Effect of Aggregate Gradation Variation on Asphalt Concrete Mix Properties

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Six asphalt concrete mixes were tested to investigate the effects of variation in the aggregate gradation on mix properties. The asphalt contents of the mixes were maintained at the job mix design contents. The gradation variations were representative of typical construction extremes. Five gradations were tested from each mix: (a) the job mix formula (JMF) gradation, (b) a fine gradation, (c) a coarse gradation, (d) a coarse-fine gradation, and (e) a fine-coarse gradation. The fine and coarse gradations deviated from the JMF gradation by the maximum amount to the fine or coarse side. The fine-coarse and coarse-fine gradations crossed over the JMF gradation curve from the maximum fine (or coarse) amount on the largest size fraction to the maximum coarse (or fine) amount on the smallest size fraction. Properties investigated were creep stiffness, split tensile strength, resilient modulus, Marshall stability, Marshall flow, air voids, and voids in mineral aggregate. Analysis of the data revealed that the fine-coarse and coarse-fine gradation variations had the greatest impact on mix properties but that none of the variations had a significant effect on resilient modulus. The data also showed that within the range normally encountered, air void content had a greater impact on split tensile strength than did gradation variation.

All highway agencies recognize the need to control the degree of variability of asphalt pavement construction. Specifications controlling the quality of construction typically include limits of acceptability of factors such as asphalt content, density, and gradation. These limits generally have been established over many years and represent the collective experience and opinions of many engineers. Nevertheless, the relationship between mix variation and service life is not well established; however, such relationships are needed to ensure that specification limits are realistic and consistent. The relationships are also needed to establish pay adjustments for construction that does not meet the specification requirements but is not so poor that it warrants removal and replacement.

A study was performed to investigate the effect of variations in the gradation of aggregates on the properties of asphalt concrete mixes. The gradation variations tested represented the extremes for a typical construction project. The specific objectives of the study were to determine the effect of gradation variation on

1. Creep behavior as a measure of rutting resistance;
2. Split tensile strength as an indicator of fatigue resistance potential;
3. Marshall mix properties (stability, flow, air voids, and voids in mineral aggregate) as a measure of mix acceptability; and
4. Resilient modulus as the parameter controlling the AASHTO thickness design structural layer coefficient.

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SELECTION OF MIXES AND GRADATION VARIATIONS

Six asphalt concrete mixes were tested in the study. Three were surface mixes and three were binder mixes. The mixes were selected to be representative of those typically used in Arkansas. The principal difference between the mixes was in the type of coarse aggregate. Three types of coarse aggregate were used: (a) crushed limestone, (b) crushed syenite, and (c) crushed gravel. The mixes are referred to as limestone surface, limestone binder, syenite surface, syenite binder, gravel surface, and gravel binder. The job mix formulas for the mixes are listed in Table 1.

The gradation variations used in the study represented the extreme variations typically encountered in construction. To identify "typical, maximum" variations, field extraction data were obtained from 11 paving projects. Standard deviations of the gradation percentage for each sieve size were computed for each mix. From these, the typical standard deviations were selected and typical, maximum variations were calculated as three standard deviations. The variations used in the test program were based on these deviations and an examination of the actual maximum variations from the field data. The selected variations are generally about the same as the specification limits set by the Arkansas State Highway and Transportation Department (AHTD).

Each of the six mixes included in the study was tested with five variations in the aggregate gradation (Figure 1 and Table 2). For each mix, only the gradation was varied; the job mix formula asphalt content was held constant for all gradation variations. The control gradation for each mix was the job mix formula (JMF) supplied by AHTD. Two other gradations were the job mix formula plus or minus the maximum variations described. These were referred to as fine and coarse mix gradations. The remaining two gradations were crossover gradations categorized as fine-coarse and coarse-fine.

The fine-coarse gradation had the maximum gradation variation to the fine side for the largest aggregate size fraction (½ in. for surface and ¾ in. for binder) and the maximum gradation variation to the coarse side for the smallest size

TABLE 1 JOB MIX FORMULAS OF MIXES TESTED

AGGREGATE GRADATION, % PASSING AGGREGATE ONLY

SIEVE SIZE	SURFACE COURSE MIXES LIMESTONE	SURFACE COURSE MIXES SYENITE	SURFACE COURSE MIXES GRAVEL	BINDER COURSE MIXES LIMESTONE	BINDER COURSE MIXES SYENITE	BINDER COURSE MIXES GRAVEL
1"				100	100	100
3/4"	100	100	100	88	90	88
1/2"	93	93	96	66	75	69
3/8"	81	84	81	56	62	59
#4	60	61	60	43	40	44
#10	45	42	43	31	30	32
#20	36	28	31	23	25	26
#40	28	21	22	18	19	21
#80	13	12	12	10	11	11
#200	6	7	7	6	6	6
ASPHALT CONTENT, % TOTAL WT.	5.6	5.3	5.4	4.3	4.5	4.4

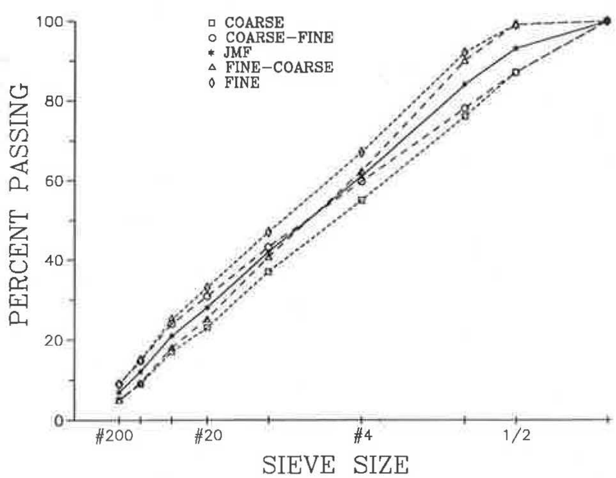

FIGURE 1 Gradation variations tested.

fraction (No. 200 sieve). The variations from the job mix formula for the other sieve sizes were prorated based on the 0.45 power gradation scale. The coarse-fine gradation was similar to the fine-coarse gradation, but the sign of the deviations from the job mix formula was reversed.

