Effect of Aggregate Shape on Stability of Bituminous Mixes

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● SINCE the early days of modern bituminous paving, highway engineers have noted that the shape of the mineral aggregate affects the strength of bituminous-aggregate mixtures in which it is used. It was noted that sharply angular and roughly textured aggregates generally produced bituminous mixes with more stability[1] than round, smooth-faced materials (*1*). Considering the types and control of the early bituminous pavings, any increase in stability was greatly desired, and angular crushed stone was used whenever possible.

In areas where gravel was abundant, methods were devised to increase the stability of bituminous-aggregate mixtures constructed with this aggregate. One of these methods was inferred from observed actions of the materials. Since angular crushed stone produced greater strength in bituminous mixes than rounded gravel, the strength of these gravel mixes was thought to be increased by making the aggregate form more angular. This was usually done by crushing part of the rounded gravel to be used in the mixture, since this produced sharper, more angular pieces.

This idea, that gravel mixes would be more stable with the addition of angular aggregates, has persisted among certain groups throughout the last 50 years and is reflected in the current specifications of many highway departments. At the same time, bituminous pavements constructed with rounded gravels have been observed to be entirely stable in many instances, and the significance of the original concept has been questioned (*7*, *9*). Even so, little actual investigation of this problem has been undertaken in either the laboratory or in pavement test sections. A knowledge of the basic behavior of the stability of bituminous mixes as influenced by different aggregate shapes is lacking.

It was the purpose of this investigation, then, to study the effects of aggregate shape on the stability of bituminous mixes. In so doing, three variables were used: (1) shape of the coarse aggregate, (2) shape of the fine aggregate, and (3) aggregate grading. Variation in the coarse aggregate shape was obtained by using angular crushed limestone, rounded uncrushed gravel, and crushed gravel. Rounded natural sand and angular crushed limestone provided the contrast in the shape of the fine aggregate. To further knowledge of the influence of crushed gravel on the strength of bituminous-aggregate mixtures, several combinations of crushed and uncrushed gravel were used also. The effect of these differently shaped aggregates on the strength characteristics of bituminous mixtures made from them were studied in three representative aggregate gradings referred to as dense, open, and one-size gradings. All of the bituminous mixtures tested were hot mixtures in which an asphalt cement was used, and asphalt content was kept constant for each grading.

TESTING METHOD

A fundamental part of this investigation was the selection of a test method for measuring the strength characteristics of the bituminous-aggregate mixtures in which the enumerated variables were incorporated. Many mechanical test methods have been devised and used to evaluate these properties in bituminous paving mixtures (*17*, *21*, *22*, *23*). Most of these tests are empirical and are not suited for the basic evaluation of the strength properties of a bituminous mix. Of all the various current methods, the triaxial-compression method appeared to provide the most-fundamental basis for the analysis of the various factors which contribute to the stability of bituminous-aggregate mixtures. The

[1] Stability may be defined as that property of a bituminous-aggregate mixture which permits the mix to withstand permanent internal distortion under stresses imposed by traffic loads.

resulting data of this test are analyzed in terms of basic properties of the cohesive granular mix, according to Mohr's theory of strength. This theory is thought to be more nearly in accordance with the observed action at failure of bituminous mixes than other theories of failure (*13*, *34*). Therefore, it provides a basic and logical approach to the measurement of the stability or shear strength of bituminous mixes. This study, then, consisted entirely of a laboratory investigation using the triaxial-compression-test method. The results have not been checked by other test methods nor correlated with the performance of paving mixtures made with differently shaped aggregates and used under the conditions imposed by traffic and weather. The evaluation of aggregate shape made in this study is definitely limited in this respect.

Mohr's theory of failure has been discussed extensively in the literature (*13*, *21*, *34*, *35*) and there is no need to review it in detail here. Basically, this theory recognizes two contributing factors to the resistance of bituminous-aggregate mixtures to compressive loads. These have been termed internal friction (ϕ) and cohesion (c). The former is made up of frictional resistance to sliding and of resistance due to interlocking of the mineral aggregate. The cohesion, though, is resistance to shear contributed by the binding material. These two factors are evaluated as the slope and vertical axis intercept, respectively, of a linear Mohr's rupture envelope. This envelope usually is obtained graphically by drawing a line tangent to different Mohr's circles of rupture which utilize the triaxial-compression data (maximum compression strength and corresponding confining pressure).

A convenient method of obtaining these two strength factors, without plotting the triaxial test data in graphical form and obtaining Mohr's rupture envelope, has been devised by Price (*19*). The method of least squares is used to obtain the vertical intercept a and slope b of the best straight line plot of the confining pressure versus maximum compressive strength. The values of a and b then are used to compute the angle of internal friction and cohesion of the material from the following equations:

$$\sin \phi = \frac{b - 1}{b + 1} \qquad c = \frac{a}{2\sqrt{b}}$$

For some bituminous mixes Mohr's rupture envelope appears to be a curved line with the angle of internal friction decreasing with increasing normal pressures. The rate of curvature may be large at low confining pressures and decrease with larger pressures until the envelope is practically a straight line. When the test results indicate such a curved envelope, they are interpreted by drawing the best straight line through the data and obtaining the cohesion and angle of internal friction values of the material from the equation of this straight line. This method is sufficiently accurate for most work (*18*). In this study, then, no confining pressures less than 15 psi. were used, in order to assure that the assumed linear Mohr's envelope would pass through a reasonably straight portion of the true envelope in all cases.

MATERIALS

Three types of coarse aggregate (material retained on the No. 4 sieve) were used in this investigation: rounded uncrushed gravel, crushed gravel, and angular crushed limestone. The gravel, as delivered to the laboratory, consisted of mixed crushed and uncrushed pieces. These pieces were separated by hand. The judgment for separation was based on the crushed pieces having two or more appreciably fractured faces or being definitely angular. The two different gravel shapes were used in varying combinations in this study: 0, 55, 70, and 100 percent crushed gravel. Samples of these gravel mixtures are shown in Figure 1.

Variation in the shape of the fine aggregate (passing No. 4 sieve) was obtained by using rounded natural sand and angular crushed limestone of sand size.

In one phase of this study two artificial gravels, with different degrees of roundness, were produced from an angular crushed limestone and used as coarse aggregate. One of these artificial gravels was produced by placing a quantity of crushed stone in the Los Angeles abrasion machine, without the steel balls, and subjecting it to the wearing action of 5,000 revolutions of the machine. To provide a greater degree of roundness, additional crushed stone was subjected to 10,000 revolutions. After every 2,500 revolutions, the aggregate in the Los Angeles machine was washed in order to remove the fine particles adhering to the coarse pieces.

