Influence of Mineral Aggregate Structure on Properties of Asphalt Paving Mixtures

V. P. PUZINAUSKAS
Associate Research Engineer, The Asphalt Institute, College Park, Maryland

•THE PERFORMANCE of asphalt concrete pavement, a mixture of mineral aggregate, asphalt and air voids, depends largely on the properties and relative proportions of these components. The influence of the aggregate, comprising by far the largest volume or weight proportion of the pavement, is extremely important on such performance. Mineral aggregates may vary widely in their mineralogical, granulometric, strength, surface texture, and shape characteristics. All these properties should be considered when suitability of mineral aggregate is evaluated. This report, however, is concerned primarily with the influence of the geometric factors, or shape and surface texture, on properties of asphalt concrete mixed and compacted by conventional laboratory methods or obtained from the actual pavements.

Visual examination of mineral aggregate, regardless of whether it is a naturally rounded gravel or highly angular crushed rock, invariably reveals that the axial dimensions of individual particles vary. These differences are caused by the presence of weak crystalline planes or soft grains within the aggregate particle. When subjected to mechanical crushing or grinding by natural forces, the aggregate tends to break in the weaker areas, resulting in irregular particles of elongated or flattened shape. In an asphalt paving mixture, the compaction process tends to orient the long axes of aggregate particles in a position perpendicular to the direction of compaction force. This alignment may cause not only different strength and rheological behavior in different directions of the compacted specimens, but also may result in different load transfer properties of the whole pavement layer, depending on the compaction method employed.

Because the anisotropic behavior of compacted asphalt mixtures is affected by the differences in aggregate structure or texture, material specifications often define such characteristics of an aggregate to be used for paving purposes. For example, the number of crushed aggregate faces may be specified and sometimes an attempt is made to limit flattened or elongated particles. U.S. Army Engineer Waterways Experiment Station developed test methods (1, 2) to determine the amount of these particles in coarse and fine aggregates. Although intended for aggregates used in portland cement concrete, these tests also are used by the Corps of Engineers when designing asphalt pavements for military installations. A rather complete description and discussion of methods for measuring particle shape and surface characteristics of mineral aggregates has been prepared by Mather (3). However, a review of the literature indicates a lack of systematic laboratory or field investigations specifically evaluating the effects of particle orientation on the rheological behavior and load-carrying properties of compacted asphalt paving mixtures. Shklarsky and Livneh (4, 5, 6) provided a direct proof for the anisotropic behavior of asphalt mixtures. These authors, using either compression or splitting tests and analyzing theoretically the mechanism of specimen rupture, concluded that the variable coefficient of cohesion in different directions is the reason for this behavior in compacted asphalt mixtures.

It can be expected that the magnitude of the effects of aggregate particle alignment, causing anisotropic physical behavior of compacted mixtures, would be affected not only

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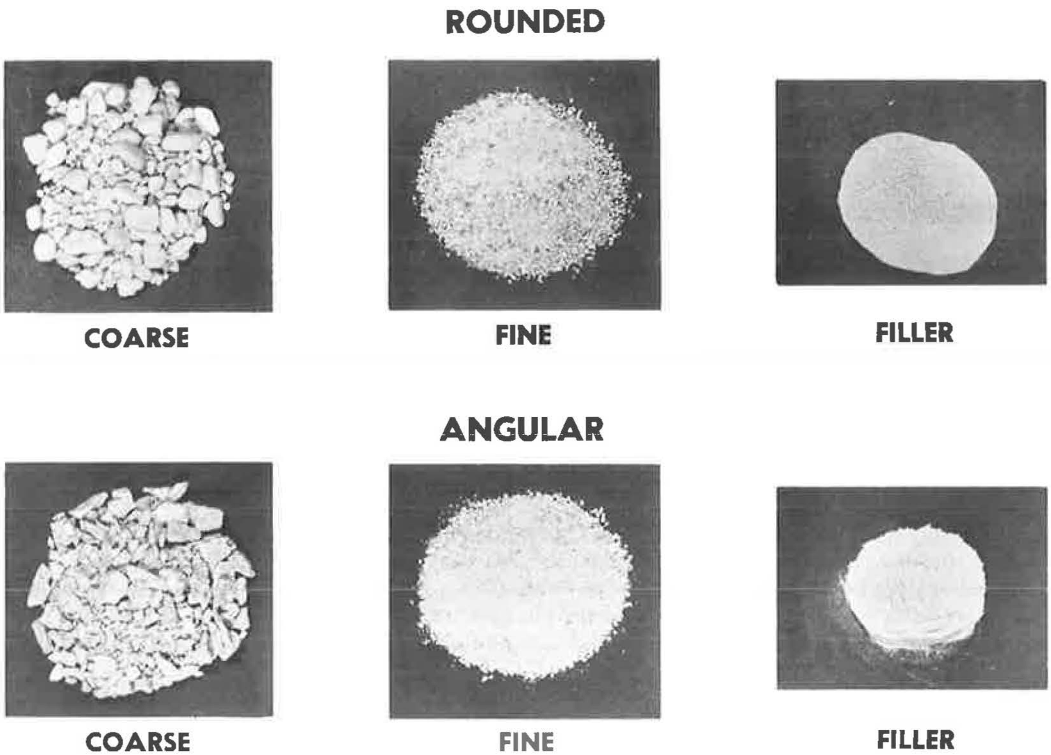

Figure 1. Types of aggregates.

by the type and relative proportions of mixture components, but also by the differences in testing environment. However, in this respect only a very limited amount of information is available in the literature. The purpose of the testing described in addition to evaluating effects on particle alignment of primary factors such as type and relative proportions of mixture components, was to evaluate secondary factors such as variable test temperature, loading rate and type of laboratory compaction. A limited number of tests assessing aggregate particle alignment in field-compacted asphalt mixtures also are described.

DESCRIPTION OF MATERIALS

Mineral Aggregates

Two types of mineral aggregates having the same gradation characteristics were used in this study. One aggregate consisted of rough, angular and flattened or elongated stone fragments and the other contained rounded and smooth-surfaced particles. For angular aggregate, crushed South Carolina granite was used as a coarse fraction while the fine aggregate fraction, including mineral filler, was prepared by crushing locally available Maryland gravel. In the case of rounded aggregate, natural Maryland gravel was used for coarse and fine fractions and Mississippi loess, consisting of rounded particles passing U.S. Standard Sieve No. 200, was used as mineral filler. Figure 1 shows the differences in shape and surface roughness characteristics of coarse and fine aggregate and mineral filler fractions of both rounded and angular aggregates.