SPECIMEN PREPARATION

To control the gradation of the test specimens, all aggregates were separated into the various size fractions (e.g., ½ in. to ⅜ in., ⅜ in. to No. 4) and stored in metal buckets. When test specimens were prepared, the aggregates were recombined to provide the desired gradation with each test specimen batched separately. In the recombination, the composition of each size fraction relative to aggregate sources was held constant. Thus, if the No. 4 to No. 10 material of the job mix formula was composed of 18 percent from the coarse aggregate source, 37 percent from the coarse sand, and 45 percent from the fine sand, these same percentages were used for the No. 4 to No. 10 fraction in all gradation variations of that mix. In this manner, all effects observed from the testing are the result

TABLE 2 GRADATION VARIATIONS USED IN STUDY

CHANGE IN PERCENT PASSING FROM JOB MIX FORMULA

SIEVE SIZE	FINE	FINE-COARSE	JMF	COARSE-FINE	COARSE
		SURFACE COURSE MIXES			
1/2"	+6	+6	0	-6	-6
3/8"	+8	+5.93	0	-5.93	-8
#4	+6	+1.29	0	-1.29	-6
#10	+5	-1.24	0	+1.24	-6
#20	+5	-2.80	0	+2.80	-5
#40	+4	-2.95	0	+2.95	-4
#80	+3	-2.68	0	+2.68	-3
#200	+2	-2	0	+2	-2
		BINDER COURSE MIXES			
SIEVE SIZE	FINE	FINE-COARSE	JMF	COARSE-FINE	COARSE
3/4"	+8	+8	0	-8	-8
1/2"	+12	+7.51	0	-7.51	-12
3/8"	+12	+4.99	0	-4.99	-12
#4	+8	-0.10	0	+0.10	-8
#10	+6	-2.33	0	+2.33	-6
#20	+6	-3.85	0	+3.85	-6
#40	+5	-3.93	0	+3.93	-5
#80	+4	-3.65	0	+3.65	-4
#200	+2.5	-2.50	0	+2.50	-2.5

of variations in the gradation rather than variations in aggregate composition.

Two types of test specimens were prepared: standard Marshall specimens and 4 × 4 (4-in. diameter by 4-in. high) cylindrical specimens. The Marshall specimens were molded in accordance with AASHTO T245 using 75 blows of the compaction hammer on each face of the specimens. The 4 × 4 specimens were prepared using rodding and static compaction.

The cylindrical molds for the 4 × 4 specimens were designed to provide a fixed volume for density control. This was accomplished by having end caps that extended a fixed distance into the mold. The distance was controlled by a lip extending beyond the cap. A spacer was used with the bottom end cap to hold it partly out of the mold during rodding. In this way, both end caps were pushed into the mold during the static compaction, obtaining compaction from both ends.

In preparing the 4 × 4 specimens, the amount of mix required to produce a specimen with 5 percent air voids was weighed out and divided into thirds. Each third was placed in the mold and rodded in place. After all three layers had been rodded, compaction was completed on a compression test device by pushing the end caps until the volume control lips were seated on the mold. The objective was to produce specimens with 5 percent air voids that were uniform top to bottom. As will be shown, this objective was not achieved.

MARSHALL SPECIMEN TESTING

Four Marshall specimens were made of each gradation variation for each mix. These specimens were tested for air voids, voids in mineral aggregate (VMA), Marshall stability, Marshall flow, and resilient modulus. Air voids and VMA were

determined based on specimen bulk specific gravities (AASHTO T166) and Rice maximum specific gravities (AASHTO T209).

Resilient modulus was determined using the diametral test developed by Schmidt (*1*). The test temperature was 77°F. The dynamic pulse load was 75 lb, and the radial displacement due to the load was measured at 0.05 sec of loading. Measurements were made on three axes 120 degrees apart, and the average was used as the specimen resilient modulus.

4 × 4 SPECIMEN TESTING

Two 4 × 4 specimens were made for each gradation variation. These specimens were used for creep testing and split tensile strength testing.

The creep testing was conducted at 104°F using the resilient modulus apparatus operated in a static load mode with the specimen loaded in the axial direction. The specimens were placed in an oven set at 104°F for at least 24 hr before testing. For temperature control during testing, an insulated chamber was placed on the test apparatus around the loading head. Temperature was controlled using a thermal couple temperature probe, which was attached as a thermostat to a hair dryer. The test specimens were stored in the chamber at least 1 hr before testing for temperature stabilization.

The top and bottom surfaces of the specimens were coated with graphite before testing to reduce surface friction. Before creep testing, each specimen was conditioned with a set loading history to reduce any influence caused by small surface irregularities. The conditioning consisted of applying the creep loading (15 psi) for 10 min followed by 10 min of no load.