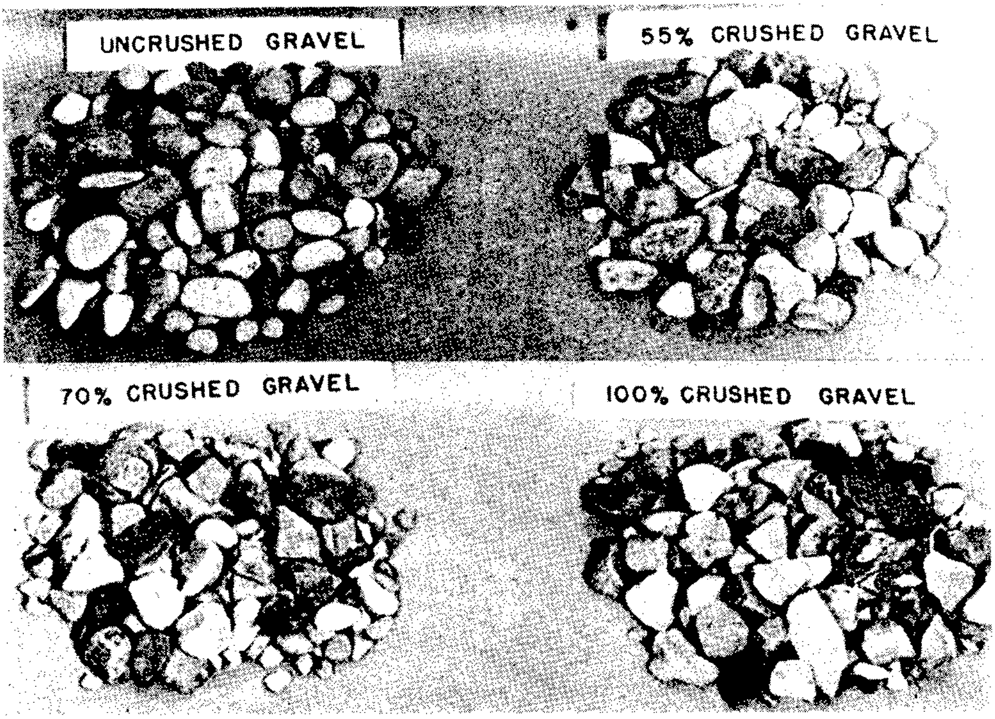

Figure 1. Gravel coarse aggregate.

Figure 2. Crushed-limestone and artificial-gravel coarse aggregate.

Samples of the original crushed limestone, and the artificial gravel resulting from 10,000 revolutions in the machine, are shown in Figure 2.

Three different gradings of these aggregates, chosen to cover a wide range of gradation, were used in this study. A densely graded mixture was represented by the Corps of Engineers, U. S. Army, Surface Course Asphalt Mix with maximum aggregate size of ¾ inch (*24*). Portland cement was used in this grading as the material that passed the No. 200 sieve. The other two gradings, an open grading and a one-size grading, corresponded to the requirements for Hot Asphaltic Concrete Binder Course and Bituminous Coated Aggregate Surface (size No. 9 aggregate), respectively, of the Indiana State Highway Department Specifications (*25*). The sieve analyses of these gradings are

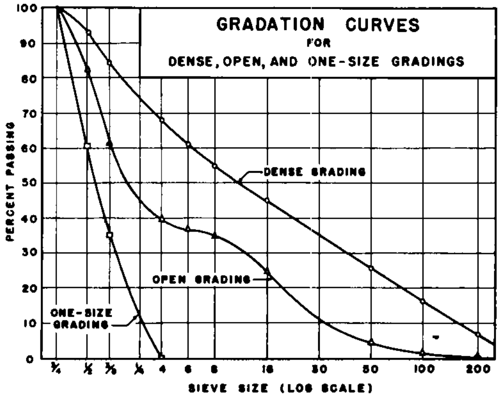

Figure 3.

presented in Table 1 and are graphically portrayed in Figure 3. A high degree of control of each gradation was exercised by drying all aggregate, sieving it into the respective sizes as given in Table 1, and recombining it by weight in the desired proportions.

Only one type of asphalt cement was used throughout this study. It was a 60–70-penetration-grade material obtained from the Texas Company and had a penetration of 66, a specific gravity of 1.015, and a ductility at 77 F. of over 150 cm. The asphalt content used in the dense grading was obtained by using the Corps of Engineers design procedure, since this grading was selected from their specifications. The percentage of asphalt used in the open and one-size gradings was that normally specified by the Indiana State Highway Department. For all types of coarse aggregate within one grading and with one type of fine aggregate, the amount of bituminous binder was held constant. The asphalt contents of the mixtures made from different gradings as used in this study, were as follows (in percent of total weight):

Dense Grading	
Natural Sand Fine Aggregate	6.0%
Crushed Stone Fine Aggregate	5.5%
Open Grading	
Natural Sand Fine Aggregate	5.0%
Crushed Stone Fine Aggregate	5.0%
One-Size Grading	5.0%

PROCEDURE

All mixes used in this study were hot mixtures in which the aggregate and asphalt cement were heated separately and then combined in a mechanical mixer. The routine procedure of mixing the materials and molding the specimens was kept constant, except for some changes found necessary when working with the one-size grading. All specimens were tested in the same manner in the triaxial compression apparatus.

The correct amount of aggregate, combined to conform to the dense or open grading, and the asphalt needed for one specimen were placed in a gas oven and heated to about 300 F. and 275 F., respectively. These constituents were mixed in a modified Hobart mixer for 2 minutes and then molded into a specimen, 4 inches in diameter and approximately 10 inches in height, by the double-plunger compaction method. The molding procedure consisted of placing the hot bituminous-aggregate mixture in a hot steel mold in four equal layers. Each layer was rodded 25 times. The entire mixture was then compacted in a hydraulic-compaction device with a static axial load of 2,160 psi. on each end of the specimen. This load was maintained for a minute. The standard procedure of molding triaxial specimens is to remove the mold from the specimen as soon as the compacting load is released (*17*). This method was altered somewhat in this study because of the instability of the warm compacted mixtures of the open and one-size gradings. Instead, the mold and specimen were placed at once in cold water and allowed to cool until the specimen was stable when removed from the mold.