Gradation characteristics of these aggregates are shown in Figure 2. The solid line represents the principal aggregate gradation used. Broken lines represent aggregate gradations whose characteristics affect particle alignment in compacted asphalt mixtures. For such supplementary studies, only angular aggregate consisting of crushed South Carolina granite and Maryland gravel mixture was used. The shape of

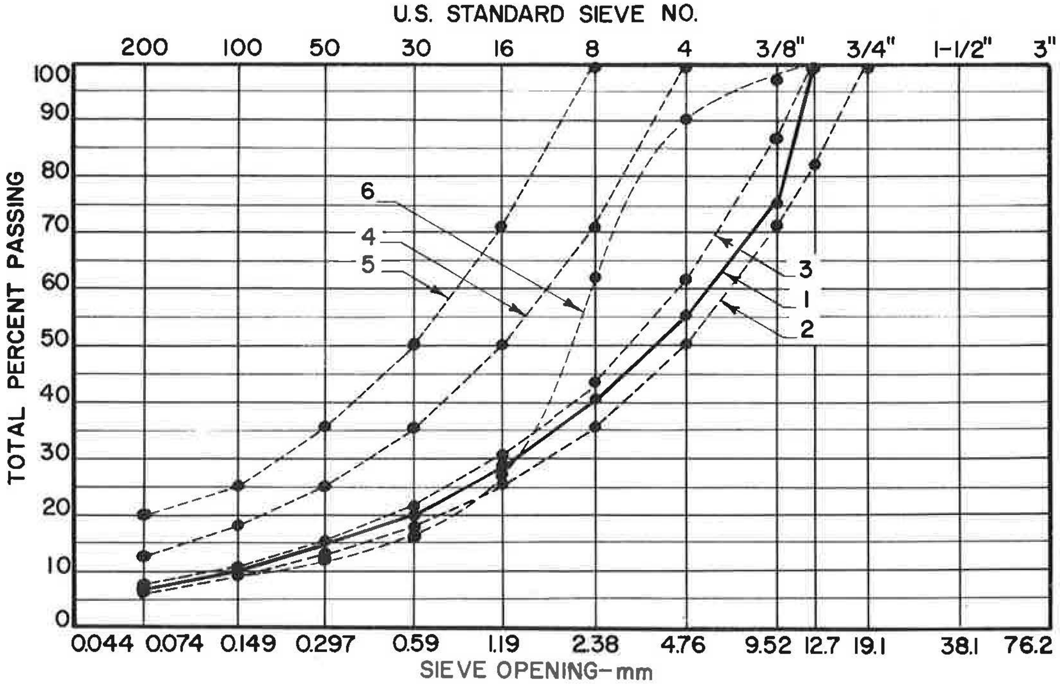

Figure 2. Gradation characteristics of aggregate.

TABLE 1

Asphalt	Pen., 77 F (cm)	Viscosity		Thin Film Oven Test Residue		Viscosity Ratio, 140 F (original: heated)
		140 F (poises × 10^3)	275 F (stokes)	Pen., 77 F (cm)	Viscosity, 140 F (poises × 10^3)	
A	88	2.54	4.49	44	11.43	2.2
B	94	1.04	2.91	54	3.56	3.4
C	61	2.46	4.0	32	7.23	3.0
D	40	4.99	5.7	19	20.37	3.8
E	21	515.0	92.6	16	725.0	1.4
F	0	1080.0	39.5	0	3050.0	2.8

lines in Figure 2 indicates that with the exception of aggregate No. 6, gradation of all other aggregates was selected to follow maximum density curves, sometimes referred to as Fuller's curves. It was believed that gradation of this type would represent a condition less favorable for alignment of the aggregate particles during compaction.

Properties of Asphalt Cements

Table 1 gives the properties of asphalt cements used in this study. Asphalt A was used for the majority of tests. Other asphalts were used only when studying the effects of asphalt viscosity on the aggregate particle alignment in the laboratory-compacted specimens.

EXPERIMENTAL PROCEDURES

Preparation of Mixtures

Accurate aggregate gradation control was achieved by separating all aggregates, in either eight or nine size fractions, by sieving through the series of U. S. Standard Sieves (Fig. 2). Before mixing with asphalt, these fractions were recombined to obtain desired gradation characteristics and the combined aggregate was heated overnight at 325 F in a forced-draft oven. Normally, the asphalt was preheated with intermittent stirring for approximately 2 hr at 275 F before mixing with aggregate. However, asphalts having considerably higher viscosity at 275 F than Asphalt A were heated at higher temperatures so that their viscosity for mixing did not exceed approximately four stokes. All ingredients were mixed for 2½ min with a Hobart laboratory mixer equipped with a 5-qt capacity mixing bowl.

Asphalt contents of 4. 5 and 3. 5 percent were used for angular and rounded aggregate, respectively. These asphalt contents were based on Marshall 50 blow design curves but are approximately one percent lower than the optimum asphalt content as established by this design method.

Compaction of Mixtures

Specimens were compacted by four different compaction methods: (a) Marshall compaction by applying 50 tamps on each face of specimen by compaction hammer, (b) Triaxial Institute Kneading Compactor using 150 tamps at 500-psi pressure on tamping foot and 1,000-psi leveling load, (c) mechanical gyratory compactor using 30 gyrations of 100-psi pressure and 1^{0} angle of gyration, and (d) static load of 3,000 psi applied for 2 min after rodding and tamping mixture for seating in the compaction mold. Molds of 4-in. diameter were used and specimens were compacted to a height slightly larger than 2. 5 in. In some instances certain deviations from standard compaction conditions were necessary to achieve a specific purpose. For example, when evaluating effects of density or air void content on aggregate particle alignment, the number of gyrations with the mechanical gyratory compactor was varied to obtain gradual changes in air void content of compacted specimens.

Preparation of Cube-Shaped Specimens

After cooling at room temperatures, density and air void contents of compacted specimens were determined by weighing specimens in air and in water. All specimens were then cut to cubes of 2. 5-in. side length with a diamond saw. To obtain cubes with opposite faces even and perfectly parallel, the flat surfaces of the cylindrical specimens also were trimmed. Figure 3 shows two 2. 5-in. cubes containing the angular and rounded aggregate particles. Close visual examination of this photograph reveals that particles of both aggregates are aligned in the direction perpendicular to that of

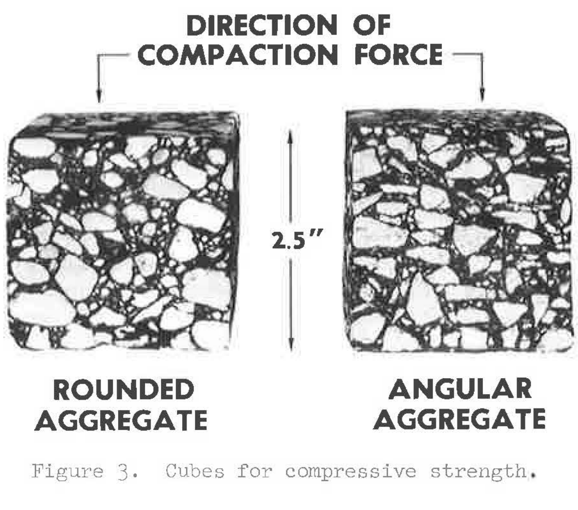

Figure 3. Cubes for compressive strength.

compaction force. However, it can also be seen that such alignment for angular aggregate is considerably more pronounced.

Measurement of Compressive Strength

To assess degree of aggregate particle alignment in compacted mixtures, compressive strengths of cube-shaped specimens were measured in directions normal and parallel to the force of compaction. These measurements were made with a Baldwin Universal Testing Machine by applying loads at a constant rate until the test specimens failed. During loading, stresses and strains on the test specimen were automatically recorded. A rate of 0.05 in./min/in. of specimen height was selected as standard. However, a number of tests using different load application rates also were performed.

During testing the temperature was held constant to within ± 0.2 F by placing specimens in a heavy gage, flat-bottom steel container and pumping water through this container from a thermostatically controlled water bath. Normally, test specimens were kept in the water bath for at least 1 hr before testing.

Measurement of Aggregate Particle Alignment

A ratio of compressive strengths, "Aggregate Structure Index," was employed as a measure indicating degree of aggregate particle alignment or aggregate structure in the compacted mixtures. This index is calculated by dividing the compressive strength of cubic specimens measured in the direction parallel to the compaction by that measured in the direction perpendicular to compaction. If the numerical value for the structure index equals unity, the aggregate particles within the compacted mixture are distributed at random, and not axially aligned in either direction. Values greater than unity indicate that aggregate particles are aligned or stacked perpendicular to the compaction force, and that such stacking causes higher strengths when cubic specimens are tested in the direction parallel to the force of compaction. Structure index values lower than unity indicate that the long axes of particles are aligned parallel to compaction force. However, regardless of aggregate type or test environment, structure index values were always greater than unity. Greater deviations of this index from unity indicated either more pronounced alignment of aggregate particles or more pronounced effects of such alignment on directional strengths of compacted mixtures.

