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EFFECT OF SUPERPAVE DEFINED RESTRICTED ZONE ON HOT MIX ASPHALT PERFORMANCE

Submitted by

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ABSTRACT

The effect of the Superpave defined restricted zone on HMA rutting performance was evaluated. One gradation that violated the restricted zone (TRZ) and two gradations that did not violate the restricted zone (BRZ and ARZ) were evaluated. Mixes evaluated represented a range of maximum aggregate sizes (MAS), design traffic levels, and aggregate types. Three laboratory tests, Asphalt Pavement Analyzer, Rotary Loaded Wheel Tester, and Marshall test, were used to evaluate the rutting performance.

From the analysis, it was found that mixes having gradations violating the restricted zone performed similarly to or better than the mixes with gradations passing outside the restricted zone with respect to laboratory rutting tests. This conclusion was drawn from the results of experiments with 12.5 mm, 19.0 mm and 25.0 mm MAS gradations at Ndesign values of 100, 75, and 50 gyrations. This conclusion is confirmed and supported by a recently completed National Cooperative Highway Research Program project - NCHRP 9-14: "The Restricted Zone in the Superpave Aggregate Gradation Specification." The results also showed that rutting performance of mixes having gradations below the restricted zone, which was commonly recognized to be rut-resistant, appears more sensitive to aggregate properties than do mixes having gradations above or through the restricted zone.

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INTRODUCTION

The Strategic Highway Research Program's (SHRP's) asphalt research was aimed at the properties of asphalt binders and paving mixes and their effect on asphalt pavement performance. The study of aggregate properties (including gradations) was intentionally excluded from the asphalt program. However, SHRP researchers recommend a set of aggregate gradation specifications without the benefit of experimental data.

SHRP formed an Aggregate Expert Task Group (ETG) to develop recommendations for aggregate properties and gradations for hot mix asphalt (HMA). The final recommendations for gradations included a restricted zone that lies along the maximum density line (MDL) between an intermediate sieve size (2.36 or 4.75 mm depending on the maximum aggregate size) and the 0.3 mm size. The restricted zone was recommended to reduce the incidence of tender or rut-prone mixes. A further gradation recommendation from the Aggregate ETG was that mixes designed for high and very high traffic levels should have gradations passing below the restricted zone. The ETG suggested mixes having gradations passing below the restricted zone have higher shear strength necessary to resist rutting because of high inter-particle contact.

Since the aggregate research during SHRP was not based upon any experimental data, many asphalt technologists believe that compliance with neither the restricted zone nor specification of coarse-graded gradations (gradations passing below the restricted zone) may be necessary to produce HMA mixes with good performance.

When the Alabama DOT (ALDOT) adopted the Superpave mix design system, recommendations of the ETG were accepted. ALDOT specified that gradations not pass through the restricted zone and that gradations pass below the restricted zone for high and very high traffic levels. Because of the lack of experimental data within the SHRP aggregate research, these requirements needed to be evaluated in a laboratory-controlled experiment.

OBJECTIVE

The objective of this research was to evaluate the necessity of the restricted zone requirement and the recommendation for coarse-graded mixes for high traffic roadways in ALDOT's specifications.

RESEARCH APPROACH

Figure 1 illustrates the overall research approach in the form of a flow diagram. The first step was to identify four mixes, designed by contractors, that reflect ALDOT requirements and recommendations. Therefore, the identified mixes were coarse-graded. Mixes had a range of maximum aggregate sizes (MAS), design traffic levels, and aggregate types.

The identified mix gradations were then altered to pass through and above the restricted zone. A number of the selected designs had more than one aggregate mineralogical type included within the design blend. Because of this, there was a concern that altering blend percentages to pass above and through the restricted zone could lead to differing overall aggregate characteristics for the blends passing above, below, and through the restricted zone. Therefore, the percentage of each stockpile retained on each sieve was determined based upon the percentage of each stockpile in the design blend and the gradation of each stockpile. These relative percentages of each stockpile on each respective sieve were maintained for all three blends.