Certain changes were necessitated in this procedure when forming specimens of the one-size grading. The coarse aggregate could not hold the required amount of asphalt when heated to the normally used temperature of 300 F. Thus in molding specimens of this grading, the mixing temperatures of the aggregate and asphalt were reduced to approximately 200 F. and 235 F., respectively. A compacting load of 500 psi. was used in this case instead of 2,160 psi. to reduce the amount of aggregate breakage, and the mold was vibrated by striking it with a leather mallet to provide better compaction. The amount of vibration provided was that required to produce a state of compaction such that further vibration did not cause the compacting load of 500 psi. to change appreciably. Experience showed that about 50 blows of the leather mallet were needed to

TABLE 1
SIEVE ANALYSES

Material	Sieve		Percent by Weight		
	Passing	Retained	Grading		
			Dense	Open	One-Size
Coarse Aggregate		3/4"	0	0	0
	3/4"	1/2"	7.0	17.5	29.2
	1/2"	3/8"	9.0	21.4	35.4
	3/8"	#4	16.0	21.4	35.4
Fine Aggregate	#4	#6	7.0	2.9	0
	#6	#8	6.0	1.7	0
	#8	#16	10.0	10.5	0
	#16	#50	19.0	20.7	0
	#50	#100	9.5	3.6	0
	#100	#200	10.0	0.3	0
Cement	#200		6.5	0	0

TABLE 2
RESULTS FOR DENSE-GRADED MIXTURES

Fine Aggregate	Coarse Aggregate	Average Density	Av. Comp. Strength		Angle of internal friction	Cohesion
			Ph = 15 psi.	Ph = 45 psi.		
		pcf.	*psi.*	*psi.*	*deg.*	*psi.*
Natural Sand	0% Cr. Gvl.	147.0	202.6	300.3	32.0	42.6
	55% Cr. Gvl.	147.3	216.6	317.7	32.8	45.2
	70% Cr. Gvl.	148.1	209.7	311.9	33.1	43.0
	100% Cr. Gvl.	145.3	205.5	306.3	32.8	42.3
	Crushed Stone	147.3	227.3	328.1	32.8	48.3
Crushed Stone	0% Cr. Gvl.	149.6	349.9	446.8	31.8	83.9
	55% Cr. Gvl.	148.9	354.7	452.8	32.8	84.5
	70% Cr. Gvl.	148.8	347.3	450.0	33.2	80.0
	100% Cr. Gvl.	146.7	349.4	447.6	32.2	83.0
	Crushed Stone	148.9	380.0	458.9	26.7	105.0

TABLE 3
RESULTS FOR OPEN-GRADED MIXTURES

Fine Aggregate	Coarse Aggregate	Average Density	Av. Comp. Strength		Angle of Internal Friction	Cohesion
			Ph = 15 psi.	Ph = 30 psi.		
		pcf.	*psi.*	*psi.*	*deg.*	*psi.*
Natural Sand	0% Cr. Gvl.	142.2	116.1	177.6	37.4	13.5
	55% Cr. Gvl.	140.8	127.4	189.5	37.7	16.0
	70% Cr. Gvl.	139.3	132.8	196.4	38.2	16.8
	100% Cr. Gvl.	140.3	132.1	197.1	38.7	16.1
	Crushed Stone	141.3	152.4	215.8	38.1	21.6
Crushed Stone	0% Cr. Gvl.	145.2	198.8	247.3	31.9	41.8
	55% Cr. Gvl.	145.4	211.8	261.6	32.5	44.5
	70% Cr. Gvl.	145.0	213.7	259.5	30.5	48.1
	100% Cr. Gvl.	145.7	215.5	265.3	32.5	45.5
	Crushed Stone	147.3	288.6	315.0	16.0	98.8

TABLE 4
RESULTS FOR ONE-SIZE MIXTURES

Coarse Aggregate	Average Density	Av. Comp. Strength		Angle of Internal Friction	Cohesion
		Ph = 15 psi.	Ph = 30 psi.		
	pcf.	*psi.*	*psi.*	*deg.*	*deg.*
0% Cr. Gvl.	113.6	39.1	74.3	23.7	1.3
55% Cr. Gvl.	110.5	49.3	90.5	27.8	2.4
70% Cr. Gvl.	110.6	51.3	97.2	30.5	1.5
100% Cr. Gvl.	110.1	58.7	108.7	32.6	2.4
Ar. Gr. (10,000 rev.)	115.5	49.9	77.6	17.3	7.8
Ar. Gr. (5,000 rev.)	113.7	54.8	90.0	23.7	6.4
Crushed Stone	114.6	70.8	118.2	31.3	6.6

reach this condition, and thereafter the standard compaction procedure for mixtures made from the one-size grading involved the use of this number of blows. Also, from experience it was learned that the specimens of this one-size grading would not retain their original shape at room temperature for more than 2 hours. Accordingly, light-weight sheet-metal containers were placed around these specimens as soon as they were taken from the mold and were not removed until the specimens were tested.

All specimens were maintained at the testing temperature of 75 ± 5 F. for at least an hour immediately prior to testing in the triaxial-compression cell. This apparatus utilized the "open system" through maintaining a constant confining air pressure and a uniform rate of deformation. The testing speed was 0.05 inch per minute. Specimens of each mixture, as identical as could be made, were tested at two confining pressures, and the maximum compressive strengths obtained. Possible influences on the strength of the mixtures which might be caused by variations in the molding and testing methods were controlled by exact repetition of the procedure and continued use of the same materials.

RESULTS

In this study strength-characteristics data were obtained on bituminous mixtures prepared with three different variables: shape of coarse aggregate pieces, shape of fine aggregate grains, and aggregate grading. Variability in the shape of the coarse aggregate was provided by using crushed and uncrushed gravels in the proportions of 0, 55, 70, and 100 percent of crushed gravel and by using a crushed limestone. Rounded natural sand and crushed-limestone sand were used to provide different shapes of grain in the fine aggregate. These shape variables were combined with three representative aggregate gradings identified as dense, open, and one-size gradings.

Hot-mix specimens containing these variables were tested in the triaxial-compression apparatus at confining pressures of 15 and 45 psi. for the dense-graded mixtures and 15 and 30 psi. for the open-graded and one-size mixtures. The resulting maximum compressive strength values were plotted against the corresponding confining pressure and a straight line drawn. This straight line was drawn through two points which were the averages of the compressive strengths of two or more specimens tested at the two confining pressures in each case. The values of cohesion and angle of internal friction were calculated from the constants of this line.

