to prevent this volume change; therefore, it induces an extra strength to the material that depends on how much tendency there is for expansion during the shear. Any factor that influences the tendency for expansion of the aggregate alone would also influence the tendency for the strength to increase when asphalt is also present. This phenomenon seems to occur too in asphaltic concrete. We ran two tests on asphaltic concrete, actually a sand-asphalt mix. In one case we allowed the volume to change, and in the other case we prevented any change completely. These tests represented the two extreme cases. There was a fivefold to tenfold increase in strength when the volume was constant. So I think that the effects of the aggregate on the volume change should be considered in any argument on texture, gradation, density, or the rest. This might have a very significant effect on the overall strength behavior.

Fred J. Benson

I would agree with these statements. I think this is exactly right. What I want to know is, How are you going to prevent volume change in a practical pavement?

Anwar Wissa

There are two ways to prevent volume change. One is by applying external load. This, to some extent, might happen in a pavement where the asphaltic concrete cannot move aside easily. The other way, which is probably of more interest, is related to the fact that, depending on the amount of air voids in the asphaltic mix, the compressibility of the pore fluid phase (asphalt plus air) changes. The fewer the air voids in the mix, the less compressible the fluid phase is and therefore the less opportunity for the volume to increase. If you had a very high air-void content in an open-graded mix, this restraining effect would be very small. On the other hand, in a very dense mix with a very small amount of air, this effect can be very significant.

James M. Rice

This does not answer Dean Benson's question. How do you prevent volume change in the pavement?

Anwar Wissa

In essence, you have asphalt there as well as air in a small amount. The air is completely compressible, and the asphalt is incompressible; therefore, the asphalt plus a very small amount of air has a low compressibility. As the aggregate tries to dilate, the pore fluid (asphalt-air) prevents the dilation. On the other hand, if there is a lot of air, it can dilate with not much change in stresses.

Charles R. Foster

The triaxial tests that were done at the Waterways Experiment Station on soil-aggregate mixtures showed a different performance when the strain at rupture was used than when the strain at a very low percentage of strain was used. The performance indicated that strain at a very low percentage agreed with what occurred under traffic and, as a result, the Waterways Experiment Station had to move from using strain at rupture to using strain at low levels. I am sure that this is true in asphalt mix. At the strains under which the asphalt mix lives, the asphalt does restrain the dilation; but at rupture the asphalt is not strong enough to restrain the dilation, and the behavior at rupture is the same as that at low strains.

Anwar Wissa

This is completely correct and by the time rupture occurs, obviously, the asphalt is no longer effective. For rupture, I was using the Mohr-Coulomb criterion for failure, which does not necessarily represent complete rupture. This is just a criterion. I would say this effect exists at lower strains as well as at the failure strain I used. Failure is a very nebulous term and depends on the criteria. Your comments are very valid, but I believe the tests I described, most of them drained tests where volume change was allowed to occur, showed volume changes at small strains. If you ran undrained tests, you would reach a point at which rupture of the asphalt would occur and you would get a sudden volume increase. But getting to that point is what we are interested in. We are interested not only in failure but also in getting to failure.

Charles R. Foster

I think we should be interested in strains in the order of ¼ to ½ percent because these are the ones the pavement lives under.

Anwar Wissa

This is correct. And we are also interested in the effect of repetitions of loads. In my work I studied only the effect of a single loading, not repetitions of loads. With repetitions of loads, strains to reach a maximum strength tend to decrease as densification occurs. After repeated loadings, very low strain may be required to reach rupture. Furthermore, the aging of the asphalt will also reduce the strain needed to cause rupture.

C. L. Monismith

An interesting point has been made here. When you are looking at the resistance of a mix to deformation, you have to distinguish one loading condition from another. We are normally concerned with the resistance of the pavement to deformation associated with repetitions of loads; thus, as Mr. Foster has indicated, we are concerned with the stress at a low strain. Accordingly, any stability test that defines the stress at a low strain is a reasonable way of examining mix design for moving traffic. Relative to the matter of drained versus undrained tests, it would seem that the undrained test would be more realistic for behavior of a pavement under moving traffic as compared with behavior of a pavement under standing traffic. I would also have to agree with Mr. Foster and note that, in the case of moving traffic, one should not use the peak characteristics but rather should examine the stress-deformation characteristics. As noted before, texture plays a very important role in defining this resistance to deformation.

James M. Rice

Are there comments on other areas of this subject?

