**EFFECT OF CRUSHED-GRAVEL
FINE AGGREGATE
ON THE STRENGTH OF
ASPHALTIC SURFACING MIXTURES**

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LAFAYETTE INDIANA**

by

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STRENGTH OF ASPHALTIC SURFACING MIXTURES

TO: K. B. Woods, Director
Joint Highway Research Project

FROM: Harold L. Michael, Assistant Director

March 13, 1956

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Attached is a paper entitled "Effect of Crushed-Gravel Fine Aggregate on the Strength of Asphaltic Surfacing Mixtures" by R. P. Lottman and W. H. Goetz of our staff. The paper was prepared from data obtained by Mr. Lottman and used in the preparation of his thesis for the degree of Master of Science in Civil Engineering.

The paper was presented at a meeting of the National Sand and Gravel Association in Chicago in February, 1956, and is also scheduled for presentation for the Purdue Road School in April, 1956.

This research was performed under a fellowship from the National Sand and Gravel Association. The paper is presented to the Board for information, inasmuch as it is applicable to Indiana use.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Assistant Director
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HLM:cjg

Attachment

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ON THE
STRENGTH OF ASPHALTIC SURFACING MIXTURES

by

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EFFECT OF CRUSHED-GRAVEL FINE AGGREGATE
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INTRODUCTION

Ever since the first days of modern bituminous paving construction, one of the prime interests of highway engineers has been centered around increasing the strength of bituminous surfacing mixtures. In this consideration, they have been aware that the shape and texture of the mineral aggregate affect the strength of the bituminous mixtures in which the aggregate is used. It has been found that mixtures containing mineral aggregate with markedly angular and rough-textured characteristics generally develop a greater strength or stability than the same mixtures made with round, smooth-textured mineral aggregates. Since an increase of stability presently is greatly desired because of the development of heavier traffic loads on pavements, highway engineers have been specifying the use of crushed mineral aggregates in the coarse aggregate fraction of bituminous pavement mixtures whenever and wherever practical.

In many areas of the country where gravels are available, the strength of local bituminous surfacing mixtures has been increased by crushing part of the round gravel used as the coarse aggregate. This was thought to be a promising approach since crushed-gravel coarse aggregate was more angular and rough-textured than the round, natural gravel. Many highway departments have accepted this method of increasing

The study on which this paper is based was accomplished through the establishment of a Research Fellowship at Purdue University by the National Sand and Gravel Association.

strength in bituminous mixtures by specifying a certain percentage of crushed coarse aggregate in their current specifications. Sand produced by crushing stone, alone or blended with natural sands, has been used to improve mixture stability in some areas.

In some instances smaller-size gravels have been crushed into sand size and used to increase the angularity and to improve the surface texture of the sand fraction in order to increase mixture stability. There are localities where this crushed-gravel fine aggregate has been used as the entire sand fraction in order to render a satisfactory use of the aggregate source for bituminous surfacing mixtures; on the other hand, there are some localities which have found it adequate to blend a certain percentage of crushed-gravel sand with natural plant-run sands to produce bituminous surfacing mixtures that will meet current requirements. This "sweetening" of a natural plant-run sand with a satisfactory percentage of crushed-gravel sand offers a means of improving mixture stability economically, in many instances.

Although crushed-gravel fine aggregate has been observed to increase the strength of bituminous surfacing mixtures, its use has been limited. There still remain questions pertaining to quantitative strength effects to be expected from its use.

It was the purpose of this investigation, then, to study the effect of crushed-gravel fine aggregate on the strength of some typical bituminous surfacing mixtures. These included a dense-graded bituminous concrete of controlled gradation, a sand-asphalt mixture in which the grading was kept constant and made equal to the sand fraction of the dense-

graded bituminous concrete, and bituminous concrete mixtures in which the grading varied but was kept within ASTM specifications. The strength evaluation was based upon data obtained from three laboratory strength tests, namely: the Marshall stability test, a triaxial compression test, and the standard ASTM Compressive Strength Test for Bituminous Mixtures (ASTM Designation: D1074-52T).

The laboratory test data have not been correlated with data from bituminous paving mixtures containing differently shaped and textured mineral aggregates from other sources than those used in this investigation, nor have they been correlated under the conditions imposed by traffic and weather. Although the strength evaluation of the crushed-gravel fine aggregate made in this study definitely is limited in this respect, it is believed that this investigation will provide the basis for further investigations of crusher-run gravel sands in bituminous mixtures.

MATERIALS

The mineral aggregates selected for use in this investigation were obtained from commercial aggregate plants. The natural sand consisted of relatively round, smooth, local materials obtained from the Western Indiana Gravel Company, Lafayette, Indiana. The natural sand components consisted of a commercial sand meeting the specifications of Indiana No. 17 sand for bituminous paving mixtures, and a fine sand obtained from the washings being discharged in the plant's fine aggregate processing unit.

The other sand used in this investigation was a commercial crushed-gravel sand obtained from the Raymond Street Plant of the American Aggregates Corporation, Indianapolis, Indiana. This sand was selected because it represented a typical crusher-run product used locally. It was observed to be sharply angular and rough-textured. This crusher-run sand is referred to locally as "crusher dust" and is designated as such in this report. It has been successfully used by the City of Indianapolis for a number of years in bituminous surfacing mixtures. Its main use has been as a blending material with a local natural sand such as Indiana No. 17 sand. The crusher dust is a fine aggregate product resulting from the crushing of a 3/8-inch gravel by a commercial 48-inch Nordberg crusher. As received, essentially all of it passed a No. 4 sieve with about 17 percent passing a No. 200 sieve.