All data of this study were analyzed by a standard statistical method called "analysis of covariance" (*29*). This was done to determine if the observed differences in the test results were actually produced by the controlled changes in the test variables or were due only to chance variations in the test data. In order to decide from which of these two sources the observed differences in the values of cohesion and angle of internal friction occurred, the differences in the averages of the compressive strengths and the differences in the slopes of the strength curves (compressive strength versus confining pressure) were subjected to covariance analysis. No significant difference in the slopes of the linear strength curves implied no important variation in the angles of internal friction, since the friction angle is related only to the slope of the strength line. The value of cohesion, however, depends upon both the slope of this basic line and its intercept with the vertical axis. Thus, when the basic strength lines had the same slope, a significant increase in the compressive strength averages was interpreted to indicate a significant increase in the value of cohesion. It must be emphasized, however, that a difference in the results that is statistically significant as determined from variability of the test data is not necessarily a difference of practical significance. Cognizance of this fact must be taken when considering the results of this analysis.

The unit weights of all specimens containing any one combination of the three variables used did not vary appreciably. In fact, within one grading and with one type of fine aggregate, the unit weight of individual specimens, regardless of the percentage of crushed gravel used, varied from their mean by only approximately 1½ percent. The densities of the compacted mixtures increased as the grading was changed from one-size, to open, to dense. Specimens of the same grading and coarse aggregate type produced with crushed-limestone fine aggregate were of larger unit weight than corresponding ones containing natural sand. This difference was expected due to the higher specific gravity of the crushed-limestone fine aggregate as compared to the natural sand.

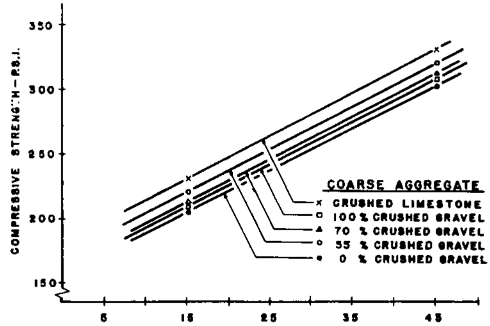

Figure 4. Compressive strength versus lateral pressure. Dense-graded mixtures, natural sand fine aggregate.

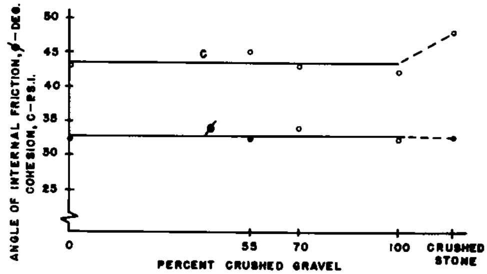

Figure 5. Cohesion and angle of internal friction versus aggregate shape. Dense-graded mixtures, natural sand fine aggregate.

Effect of Coarse Aggregate

The variations in the strength of the dense- and open-graded mixtures produced by changes in coarse aggregate shape were similar regardless of the type of fine aggregate used. The results discussed in this section in relation to coarse aggregate, then, are applicable for mixtures made with either type of fine aggregate, unless otherwise noted.

Dense Grading. The results of the triaxial-compression testing of the dense-graded mixtures containing natural-sand and crushed-stone fine aggregate are shown in Figures 4

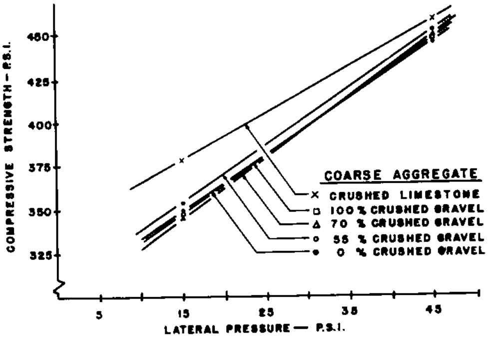

Figure 6. Compressive strength versus lateral pressure. Dense-graded mixtures, crushed stone fine aggregate.

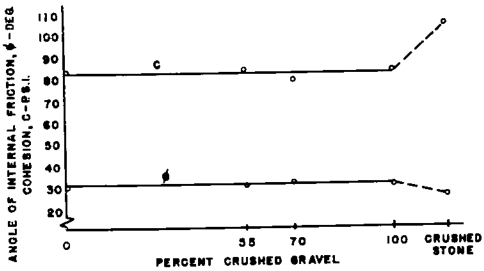

Figure 7. Cohesion and angle of internal friction versus aggregate shape. Dense-graded mixtures, crushed stone fine aggregate.

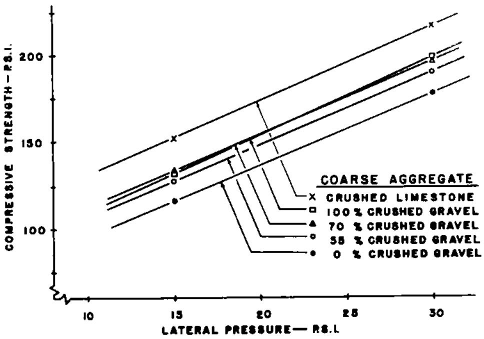

Figure 8. Compressive strength versus lateral pressure. Open-graded mixtures, natural sand fine aggregate.

and 6, respectively. As shown in these figures, the compressive-strength curves of all the combinations of crushed- and uncrushed-gravel mixtures were approximately parallel and closely grouped for mixtures made with each type of fine aggregate. No general trend existed of increased compressive strengths with larger amounts of crushed gravel in either case. Statistically, there was no difference in these strength lines of the mixtures containing gravel. The strength of all four gravel mixtures, then, could be considered to be the same and may be represented by one curve through the averages of the test results in both Figures 4 and 6. However, an increase in the compressive strengths was obtained by using crushed-stone coarse aggregate in the mixtures.

The variations in the values of cohesion and angle of internal friction for dense-graded mixtures containing natural sand are shown in Figure 5, while those for the mixtures with crushed-stone fine aggregate are presented in Figure 7. Both figures indicate there was little change in the values for friction angle and cohesion as the amount of crushed gravel was increased in the mixtures. Since there was no statistical difference in the strength curves for the various combinations of crushed and uncrushed gravel, all gravel mixtures containing the same type of fine aggregate could be considered to have approximately the same values of cohesion and angle of internal friction. However, a definite increase in the values for cohesion was produced when crushed-stone coarse aggregate was used with either type of fine aggregate. The angle of internal friction of the mixtures with this latter type of coarse aggregate was approximately the same as those for the gravel mixtures when natural sand was used as the fine aggregate. However, the specimens containing crushed-stone coarse and fine aggregate had a smaller friction angle than specimens made with crushed-stone fine aggregate and gravel coarse aggregate.

No increase in the compressive strength of the dense-graded mixtures was produced by any increase in the amount of crushed gravel with either type of fine aggregate. An increase in strength was produced in each case by changing the coarse aggregate from gravel to crushed stone. This increase was only slight and probably is not of practical significance.