TEST RESULTS

In general, agreement between test values measured on individual specimens was relatively good, provided the aggregate for each specimen was obtained from the same batch. For example, densities as measured on individual specimens differed from the average value by less than ½ pcf and differences in air void contents did not exceed ½ of 1 percent. Variations in compressive strength between duplicate specimens seldom exceeded 10 percent of the average value. If such variation in compressive strengths exceeded 15 percent, new specimens normally were compacted and the experiment was repeated.

However, if aggregate from another batch were used, differences between test values of specimens prepared from the two aggregate batches usually were greater than the differences between specimens prepared from the same batch. Such variation normally was more pronounced with the crushed-angular aggregate than with rounded gravel because of the difficulty in control and reproduction of aggregate angularity when crushing and processing the stock material at different times.

Densities and air void contents were obtained on cylindrical specimens before cutting to cubical shape. Tests indicate that densities (unity weights) of specimens containing both aggregates were normally higher and air void contents lower for the cut, cubic specimens than for the cylindrical specimens before cutting because the metal walls of the compaction mold tend to hinder the densification of mixture. Therefore, cutting and removal of the less dense mixture in the proximity of the compaction mold wall results in a greater density of the remaining test cube.

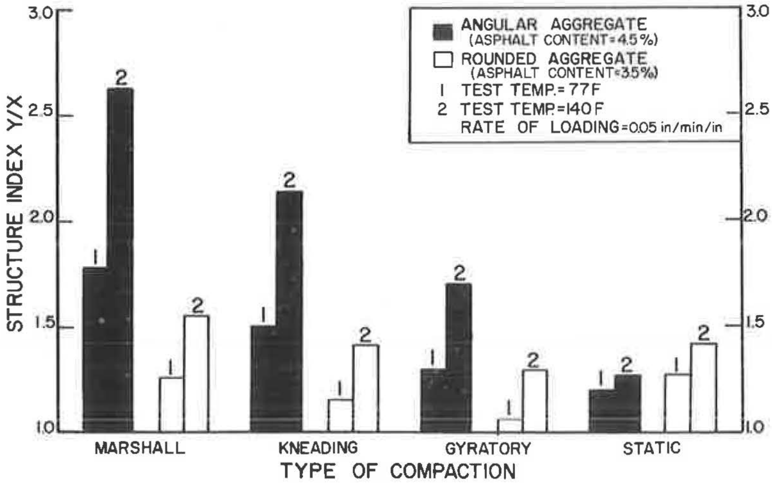

Figure 4. Effect of type of compaction on alignment of angular and rounded aggregate particles.

TABLE 2

INFLUENCE OF AGGREGATE TYPE AND COMPACTION METHOD ON PARTICLE ALIGNMENT AT TWO TEST TEMPERATURES

Type of Compaction	Aggregate Type	Asphalt Content[1] (%)	Unit Weight[2] (pcf)	Void Cont.[2] (vol. %)	Test Temp. (°F)	Compr. Strength[3] Y Direct. (psi)	X Direct. (psi)	Structure Index (Y/X)
Marshall,	Angular	4.5	146.3	5.2	77	498	281	1.77
50 blows on each	Angular	4.5	146.4	5.1	140	207	78	2.63
specimen face	Rounded	3.5	150.7	4.8	77	313	247	1.26
	Rounded	3.5	150.6	4.5	140	85	54	1.56
Triaxial Institute	Angular	4.5	147.2	4.6	77	520	345	1.51
Kneading Compactor,	Angular	4.5	147.8	4.3	140	212	101	2.13
500 psi, 150 tamps	Rounded	3.5	153.3	3.0	77	470	405	1.16
	Rounded	3.5	153.3	3.0	140	132	94	1.41
Gyratory compactor,	Angular	4.5	148.0	4.0	77	371	258	1.30
100 psi, 1° angle,	Angular	4.5	147.8	4.2	140	189	111	1.70
30 gyrations	Rounded	3.5	151.2	4.3	77	323	304	1.06
	Rounded	3.5	151.5	4.0	140	77	61	1.27
Static compaction,	Angular	4.5	144.5	6.5	77	505	422	1.20
3,000 psi	Angular	4.5	144.7	6.4	140	87	69	1.26
	Rounded	3.5	147.5	6.6	77	467	371	1.26
	Rounded	3.5	147.6	6.5	140	62	44	1.41

[1] Asphalt A used for specimen preparation. [2] Average values of four specimens.
[3] Rate of loading 0.05 in./min/in. of specimen height. Average values of two specimens.

DISCUSSION OF TEST RESULTS

Influence of Type of Compaction on Alignment of Angular and Rounded Aggregate Particles

Figure 4 shows effects of four compaction methods on particle alignment of angular and rounded particles, as indicated by the Aggregate Structure Index. Compaction methods included in Figure 4 represent dynamic-impact (Marshall), kneading (Triaxial Kneading Compactor), and gyratory and static compaction. For mixtures containing angular aggregate, 4.5 percent of Asphalt A was used and for mixtures with rounded aggregate, 3.5 percent was used. Compressive strengths in two directions of cubic specimens were measured at 77 and 140 F using a standard loading rate of 0.05 in./min/in. of specimen height. Complete test properties for these mixtures are given in Table 2.

Figure 4 indicates that regardless of aggregate type and method of compaction, aggregate particles when subjected to compactive forces always tend to align themselves perpendicular to force of compaction. As indicated by greater than unity Index values, such alignment always results in higher strengths when measured by loading parallel to the force of compaction (Y direction) than perpendicular to that force (X direction).

Although Figure 4 shows that both shape of aggregate particles and type of compaction greatly influence alignment of aggregate particles, the effect of the former usually is somewhat more pronounced. With the exception of static compaction, comparison of structure indices for mixtures compacted by any other method reveals that at both 77 and 140 F these indices for angular aggregate are more than double those for rounded aggregate mixtures. In static compaction, at both test temperatures the structure index for rounded aggregate is somewhat larger than for mixtures with angular aggregate. This is probably caused by high friction between rough and angular surfaces that hinders densification when compacted under confining static loads. Such resistance is markedly lower with rounded and smooth-surfaced aggregate particles. However, when the intermittent impact-type loads are applied, as with Marshall or kneading compaction, the influence of friction appears to be considerably less and the alignment of the elongated or flattened particles more pronounced.

Figure 4 shows that for angular aggregate mixtures, the intermittent impact (Marshall type) compaction represents the most favorable condition for particle alignment. The next is kneading compaction which also can be classified as an intermittent impact condition, although of a different type. This is followed by the gyratory and, finally, by the static compaction types. The two latter methods may be described as confined and continuous loading compaction methods which, apparently, allow considerably less chance for aggregate particle movement and, therefore, axial alignment. For mixtures with rounded aggregate, similar trends are indicated by Figure 4. However, static compaction again is an exception to this general trend.