A sample of each sand (predominantly large sizes for observation of shape) showing aggregate shape characteristics is shown in Figures 1 and 2, respectively.

NATURAL FINE AGGREGATE

Figure 1.

CRUSHER DUST FINE AGGREGATE

Figure 2.

The coarse aggregate selected was a uniform quartzite gravel from White Marsh, Maryland. This gravel was sent to Purdue University for use in this investigation by the National Sand and Gravel Association Laboratory at the University of Maryland. Visual inspection showed this gravel to be predominantly round in shape and smooth-textured. A sample of this gravel is shown in Figure 3. It was chosen as a material uniform in shape, texture, and composition that would permit mixture strength as contributed by the fine aggregate fraction to be emphasized. The specific gravity and the absorption values of these mineral aggregates were obtained by following procedures specified in ASTM Designations C127-42 and C128-42. The test results are shown in Table 1.

Table 1.

SPECIFIC GRAVITY AND ABSORPTION OF AGGREGATE

Aggregate	Apparent Sp. Gr.	Bulk Dry Sp. Gr.	% Absorption
Quartzite Gravel	2.64	2.63	0.28
Natural Sand	2.69	2.54	2.04
Crusher Dust	2.77	2.61	2.42

QUARTZITE GRAVEL COARSE AGGREGATE

Figure 3.

A dense-graded bituminous-concrete mixture was selected on the basis that it represented a gradation within the limits of several well-known specifications, namely: Corps of Engineers' dense-graded asphaltic-concrete surface mixtures, the ASTM specification limits for bituminous-concrete mixtures, and near the lower limit of the Asphalt Institute's gradation limits for this type of mixture. The specific gradation selected was the lower limit of the Corps of Engineers' gradation for asphaltic-concrete with 3/4-in. maximum aggregate size (1) and is shown in Figure 4.

Since it was desired to investigate the sand fraction alone, a sand-asphalt mixture was selected with a gradation identical to that of the fine aggregate fraction used in the dense-graded bituminous-concrete mixtures. The material passing a No. 200 sieve from the crusher dust was used in these mixtures as mineral filler.

Table 2 gives the laboratory-controlled sieve analyses for the dense-graded bituminous-concrete and sand-asphalt mixtures.

To study the application of blending a crusher-run sand with a natural sand from the commercial viewpoint, the Indiana No. 17 sand was blended, as received, with the plant-run crusher dust, as received, in the proportions of 25, 50, 75, and 100 percent crusher dust. These fine aggregate blends were combined with the quartzite gravel in the proportion of 52 percent coarse aggregate and 48 percent fine aggregate. The gradation of each sand from laboratory sieve analyses of representative samples is shown in Table 3, along with the gradation of the

FIGURE 4
 SIEVE SIZE (LOG SCALE)

Table 2.
SIEVE ANALYSIS OF CONTROLLED DENSE-GRADED
BITUMINOUS-CONCRETE AND SAND-ASPHALT MIXTURES
(Percent by Weight)

MATERIAL	SIEVE		GRADING	
	Passing	Retained	Bit. Conc.	Sand Asph.
Coarse Aggregate	-	3/4"	0	0
	3/4"	1/2"	14	0
	1/2"	3/8"	11	0
	3/8"	1/4"	10	0
	1/4"	# 4	10	0
Fine Aggregate	# 4	#10	15	27
	#10	#40	18	33
	#40	#80	10	18
	#80	#200	8	15
Filler	#200	-	4	7

quartzite gravel. The resulting gradations of the aggregate blends were within the ASTM Specifications for Hot-Mixed, Hot-Laid Asphaltic Concrete for Base and Surface Courses (ASTM Designation: D947-54T). These gradings are shown in Table 4 and in Figure 5.

Table 3.

SIEVE ANALYSES OF CRUSHER DUST, INDIANA NO. 17 SAND
AND QUARTZITE GRAVEL
(Percent by Weight)

PASSING	RETAINED	CRUSHER DUST	INDIANA NO. 17 SAND	QUARTZITE GRAVEL
3/4"	1/2"	0	0	34.6
1/2"	3/8"	0	0	26.9
3/8"	1/4"	0.2	0	23.1
1/4"	# 4	2.6	0	15.4
# 4	#10	28.5	1.0	0
#10	#40	33.1	80.5	0
#40	#80	10.2	15.5	0
#80	#200	3.1	2.3	0
#200	-	17.3	0.7	0

Table 4.