Each of the new gradations was optimized at 4 percent air voids. Verifications of the selected mixes were also conducted. To evaluate the three different gradation shapes for performance, all mixes were subjected to the following performance tests: Marshall stability and flow, Asphalt Pavement Analyzer, and the CPN rutting device.

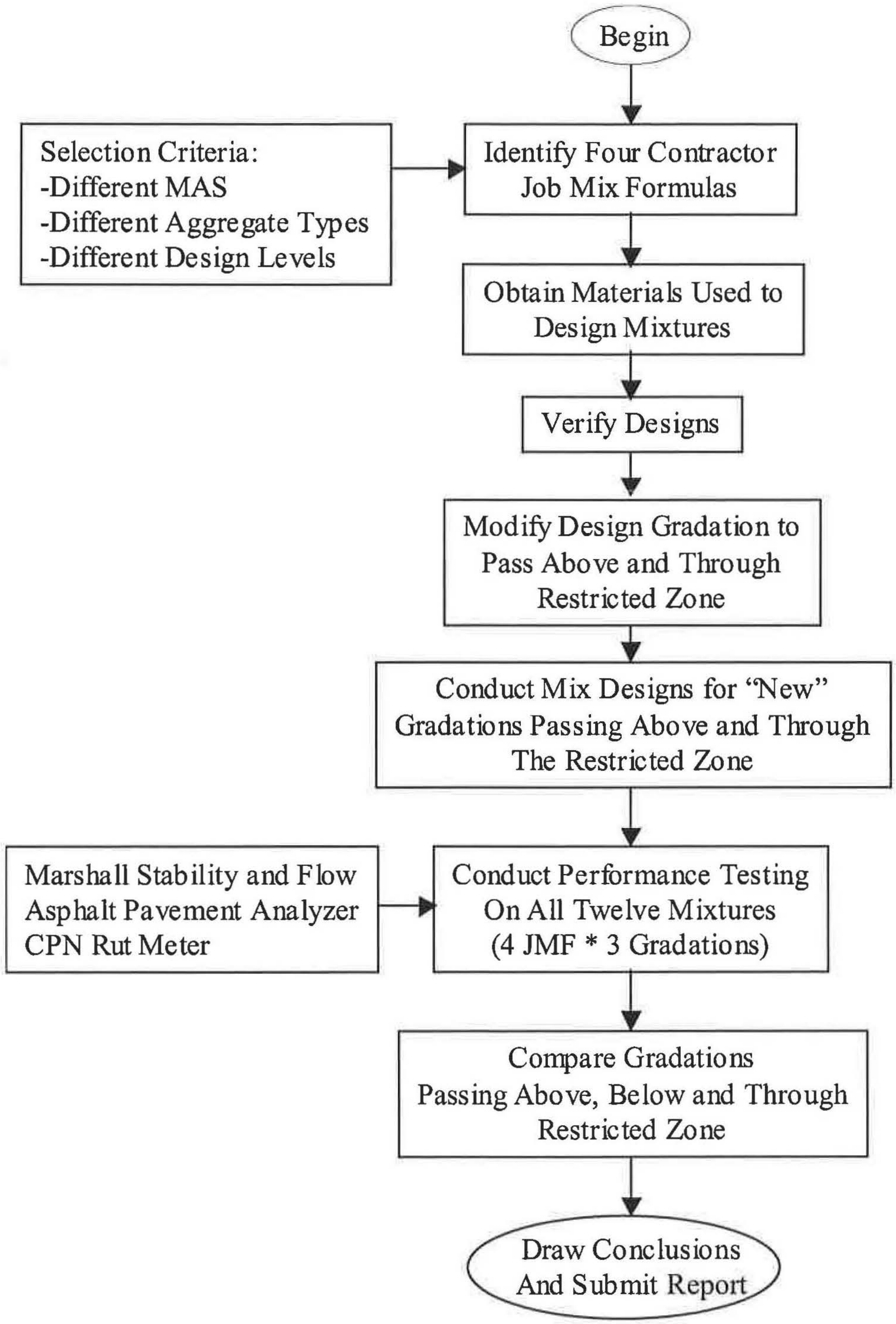

Figure 1: Overall Research Approach

MATERIALS

Four contractor designs were identified: two were wearing/surface course mixes, one an upper binder mix, and one a base/binder mix. Maximum aggregate sizes (MAS) included two 19.0 mm, one 12.5 mm, one 25.0 mm. Design ESAL levels were included B, C, D, and E.