Open Grading. In Figures 8 and 10 the compressive strengths of the open-graded mixtures containing natural-sand and crushed-stone fine aggregate, respectively, are shown. The strength of the mixture containing uncrushed gravel appeared to be less than the

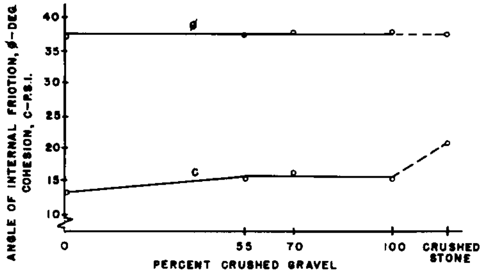

Figure 9. Cohesion and angle of internal friction versus aggregate shape. Open-graded mixtures, natural sand fine aggregate.

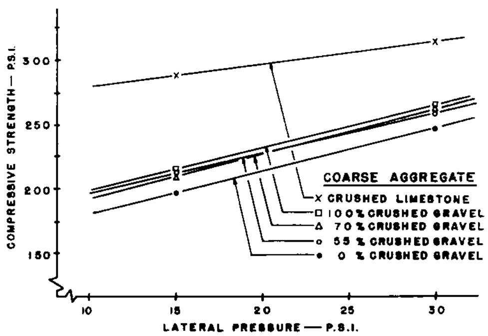

Figure 10. Compressive strength versus lateral pressure. Open-graded mixtures, crushed stone fine aggregate.

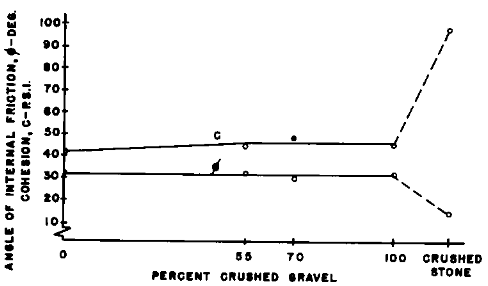

Figure 11. Cohesion and angle of internal friction versus aggregate shape. Open-graded mixtures, crushed stone fine aggregate.

strengths of those with crushed gravel, regardless of which type of fine aggregate was used. Depending upon the confining pressure and type of fine aggregate, the compressive strength of mixtures with 0 percent crushed gravel was 11 to 20 psi. less than the strength of the mixtures containing 55 percent or more crushed gravel. The statistical analysis indicated neither a difference in the slopes of these curves for all gravel combinations with one type of fine aggregate nor variations in the compressive strengths between mixtures with 55 percent crushed gravel and those with larger amounts of crushed gravel in each case. However, the strength of the mixtures with 55 percent crushed gravel was significantly greater than those with 0 percent of crushed gravel in the case of each fine aggregate.

Similar to the results of the dense-graded mixtures, specimens of the open grading with crushed-stone coarse aggregate had greater strength than those containing crushed gravel, regardless of which fine aggregate was used. However, the difference between the strengths of mixtures with these two types of coarse aggregate were greater when crushed-stone sand was used as the fine aggregate than when natural sand was used.

From statistical analysis of the strength data for the open-graded mixtures, it has been concluded that the values of cohesion were definitely increased as the percentage of crushed gravel in the mixtures containing both types of fine aggregate was changed from 0 to 55 percent. However, there was no material change in the values of cohesion with additional amounts of crushed gravel in these open-graded mixtures, regardless of which fine aggregate was used. For mixtures with either type of fine aggregate, there were no important differences in the angles of internal friction as the amount of crushed gravel was changed from 0 to 100 percent. These variations in the values of cohesion and angle of internal friction are shown in Figure 9 for those mixtures with natural sand, and in Figure 11 for those mixtures containing crushed-stone fine aggregate.

Figures 9 and 11 also indicate that the values of cohesion for mixtures with gravel and either type of fine aggregate were increased by the use of crushed-stone coarse aggregate. In contrast, mixtures containing crushed-stone fine aggregate in combination with this type of coarse aggregate had a smaller angle of internal friction than mixtures of this grading with gravel. When natural sand was used, there was little difference in the friction angle between the mixes with crushed-stone and gravel coarse aggregate.

By increasing the amount of crushed gravel in the coarse aggregate from 0 to 55 percent, then, the compressive strengths of the open-graded mixtures were increased in the case of each fine aggregate. Although this increase in strength was statistically significant, it was less than 10 percent and may not be of practical importance. No further increase in the strength of these mixtures occurred as the amount of crushed gravel in the mixtures was increased from 55 to 100 percent. As was the case for the dense-graded mixtures, greater compressive strength was produced in the open-graded mixtures when crushed-stone coarse aggregate was used instead of gravel. However, in contrast to the results for the dense-graded mixtures, the increase in this case was material, particularly for those mixtures made with crushed-stone fine aggregate.

One-Size Grading. Since no fine aggregate was present, the only variable in the mixtures of the one-size grading was the type of coarse aggregate. As shown in Figure 12, the compressive strength of these one-size mixtures became greater with increasing amounts of crushed gravel. This change was indicated by an increase in the slope of the strength lines, not by an increase in the intercept of the lines with the vertical axis as was the case for the open-graded mixtures. Statistically, there was a significant increase in the slope when 55 percent of crushed gravel was used instead of 0 percent. However, there was no change of statistical significance in the slope when the amount of crushed gravel was increased from 55 to 70 percent or from 70 to 100 percent. There was a significant increase in the slope of the strength line for the mixture with 100 percent of crushed gravel as compared to that for 55 percent. Although the variability of the data was such that a difference could not be distinguished between the slopes of the strength lines for mixtures containing 55 and 70 percent or 70 and 100 percent of crushed gravel, a definite trend of increasing slope with increasing amounts of crushed gravel did occur. The strength of these mixtures, varied directly with the amount of crushed gravel present in the mixture.

Figure 12 also shows that the mixture of this one-size grading with crushed limestone had greater strength than the one with 100 percent of crushed gravel. This change in strength was indicated not by an increase in

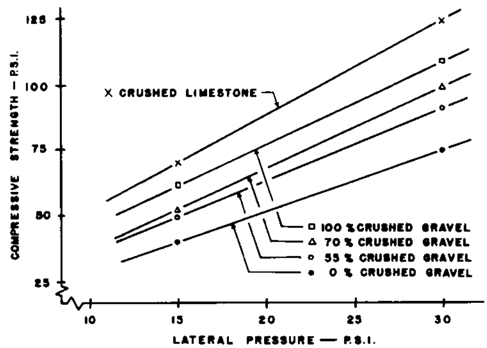

Figure 12. Compressive strength versus lateral pressure. One-size mixtures, gravel and crushed stone.