Figure 4 also indicates that differences among structure indices for rounded aggregate mixtures compacted by the four methods are far less pronounced than for mixtures with angular aggregate. This implies that the strength, and possibly the other properties, of rounded aggregate mixtures is considerably less influenced by the laboratory compaction method than similar properties of mixtures containing rough-surfaced and irregularly shaped aggregate particles. In regard to compaction of actual pavements this may mean that for paving mixtures containing naturally rounded gravels, the selection of the type of compaction equipment for efficient mixture densification may be less important than for the mixtures containing difficult to compact, rough and angular crushed stone.

Further, differences in the structure index for different compaction methods (Fig. 4) imply that the correlations between test values as obtained by currently used laboratory mixture design methods should not be expected. This is true for the Marshall method, because Marshall stabilitites are measured by compressing the specimen in a direction other than the direction of the force applied during the compaction process.

The variability in structure index values also raises questions concerning the precision of laboratory design methods for asphalt paving mixtures. Often, stability test results as measured on the individual specimens vary considerably even when prepared by the same operator using identical asphalt-aggregate mixtures, particularly those containing crushed, large maximum size aggregate particles. The slight differences in the initial placement or seating procedures of mixtures in compaction molds may affect the alignment of the aggregate particles during the subsequent compaction process resulting in pronounced differences between stability values for the individual specimens.

Effect of Asphalt Content on Aggregate Particle Alignment

Data shown in Figure 4 and Table 2 represent tests made at a single asphalt content for each type of aggregate mixture. To evaluate the influence of asphalt content on particle alignment, standard Marshall design tests, and determination of structure indices, were made at different asphalt contents (Figs. 5, 6, Table 3). For these tests, Asphalt A was mixed at different proportions with both rounded and angular aggregates having the same gradation characteristics, as represented by the solid line in Figure 2.

Figure 5 shows changes in unit weights and air void contents for both rounded and angular aggregates when mixed and compacted with variable amounts of asphalt. Data presented indicate that the compaction characteristics of rounded and angular aggregates differ appreciably, regardless of the fact that both aggregates have the same gradation

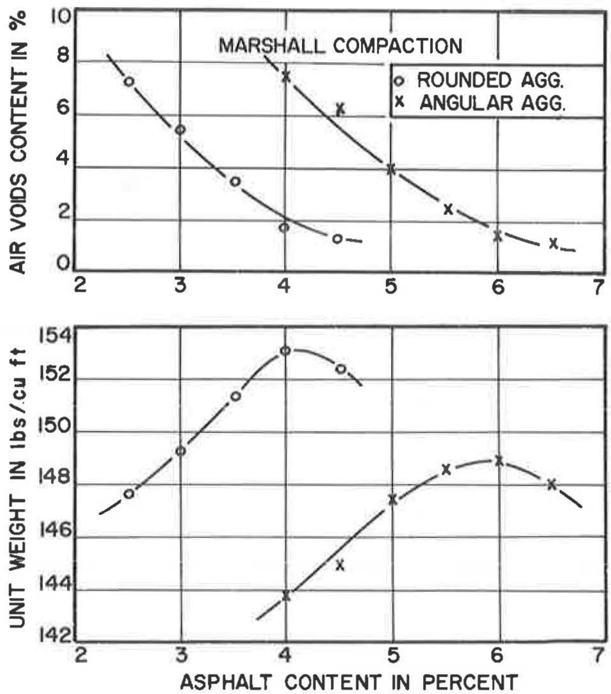

Figure 5. Compaction characteristics of rounded and angular aggregate mixtures.

TABLE 3

EFFECT OF ASPHALT CONTENT ON ALIGNMENT OF ROUNDED AND ANGULAR AGGREGATE PARTICLES IN PAVING MIXTURES

Aggregate Type	Asphalt Content[1] (%)	Unit Weight[2] (pcf)	Air Void Content[2] (vol. %)	Compr. Strength[3]		Structure Index (Y/X)	Marshall Stability (lb)
				Y Direct. (psi)	X Direct. (psi)		
Rounded	2.5	147.6	7.2	64	47	1.37	1,170
	3.0	149.2	5.5	82	65	1.25	1,360
	3.5	151.3	3.5	99	71	1.40	1,290
	4.0	153.0	1.6	102	72	1.42	1,210
	4.5	152.3	1.4	90	60	1.50	918
Angular	4.0	143.8	7.6	216	64	3.39	1,332
	4.5	144.9	6.2	219	78	2.80	1,390
	5.0	147.3	3.9	198	83	2.39	1,432
	5.5	148.6	2.4	176	84	2.10	1,462
	6.0	148.9	1.5	162	82	1.98	1,420
	6.5	148.0	1.4	146	60	2.43	1,260

[1] Asphalt A used for specimen preparation.
[2] Marshall compaction, 50 tamps on each end of specimen. Average values of six specimens.
[3] Test temperature 140 F; loading rate 0.05 in./min/in. of specimen height. Average values of two specimens.

characteristics. At the same asphalt contents, rounded aggregate mixtures compact to a considerably higher density and lower air void content than do similar mixtures with angular aggregates. In addition, asphalt contents for maximum densities for mixtures containing rounded aggregate are appreciably lower than for mixtures containing angular aggregate.

Figure 6 illustrates the relationship of asphalt content to directional compressive strengths and structure indices for mixtures with rounded and angular aggregates. Regardless of the asphalt content and type of aggregate, compressive strengths as measured in the Y direction are always higher than those measured in the X direction. For the rounded aggregate mixtures, however, differences in directional strengths are small and appear to be nearly constant over the whole range of asphalt contents, resulting in a relatively small change in the structure index with changing asphalt content.

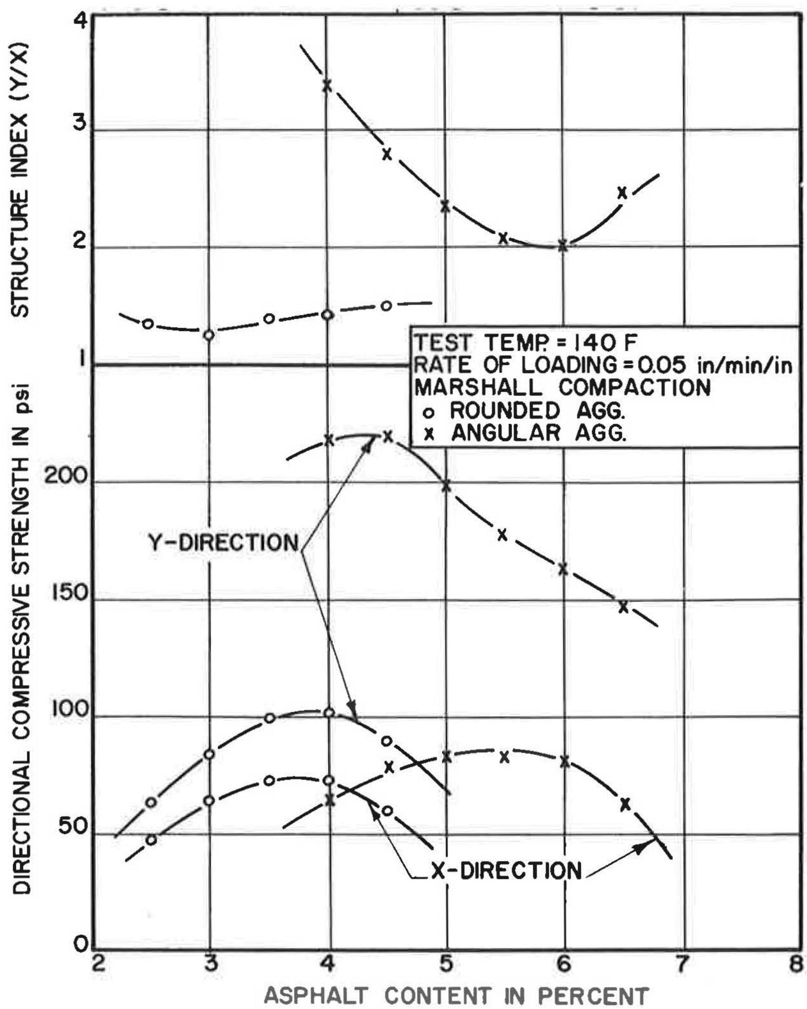

Figure 6. Effect of asphalt content on structure index of mixtures of rounded and angular aggregates.