The creep load (15 psi) was then applied for 1 hr with the creep deformation being measured at 5 sec, 30 sec, 2 min, 30 min, and 60 min. The creep stiffness was calculated for each interval as

$$Sx = l*h/d$$

where

Sx = creep stiffness at time x;
l = creep loading stress (15 psi);
h = original height of specimen; and
d = specimen vertical deformation at time x.

After creep testing, each 4 × 4 specimen was sawed in half to provide two specimens for the split tensile strength test. The split tensile strength was determined at 77°F using the Marshall test apparatus but with the Marshall breaking head replaced by loading caps that would apply the diametral load over ½-in. bearing width. The rate of loading was the same as the Marshall loading rate, 2 in./min.

ANALYSES OF MARSHALL SPECIMEN DATA

Methods of Analysis

The data from testing the Marshall specimens were analyzed to identify the effect of gradation variation. Two types of analyses were used: analysis of variance and *t*-test groupings.

Analysis of variance examines the variation in the test parameters (i.e., air voids, VMA, stability, flow, and resilient modulus). It compares the variation observed between replicate mix specimens with the variation observed between mix specimens having different gradations. If gradation has no effect, the degree of variation will be the same for replicate specimens and for specimens of different gradation. However, if gradation does affect the value of the test parameter, the degree of variation for all the test specimens will be greater than the degree of variation for test specimens from a single gradation.

The measure of statistical significance in the analysis of variance is the *F*-ratio. The level of significance is indicated by the probability of finding a higher *F*-ratio if, in fact, no effect due to gradation exists. Low probabilities of a higher *F*-ratio indicate a high probability of an effect attributable to gradation. In this study, probabilities less than 0.05 indicated a statistically significant effect due to gradation.

Analysis of variance provides a statistical determination of whether the test parameter values have differences that might be caused by the gradation variation. However, if differences are identified, analysis of variance does not indicate where those differences occur (i.e., which gradations cause the differences). To make this type of determination, the *t*-test groupings were used.

The *t*-test groupings examine the mean values of the test parameters relative to the various mix gradation categories. The means are compared one by one using the standard *t*-test. Based on the individual comparisons, the gradations are placed in groups having similar means. The separation of the various gradations into two or more groups indicates a significant difference between the mean values of the test parameter being examined. This, then, indicates an effect attributable to the gradation variation.

These two methods were used to analyze the Marshall specimen data from each of the mixes individually and to analyze all of the data together. When all of the data were analyzed together, the analysis of variance was performed to identify effects attributable to the type of aggregate (limestone, gravel, and syenite) and the type of mix (surface and binder).

Air Void Analyses

Analysis of variance showed that air voids were affected by gradation variation, mix type, and aggregate type (Table 3). The *t*-test groupings showed that the fine-coarse gradation had the highest air voids and the coarse-fine mix had the lowest (Table 4). The other gradation variations (fine, coarse, and JMF) tended to have nearly equal air void contents.

These data show that the crossover gradation variations (coarse-fine or fine-coarse) have the greatest effect on air voids. Gradation variations that tend to parallel the job mix gradation do not cause significant changes in the mix air void contents. However, gradation variations that cross from coarse on the large size fractions to fine on the small size fractions cause a significant decrease in air voids. Conversely, gradation variations that cross from fine to coarse cause an increase in the air voids. For the mixes tested, the coarse-fine gradation would be judged to be most detrimental because it resulted in unacceptably low air void contents.

TABLE 3 AIR VOIDS, ALL MARSHALL SPECIMENS: ANALYSIS OF VARIANCE

ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob. of > F
Gradation (G)	4	60.102	15.025	84.99	0.0001
Aggregate (A)	2	29.119	14.559	82.35	0.0001
Mix Type (M)	1	7.047	7.047	39.86	0.0001
G*A	8	4.450	0.556	3.15	0.0035
G*M	4	1.061	0.265	1.50	0.2088
A*M	2	2.347	1.173	6.64	0.0020
G*A*M	8	4.913	0.614	3.47	0.0016
Error	90	15.911	0.177		
Total	119	124.950			

The level of significance is indicated by the probability of greater F. Probabilities less than 0.05 are generally judged as being indicative of a significant effect.

TABLE 4 AIR VOIDS, ALL MARSHALL SPECIMENS: T-TEST GROUPINGS

T Grouping	Mean (%)	Gradation Variation
A	3.591	FINE-COARSE
B	2.298	FINE
B	2.202	JOB MIX FORMULA
B	2.126	COARSE
C	1.405	COARSE-FINE

Means in the same T Grouping are not significantly different at alpha equal to 0.05.

VMA Analyses

Analyses of the VMA data produced results nearly identical to the air void analyses. VMA content was found to be affected by gradation variation, mix type, and aggregate type (Table 5). The *t*-test groupings showed that the fine-coarse gradation had the highest VMA and the coarse-fine had the lowest (Table 6). The other gradation variations (fine, coarse, and JMF) tended to have nearly equal VMA contents.

Similarly, to the air void analyses, the crossover gradation variations (coarse-fine or fine-coarse) had the greatest effect on VMA. No significant changes in VMA were observed for gradation variations that tend to parallel the job mix gradation. However, coarse-fine gradations caused a significant decrease in VMA, and fine-coarse gradations caused an increase in VMA. The coarse-fine gradation would be judged to be most detrimental because it resulted in an unacceptably low VMA content.