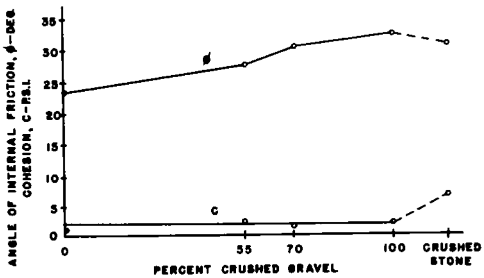

Figure 13. Cohesion and angle of internal friction versus aggregate shape. One-size mixtures, gravel and crushed stone.

the slope of the strength line as with the lines for mixes with different percentages of crushed gravel but by an increase in the intercept of the strength line with the vertical axis.

Since the slope of the strength lines increased with additional amounts of crushed gravel, the angles of internal friction also increased in like manner. This variability is shown in Figure 13, which also shows that the values of cohesion for all of the mixtures containing gravel were approximately the same and were quite small. A slight increase in the value of cohesion was produced when crushed stone was used as the aggregate rather than gravel. The mixture with crushed-stone aggregate had a friction angle slightly less than the mixture with 100 percent of crushed gravel.

As mentioned previously, to eliminate any variability of surface characteristics and lithologic variance in the coarse aggregate and to reduce the variability caused by the

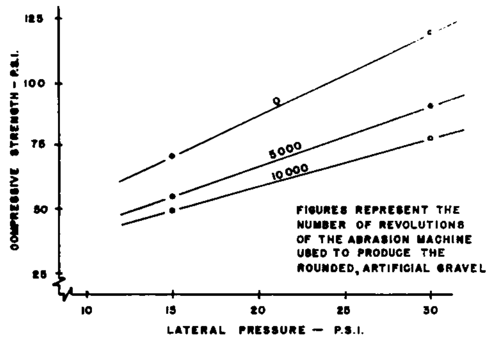

Figure 14. Compressive strength versus lateral pressure. One-size mixtures, artificial gravels and crushed stone.

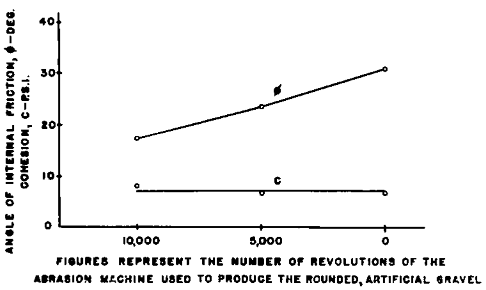

Figure 15. Cohesion and angle of internal friction versus aggregate shape. One-size mixtures, artificial gravels and crushed stone.

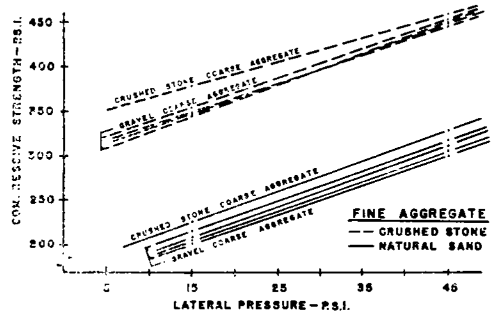

Figure 16. Effect of fine aggregate type on compressive strength. Dense-graded mixtures.

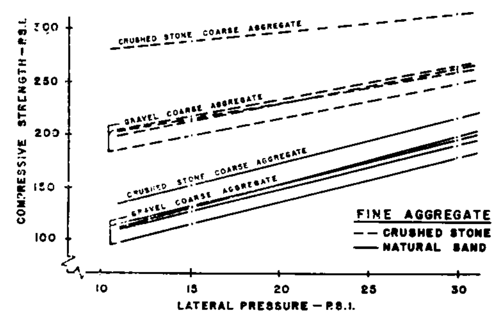

Figure 17. Effect of fine aggregate type on compressive strength. Open-graded mixtures.

human factor in the separation of the crushed and uncrushed natural gravel, two types of artificial gravel were produced from crushed limestone and were used as aggregate in the one-size grading. These two artificial gravels had different degrees of roundness as indicated by the number of revolutions of the Los Angeles abrasion machine used to produce them. The strengths of mixtures containing these artificial gravels, as well as the one containing crushed limestone, are presented in Figure 14. The mixture containing angular crushed limestone had a greater strength than those produced with the artificial gravels. The strength relationship between the mixtures with artificial gravels and the crushed limestone was similar to those with the crushed and uncrushed natural gravels. In both, the strength tended to increase as the aggregate shape became more angular, and this change in strength was indicated by an increase in the slope of the compressive strength lines (see Figure 12). Also, as with the mixes containing natural gravel, the angle of internal friction increased as the aggregate shape became more angular (see Figure 15). Similarly, the value of cohesion was not altered appreciably as the shape of the aggregate was changed. The cohesion values, however, for the mixes containing artificial gravel and crushed limestone were a little larger than the cohesion value for one-size mixtures made with natural gravel.

The compressive strength of the one-size mixtures, then, was affected materially by a change in shape of the mineral aggregate. As the aggregate became more angular in shape, the strength was increased. This trend existed whether the aggregate was natural or artificial gravel. Greater strengths were obtained, however, from the mixtures containing crushed-limestone coarse aggregate than from mixtures made with the most angular type of gravel.

Effect of Fine Aggregate

The strengths of the dense-graded mixtures containing rounded natural sand and angular crushed stone as the fine aggregate are presented in Figures 4 and 6, respectively. These two plots are combined in Figure 16 in order that a better comprehension of the variability in the strengths of mixtures with this grading containing both types of fine aggregate may be obtained. Similarly, the strengths of the open-graded mixtures containing these two types of fine aggregate are presented in Figure 17. This plot is a combination of Figures 8 and 10.

Irrespective of the type of grading, the strengths of the mixtures were increased materially when crushed-stone fine aggregate was used instead of natural sand. Within either grading, this increase in strength for the mixtures containing gravel was approximately the same regardless of the amount of crushed gravel used. That is, the strength of each mixture with uncrushed gravel was increased about the same amount by the change in type of fine aggregate as that of the same mixture with 100 percent crushed gravel.