V. P. Puzinauskas

I believe the main theme of Mr. Foster's presentation is that the behavior of paving mixtures is determined by the fine aggregate. Dean Benson's review of literature disclosed that some other workers assign special importance to fine fraction of aggregate. It is well known that the gradations of combined mineral aggregates in paving mixtures vary over a wide range. For example, based on gradation differences, The Asphalt Institute recognizes eight distinctly different types of general paving mixtures. In this context then, the question may be raised whether the fine aggregate is equally important for all types of paving mixtures. Mr. Tons dealt in his studies primarily with the coarse portion of the mineral aggregate. Thus, if fine aggregate is more important in influencing the behavior of paving mixtures, the question may be asked whether the path of his good study is misdirected, or the value of his test data is minimized. This apparent controversy should generate some additional thinking in this regard.

Charles R. Foster

The preface to my remarks, I thought made quite carefully, was that I referred only to dense-graded mixes, and I even defined a dense-graded mix as one that, when compacted with a standard effort over a range of asphalt contents, will eventually reach a condition where the voids are around 5 or 6 percent. I contend only that the fine aggregate dominates the strength of dense-graded mixes. Factors other than strength are involved in the selection of gradation. As a typical example, coarse aggregate takes up space and reduces the asphalt content and may make a coarse mix more economical than a fine mix.

Bob M. Gallaway

I feel constrained to comment on the question of the importance of fine aggregate for dense-graded mixes as compared to open-graded mixes. When you are dealing with pavement-tire friction, the fine aggregate becomes of rather insignificant importance for mixes that have a top size of approximately ½ in. because it is the larger aggregate that ultimately, when the pavement wears, comes in contact with the tire and therefore determines the coefficient of friction. This is a very critical factor on our high-speed traffic facilities.

James M. Rice

This is a very important point to bear in mind. I believe that during this Annual Meeting the New York State Department of Transportation is giving a paper that points out the importance of the coarse aggregate in controlling the ultimate skid-resistance characteristics. Mr. Britton, do you want to expand on the factor that coarse aggregate provides more lasting pavements, thus longer life?

W. S. G. Britton

I do not know that there is much more to add. I made the statement, I am convinced of it, and our records will show it very well. In performance and under traffic on the road, particularly under a great deal of truck traffic, coarse aggregate mixes will not have to be replaced, other things being equal, as soon as finer mixes.

Egons Tons

I would like to make two points to clarify our approach. First, the reason we started to work with the coarse aggregate fraction was the simplicity in the method of measuring packing volumes of the individual rock pieces. The next step would be to extend this measurement to fine aggregates and graded systems. The same packing volume principles may be applicable down to the filler level. The very small particles in the filler range may cause some unexpected problems with the packing volume concept. Second, the results we have obtained so far are already helpful in explaining the behavior of mixes that are not "overdosed" with fine aggregates—some base course and binder mixes. Published research data indicate that the majority of coarse aggregate pieces touch each other when fine aggregate content is below 30 to 40 percent. This approaches the condition of mixes investigated in our work.

Bob M. Gallaway

I think I would like to add to the problem rather than to the solution by talking a little about gap-graded mixtures. We have dealt with gap-graded mixtures to a considerable extent in Texas primarily because the grading requirements of the Texas Highway Department invite gap-graded mixtures. Many contractors take advantage of this invitation.

These mixtures are promoted with economics because often you can get materials that introduce a gap in the grading at a lower cost. If you make laboratory measurements of the Hveem stability of mixes of different top sizes that have a gap in grading at the same place, you find a maximum stability in most instances for a given type of aggregate with respect to surface texture and particle shape. We work with slag and have done so for about 8 years. The top size is about $^{3}/_{16}$ in. We put a gap in the grading of this material in the No. 30 to No. 80 sieve-size range, and this material exhibits a Hveem stability of about 30. It is relatively insensitive to asphalt content in the range of 5 percent to about $8^{1}/_{2}$ percent, and the stability stays around 30. We tested another series of materials in which the top size was $^{1}/_{2}$ in. and the gap was between the No. 10 and No. 30. The material between the $^{1}/_{2}$ in. and the No. 10 was a highly textured, lightweight material from seven different sources. This material gives a Hveem stability in the range of 45, almost independent of asphalt content from 5 or 6 percent to 10 or 12 percent. The stability still holds around 45. Then we cored samples from the road after service for 1 or 2 years and measured the stability again by both the Marshall method and the Hveem method. Out of 200 or 300 cores from two different sites, we did not find one sample tested by the Hveem method that met the minimum requirement for that mix when it went into service. Hveem stabilities were all less than 30. All the Marshall stabilities were about 2,000.