Differences between directional compressive strengths with angular aggregate are by far more pronounced, varying with asphalt content. For example, at asphalt content of 4 percent, compressive strength in the Y direction is nearly four times as great as in the X direction. At 6 percent asphalt content, however, this difference is reduced by a factor of 2. Thus, as shown in the upper part of Figure 6, the structure index for mixtures with angular aggregate is much more strongly influenced by the variations in asphalt content than is the similar index for rounded aggregate mixtures.

Marshall stabilities, as far as mixture strength properties are concerned, do not provide similar information. Test results in Table 2 show that the maximum values are approximately the same for angular and rounded aggregates. The variation of Marshall stability with varying asphalt content is more similar to the variation of compressive strengths when measured in X direction. This is not surprising because Marshall stabilities are also measured by applying compressive loads in the same direction.

Relationship Between Air Void Content and Alignment of Aggregate Particles

The relationships between air void content, directional compressive strengths, and

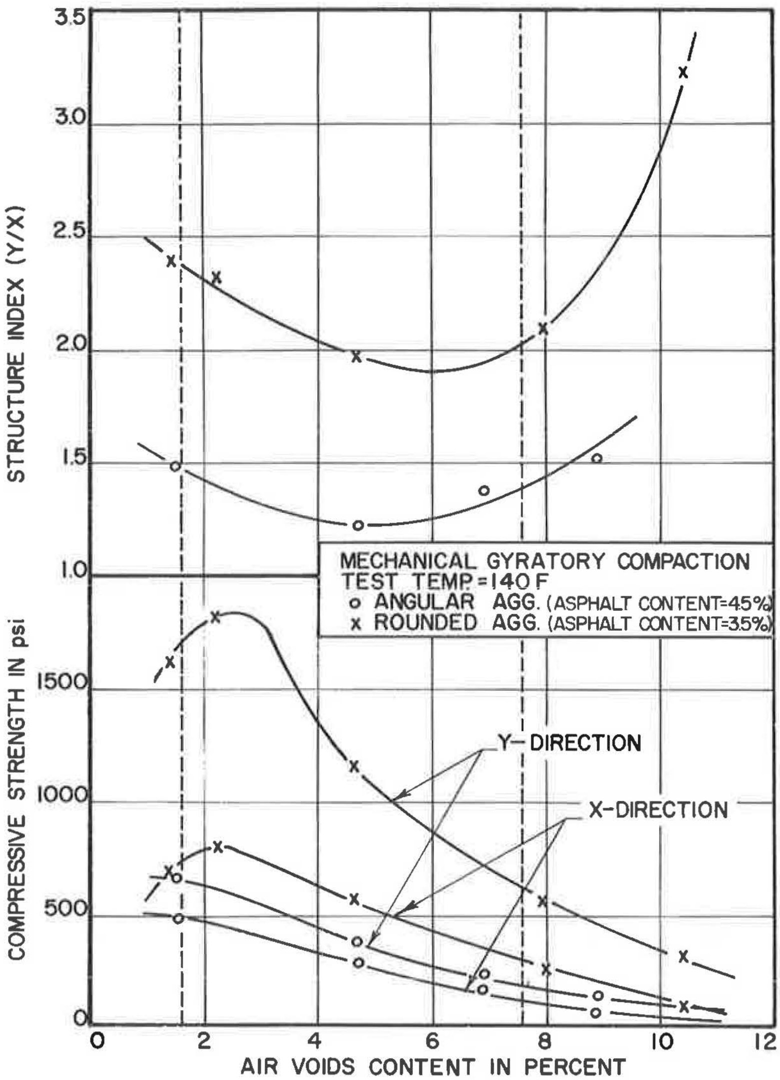

Figure 7. Effect of air void contents on alignment of rounded and angular aggregate.

aggregate particle alignment are illustrated in Figure 7. Rounded and angular aggregate mixtures were compacted to different air void contents with the mechanical gyratory compactor. Air void volumes were controlled between approximately 2 and 10 percent by continually measuring specimen height during compaction. For these tests, constant asphalt contents of 4.5 and 3.5 percent were used for angular and rounded aggregates, respectively. Compressive strength determinations in both directions were carried out at 140 F, using a loading rate of 0.05 in./min/in. of specimen height.

The lower part of Figure 7 shows that regardless of aggregate type or air void content, compressive strength measured parallel to compaction force is always higher than the strength perpendicular to such a force. Such differences are far more pronounced for angular than for rounded aggregates. Furthermore, the compressive strengths in both testing directions increase with decreasing air void contents. For angular aggregate, compressive strengths appear to reach a maximum value at approximately 2 percent air voids. For rounded aggregate, however, such trends are not clearly established.

The upper part of Figure 7 indicates that at air void contents of 6 percent for angular aggregate and 5 percent for rounded aggregate, the structure indices reach minimum values of 1.9 and 1.2, respectively. Below and above such air void contents they tend to be higher. Again, as in the case of compressive strengths, changes in structure index with changing air void contents for the angular aggregate are by far more pronounced than for mixtures containing rounded aggregate.

In general, influence of air void contents on the structure index or particle alignment is considerably less than the influence of factors such as type of aggregate, type of compaction or asphalt content. This is especially true within the range of air voids between approximately 2 and 8 volume percent as indicated by the vertical broken lines in Figure 7. This range represents variation in air voids of mixtures containing both aggregates, and compacted either by different compaction methods or at different asphalt contents (Figs. 4, 5 and 6). Figure 7 indicates that within this air void content range variations in structure index are relatively small, implying that effects of air void content on aggregate particle alignment (Figs. 4 and 6) generally were not great.

Effect of Rate of Loading on Structure Index

Test data discussed so far were concerned with compressive strengths measured at a single, constant rate of loading. Figure 8 represents compression tests at variable rates of loading. In this figure, test results only with angular aggregate mixtures compacted by the Marshall method at 4.5 percent asphalt content are shown. Directional compressive strength tests were performed at 77 and 140 F.