The strengths of the mixtures when made with both crushed-stone coarse and fine aggregate also were greater than the corresponding mixtures containing crushed-stone coarse aggregate and natural sand. As noted previously, the strengths of both the dense- and open-graded mixtures with crushed-stone coarse aggregate were greater than those with gravel, regardless of the type of fine aggregate used. Figures 16 and 17 indicate the amount of this increase in strength was influenced by the type of fine aggregate. A greater increase was provided by using crushed stone as the fine aggregate than by using natural sand. Also, by comparing Figures 16 and 17 it may be noted that the difference in the strength of the mixtures made with crushed-stone coarse aggregate as compared to those made with gravel was greater in the open-graded mixtures than in the dense-graded ones.

The results presented in Figures 16 and 17 indicate further that the strength of the open- and dense-graded mixtures were influenced by the change in the shape of the fine aggregate more than by the variations in shape of the coarse aggregate. The change in shape of the fine aggregate as provided by the change from natural sand to crushed-stone sand produced greater increases in the strength of both the dense- and open-graded mixtures than was produced by changing the coarse aggregate shape from rounded, uncrushed gravel to angular, crushed stone. The shape characteristics of the fine aggregate appeared to have more influence on the strength of bituminous-aggregate mixtures, within the grading range investigated, than did the shape of the coarse aggregate.

In this discussion the distinguishing characteristic between the natural sand and crushed-stone sand usually cited was the grain shape. It is recognized that this was not the only characteristic that varied between these two types of fine aggregate, since the natural sand had fairly smooth surfaces and the crushed stone had more-roughly textured ones. In this investigation the relative effect of these two characteristics, aggregate shape and surface texture, on the strength of bituminous-aggregate mixtures was not determined. The increase in compressive strength provided by the change in type of fine aggregate must be considered to have been produced by the use of an aggregate with both rougher surface texture and more-angular shape.

Effect of Aggregate Grading

Although an increase in the angularity of the coarse aggregate resulted in increased strength in many cases and even though the angular crushed-stone fine aggregate produced mixtures with greater strengths than corresponding ones with natural sand in all cases, the most-significant changes in strength for the range of mixtures tested in this investigation resulted from a change in grading. In Figure 18 the compressive strengths of all mixtures of each grading are presented graphically. The mixtures of the one-size grading had the lowest strengths, regardless of the aggregate shape used. The greatest strengths were produced by the dense-graded aggregate, while the strengths of the open-graded mixtures were less than those of the corresponding dense-graded ones but were greater than mixtures of the one-size grading. These differences in strength between the mixtures with the three types of grading were due primarily to differences in the values for cohesion and not to differences in angle of internal friction.

The percentages of fine aggregate in the

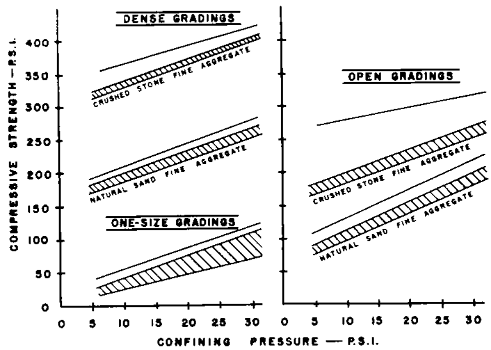

Figure 18. Effect of grading and aggregate type on compressive strength.

dense, open, and one-size gradings were 68.0, 39.7, and 0 percent, respectively. Although it can be stated that the strength of mixtures made with the three gradings varied directly as the amount of fine aggregate in the grading, this fact is not of primary importance, because the grading of the fine aggregate was not kept constant. However, the results of this study demonstrate conclusively that grading of the aggregate is an important factor affecting the strength of bituminous-aggregate mixtures and that, over a wide range of aggregate gradings, this factor has more effect on strength than does the shape of the aggregate.

SUMMARY OF RESULTS

The following is offered as a summary of the results obtained in this investigation. In drawing conclusions from them, it must be remembered that the study was limited with respect to materials and methods. Only one asphalt was used throughout the study, and asphalt content was not a variable. Of particular significance is the fact that the study was a laboratory one utilizing the triaxial-test method for the evaluation of the effect of aggregate shape on mixture strength. These results have not been verified by other laboratory test procedures nor have they been correlated with results of field performance:

1. The influence of an increase in the amount of crushed gravel in the coarse aggregate fraction on the strength of the bituminous-aggregate mixtures tested varied with the type of grading, the effect on strength becoming less as the grading of the mixtures became more dense. This was true regardless of whether natural sand or crushed-stone sand was used as the fine aggregate.

2. The strength of the mixtures with one-size grading was influenced materially by a change in the amount of crushed gravel in the coarse aggregate. The strength was increased as the percentage of crushed gravel in the mixtures was increased. In these mixtures, greater amounts of crushed gravel produced larger angles of internal friction but did not affect materially the value of cohesion.

3. In the open-graded mixtures, an increase in the percentage of crushed gravel from 0 to 55 percent produced a slight increase in strength. This increase probably is not of practical importance. No material increase in the strength of mixtures of this grading was effected by using amounts of crushed gravel greater than 55 percent. The values of cohesion increased as the percentage of crushed gravel was changed from 0 to 55 percent but did not change with additional amounts of crushed gravel. The angle of internal friction was not changed by varying the quantity of crushed gravel in the open-graded mixtures.

4. The strengths of the dense-graded mixtures were not influenced by increasing the crushed gravel content. Neither the values of cohesion nor the angles of internal friction were affected appreciably by a change in the amount of crushed gravel in the coarse aggregate from 0 to 100 percent.

5. In all three gradings, dense, open, and one-size, and with either type of fine aggregate, the strength of the mixtures was increased to some extent by changing the type of coarse aggregate from gravel to crushed stone. This increase in strength was indicated primarily by an increase in the values for cohesion.

6. Irrespective of the type of coarse aggregate used, the strengths of both the dense- and open-graded mixtures were increased materially when the fine aggregate was changed from a rounded natural sand to an angular crushed-stone sand. This increase in strength, produced by changing the type of fine aggregate in the dense- and open-graded mixtures, was much greater in each case than that obtained by increasing the angularity of the coarse aggregate from rounded gravel

to crushed limestone. The values of cohesion for the different mixtures were materially increased by this change in type of fine aggregate, but the angles of internal friction were not appreciably affected.

7. Although the evaluation of aggregate grading as a factor affecting the strength of bituminous-aggregate mixtures was not an objective of this investigation, the test results clearly demonstrate that this factor may have a more determining influence on mixture strength than aggregate shape over a wide range of aggregate gradings.