GRADATIONS OF GRAVEL AND CRUSHER DUST - INDIANA NO. 17 SAND BLENDS
WITHIN
ASTM SPECIFICATIONS FOR BITUMINOUS-CONCRETE MIXTURES

Fine Aggregate \ Sieve Size				Percent Passing					
	3/4	1/2	3/8	1/4	4	10	40	80	200
25% - Crusher Dust 75% - Ind. No. 17	100	82.0	68.0	56.0	48.0	44.2	10.6	3.8	2.3
50% - Crusher Dust 50% - Ind. No. 17	100	82.0	68.0	56.0	47.5	40.4	12.0	5.8	4.3
75% - Crusher Dust 25% - Ind. No. 17	100	82.0	68.0	56.0	47.0	36.6	13.2	7.7	6.3
100% - Crusher Dust	100	82.0	68.0	56.0	46.5	32.8	14.5	9.6	8.3

Only one type of asphaltic cement was used throughout this investigation. It was an ASTM Penetration Grade 85-100 asphaltic paving cement obtained from the Standard Oil Company of Indiana having a penetration of 91, a specific gravity of 1.021, and a ductility at 77°F of over 150 cm.

The asphalt content used in each aggregate blend was obtained by using the Corps of Engineers' design procedure (1, 2), since the gradings generally were within their specifications.

FIGURE 5

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 for triaxial, ASTM, and Modified ASTM test specimens was kept constant, but specimen compaction procedure was varied according to the type of specimen being formed. The ASTM and Modified ASTM specimens were tested according to the standard ASTM compression test procedure (3), and the triaxial specimens were tested in a triaxial compression cell made for the purpose of these tests.

The correct amount of aggregate, combined to conform to the grading being used, 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 two minutes and then molded into specimens four inches in diameter and ten inches in height, in the case of the triaxial test, at the density determined from the Corps of Engineers' procedure and at design asphalt content. All specimens were molded by the double-plunger compaction method. The molding procedure consisted of placing the hot asphaltic-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 Richle compression-testing machine. Triaxial specimens contained the correct amount of asphaltic-aggregate mixture that, when compacted to a height of ten inches in the mold, the specimen would have the required density. An Ames dial

set-up was used to measure the ten-inch height of mixture in the mold. The load was maintained for two minutes on all specimens in the compaction procedure. The mold, containing the compacted specimen, then was placed in a circulating cold-water bath and allowed to cool from eight to twelve minutes. After cooling, the mold was replaced in the Riehle compression-testing machine, a slight load was applied to the upper plunger, and the specimen was forced to move a short distance inside the mold in order to break the adhesion between the specimen and the sides of the mold. The mold was then taken from the compaction device and the specimen removed from the mold.

Certain changes were necessitated in this procedure when forming the ASTM and Modified ASTM test specimens.

In the case of the Modified ASTM test specimens, the asphaltic-aggregate mixture was compacted to the density required as outlined. The resulting specimen of ten inches in height was sawed into two four-inch high specimens. This was achieved by cutting a two-inch section from the center of each ten-inch specimen. A "Clipper" masonry saw equipped with a diamond blade was used for this purpose. The resulting specimens were measured and found to be within $4 \pm 1/8$ inches in height.

The other phase of this study, which consisted of forming ASTM test specimens, involved several important changes in procedure for forming specimens. The amount of asphaltic-aggregate mixture was selected by a trial-and-error procedure so that the resulting height of the test specimen would be $4 \pm 1/8$ inches. The required amount of

asphaltic-aggregate mixture was placed in the mold and compacted under a constant load of 3000 psi in the Richle testing machine for two minutes (3). This differs from the procedure used for triaxial and Modified ASTM test specimens where different compactive efforts were applied to obtain a desired predetermined density.

Figure 6 shows typical ASTM and Modified ASTM test specimens.

For the triaxial test, all specimens were maintained at the testing temperature of $80 \pm 5^{\circ}\text{F}$ 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 were tested at two confining pressures, 15 and 30 psi, and the maximum compressive strengths obtained. The triaxial strength characteristics of cohesion and angle of internal friction were obtained for these mixtures from Mohr's theory of failure (4, 5, 6).

Testing of ASTM and Modified ASTM specimens did not differ in any respect from the standard ASTM procedure as outlined in "ASTM Compressive Strength Test for Bituminous Mixtures (ASTM Desig. D1074-52T)" (3). The test specimens were prepared for test after they had been cured for at least 24 hours in the oven at $140 \pm 5^{\circ}\text{F}$. After removal from the oven, the test specimens were placed in an air bath for four hours at $77 \pm 1^{\circ}\text{F}$. The specimens were loaded under at a rate of 0.2 inch per minute until the maximum compressive load was reached.

TYPICAL TEST SPECIMENS AND UNASSEMBLED MOLD
(Triaxial, Modified ASTM, ASTM and Marshall)

Figure 6.

Marshall stability values were obtained on all mixtures as a part of determining design asphalt content by Corps of Engineers' procedure. In this test, the specimens are loaded at a rate of two inches per minute at a temperature of $140 \pm 1^{\circ}\text{F}$.

Asphalt extraction tests were performed on the controlled dense-graded bituminous-concrete mixtures (Corps of Engineers' Minimum Gradation) in order to develop a possible relationship between the distribution of asphalt within these mixtures and the properties of cohesion and internal friction as compared with those in sand-asphalt mixtures.

The primary purpose of the test in this investigation was to determine the percentage of asphalt contained in both the fine-aggregate and coarse-aggregate portions of the bituminous-concrete mixtures. These test values were then used to determine a change in the distribution of asphalt between fine and coarse aggregate as the percentage of crushed-gravel fine aggregate, or crusher dust, changed in the fine aggregate fraction of the bituminous-aggregate mixture.