TABLE 5 VMA, ALL MARSHALL SPECIMENS: ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob. of > F
Gradation (G)	4	45.101	11.275	83.23	0.0001
Aggregate (A)	2	17.834	8.917	65.82	0.0001
Mix Type (M)	1	226.051	226.051	1668.61	0.0001
G*A	8	4.712	0.589	4.35	0.0002
G*M	4	0.877	0.219	1.62	0.1764
A*M	2	1.718	0.859	6.34	0.0027
G*A*M	8	3.548	0.443	3.27	0.0025
Error	90	12.193	0.135		
Total	119	312.033			

The level of significance is indicated by the probability of greater F. Probabilities less than 0.05 are generally judged as being indicative of a significant effect.

TABLE 6 VMA, ALL MARSHALL SPECIMENS: T-TEST GROUPINGS

T Grouping	Mean (%)	Gradation Variation
A	14.721	FINE-COARSE
B	13.575	FINE
B	13.508	JOB MIX FORMULA
B	13.454	COARSE
C	12.829	COARSE-FINE

Means in the same T Grouping are not significantly different at alpha equal to 0.05.

Stability Analyses

Analysis of variance of the Marshall stability data from all the mixes showed significant effects due to gradation, aggregate type, and mix type (Tables 7 and 8). In general, the fine gradation had the highest stability and the fine-coarse gradation had the lowest stability.

These trends, however, were not observed in every mix. The highest stability occurred with the fine gradation in five of the six mixes; the stability was second highest in the sixth mix. Similarly, the fine-coarse gradation had the lowest stability in four of the six mixes and was second lowest in the other two.

The stabilities of all the mixes were quite high, and the lowest stabilities observed would not indicate a mixture problem. Consequently, the effect of gradation variation on the stability of these mixes did not appear to be significant.

Flow Analyses

Marshall flow was also found to be affected by gradation, aggregate type, and mix type (Tables 9 and 10). The *t*-test groupings showed that for five of the six mixes, the coarse-fine gradation had the highest flow and the fine-coarse gradation had the lowest flow. The other gradation variations (fine, JMF, and coarse) did not show any consistent pattern.

The *t*-test grouping analysis for all the data showed the flow data to fit into three gradation groups. The coarse-fine gradations were alone in the high flow group, and the fine-coarse gradations were alone in the low flow group. The other gradations were grouped together.

TABLE 7 STABILITY DATA, ALL MARSHALL SPECIMENS: ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob. of > F
Gradation (G)	4	12869657	3217414	25.70	0.0001
Aggregate (A)	2	18954544	9477272	75.69	0.0001
Mix Type (M)	1	9403521	9403521	75.10	0.0001
G*A	8	2741912	342739	2.74	0.0095
G*M	4	1249571	312393	2.50	0.0484
A*M	2	4854283	2427141	19.39	0.0001
G*A*M	8	1550071	193759	1.55	0.1522
Error	90	11268529	125206		
Total	119	62892086			

The level of significance is indicated by the probability of greater F. Probabilities less than 0.05 are generally judged as being indicative of a significant effect.

TABLE 8 STABILITY DATA, ALL MARSHALL SPECIMENS: T-TEST GROUPINGS

T Grouping	Mean (lb)	Gradation Variation
A	4206.7	FINE
A & B	3966.5	COARSE-FINE
B & C	3807.3	JOB MIX FORMULA
C & D	3471.8	COARSE
D	3302.8	FINE-COARSE

Means in the same T Grouping are not significantly different at alpha equal to 0.05.

TABLE 9 FLOW DATA, ALL MARSHALL SPECIMENS: ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob. of > F
Gradation (G)	4	221.686	55.421	19.76	0.0001
Aggregate (A)	2	86.565	43.283	15.43	0.0001
Mix Type (M)	1	71.765	71.765	25.59	0.0001
G*A	8	70.329	8.791	3.13	0.0036
G*M	4	33.529	8.382	2.99	0.0229
A*M	2	25.817	12.909	4.60	0.0125
G*A*M	8	15.674	1.959	0.70	0.6920
Error	90	252.430	2.805		
Total	119	777.795			

The level of significance is indicated by the probability of greater F. Probabilities less than 0.05 are generally judged as being indicative of a significant effect.

TABLE 10 FLOW DATA, ALL MARSHALL SPECIMENS: T-TEST GROUPINGS

T Grouping	Mean (.01")	Gradation Variation
A	15.893	COARSE-FINE
B	13.858	JOB MIX FORMULA
B	13.554	FINE
B	13.346	COARSE
C	11.633	FINE-COARSE

Means in the same T Grouping are not significantly different at alpha equal to 0.05.

Thus, similarly to the air void and VMA data, the flow data suggest that gradation variations that parallel the job mix gradation do not significantly affect the mix. The crossover variations that change the shape of the gradation curve do have a significant effect. The flow values of some of the coarse-fine gradations approached and exceeded the maximum value generally considered to be acceptable for heavy traffic conditions.

Resilient Modulus Analyses

Analysis of variance found no significant differences in the resilient modulus values that might be attributed to the gradation variation (Tables 11 and 12). Analysis of all the data indicated significant effects attributable to aggregate type and mix type but no significant effect caused by gradation. Overall, within the range used in this study, gradation variation appeared to have little effect on the resilient modulus of the mix.