Properties of the four selected mixes are shown in Table 1. Gradations were then developed for each mix that passed above and through the restricted zone (ARZ and TRZ). Table 2 presents the designed and developed gradations, and Figures 2 through 5 illustrate these gradations.

Table 1: Design Properties of Selected Mixtures

Properties	Mix 1	Mix 2	Mix 3	Mix 4
Mix Type	Wearing	Base/Binder	Upper Binder	Wearing
Maximum Agg. Size,mm	19.0	25.0	12.5	19.0
Predominant Agg. Type	Granite	Limestone	Gravel	Gravel
Design Gyrations	100	50	100	75
Design P_b, %	4.70	4.50	5.30	5.25
Design VMA, %	15.7	14.0	15.2	16.3
Design P_{be}, %	4.67	4.22	4.87	5.13
$P_{0.075}/P_{be}$	0.84	1.14	1.03	1.11
Coarse Agg. Angularity	99/98	100/99	95/92	85/81
Fine Agg. Angularity	45	45	46	46
G_{sb}	2.666	2.742	2.641	2.654
ESAL Range	E	B	D	C

Table 2: Design and Developed Gradations Used in Study

Sieve, mm	Mix 1			Mix 2			Mix 3			Mix 4		
	BRZ[1]	ARZ	TRZ	BRZ[1]	ARZ	TRZ	BRZ[1]	ARZ	TRZ	BRZ[1]	ARZ	TRZ
25	100	100	100	100	100	100	100	100	100	100	100	100
19	100	100	100	99	99	99	100	100	100	100	100	100
12.5	99	99	99	87	87	87	100	100	100	98	98	98
9.5	90	90	90	70	70	70	95	95	95	89	89	89
4.75	50	50	50	41	41	41	69	69	69	67	67	67
2.36	31	41	38	28	36	33	45	52	49	37.5	48	46
1.18	24	35	30	22	32	26	30	39	35	24.1	34	28
0.6	18	26	22	16	22	19	20	30	25	17.9	24	20
0.3	9	19	15	9	15	13	13	23	16	9.9	16	14
0.15	5	6	6	7	7	7	8	8	8	7.6	10	10
0.075	3.9	3.9	3.9	4.8	4.8	4.8	5.0	5.0	5.0	5.7	5.7	5.7