The asphalt extraction procedure followed closely the standard Centrifugal Method suggested by the American Association of State Highway Officials (AASHTO Designation: T59-57). This method is outlined in Reference (7).

RESULTS

Strength or stability test data were collected in this investigation on bituminous-concrete and sand-asphalt surface mixtures prepared with variable percentages of crushed-gravel fine aggregate. In addition, data were obtained on the distribution of asphalt between coarse and fine aggregate in the controlled dense-graded bituminous-concrete mixtures.

Strength or stability data from laboratory tests were obtained on sand-asphalt mixtures and two groups of bituminous-concrete mixtures that differed in gradation. The sand-asphalt mixtures and one of the groups of bituminous-concrete mixtures adhered to specific dense-gradation as the percent of crushed aggregate was varied. They were made with a laboratory-controlled crusher dust-natural aggregate gradation adhering to the Corps of Engineers' minimum specifications. The other group of bituminous-concrete mixtures contained crusher dust-natural aggregate gradations within ASTM specifications for these types of mixtures. In these latter mixtures two plant-run sands, crusher dust and Indiana No. 17 sand, were blended as received with the gravel coarse aggregate.

Mixture Density and Design Data

Mixture density and design data are given in Table 5. The data show increased values of the design asphalt content for all the mixtures as the percentage of crusher dust in the fine aggregate was increased. The sand-asphalt mixtures had the highest design asphalt contents. For

Table 5.

CORPS OF ENGINEERS' DESIGN DATA

BITUMINOUS-CONCRETE MIXTURES, CONTROLLED DENSE-GRADED						
PERCENT CRUSHER DUST	DESIGN ASPHALT CONTENT*	MARSHALL STABILITY lbs.	MARSHALL FLOW 1/100-in.	PERCENT VOIDS	PERCENT VOIDS FILLED WITH ASPHALT	UNIT WEIGHT lb/cu. ft.
0	4.6	1500	12.0	3.3	77	151.3
25	4.8	1790	11.7	3.5	75	150.9
50	4.9	2200	11.0	3.2	80	151.3
75	5.1	2190	11.8	3.2	80	151.0
100	5.5	2050	11.5	3.8	78	151.0
SAND-ASPHALT MIXTURES, CONTROLLED DENSE-GRADED						
0	6.3	860	10.0	6.0	70	144.7
25	6.6	1100	10.7	6.0	72	144.3
50	6.9	1410	11.0	5.8	73	146.5
75	7.1	2040	14.9	5.0	75	146.3
100	7.2	2425	16.0	5.5	75	145.7
CRUSHER DUST - NATURAL AGGREGATE BLENDS						
WITHIN ASTM SPECIFICATIONS FOR BITUMINOUS-CONCRETE MIXTURES						
0	-	-	-	-	-	-
25	5.4	650	15.4	3.9	74	144.1
50	5.5	1260	12.9	3.7	77	147.5
75	5.5	1720	13.2	3.0	79	148.8
100	5.6	2010	12.7	3.0	83	149.3

* Design asphalt content given in terms of percent by weight of total aggregate.

the bituminous-concrete mixtures within ASTM specifications, the design asphalt content values did not vary greatly as the amount of crusher dust was increased, and they were near the upper values for the design asphalt contents determined for the controlled dense-graded bituminous-concrete mixtures. For the controlled dense-graded bituminous-concrete and sand-asphalt mixtures, the design asphalt content increased almost one percent as the percent crusher dust was increased from 0 to 100 percent.

Marshall flow values, given in Table 5, generally show a trend of decreasing or constant values in both the controlled dense-graded and ASTM specification-type bituminous-concrete mixtures as amounts of crusher dust increased, while in the controlled dense-graded sand-asphalt mixtures the flow values increased as the percentage of crusher dust in the fine aggregate was increased.

Marshall test unit weight data are included in Table 5, and unit weight data for specimens compacted by ASTM procedure are found in Tables 8, 9, and 10 (Appendix). Figure 7 shows plots of test-specimen density versus percent crusher dust in the fine aggregate for all mixtures. There was a change in density depending upon the compaction method and the gradation of the aggregate used in the mixture.

The variation in density that resulted from the compaction method is illustrated by the plots of the density values resulting from the ASTM method of compaction and the density values resulting from the Corps of Engineers' compaction method. These density values are shown in Figure 7 and identified by ASTM notation on the one hand and Marshall,

COMPARATIVE DENSITIES OF TEST SPECIMENS VS. PERCENT CRUSHER DUST

FIGURE 7

triaxial, and Modified ASTM notation on the other. The greatest range in density of the test specimens that resulted from varying percentages of crusher dust in the fine aggregate occurred with the ASTM compaction procedure.

The type of mixture influenced density when the compaction procedure for the test specimens remained the same. The greatest density values were those that resulted from the compaction of the controlled dense-graded bituminous-concrete mixtures and the bituminous-concrete mixtures within ASTM specifications. The test specimens that consisted of bituminous-concrete mixtures within ASTM specifications had the greatest change in density when the percentage of crusher dust increased in the fine aggregate.