TABLE 11 RESILIENT MODULUS DATA, ALL MIXES: ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob. of > F
Gradation (G)	4	54785	13696	1.43	0.2298
Aggregate (A)	2	521449	260724	27.27	0.0001
Mix Type (M)	1	4443671	4443671	464.71	0.0001
G*A	8	283344	35418	3.70	0.0009
G*M	4	52188	13047	1.36	0.2526
A*M	2	275998	137999	14.43	0.0001
G*A*M	8	266125	33266	3.48	0.0015
Error	90	860602	9562		
Total	119	6758162			

The level of significance is indicated by the probability of greater F. Probabilities less than 0.05 are generally judged as being indicative of a significant effect.

TABLE 12 RESILIENT MODULUS DATA, ALL MIXES: T-TEST GROUPINGS

T Grouping	Mean, ksi	Gradation Variation
A	812	JOB MIX FORMULA
A	809	FINE
A	803	COARSE
A	780	COARSE-FINE
A	755	FINE-COARSE

Means in the same T Grouping are not significantly different at alpha equal to 0.05.

ANALYSES OF 4 × 4 SPECIMEN DATA

Methods of Analysis

The data from the 4 × 4 specimens were analyzed in much the same manner as the data from the Marshall specimen. However, analysis of covariance was used in lieu of analysis of variance for some of the analyses.

Analysis of covariance is quite similar to analysis of variance except that it is used when some of the variables being analyzed are continuous, measured values rather than classifications. Gradation category, aggregate type, and mix type are all classification variables. Data from a given mix fit into specific categories of gradation, mix, and aggregate. Air void content, on the other hand, is a measured value that covers a continuous range.

Because air voids could not be controlled precisely but have a strong impact on strength, the analyses of the 4 × 4 specimen data included examination of the effects of air voids. The analysis of covariance was used, which in effect provides a means to compensate for the influence of differences in air void contents.

The analyses of covariance listings are somewhat different than the analyses of variance listings. The analyses of covariance show both Type I and Type III sums of squares. The Type I sums of squares pertain to the model analysis, and the corresponding F ratios relate to the significance of the mix parameters as they are added sequentially in the analysis. In this respect, they do not necessarily reflect the level of significance for the individual parameters (i.e., gradation, mix type, or aggregate type). The Type III sums of squares and corresponding F ratios provide a measure of the significance of the individual parameters.

Like it is in the analysis of variance, the measure of statistical significance in the analysis of covariance is the *F*-ratio. However, for the individual mix parameters, the *F*-ratio from the Type III sums of squares should be examined.

The analysis of covariance was used primarily with the split tensile strength data. Preliminary analyses of the creep data using analysis of covariance revealed that air void variation did not have a significant effect on the creep stiffnesses. Therefore, analysis of variance was used and is reported for the creep data.

The *t*-test groupings were again used to examine the mean values of the test parameters relative to the various mix gradation categories. In addition, the split tensile strength data were examined with the mean strengths adjusted for the effects of density.

These methods of analysis were used to analyze the 4 × 4 specimen data from each of the mixes individually and to analyze all of the data together. When all of the data were analyzed together, the analysis was performed to identify effects attributable to the type of aggregate (limestone, gravel, and syenite) and the type of mix (surface and binder).

Split Tensile Strength Analyses

Analysis of covariance showed split tensile strength to be affected by gradation variation and air void content (Table 13). Aggregate type and mix type were not found to be significant as individual parameters, but the interaction between them ($A*M$) was found to be significant. An examination of the strength data reveals the reason for this finding. With the limestone and gravel aggregate, the binder mixes had higher strengths than the surface mixes. However, the surface mix was stronger with the syenite aggregate. Also, the syenite aggregate had the highest strength for surface mixes but the lowest for binder mixes.

The *t*-test groupings from all the data show the JMF gradation to have the highest strength (Table 14). The coarse gradation has the lowest strength and is grouped alone, indicating that its strength is significantly lower than any of the other gradation variations. In the individual mix analyses, JMF was found to have the highest strength for four of the six mixes, and coarse was found to be lowest for five of the six. However, because of the very strong influence of air void content on strength, additional analyses were performed to compensate for the influence of differences in air void content.

This testing was done by performing regression analyses on the data for each gradation variation. These analyses produced a series of equations that predict the split tensile strength for any given air void content. The regression equations and the predicted strengths for air void contents of 4 to 7 percent are shown in Table 15. At 6 and 7 percent air voids, the fine gradation is predicted to have the highest strength and the JMF gradation the second highest. The coarse gradation has the lowest predicted strength at each air void content.

TABLE 13 SPLIT TENSILE STRENGTH DATA, ALL MIXES: ANALYSIS OF COVARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob. of > F
Model					
Gradation (G)	4	6781.7	1695.4	15.02	0.0001
Aggregate (A)	2	9084.8	4542.4	40.25	0.0001
Mix Type (M)	1	3809.4	3809.4	33.75	0.0001
G*A	8	1253.1	156.6	1.39	0.2131
G*M	4	591.6	147.9	1.31	0.2725
A*M	2	5632.7	2816.4	24.95	0.0001
G*A*M	8	696.9	87.1	0.77	0.6284
Air Voids	1	19022.5	19022.5	168.55	0.0001
Error	87	9818.7	122.9		
Total	117	56691.5			
TYPE III SUM OF SQUARES					
Gradation (G)	4	9864.2	2466.0	21.85	0.0001
Aggregate (A)	2	25.5	12.7	0.11	0.8935
Mix Type (M)	1	25.7	25.7	0.23	0.6347
G*A	8	371.1	46.4	0.41	0.9115
G*M	4	1064.5	266.1	2.36	0.0597
A*M	2	3800.2	1900.1	16.84	0.0001
G*A*M	8	703.4	87.9	0.78	0.6222
Air Voids	1	19022.5	19022.5	168.55	0.0001

The level of significance is indicated by the probability of greater F. The Type III sum of squares is indicative of individual effects. Probabilities less than 0.05 are generally judged as being indicative of a significant effect.