James M. Rice

This question of gap-grading brings up a rather new area for this conference. Of course, it has been studied. It has always been my impression that a gap in the grading tended to reduce the void content. But then I heard of some work being done in South Africa where gaps were introduced for the purpose of increasing the voids in the compacted aggregate in order to get additional asphalt in the mixture for increased fatigue resistance. Some recent work done in Ontario showed that where the gap is put—what sieve fractions—controls the effect on voids.

Bob M. Gallaway

I believe that the grading specifications of the Texas Highway Department were designed to allow a flexibility that might be used to put more asphalt in the mix and to ensure greater durability and possibly better flexibility.

Charles R. Foster

I am afraid the impression is left that all one has to do to increase the voids in the mineral aggregate is to gap the gradings. This is not true. We had some studies of gap-grading and some experience in the field of trying to produce gap-gradings to get more asphalt in the mix. Every time we touched it we made it denser. All of these studies showed that the only sure way to get more voids in the mineral aggregate is to make it finer. This is the only thing that works all the time because the voids that develop in the field are a very complex function of the surface texture and the gradation, and you do not know whether you are improving it by gapping it or making it worse from the standpoint of getting low voids.

James M. Rice

I did not mean to give the impression that I agree wholeheartedly with Mr. Gallaway either. My point is that the results of gap-grading can be variable depending on the location of the gap.

Bob M. Gallaway

This was a supposition on my part, and I was just looking into a crystal ball with respect to the possible thinking of some members of the Texas Highway Department. I would be willing to admit that where you put the gap is very critical. You could put the gap in the upper end of sizes and then Mr. Foster's statement would be true. If you put it in the other end, it might not be true.

James M. Rice

Our Task Group Chairman, Mr. Frank Nichols, and his assistant, Mr. Kalcheff, are associated with the crushed stone industry and have been working on large-sized aggregates. Mr. Kalcheff's prepared discussion reports briefly on what they have been doing. I think it is important that we are now looking at the fabrication and testing of specimens with large-sized aggregates. The Virginia Highway Research Council has also done some work in this area, and the U.S. Bureau of Public Roads is now doing some. With these capabilities, we can learn more about the properties and the possible advantages or disadvantages of mixes with large-sized aggregates. There are certain economic considerations involved in using larger aggregates that can be produced with a minimum of crushing.

William H. Goetz

I am not sure what point of conflict is being pointed out here. I do not have our results at hand so I must speak in qualitative terms. Mr. Kalcheff has curves that show combinations of gravel coarse aggregate with sand fine aggregate, gravel coarse aggregate with stone fine aggregate, and then stone coarse aggregate in two cases with sand fine aggregate in one and stone screenings in the other. As I look at these and remember our results, it appears to me that there is no quarrel in the lower curve—the gravel and sand combination. There is no quarrel with the last statement that the best results were with the combination of crushed coarse aggregate and crushed fine aggregate. And so if there is a point of conflict, it is with the two intermediate curves. I would point out that our own results likewise show reversals here depending on what the gradation is, and what the proportions are between coarse and fine aggregate. So not knowing how these compare, I do not know that there is any point of conflict at all. In fact, I rather suspect that there is not.

James M. Rice

Dean Benson, have you any comments?

Fred J. Benson

With regard to confining pressure, the theoretical solutions for multilayered pavements, where there is any appreciable difference in stiffness between an upper and lower layer, indicate that the lower area is in tension and is not confined at all when the load comes on. The studies we have done indicate that structural failures occur in the lower layer. So this matter of confining pressure gives no answers as to exactly what is going to happen to the pavement in the field.

C. L. Monismith

When we have a conference session of this type, one hopes that we might put together some answers that we might all agree on and that would provide guidance to the profession. In this session we have concentrated our discussions primarily on stability. We should, however, examine a number of different properties and the effects, in turn, of shape, surface texture, particle size, and size distribution. One approach might be as in the following, considering stability first because this has been discussed most extensively. To begin with, we should distinguish between moving and static loads to establish the rate of deformation used in arriving at the test results and, in the case of moving loads, perhaps to consider the use of undrained conditions. Perhaps we have to look at the effects of confining pressures in defining the resistance to deformation. Also very important to consider when we are evaluating laboratory specimens is how they are prepared, because results can be influenced very significantly by the method of specimen preparation. When these factors have been defined, the effect of size can then be considered. It should also be noted that we should consider the effect of size relative not only to the test configuration used, but also the effect of size relative to the layer in which the mix will be placed. The effects of surface texture, shape, and size distribution must then be evaluated in the same framework. Such an evaluation would then provide the desirable information that could be used by the profession. Of course, in addition to stability, we should also consider other characteristics including compaction characteristics, fatigue resistance, and skid resistance, to name a few. I am not certain that we have answered many of these questions this afternoon.

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