Figure 7 shows that density produced by ASTM compaction was less than density produced by Modified ASTM (Marshall) compaction for any given percentage of crusher dust in the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures. For the controlled dense-graded sand-asphalt mixtures, the density values of the ASTM specimens are less than the density values of the Modified ASTM test specimens up to 50 percent crusher dust in the mixture, and thereafter as the percentage of crusher dust increased from 50 to 100 percent, the density values of the ASTM test specimens were greater. For the bituminous-concrete mixtures within ASTM specifications, Figure 7 shows the density values of the test specimens compacted by ASTM procedure to be greater than the density values of the Modified ASTM test specimens when more than 50 percent of crusher dust was used in the fine aggregate.

To summarize the results shown in Figure 7, it can be said that, in general, the mixture density at design asphalt content increased with increased percentages of crusher dust in the fine aggregate for all mixtures and compaction methods.

Strength Test Results of Controlled Dense-Graded Bituminous-Concrete Mixtures

Compressive strength or stability values versus percent crusher dust in the fine aggregate are shown graphically in Figure 8 for the bituminous-concrete mixtures with controlled (Corps of Engineers¹) dense grading. The data for Figure 8 are presented in Tables 5, 6, and 8. Tables 6 and 8 are included in the Appendix.

In general, the results of the strength tests used in this investigation show increased compressive strength or stability values for these mixtures when the percentage of crusher dust in the fine aggregate was increased.

The triaxial strength data show that with a given percentage of crusher dust, the compressive strength values at lateral pressures of 30 psi were greater than those at lateral pressures of 15 psi. The compressive strength curves representing each lateral pressure had approximately the same shape, and the compressive strength values at each lateral pressure increased with an increased percentage of crusher dust in the fine aggregate.

The Marshall stability values of Figure 8 increased to a maximum load value when the percentage of crusher dust in the fine aggregate increased to fifty percent, and as the percentage of crusher dust in the fine aggregate was increased beyond fifty percent, the Marshall

COMPRESSIVE STRENGTH OR STABILITY VS. PERCENT CRUSHER DUST

BITUMINOUS-CONCRETE MIXTURES

(Controlled Dense — Graded)

FIGURE 8

stability values remained approximately the same. The Marshall stability values were lower than the compressive strength values obtained from other tests used in this investigation for any given percentage of crusher dust in the fine aggregate. However, it should be recalled that Marshall test temperature is high as compared to the test temperatures used in the other strength tests.

ASTM and Modified ASTM compressive strength data are presented in the two uppermost curves of Figure 8. Increased compressive strength values were obtained for the Modified ASTM and the ASTM test specimens when the percentage of crusher dust increased in the fine aggregate. The compressive strength values for the Modified ASTM specimens were greater than those for the ASTM specimens for any given percentage of crusher dust in the fine aggregate fraction. The difference is due to compaction. The compressive strength values for Modified ASTM and ASTM specimens were appreciably higher than the triaxial test and Marshall stability values at any given percentage of crusher dust in the fine aggregate.

Strength Test Results of Controlled Dense-Graded Sand-Asphalt Mixtures

Compressive strength or stability values versus percent crusher dust for the controlled (Corps of Engineers') dense-graded sand-asphalt mixtures are shown graphically in Figure 9. The data for Figure 9 are presented in Tables 5, 6, and 9. (For Tables 6 and 9 see Appendix.)

The results of all the tests used in this investigation on these mixtures showed increased compressive strength or stability values when

COMPRESSIVE STRENGTH OR STABILITY VS. PERCENT CRUSHER DUST

SAND-ASPHALT MIXTURES

(Controlled Dense - Graded)

the percentage of crusher dust was increased. It is apparent that the trends are the same as those for the controlled, dense-graded bituminous concrete mixtures shown in Figure 8. Also, strength values from the various tests have the same general relationship to each other, with the triaxial test curves for 15 and 30 psi again being essentially parallel. However, in this case, differences in strength values obtained on the ASTM and Modified ASTM specimens are not great, and, contrary to the bituminous concrete results, Marshall stability shows a continual increase with increases in percentages of crusher dust for those mixtures.

Strength Test Results of Bituminous-Concrete Mixtures Within ASTM Specifications

Compressive strength or stability values versus percent crusher dust in the fine aggregate are shown graphically in Figure 10 for bituminous concrete mixtures within ASTM specifications. The data for Figure 10 are presented in Tables 5, 7, and 10. (For Tables 7 and 10 see Appendix.)

The results of all the tests used in this investigation on these ASTM bituminous-concrete mixtures show increased compressive strength or stability values when the percentage of crusher dust in the fine aggregate was increased. The strength values followed the same general trends as those for the bituminous-concrete and sand-asphalt mixtures shown in Figures 8 and 9, respectively.

Strength curves from the various tests occupy the same relative positions as those of Figures 8 and 9, and the two triaxial test curves again are essentially parallel. The curves for the tests on the ASTM

COMPRESSIVE STRENGTH OR STABILITY OR STABILITY VS. PERCENT CRUSHER DUST

CRUSHER DUST-NATURAL AGGREGATE BLENDS
WITHIN ASTM SPECIFICATIONS
BITUMINOUS-CONCRETE MIXTURES

FIGURE 10

and Modified ASTM test specimens cross, as was the case for the sand-asphalt mixtures (Figure 9), and Marshall stability values increase over the whole range of percentage crusher dust used.