The shapes of both lines in Figure 8 indicate that effects of rate of loading on structure

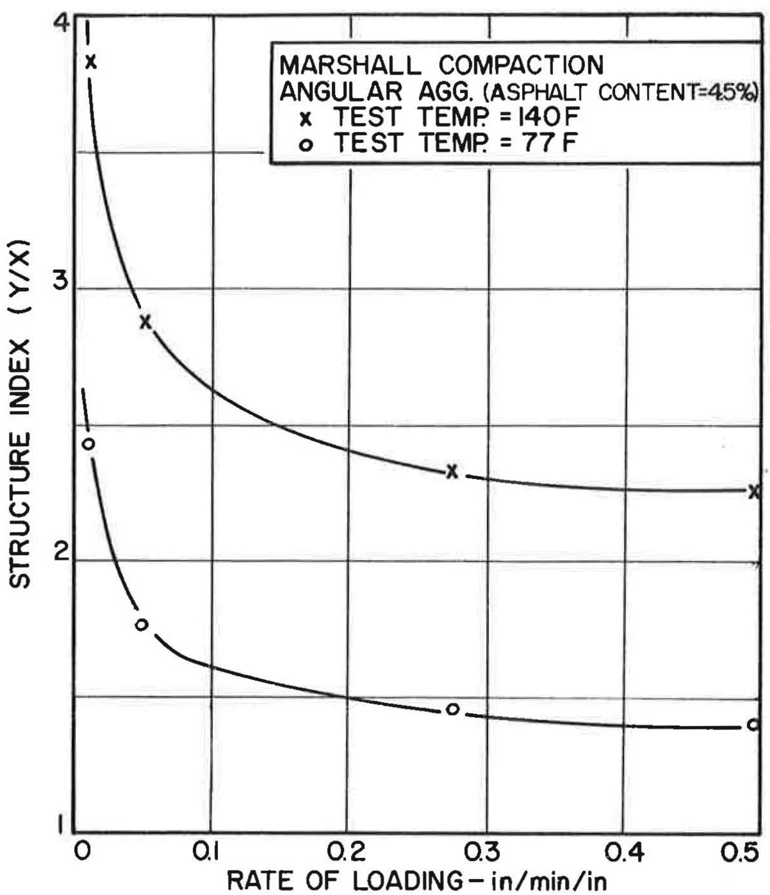

Figure 8. Effect of loading rate on ratio of directional compressive strength.

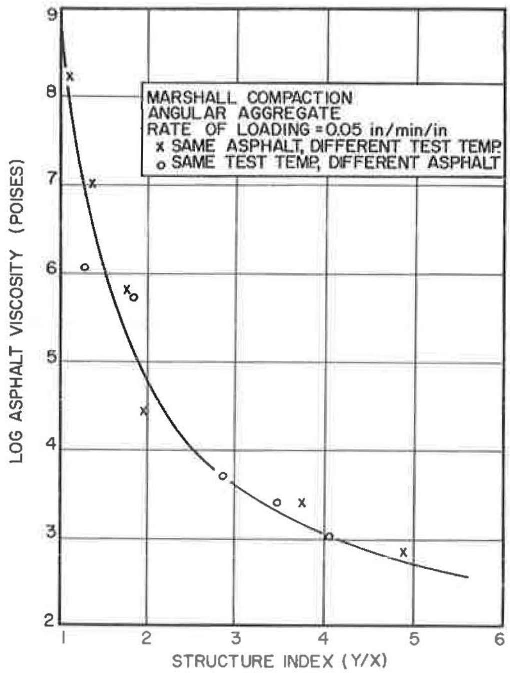

Figure 9. Effect of asphalt viscosity or test temperature on directional compressive strengths.

index are quite similar for both test temperatures. Structure index values tend to increase with decreasing rates of loading. At high rates of loading such increases are relatively small. However, at the rates of loadings close to 0.05 in./min these lines inflect, and increases in structure index with decreasing rate of loading become very pronounced. Generally compressive strengths in both directions increase with increasing rate of loading. However, at low rates of loading, increases of compressive strength in the Y direction are far more pronounced. This, then, causes the inflection point in structure index vs loading rate lines shown in Figure 8. This inflection point coincides approximately with rate of loading selected as standard for tests described in this report and with that required in a number of ASTM or AASHO tests for compressive strength measurements.

Effect of Asphalt Viscosity and Test Temperature on Structure Index of Paving Mixtures

The influence of asphalt viscosity or test temperature on structure index of mixtures containing angular aggregate is illustrated in Figure 9 and data were obtained by two different methods. Test values represented by crosses were obtained on mixtures containing Asphalt A only. Viscosities of this asphalt and directional compressive strength of mixtures were measured at 39.2, 60, 80, 100, 140 and 160 F. Test data represented by open circles were obtained on mixtures containing asphalts of different viscosity from compressive strength tests at 140 F. (Viscosity values at 140 F for different asphalts are given in the section on Description of Materials.) For all these tests, mixtures were prepared at an asphalt content of 4.5 percent with standard Marshall compaction and standard rate of loading were used.

Figure 9 shows that structure index is strongly dependent on either the test temperature or the asphalt viscosity and that effects of both of these factors are very similar. With the decreasing viscosity these indices increase. For example, at an asphalt viscosity of about one billion poises, commonly encountered near freezing temperatures, the structure index value is close to unity. At viscosities of approximately one thousand poises, representing pavement temperatures near the maximum reached in service, the structure index is about four for these angular aggregates. The value of unity for structure index means that strengths of mixture in all directions are equal. A structure index value of 4 means that the strength in Y direction is four times greater than that in X direction. Thus, the strength properties of mixtures at freezing temperatures are predominantly dependent on the viscosity of asphalt binder. However, as the viscosity of asphalt decreases or temperature of pavement increases, the influence of aggregate characteristics gradually becomes greater, until at close to 140 F they become the most important factor determining the properties and behavior of paving mixtures.

Influence of Aggregate Gradation on Structure of Paving Mixtures

Figure 10 illustrates effects of different aggregate gradations and maximum aggregate particle sizes on alignment of these particles when subjected to compactive forces. For these tests, mixtures of only the angular aggregate and Asphalt A were used. With the exception of gradation No. 6, particle size distributions shown in Figure 2 represent

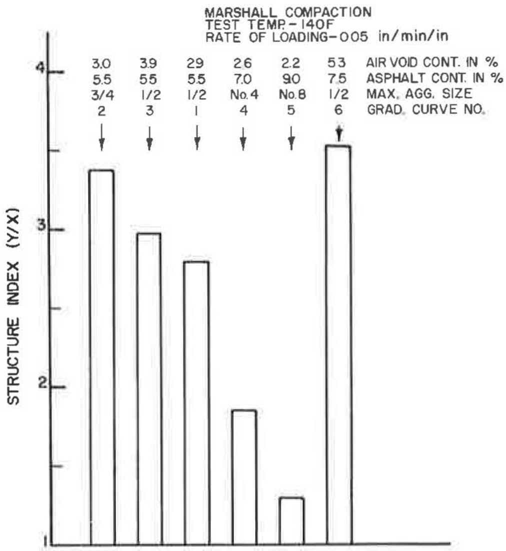

Figure 10. Effect of aggregate gradation on particle alignment.

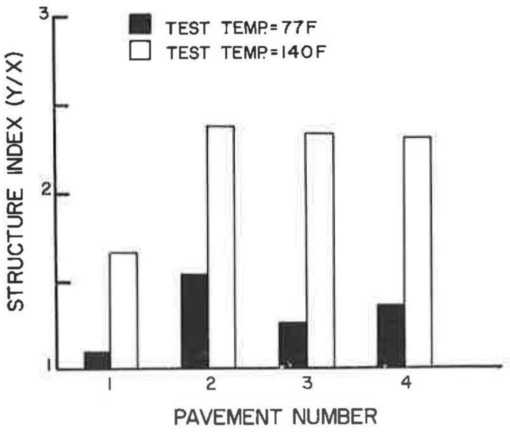

Figure 11. Alignment of aggregate particles in actual pavements.

maximum density (Fuller's) curves for a given maximum aggregate size. Aggregate No. 6 represents the so-called "skip-graded" aggregate that is deficient in coarse and fine sizes. Test cubes cut from cylindrical Marshall specimens were tested only at 140 F by applying compression loads in two directions at the standard loading rate. These mixtures were compacted to approximately the same air void content requiring changes in asphalt contents for mixtures with finer graded aggregates. Asphalt and air void content values are shown above each bar representing the different aggregate gradations.