The results of this study show that mixtures containing crushed-stone coarse aggregate produced greater strengths than the same mixtures with any percentage of crushed gravel. However, a change in the amount of crushed gravel in the coarse aggregate fraction materially affected mixture strength only in the one-size, very-open mixtures. For dense-graded mixtures and graded mixtures of the binder type, mixture strength was affected little or none at all by varying the percentage of crushed gravel in the coarse-aggregate fraction. In these latter cases, much greater variation in strength was effected by changing the shape of the fine aggregate from natural sand to crushed-stone sand than by increasing the percentage of crushed gravel.

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DISCUSSION

W. H. Campen, *Manager, Omaha Testing Laboratories*—Herrin and Goetz have studied the effects of aggregate shape on the stability of bituminous mixtures by the use of the Triaxial device. They employed three types of gradation: dense, open, and one-sized. I wish to confine my comments to densely graded aggregates.

The authors conclude that the angularity of the coarse aggregate in densely graded asphaltic concrete does not have much, if any, beneficial effect on the stability. On the other hand, they find that the angularity of the fine aggregate is very beneficial.

In 1948 I presented[1] the results of "A Study of the Role of Angular Aggregates in the Developement of Stability in Bituminous Mixtures." This study showed emphatically that the angularity of both the coarse and fine portions of asphaltic concrete mixtures affect the stability. The evaluations were made by our own bearing-index method.[2]

I do not know whether the difference in results is due to the methods employed for the evaluations or to the asphaltic contents used. However, I do know from actual field performance that angular coarse aggregate is necessary in asphaltic concrete to prevent shoving and rutting under heavy traffic.

As a result of 30 years of field experience, coupled with laboratory tests, we have come to the conclusion that asphaltic concrete for heavy duty streets or roads must contain at least 65 percent of crushed particles in the plus-10 portion and at least 35 percent crushed particles in the minus-10 portion.

The authors are to be complimented for doing research on a most important phase of the design of bituminous mixtures for strength.

W. H. Goetz and M. Herrin, *Closure*—We are happy to have the discussion offered by Campen, because we have been aware even as our data were developed that there was some apparent conflict between the results of his studies and ours. We have not been able to resolve this conflict completely, but we do feel that Campen may be interpreting his test results too broadly.

Our study definitely is limited by the fact that we do not have correlating field or service information for the direct evaluation of variables incorporated. On the other hand, Campen's data were obtained with an arbitrary testing procedure while we utilized a rational testing method in an attempt to provide data of a fundamental character.

In evaluating the overall results of our study, we have been impressed with the importance of the gradation variable, not only as it affects stability in itself, but also as it affects the evaluation of aggregate shape as a factor contributing to stability. In this regard, we have compared the gradation used by Campen for his aggregate having a ¾-inch maximum size with the gradings used in our study and have found that the grading he used occupies a position intermediate between the gradings we have referred to as "dense" and "open." If this is taken into account, the results of our studies may be in better agreement.

Also, we have been aware of the fact that aggregate surface texture is probably an important factor with respect to bituminous mixture stability. We have tried in several ways to isolate the effect of this variable, but we have not been successful. Our data on this factor give strong indication that aggregate surface texture is important and that the part it plays in mixture stability varies with gradation. We mention this factor in this discussion because we believe that it is possible for two people working with aggregates from different sources to come to conflicting conclusions regarding the effect of aggregate shape on mixture stability if the surface texture variable is not recognized.

We realize, too, that asphalt content is a factor important to stability and that, at any given asphalt content for a given mixture, the quantitative effect on stability of a change in aggregate shape may be quite different than at some other asphalt content. The data reported are based upon a realistic approach wherein the asphalt content for the dense-graded mixtures was determined by utilizing voids criteria in the design as well as criteria for stability. We have carried our study somewhat further in this respect than is reported in our paper in an attempt to determine the basic factors contributing to bituminous-mixture stability, but our efforts have not produced conclusive information to date.

It is our belief that the apparent conflict between the results of our study and those of Campen only emphasizes the need for a more-basic understanding of the factors contributing to the stability of bituminous mixtures. We are of the opinion that progress in this regard can be made only if tests for stability are performed that provide rational data capable of analysis by the laws of mechanics. We have attempted to provide such data with respect

[1] Volume 17 Assn. Asphalt Paving Technologists.
[2] Volume 19 Assn. Asphalt Paving Technologists.

to the aggregate shape factor. But until a more-complete rational evaluation has been made, we would not suggest that the evaluation obtained with an arbitrary test procedure be ignored, especially if correlating field data are available.

Performance of Bituminous-Mix Designs

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North Carolina State Highway and Public Works Commission

This paper reports the observed behavior and performance of 14 sections, each 1,000 feet long, of bituminous concrete and various types of bituminous surface treatment overlay pavements on old portland-cement concrete.

Three types of coarse aggregate were used: crushed granite, crushed gravel (about 50 percent crushed particles), and uncrushed gravel. Approximately 550 samples were taken from the plant and roadway, during construction and after the pavement had been in service a year, with the location of every load placed in the road accurately identified in order to determine the uniformity of the proportioning and mixing operations.

One of the most-important factors in this test is the degree of compaction utilized in the design process and the correlation with that which can be obtained in the field. The compactive effort in the laboratory in the preparation of test specimens should be the same as, or bear a known relation to, the field compactive effort and the effect of traffic in relation to density after one year of service.

In connection with the overlay using asphaltic-pavement mixtures, two matters of general interest did not receive any special attention, namely, the treatment of cracks and the treatment of joints in the existing cement-concrete pavement before resurfacing.

The data should make it possible to develop satisfactory control for future asphalt-pavement construction for heavy-duty highways and aid in obtaining correlation between the results of mechanical tests on the materials and their road behavior.

● FOR several years the Research Branch of the Division of Materials has utilized the three factors, stability, density, and resistance to moisture, as measures of quality in evaluating and designing bituminous-concrete paving mixtures in the laboratory.

Density determinations are of first importance in the laboratory design and it is the practice in North Carolina, as in most other states, to endeavor to obtain a minimum void content of 15 to 20 percent through aggregate gradation—the denser the aggregate the greater the strength or stability to be expected. Asphalt is added to the extent necessary to leave approximately 5 percent of voids in the final mix when compressed as it is intended to be compacted on the road. Under no circumstances should this value be less than 3 percent, and it is desirable, in order to assure resistance to percolation of water and the effects of weather, that the value be not greater than 6 percent.

The density criteria are used in judging the quality of the road samples taken in conjunction with studies of old pavement. It has been found that most of the failures of bituminous pavements in North Carolina have been the result of the presence of an excess of asphalt as indicated by the absence of a safe amount of air voids.

One of the most-rapid and most-serious failures took place on US 301 north of Fayetteville. It has been necessary from time to time to reshape the surface by scraping off some of