[1] Contractor design gradation

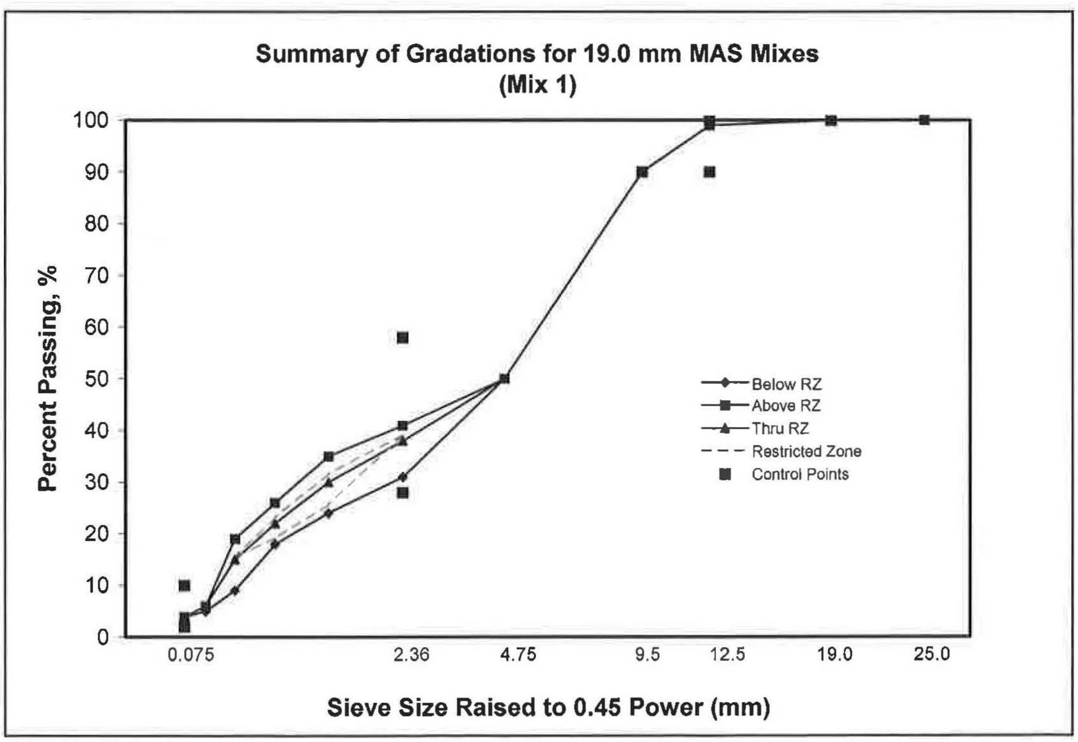

Figure 2: Gradations for Mix 1

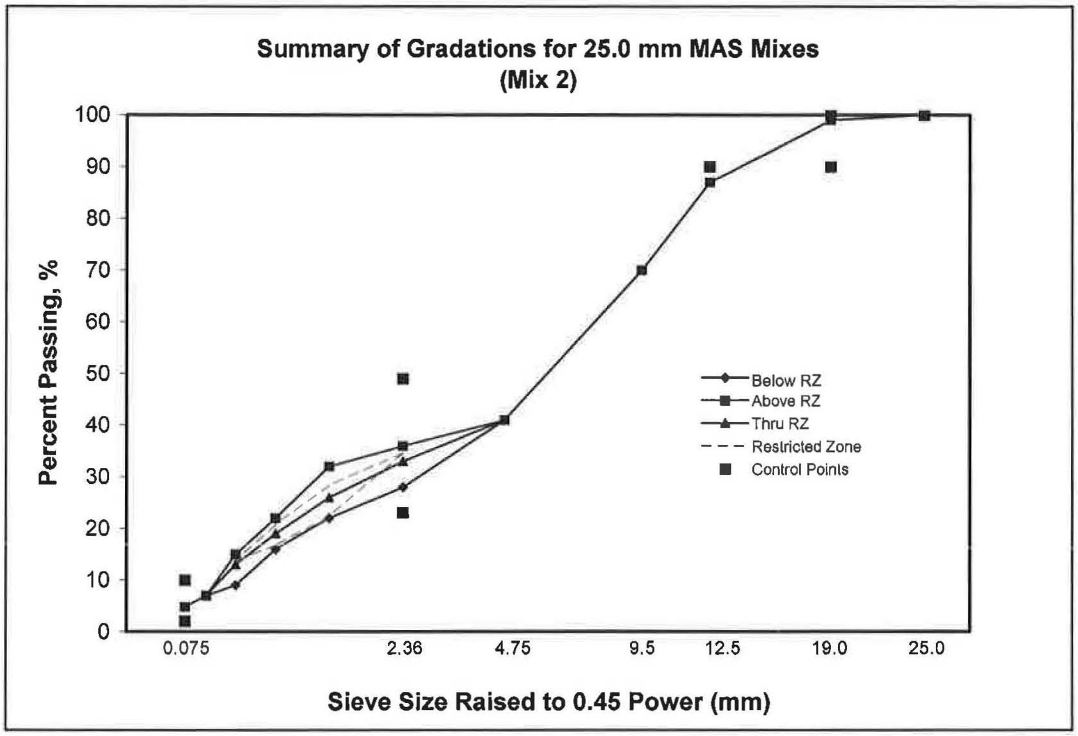

Figure 3: Gradations for Mix 2

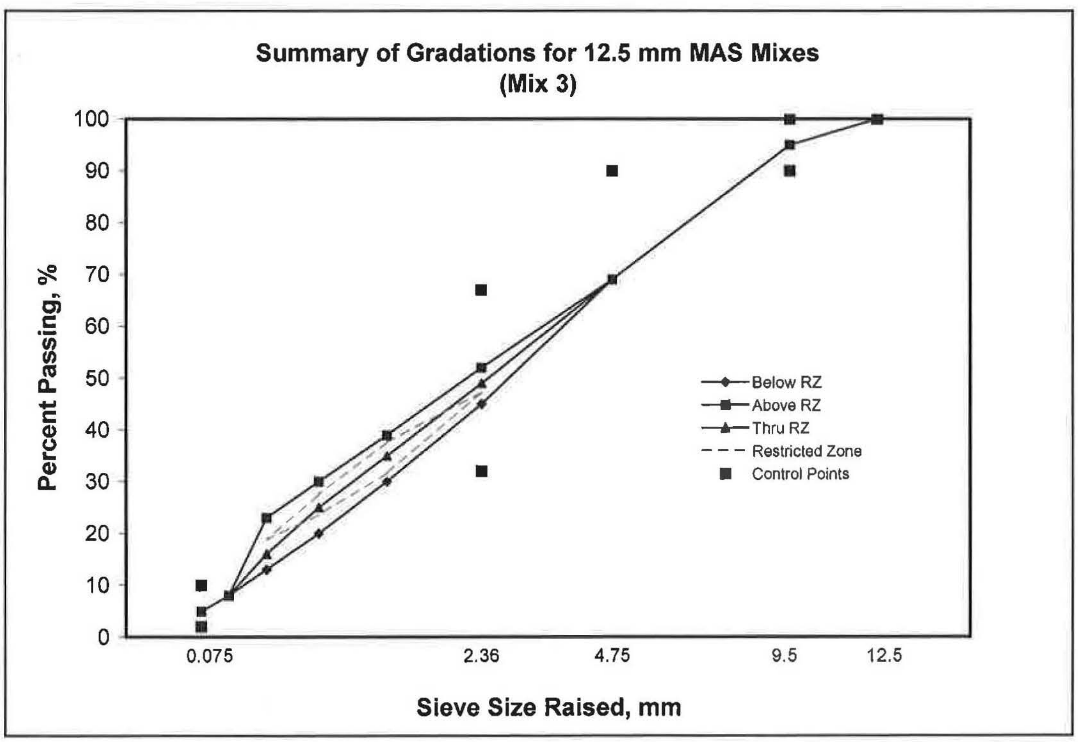

Figure 4: Gradations for Mix 3

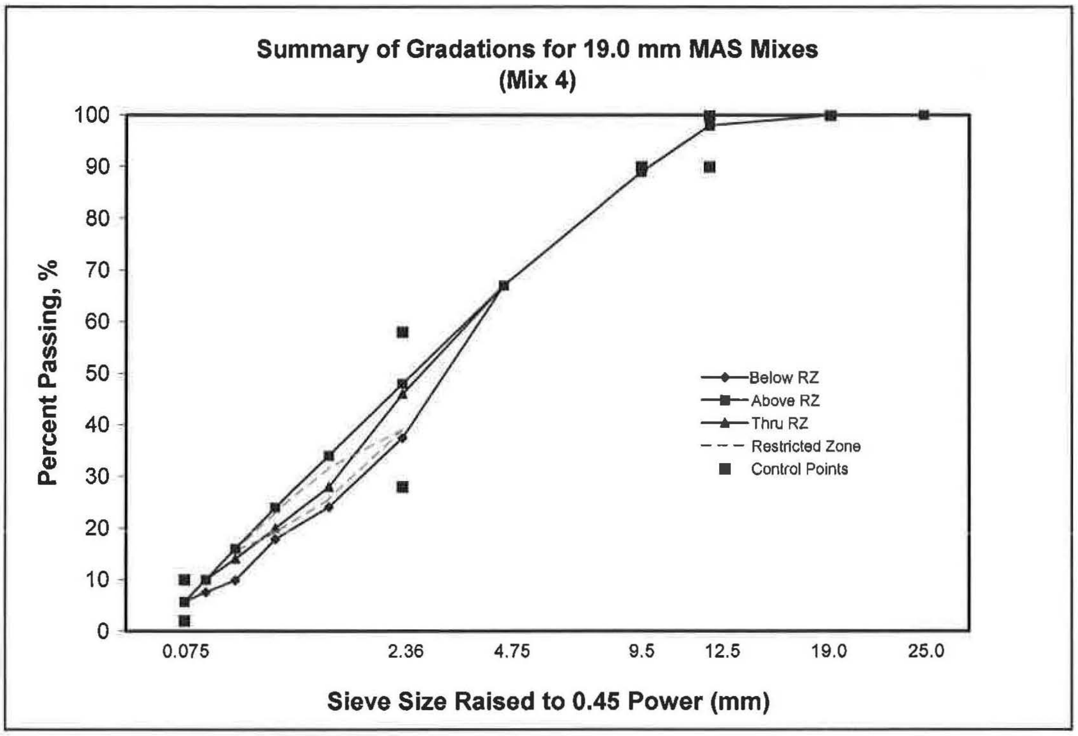

Figure 5: Gradations for Mix 4

After developing gradations that passed above and through the restricted zone, asphalt contents were selected to provide 4 percent air voids using respective design number of gyrations.

The asphalt binder selected for this study was a Superpave performance-based PG 67-22. This binder is also one of the NCAT labstock asphalt binders and has been used on numerous research projects with success. Properties of this asphalt binder are provided in Table 3.

Table 3: Properties of Asphalt Binder