Comparison of Bituminous-Concrete and Sand-Asphalt Triaxial Strength Characteristics

The triaxial strength characteristics of cohesion and angle of internal friction for the bituminous surface mixtures studied in this investigation are presented in Tables 6 and 7 in the Appendix and shown graphically in Figures 11, 12, and 13.

Triaxial test results showing the relationships between cohesion and angle of internal friction and the percent of crusher dust in the fine aggregate for dense-graded bituminous-concrete mixtures are presented in Figure 11. These curves show increased values of cohesion and angle of internal friction when the percentage of crusher dust in the fine aggregate fraction was increased. Cohesion increased from 39.0 to 47.0 psi and the angle of internal friction increased from 26.1 to 38.7 degrees when the percentage of crusher dust in the fine aggregate was increased from 0 to 100 percent.

Triaxial test results showing the relationship between cohesion and angle of internal friction and percent of crusher dust for dense-graded sand-asphalt mixtures are presented in Figure 12. These curves show increased values of cohesion and decreased values of angles of internal friction when the percentage of crusher dust increased. Cohesion increased from 17.1 to 69.4 psi and the angle of internal friction decreased from 34.8 to 23.5 degrees when the percentage of crusher dust increased from 0 to 100 percent.

COHESION & ANGLE OF INTERNAL FRICTION

VS.

PERCENT CRUSHER DUST

BITUMINOUS-CONCRETE MIXTURES

FIGURE 11

COHESION & ANGLE OF INTERNAL FRICTION
VS.
PERCENT CRUSHER DUST
SAND-ASPHALT MIXTURES

FIGURE 12

COHESION & ANGLE OF INTERNAL FRICTION vs. PERCENT CRUSHER DUST

CRUSHER DUST-NATURAL AGGREGATE BLENDS
WITHIN ASTM SPECIFICATIONS
BITUMINOUS-CONCRETE MIXTURES

FIGURE 13

Triaxial test results showing the relationship between cohesion and angle of internal friction and percent of crusher dust in the fine aggregate for bituminous-concrete mixtures within ASTM specifications are presented in Figure 13. Figure 13 shows increased values of cohesion and angle of internal friction when the percentage of crusher dust in the fine aggregate was increased. Cohesion increased from 33.0 to 41.5 psi and the angle of internal friction increased from 37.4 to 40.5 degrees when the percentage of crusher dust in the fine aggregate increased from 25 to 100 percent.

Extraction Test Results

In an attempt to determine why increasing the percentage of crusher dust in the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures resulted in increased values of angle of internal friction while similar changes in the sand-asphalt mixtures had the opposite effect on friction angle, extraction tests were performed on the bituminous-concrete mixtures to determine distribution of asphalt between the fine and coarse aggregate fractions.

The data obtained from the extraction tests on the controlled dense-graded bituminous-concrete mixtures are presented in Table 11 (Appendix) and shown graphically in Figure 14. Figure 14 shows the distribution of asphalt between the coarse aggregate and fine aggregate portions of the bituminous-concrete mixtures, and the relation of this asphalt distribution to the triaxial strength characteristics of these mixtures when the percentage of crusher dust in the fine aggregate was changed.

DISTRIBUTION OF ASPHALT AND TRIAXIAL STRENGTH CHARACTERISTICS VS. PERCENT CRUSHER DUST BITUMINOUS-CONCRETE MIXTURES

FIGURE 14

The plotted data in Figure 14 show that the amount of asphalt coating the coarse aggregate decreased from 3.5 to 2.4 percent when the percentage of crusher dust increased from 0 to 75 percent. However, an increase from 75 to 100 percent of crusher dust in the fine aggregate resulted in an increase of asphalt coating the coarse aggregate from 2.4 to 3.0 percent. The amount of asphalt coating the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures increased from 5.5 to 7.6 percent when the percentage of crusher dust in the fine aggregate increased from 0 to 100 percent. However, with percentages of crusher dust from 75 to 100 percent the increase of asphalt coating the fine aggregate was relatively small (7.3 to 7.6 percent).

In Figure 14 the design asphalt contents of the controlled dense-graded sand-asphalt mixtures are plotted against percent of crusher dust in the sand. It should be repeated here that the controlled dense-graded sand-asphalt mixtures and the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures consisted of the same aggregates and aggregate gradation. The range in amounts of asphalt coating the fine aggregate when percentage of crusher dust was varied was greater in the fine aggregate fraction of the controlled dense-graded bituminous-concrete mixtures than in the controlled dense-graded sand-asphalt mixtures. The amount of asphalt coating the fine aggregate portion of the controlled dense-graded bituminous-concrete mixtures exceeded the percentage of asphalt in the sand-asphalt mixtures with percentages of crusher dust greater than 50 percent and was less with percentages of crusher dust less than 50 percent.

Figure 14 shows increased amount of asphalt coating the fine aggregate and decreased amount of asphalt coating the coarse aggregate for the controlled dense-graded bituminous-concrete mixtures when the percentage of crusher dust in the fine aggregate increased from 0 to 75 percent; at the same time, cohesion and angles of internal friction increased for these mixtures. The angle of internal friction did not increase when these mixtures contained 75 to 100 percent of crusher dust in the fine aggregate and the amount of asphalt coating the coarse aggregate increased with this increase in percentage of crusher dust.