TABLE 14 SPLIT TENSILE STRENGTH DATA, ALL MIXES: T-TEST GROUPINGS

T Grouping	Mean (psi)	Gradation Variation
A	144.1	JOB MIX FORMULA
A & B	139.0	COARSE-FINE
B & C	134.8	FINE
C	129.5	FINE-COARSE
D	122.0	COARSE

Means in the same T Grouping are not significantly different at alpha equal to 0.05.

TABLE 15 SPLIT TENSILE STRENGTHS ADJUSTED FOR AIR VOID CONTENT

Gradation Variation	Mix Air Void Content 4%	5%	6%	7%
	Predicted Split Tensile Strength, psi			
JMF	181	164	148	132
FINE	172	161	150	139
FINE-COARSE	171	158	144	130
COARSE-FINE	167	154	140	126
COARSE	142	133	124	114

Prediction Equation: ST = a + b*AV

where ST = predicted strength
a & b = regression constants that have the following values

	a	b
JMF	245.8	-16.30
FINE	215.5	-10.92
FINE-COARSE	226.0	-13.65
COARSE-FINE	222.7	-13.81
COARSE	180.1	- 9.41

(R^2 = .74, Std. Error of Est. = 11.7)

There is some question about the legitimacy of the air void adjustment. If the air void differences were caused by the gradation variations, the adjustments should not have been made. However, because of manner in which these specimens were made (static compaction to a controlled volume), they were all expected to have the same air void content. Consequently, the air void differences can only be attributed to laboratory procedures, so the adjustments are considered appropriate. In retrospect, a better approach might have been to prepare the specimens using a fixed compactive effort. Any air void variation could have been attributed to gradation variation, and no adjustment for air voids would have been needed.

Creep Data Analyses

Preliminary analyses of the creep data examined the effect of air voids. These analyses showed that air void content variation was not a significant factor relative to creep stiffness. As an example, the analysis of covariance for the 60-min creep stiffness for all the data had a probability of greater F of 0.1474 (Table 16). Similar results were obtained for each of

TABLE 16 ANALYSIS OF COVARIANCE OF 60-MIN CREEP DATA

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob. of > F
Model					
Gradation (G)	4	2933400	733350	2.84	0.0421
Aggregate (A)	2	24890594	12445297	48.21	0.0001
Mix Type (M)	1	372740	372740	1.44	0.2392
G*A	8	3493348	436668	1.69	0.1430
G*M	4	287244	71811	0.28	0.8897
A*M	2	800213	400107	1.55	0.2293
G*A*M	8	6545629	818204	3.17	0.0105
Air Voids	1	572154	572154	2.22	0.1474
Error	29	7486454	258154		
Total	59	47381776			
TYPE III SUM OF SQUARES					
Gradation (G)	4	3026974	756744	2.93	0.0376
Aggregate (A)	2	2947324	1473662	5.71	0.0081
Mix Type (M)	1	139284	139284	0.54	0.4685
G*A	8	4065483	508185	1.97	0.0871
G*M	4	566694	141673	0.55	0.7013
A*M	2	538552	269276	1.04	0.3652
G*A*M	8	7063870	882984	3.42	0.0069
Air Voids	1	572154	572154	2.22	0.1474

The level of significance is indicated by the probability of greater F. The Type III sum of squares is indicative of individual effects. Probabilities less than 0.05 are generally judged as being indicative of a significant effect.

the other time intervals and in the analyses of the data from the individual mixes.

Subsequent analyses tested variance and examined the influence of gradation variation, aggregate type, and mix type. Tables 17 and 18 show the analyses for the 60-min creep stiffness. The analysis of variance shows that gradation variation and aggregate type had a significant effect on creep stiffness but that mix type was not significant. Analyses of the creep stiffnesses at the other time intervals were similar except gradation was not significant at the 5-sec interval and mix type was significant at 2 min, 30 sec, and 5 sec.

For each time interval, the *t*-test groupings for all the data show that the JMF had the highest creep stiffness and the coarse-fine and fine-coarse gradations had the lowest creep stiffness. Fine and coarse had about the same stiffness and alternated with one another for second and third highest. Thus, similarly to the results from the Marshall specimens, the crossover gradation variations were found to have greater impact on the properties of the mix than do gradation variations that result simply in a finer or coarser mix.

However, the differences between creep stiffnesses for the various gradations are not great and the relative rankings are not consistent when the data from the individual mixes are examined. At the 60-min, 30-sec, and 5-sec intervals, four gradations were placed in a single group, indicating no significant difference. When the individual mixes were examined, JMF is found to have the highest creep stiffness in only two cases; coarse-fine is lowest or second lowest in four cases; and fine-coarse is lowest or second lowest in only three cases.