Particle alignment becomes less pronounced with finer graded asphalt paving mixtures. For example, structure index for aggregate gradation No. 2 (maximum particle size $^3/_4$ in.) is approximately 3.5. For the finest graded aggregate No. 5 (all passing U.S. Standard sieve No. 8), this index is approximately 1.3. In the case of fine-graded mixtures, such as sand or sheet asphalt, relative differences in axial particle dimensions are smaller and, therefore, the effects of alignment of such particles on strength characteristics of compacted mixtures become less pronounced. Therefore, it may be assumed that asphalt mastics, mixtures of filler and fine sand with relatively large amounts of asphalt, would behave almost entirely in an isotropic manner.

The particle alignment is the most pronounced for mixtures containing skip-graded aggregate, because such uniformly graded mixtures, lacking in the intermediate particle sizes, contain fewer contact points between aggregate particles.

Aggregate Particle Alignment in Field Compacted Mixtures

For assessment of aggregate particle alignment in actual pavements, directional compressive strengths of cubes cut from pavement cores were measured at 77 and 140 F using standard loading rates. Such evaluations were performed on the following pavements: (a) Virginia experimental pavement after 4 yr of service, (b) North Carolina filler test section 1 mo after completion of construction, (c) base course of Northeastern Expressway in Maryland approximately 1 wk after placement and compaction, (d) test section for pavement temperature measurements at Asphalt Institute Headquarters 2 wk after construction.

The alignment of aggregate particles as reflected by the structure indices at two test temperatures for all four pavements is illustrated in Figure 11. Other properties of these paving mixtures are summarized in Table 4. In all these pavements either the entire aggregate, or at least the coarse aggregate fraction, consisted of crushed and angular particles. Additionally, in all four cases, the maximum aggregate size, asphalt content and air void content also varied.

TABLE 4

ALIGNMENT OF AGGREGATE PARTICLES IN ACTUAL PAVEMENTS

Pavement	Aggregate Type			Asphalt Cont.[1] (%)	Unit Weight (pcf)	Void Cont. (vol. %)	Test Temp. (°F)	Compr. Strength		Structure Index (Y/X)
	Coarse	Fine	Filler					Y Direct. (psi)	X Direct. (psi)	
Virginia exper. pavement	Crushed limestone			6.0	-	-	77	359	327	1.10
				6.0	-	-	140	241	145	1.66
North Carolina filler test section	Crushed limestone	Quartz	Kaolin	6.2	144.0	5.8	77	367	240	1.54
				6.2	144.0	5.8	140	195	82	2.37
Maryland Northeastern Expressway (base)	Maryland trap rock	Sand		4.4	142.4	9.2	77	264	214	1.25
				4.4	144.4	7.9	140	30	13	2.31
Test section at Asphalt Institute	Crushed limestone	Sand		4.9	141.7	9.7	78	254	188	1.35
				4.9	143.4	8.4	140	18	8	2.29

[1] Asphalt of 85-100 penetration grade used in all pavements.

In all four pavements, aggregate particles tended to align with the long axis perpendicular to the compaction force. Such alignment appears to be nearly equal in all but the Virginia test road. This road was subjected to traffic for a considerably longer time than the other three pavements. During this service time, viscosity of asphalt increased appreciably and, as indicated in Figure 9, such increases result in lower structure index values.

Although Figure 11 shows that all four pavements contained aligned aggregate particles, comparison of the alignments between different pavements may not be entirely justifiable because the thickness of pavements and, therefore, size of test cubes cut from different pavements varied. Furthermore, the ratio between maximum aggregate particle size and test cube side length also was variable. Preliminary tests for this study indicated, however, that for accurate compressive strength determination, side length of the test cube must exceed the maximum aggregate size by a factor of 3. This was not always the case with test cubes cut from in-service pavements.

SUMMARY AND CONCLUSIONS

The purposes of the tests described in this report were (a) to assess aggregate particle alignment in compacted asphalt paving mixtures, and (b) to evaluate the influence of such alignment on properties of these mixtures. For these evaluations, the compressive strength of cubic specimens in two different directions was determined and the ratio of the directional strengths (structure index) was employed as a measure indicating the alignments of aggregate particles.

Test data collected in this study lead to the following tentative conclusions:

1. Visual observation and larger than unity values for the structure index indicate that, regardless of the type of aggregate or the method of compaction, aggregate particles in compacted asphalt concrete tend to become axially aligned in a direction perpendicular to the direction of the compaction force.

2. Greater ratios of the directional compressive strength (structure index) indicate that the effects of the particle alignment on the properties of mixtures containing elongated or flattened aggregates tend to be more pronounced than for mixtures containing rounded and smooth-textured aggregates.

3. The alignment of aggregates strongly depends on the method of compaction. Generally, compaction methods utilizing intermittent, impact-type compactive forces represent a more favorable condition for particle alignment than those methods employing continuous and confining compaction forces.

4. Because of differences in aggregate particle alignment, comparisons between test results obtained by different laboratory design methods are difficult and may not be valid. This may be particularly true for mixtures containing crushed and angular aggregates.

5. The effects of asphalt and air void contents on the ratio of directional compressive strength are only moderate, particularly within the ranges of asphalt and air void contents commonly encountered in compacted asphalt paving mixtures.

6. The influence of asphalt viscosity or test temperature on the ratios of directional compressive strength is quite pronounced. With increasing viscosity or decreasing temperature these ratios decrease and approach unity. This appears to indicate that at temperatures near freezing, the strength properties of a mixture depend more on the characteristics of the asphalt. At higher pavement temperatures, however, the characteristics of aggregate become predominant.

7. Regardless of test temperature, directional strength ratios decrease with an increasing rate of load application. However, such changes at a loading rate of 0.05 in./min/in. of specimen height and higher become increasingly insignificant.

8. Alignment of particles tends to increase with increasing size of aggregate particles. For paving mixtures such as sand or sheet asphalt, the structural index tends to approach unity.

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

10. Systematic evaluations of the effects of aggregate type and alignment on load transfer properties and performance of in-service pavements are needed. Such evaluations may lead to the more rational use of different types of aggregates and improved pavements.

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Discussion

W. H. CAMPEN and L. G. ERICKSON, Omaha Testing Laboratories.—Mr. Puzinauskas' paper interests us because it deals with practical aspects of the design problem which are not only easily understood but also very timely.

We wish to make two comments concerning Mr. Puzinauskas' paper. The first pertains to aggregate alignment. Conclusions 3 and 9 taken together indicate that intermittent impact methods of compaction produce aggregate alignment more similar to that produced by the action of traffic than do other methods. Because of this, one wonders why the advocates of the use of the gyratory method of compaction reached the conclusion that this method comes nearer to duplicating aggregate orientation in the pavement than any other method. Perhaps Mr. Puzinauskas can elaborate on this point.

The other comment concerns the gradation of Aggregates 1 and 3 (Fig. 2). Mr. Puzinauskas states that they are dense-graded. We wish to disagree with him and say that they are more nearly in the region of open-graded mixtures.