Ageing	Test	Test Result	Temperature	Requirement	Test Method
Original Binder	Flash Point	313°C	-	230 °C min	AASHTO T 48
	Rotational Viscosity (Pa•s)	0.400	135 °C	3 max	AASHTO TP48
	DSR, G*/sinδ (kPa)	1.078	67 °C	1.00 min	AASHTO TP5
RTFO	Mass Loss	0.08 %	-	1.00 % max	AASHTO T 240
	RTFO Aged DSR, G*/sinδ (kPa)	2.279	67 °C	2.20 min	AASHTO TP5
PAV	PAV Aged DSR, G*/sinδ (kPa)	4752	25 °C	5000 max	AASHTO TP5
	PAV Aged BBR, Stiffness (MPa)	226	-12 °C	300 max	AASHTO TP1
	PAV Aged BBR, m-value	0.325	-12 °C	0.300 min	AASHTO TP1

TEST METHODS

All of the mixes were subjected to three different performance tests: Asphalt Pavement Analyzer, Rotary Loaded Wheel Tester, and Marshall test.

The Asphalt Pavement Analyzer (APA) is a modification of the Georgia Loaded Wheel Tester (GLWT). The APA, shown in Figure 6, can be used to evaluate rutting, fatigue, and moisture resistance of HMA mixtures.

Test specimens for the APA can be either beam or cylindrical. Three pairs of gyratory-compacted cylindrical specimens were typically tested in this project. Due to the limitation of some aggregate sources, some mixes were tested using two pairs (4 samples) specimens instead of three pairs (6 samples). This issue will be addressed later in the analysis portion. Test samples for each mix were specimens compacted to their respective design number of gyrations at optimum asphalt content. Sample was approximately 115 mm in height and has an air void content of 4 percent. The APA test was conducted at 64°C to 8000 cycles, and rut depths were measured continuously. Wheel load and hose pressure were 445 N and 690 kPa (100 lb and 100 psi), respectively.