Comments on Air Voids

Although this study was not intended to study the effect of air voids, the inability to control the air voids in the 4 × 4 specimens and the impact of air voids on the test results warrant comment. The 4 × 4 specimens were molded in a manner intended to produce uniform specimens of controlled (5 percent) air void content. Examination of the creep data showed that the control of air voids was not successful. After the creep testing, the 4 × 4 specimens were sawed in half and used for the split tensile testing. The split tensile data showed that the specimens were also not uniform. In all cases, the top half of the specimen had lower air voids than did the bottom half. The top half also always had the higher split tensile strength.

Regression analysis of all the split tensile strength data showed that, in general, a 1 percent decrease in air voids results in a 12.7 psi increase in split tensile strength. For the individual gradation variations (Table 15), this effect ranged from 9.4 psi/percent for the coarse gradations to 16.3 psi/percent for the JMF gradations. This suggests that, within the typical range of variation encountered on asphalt construction projects, split tensile strength is more sensitive to the density achieved than it is to gradation variation.

TABLE 17 60-MIN CREEP DATA, ALL MIXES: ANALYSIS OF VARIANCE

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	Prob. of > F
Gradation (G)	4	2933400	733350	2.73	0.0475
Aggregate (A)	2	24890594	12445297	46.33	0.0001
Mix Type (M)	1	372740	372740	1.69	0.2481
G*A	8	3493348	436668	1.63	0.1592
G*M	4	287244	71811	0.27	0.8966
A*M	2	800213	400107	1.49	0.2417
G*A*M	8	6545629	818204	3.05	0.0125
Error	30	8058608	268620		
Total	59	47381776			

The level of significance is indicated by the probability of greater F. Probabilities less than 0.05 are generally judged as being indicative of a significant effect.

TABLE 18 60-MIN CREEP DATA, ALL MIXES: T-TEST GROUPINGS

T Grouping	Mean, psi	Gradation Variation
A	5994	JOB MIX FORMULA
A & B	5702	FINE
A & B	5680	COARSE
B	5442	COARSE-FINE
B	5367	FINE-COARSE

Means in the same T Grouping are not significantly different at alpha equal to 0.05.

RELATIVE LIFE EFFECTS

The split tensile strength and creep tests were performed to provide data that could be used to examine the relative effects of gradation variation on the life of an asphalt pavement. The relative life analyses were to follow procedures established by Elliott and Herrin (*2*). Because the various gradations were examined relative to the job mix formula, the JMF gradation was assigned a relative life of 100 percent.

Fatigue Life Analyses

The split tensile strength data were to be used to estimate the effect of gradation variation on the fatigue life of an asphalt pavement. The fatigue procedure is based on work by Maupin and Freeman (*3*), who showed that the split tensile strength can provide a reasonable estimate of the fatigue properties of a mix. Using Maupin's relationships, Elliott and Herrin developed the following relative life equation:

$$\log (Na/Nb) = SF * (ST_a - ST_b)$$

where

Na/Nb = relative life ratio for two mix variations (a and b);
ST_a and ST_b = split tensile strengths of the two mix variations; and
SF = strain factor, which Elliott and Herrin found to be 0.0163 for typical asphalt pavements.

The relative life equation was applied to the mean strength data and to the split tensile strengths adjusted for air void content. Table 19 shows the relative life predictions based on the mean strength data and on the strengths predicted for 5 percent air voids, which was the target air void content for the study. The relative life predictions for air void contents of 4 to 7 percent are shown in Figure 2.

These results indicate that the relative life prediction is quite sensitive to variations in split tensile strength. They show that the coarse gradation variation can be expected to have a significantly greater detrimental impact on fatigue life than do the other variations. The results also suggest that, within the

TABLE 19 RELATIVE FATIGUE LIFE ANALYSES USING MEAN STRENGTH DATA AND PREDICTED STRENGTH AT 5 PERCENT AIR VOIDS

Gradation Variation	Mean Strength	Relative Life	Predicted Strength, 5% AV	Relative Life
JMF	144 psi	100%	164 psi	100%
FINE	139 psi	83%	161 psi	88%
FINE-COARSE	135 psi	71%	158 psi	78%
COARSE-FINE	130 psi	58%	154 psi	67%
COARSE	122 psi	44%	133 psi	31%

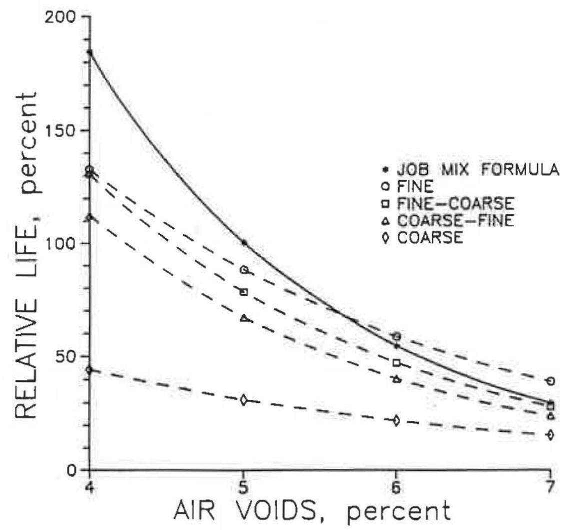

FIGURE 2 Effects of gradation and air void variations on relative fatigue life.

normal range of air void and gradation variation, fatigue life is generally more sensitive to air void content (i.e., compaction) than it is to gradation.