Figure 12 shows increased cohesion and decreased angle of internal friction when the percentage of crusher dust was increased in the controlled dense-graded sand-asphalt mixtures; at the same time, Figure 14 shows the design asphalt content to have increased for these mixtures.

It is apparent from these test results that distribution of asphalt in a bituminous-concrete mixture may vary with shape and texture changes in the fine aggregate even though grading is constant. However, it seems that more work will be needed to develop a completely rational explanation for the strength changes that occurred in the bituminous-concrete and sand-asphalt mixtures with changes of percentage of crusher dust as used in this study.

SUMMARY OF RESULTS AND CONCLUSIONS

The following summary of results from this investigation are presented. The results are limited to the types of bituminous surfacing mixtures employed in this investigation and to the methods of testing described herein. Because of the scope and nature of this study, these results have not been evaluated by testing similar materials under field conditions.

1. In general, the results from the laboratory tests used showed appreciable strength increases in the mixtures studied when the percentage of crusher dust in the fine aggregate was increased, regardless of the type of mixture tested or the laboratory strength test used. However, quantitative strength increases effected by the addition of crushed fine aggregate were dependent upon the type of mixture being tested and the laboratory test employed for strength evaluation.

2. Compressive strength values that resulted from ASTM tests on ASTM and Modified ASTM test specimens were the highest strength values obtained, and were followed in decreasing order by triaxial test and Marshall stability values. These strength differences were due in part to variations in specimen size, specimen density, testing speed and testing temperature.

3. ASTM tests on ASTM and Modified ASTM test specimens resulted in compressive strength values of greater magnitude in the controlled dense-graded sand-asphalt mixtures than the lower and more equal values

that resulted from these tests on controlled dense-graded and ASTM specification-type bituminous-concrete mixtures. The compressive strength data from the triaxial test showed a lesser variance in strength values than the ASTM and Modified ASTM test data when the percentage of crusher dust varied. Marshall stability values for the controlled dense-graded bituminous-concrete mixtures varied less and were greater at small percentages of crusher dust, 0 to 50 percent, in the fine aggregate when compared to the controlled dense-graded sand-asphalt mixtures and the bituminous-concrete mixtures within ASTM specifications.

4. The presence of crusher dust in the fine aggregate increased the design asphalt content of all the mixtures studied. The greatest increase in design asphalt content due to increased percentages of crusher dust in the fine aggregate was in the controlled dense-graded bituminous-concrete and sand-asphalt mixtures; a lesser increase in design asphalt content due to increased percentages of crusher dust in the fine aggregate was observed in the bituminous-concrete mixtures where the crusher dust-Indiana No. 17 sand fine aggregate grading varied within ASTM specifications.

5. Similar compressive strength characteristics were found from the tests used in this investigation for the controlled dense-graded and ASTM specification-type bituminous-concrete mixtures. Bituminous-aggregate mixture strength was approximately duplicated for these bituminous-concrete mixtures. The design asphalt contents of the bituminous-concrete mixtures within ASTM specifications were greater than those in the controlled dense-

graded bituminous-concrete mixtures at lower percentages of crusher dust, 0 to 50 percent, in the fine aggregate; and in these two groups of mixtures with this percentage range of crusher dust in the fine aggregate, the bituminous-concrete mixtures within ASTM specifications were less densely graded than the controlled dense-graded bituminous-concrete mixtures.

6. The causes for increased compressive strength in the controlled dense-graded bituminous-concrete mixtures and the bituminous-concrete mixtures within ASTM specifications were the increased values of cohesion and the increased values of angles of internal friction which occurred with increased percentages of crusher dust in the fine aggregate.

7. The cause for the increased compressive strength in the controlled dense-graded sand-asphalt mixtures was the large increase in cohesion which occurred when the percentage of crusher dust in the fine aggregate was increased. A simultaneous decrease in the angle of internal friction had a relatively small effect on mixture strength.

8. Triaxial strength characteristics of cohesion and angle of internal friction for the controlled dense-graded bituminous-concrete mixtures studied seemed to have been influenced by the distribution of asphalt between the coarse aggregate and fine aggregate fractions of these mixtures; this distribution of asphalt was influenced by the amount of crushed-gravel fine aggregate.

Figure 14 has shown that cohesion and angle of internal friction increased when the asphalt in the coarse aggregate fraction decreased. At the same time the asphalt in the coarse aggregate fraction decreased, the asphalt in the fine aggregate fraction increased by an amount equal to the loss of asphalt in the coarse aggregate fraction. These results could be explained by a theory of bituminous-aggregate mixture strength that angle of internal friction is largely dependent upon the characteristics and amount of relatively large aggregate (coarse aggregate) in the mixture, and cohesion is largely dependent upon the characteristics of the fine aggregate and the amount of bituminous binder therein.

9. Generally, for all mixtures and compaction methods used in this investigation, except for the controlled dense-graded bituminous-concrete mixtures compacted by the Corps of Engineers' procedure, the density resulting from each compaction procedure for each mixture increased when the percentage of crusher dust in the fine aggregate increased; at the same time, the compressive strength of these mixtures increased. This increase in density seemed primarily due to the higher specific gravity and angularity of the crusher-dust fine aggregate when compared to the natural-sand fine aggregate.