In 1940 (7), we presented a paper to the Association of Asphalt Paving Technologists

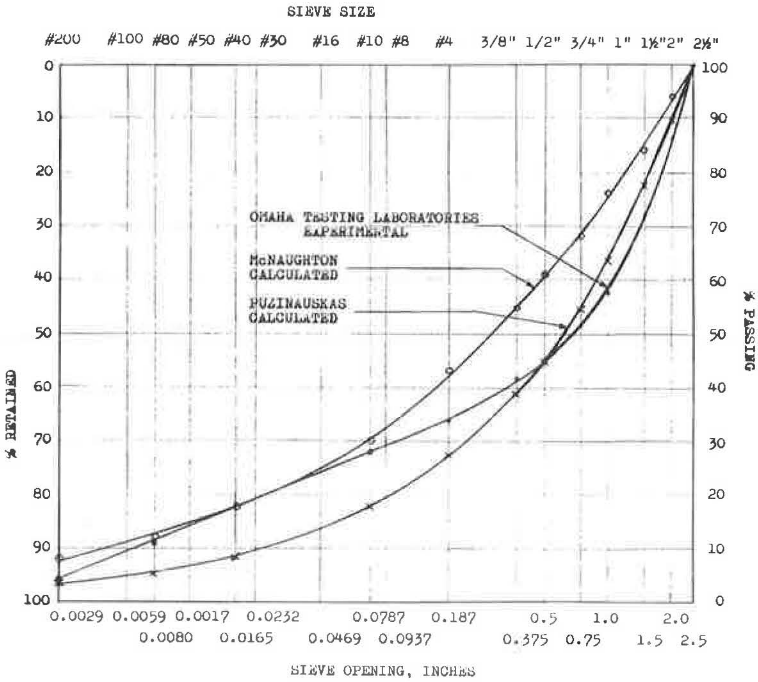

Figure 12. Gradation curves, $2\frac{1}{2}$ in. maximum size.

entitled "The Development of Maximum Density Curve . . . ." The curve (Fig. 12) was developed by preparing 11 sizes of aggregate starting with the No. 200 and ending with the $2^1/_2$ in. sieves. The various sizes were combined in a systematic manner and compacted by vibration. Figure 12 also shows a curve which we calculated from Mr. Puzinauskas' formula, and a curve submitted by T. F. Macnaughton in a discussion of our paper, which he based on research by C. C. Furnas and W. G. Weymouth.

Figure 13 shows five curves for $^1/_2$ in. maximum aggregates. The three solid curves were calculated from curves in Figure 12. One of the dashed curves is Puzinauskas' gradation 1 and the other represents a gradation that we have adopted after observing field performance for many years.

A study of the curves indicates in the case of Figure 12 that: (a) the Puzinauskas and OTL curves are similar at greater than $^1/_2$ in. but the former is much coarser at less than $^1/_2$ in.; (b) the Macnaughton and OTL curves are similar at less than No. 10 sieve but the latter is much finer at greater than No. 10 sieve; (c) the Puzinauskas curve shows a coarser gradation than the Macnaughton curve throughout. Figure 13 indicates that: (a) both the Puzinauskas curves show coarser gradations than both the Macnaughton and OTL experimental curves, and Puzinauskas curve No. 1 shows coarser gradation than his curve No. 3; (b) the Macnaughton curve shows coarser grading generally than the OTL experimental curve; (c) the OTL typical design curve is similar to the Macnaughton curve at greater than No. 10 sieve but is coarser at less than the same sieve.

The data as a whole in Figure 13 show that the Puzinauskas' gradations are much coarser than the one presented by Mr. Macnaughton or the ones developed and derived by us. Therefore, it is our opinion that the former are open-graded.

In conclusion we wish to add that our remarks are not intended to detract from the main purpose of Mr. Puzinauskas' paper which he accomplished very well. Instead they are made for the purpose of keeping the record straight in regard to dense and open-graded mixtures.

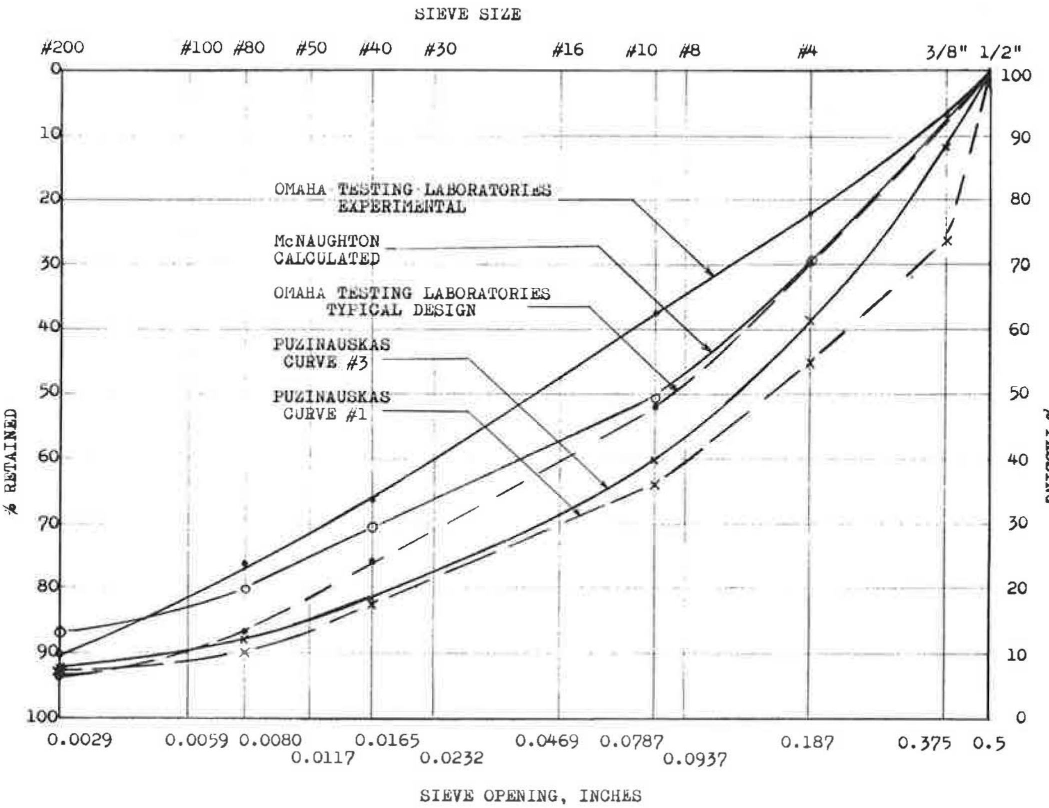

Figure 13. Gradation curves, $\frac{1}{2}$ in. maximum size.

Reference

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V. P. PUZINAUSKAS, Closure. —The principal purpose of this paper is to illustrate and evaluate the effects of aggregate structure or shape on the properties and behavior of compacted paving mixtures. Only the first of the two comments by Messrs. Campen and Erickson is directly related to this purpose.

In regard to this first comment, it is rather difficult to agree with the discussers' interpretation of conclusions 3 and 9, even when these conclusions are taken out of the context of the paper. These two conclusions do not state, nor do they imply, that some laboratory compaction methods are better than others in reproducing aggregate alignment under the action of traffic.

The writer is also unaware of any published papers stating that the gyratory compaction in laboratory duplicates aggregate particle orientation in the actual pavement better than the other laboratory compaction methods. If such a statement does exist, it would be rather difficult to agree with it because compaction methods differ not only in the laboratory but also in the field. Furthermore, such duplication of aggregate particle orientation would depend on a number of additional factors, such as the type of aggregate, the method of initial placement of the mixture, temperature of compaction and consistency and relative cooling rate of the mixture.

The second comment is a source of puzzlement. The author could not find in the text of the paper a statement implying that aggregates Nos. 1 and 3 are dense-graded.

In the section of the paper describing mineral aggregates it is stated that all aggregates except No. 6 follow maximum density curves, sometimes referred to as Fuller's curves. This, of course, is not the same as stating that these aggregates are dense-graded.

It is interesting to note, however, that according to The Asphalt Institute criteria (i.e., percentage of aggregate passing U.S. Standard Sieve No. 8) aggregates Nos. 1 and 3 could be classified as dense-graded aggregates.