Rut Depth Analyses

The creep data were to be used to examine relative life effects in terms of rut development. The simple creep data are used in the Shell method (*4*) of asphalt pavement design to predict rutting in asphalt layers. In its simplest form, the Shell rut prediction equation is

$$RD = h * s/S_{mix}$$

where

RD = predicted depth of rutting,
h = thickness of asphalt layer,
s = average load-induced stress in the layer, and
S_{mix} = stiffness of mix at total (accumulated) time of all axle loadings applied.

The stiffness of the mix used in the prediction is for the mix at a temperature representative of local climatic conditions and at the accumulated total time of heavy vehicle applications. The stiffness is selected based on a relationship developed from the simple creep test between the stiffness of the mix and the stiffness of the asphalt cement.

Shell has shown that a linear logarithmic relationship exists between mix stiffness and asphalt stiffness. The specific relationship for a given mix is developed by (a) measuring the mix stiffness at various time intervals using the simple creep test, (b) determining the asphalt stiffness at those time intervals and the creep test temperature using Van der Poel's nomograph (*4*), and (c) performing a best fit linear logarithmic regression analysis on the stiffness values.

In the rut depth prediction for a given mix, the total time of axle loading and the representative mix temperature are determined. These are used with Van der Poel's nomograph to determine the asphalt cement stiffness. This asphalt mix stiffness is then used with the linear logarithmic relationship to determine the mix stiffness that goes into the rut depth prediction equation.

The data from this study were analyzed to develop the "typical" linear logarithmic relationships for each gradation variation. The resulting relationships were subsequently used with the Shell method of rut prediction to examine the effect of the gradation variations on rut development in a 6-in. asphalt layer.

The results of the rut depth analyses are shown in Table 20. The table shows the relative depth of rutting for the two traffic levels (1 million and 50 million axle applications). These analyses indicate that, in comparison with the JMF gradation, the fine and coarse gradation variations would experience 7 to 10 percent greater depth of rutting, and the coarse-fine and fine-coarse gradation variations would experience 13 to 19 percent greater depth of rutting.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This study investigated the effect of aggregate gradation variation on the behavior of asphalt concrete hot mixes. The study was specifically aimed at the effects of typical construction variability. As a result, the gradation variations tested were selected to represent the extremes typically encountered on actual construction projects. If the study had been directed toward a more general determination of gradation effects, a

TABLE 20 RELATIVE RUT DEPTH PREDICTION ANALYSES

	DEPTH OF RUTTING TO FIXED NUMBER OF AXLE LOADS			
	One Million Axle Loads		Fifty Million Axle Loads	
Gradation Variation	Rut Depth	% of JMF	Rut Depth	% of JMF
JOB MIX FORMULA	.160"	100	.210"	100
FINE	.172"	107	.230"	109
COARSE	.172"	107	.232"	110
COARSE-FINE	.180"	113	.246"	117
FINE-COARSE	.186"	116	.249"	119

	PREDICTED APPLICATIONS TO FIXED DEPTH OF RUTTING			
	Rut Depth = .160"		Rut Depth = .210"	
Gradation Variation	Applications	% of JMF	Applications	% of JMF
JOB MIX FORMULA	1,000,000	100	50,000,000	100
FINE	401,000	40	14,960,000	30
COARSE	389,000	39	13,540,000	27
COARSE-FINE	226,000	23	6,810,000	14
FINE-COARSE	165,500	17	5,360,000	11

wider range of gradation would have been tested. In particular, wider ranges of the fine aggregate fractions would have been used because these fractions generally control the mix behavior.

Six mixes were tested: three surfaces and three binders. Each mix was tested at five different aggregate gradations (Figure 1): (a) the job mix formula (JMF); (b) a coarse gradation (coarse); (c) a fine gradation (fine); (d) a gradation that crossed from coarse on the large size fractions to fine on the small size fractions (coarse-fine); and (e) a gradation that crossed from fine on the large size fractions to coarse on the small size fractions (fine-coarse). The job mix formula asphalt content was used with all gradation variations.

The measures of effect were the Marshall mix design parameters (i.e., stability, flow, air voids, and VMA), resilient modulus, tensile strength, and creep stiffness. The tensile strength data and creep stiffness data were used to estimate the relative pavement life effects of the variations.

Based on analysis of the data from this study, the following conclusions are in order:

1. Gradation variations within the magnitude tested have the greatest effect when they result in a change in the general shape of the gradation curve (the fine-coarse and coarse-fine gradations).

2. Fine-coarse gradation variations cause the highest Marshall air voids and VMA. Coarse-fine gradation variations cause the lowest Marshall air voids and VMA.

3. Coarse-fine gradation variations produce the highest Marshall flow and fine-coarse gradation variations produce the lowest.

4. Creep stiffness is lowest for coarse-fine and fine-coarse gradation variations.

5. Relative to air voids, VMA, and flow, the coarse-fine gradation produced the most detrimental effect on the mixes tested. Some of the air void and VMA values were less than those normally considered to be acceptable, and some of the flow values were greater than those normally acceptable.

6. Marshall stability is affected by gradation variations with the fine gradations producing the highest stability and the fine-coarse gradations producing the lowest. However, for the mixes tested, all of the gradations were found to have stabilities that are considered to be more than adequate.

7. Coarse gradation variations produce the lowest tensile strengths. The JMF gradation generally produced the highest strength, but when adjusted for differences in air voids, all gradations except coarse had about the same strength.

8. Within the range of variations normally encountered, tensile strength is more sensitive to air void content (i.e., compaction) than it is to gradation variation.

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