10. The increased strength of bituminous surface mixtures made with crushed-gravel fine aggregate, or crusher dust, when compared to similar mixtures made with natural-sand fine aggregate, was thought to be due to the angularity and surface texture of the crushed aggregate.

11. Since, in many cases as little as 25 percent crusher dust produced a significant increase in mixture strength for those mixtures tested,

it appears that this means of providing stability increase should be given consideration in those areas where mixtures produced with natural sands lack sufficient stability.

APPENDIX

Table 6.

TRIAxIAL TEST RESULTS

BITUMINOUS-CONCRETE MIXTURES, CONTROLLED DENSE-GRADED										
Percent Crusher Dust	0		25		50		75		100	
Lateral Pressure psi.	15	30	15	30	15	30	15	30	15	30
Compressive Strength-psi.	153 157	188 193	173 181	221 213	206 196	251 241	214 208	262 260	216 220	272 262
Ave. Compressive Strength-psi.	155	190	177	217	201	246	211	261	218	267
ϕ , deg.	26.1		30.2		35.4		38.7		38.7	
c, psi.	39.0		42.7		44.5		45.0		47.0	
SAND-ASPHALT MIXTURES, CONTROLLED DENSE-GRADED										
Percent Crusher Dust	0		25		50		75		100	
Lateral Pressure psi.	15	30	15	30	15	30	15	30	15	30
Compressive Strength-psi.	107 101	138 157	162 147	188 206	198 202	238 236	215 218	255 247	232 241	263 277
Ave. Compressive Strength-psi.	104	148	155	197	200	237	217	251	237	270
ϕ , deg.	34.8		32.7		28.5		25.8		23.5	
c, psi.	17.1		33.0		51.0		59.2		69.4	

Table 7.
TRIAXIAL TEST RESULTS

CRUSHER DUST - NATURAL AGGREGATE BLENDS WITHIN ASTM SPECIFICATIONS FOR BITUMINOUS-CONCRETE MIXTURES										
Percent Crusher Dust	0		25		50		75		100	
Lateral Pressure psi.	15	30	15	30	15	30	15	30	15	30
Compressive Strength-psi.	-	-	153	207	190	238	199	217	211	251
	-	-	175	217	178	226	193	273	197	258
Ave. Compressive Strength-psi.	-	-	164	212	184	232	196	245	204	254
ϕ , deg.	-	-	37.4		38.2		40.0		40.5	
c, psi.	-	-	33.0		36.0		40.0		41.5	

Table 8.

ASTM AND MODIFIED ASTM TEST RESULTS
CONTROLLED DENSE-GRADED BITUMINOUS-CONCRETE MIXTURES

ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	223 216	259 265	284 278	325 343	380 364
Ave. Compressive Strength-psi.	219	262	281	334	372
Unit Weight lb./cu. ft.	147.1	148.5	149.1	149.7	150.5
MODIFIED ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	284 293	304 315	376 372	420 431	429 439
Ave. Compressive Strength-psi.	288	309	374	425	434
Unit Weight lb./cu. ft.	151.3	150.9	151.3	151.0	151.0

Table 9.

ASTM AND MODIFIED ASTM TEST RESULTS
CONTROLLED DENSE-GRADED SAND-ASPHALT MIXTURES

ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	261 257	334 322	427 433	495 492	570 561
Ave. Compressive Strength-psi.	259	328	430	494	566
Unit Weight lb./cu. ft.	141.0	143.2	146.5	147.5	148.0
MODIFIED ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	278 284	351 342	385 391	488 494	512 525
Ave. Compressive Strength-psi.	281	346	388	491	518
Unit Weight lb./cu. ft.	144.7	144.3	146.5	146.3	145.7

Table 10.

ASTM AND MODIFIED ASTM TEST RESULTS

CRUSHER DUST - NATURAL AGGREGATE BLENDS

WITHIN ASTM SPECIFICATIONS FOR BITUMINOUS-CONCRETE MIXTURES

ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	- -	213 205	289 303	324 328	359 340
Ave. Compressive Strength-psi.	-	209	296	326	350
Unit Weight lb./cu. ft.	-	141.7	147.5	149.0	150.3
MODIFIED ASTM TEST					
Percent Crusher Dust	0	25	50	75	100
Compressive Strength-psi.	- -	274 268	290 306	306 330	322 338
Ave. Compressive Strength-psi.	-	271	298	318	330
Unit Weight lb./cu. ft.	-	144.1	147.5	148.8	149.3

Table 11.

ASPHALT EXTRACTION TEST RESULTS
CONTROLLED DENSE-GRADED BITUMINOUS-CONCRETE MIXTURES

Percent Crusher Dust	0	25	50	75	100
Design Asphalt Content (Percent Aggregate Wt.)	4.6	4.8	4.9	5.1	5.5
Design Asphalt Content (Percent Total Mix)	4.4	4.6	4.7	4.9	5.2
Percent Asphalt in Mix Coating Coarse Aggregate	34	28	24	22	24
Percent Asphalt in Mix Coating Fine Aggregate	66	72	76	78	76
Percent Asphalt Coating Coarse Aggregate (Percent of Coarse Aggregate Wt.)	3.5	3.0	2.7	2.4	3.0
Percent Asphalt Coating Fine Aggregate (Percent of Fine Aggregate Wt.)	5.5	6.3	6.8	7.3	7.6

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