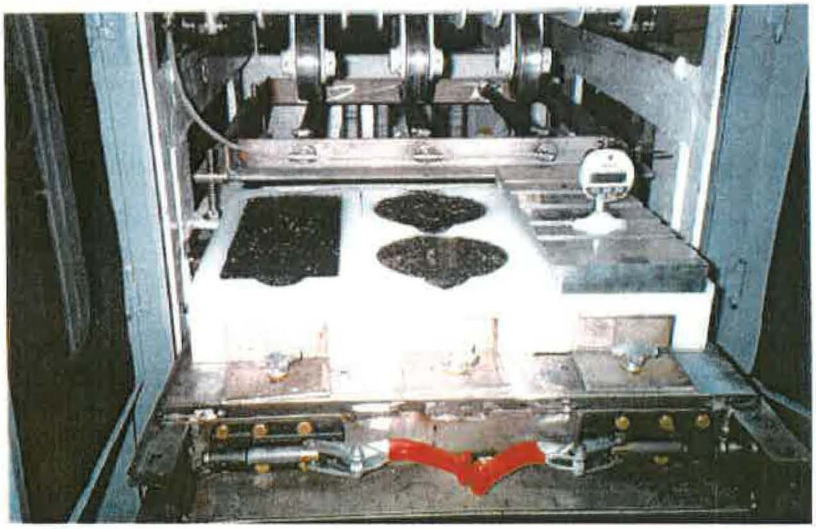

Figure 6: Asphalt Pavement Analyzer

The Rutmeter (or Rotary Loaded Wheel Tester), shown in Figure 7, was developed by CPN International, Inc. The Rutmeter automatically measures the plastic deformation of HMA samples as a function of repetitive wheel loadings. The Rutmeter utilizes a unidirectional rotary load wheel and most testing is carried out to 16,000 individual wheel loadings. The Rutmeter is capable of applying 125 N (28 lb) loads to each spinning single wheel in the load application assembly. The load is provided by static weight such that no external load calibration is required, and is designed to approximate a contact pressure of 690 kPa (100 psi). The device utilizes an integrated temperature controller to heat samples. Gyratory samples compacted at the design number of gyrations were tested at 64°C.

Figure 7: Rutmeter (Rotary Loaded Wheel Tester)

Marshall stability and flow testing were conducted on 150-mm (6-inch) diameter gyratory compacted samples at 60°C. Compaction efforts were adjusted for 95-mm (3.75-inch) thick gyratory samples. All specimens for Marshall testing were fabricated at 4.0 ± 0.5 percent air voids.

TEST RESULTS AND ANALYSIS

Mix design results for the four mixes using three different gradations are presented in Table 4. Results for voids in mineral aggregate (VMA), optimum binder content (P_b), effective binder content (P_{be}), dust to asphalt ratio ($P_{0.075}/P_{be}$), and the percent maximum density at the initial number of gyrations ($\%G_{mm}@N_{ini}$) are presented in the table.

Table 4: Mix Design Summary

Mix	Gradation	Gyrations	VMA, %	Design P_b, %	Design P_{be}, %	$P_{0.075}/P_{be}$	% $G_{mm}@N_{ini}$
1	BRZ	100	15.0	5.2	5.1	0.76	88.5
	ARZ	100	13.8*	4.5	4.3	0.91	90.3*
	TRZ	100	13.7*	4.5	4.3	0.91	89.6*
2	BRZ	50	14.0	4.5	4.2	1.14	87.2
	ARZ	50	14.1	4.5	4.2	1.14	89.4
	TRZ	50	12.3*	3.7	3.4	1.41	87.6
3	BRZ	100	14.7*	5.2	4.6	1.09	87.8
	ARZ	100	14.4*	4.9	4.3	1.16	88.9
	TRZ	100	14.1*	4.8	4.2	1.19	88.9
4	BRZ	75	16.3	5.3	5.1	1.11	86.3
	ARZ	75	13.9*	4.5	4.3	1.33	88.5
	TRZ	75	14.0	4.5	4.3	1.33	88.1

* Does not meet ALDOT Superpave requirements (*1*)

Mix design data were analyzed with two-way analysis of variance (ANOVA) on the VMA, optimum binder content, and $\%G_{mm}@N_{ini}$. Factors included in each of these analyses were gradation types (BRZ, ARZ, TRZ) and mixes (Mix 1, 2, 3, 4). Even though the objective of the ANOVA was to differentiate the effect of gradations, mix was also treated as a factor in the analysis because of the different aggregate properties, maximum aggregate sizes, and different design gyrations levels used in the four types of mixes. Without the inclusion of mix type as a factor in the ANOVA, the variability caused by the different mix properties would have likely overshadowed the effect of gradation type. Because the responses are volumetric properties, there was only one response per factor-level combination. The interaction between mix and gradation was sacrificed to yield an ANOVA term. Therefore, no conclusion can be made about the significance of the two factors, but rather a relative impact of each factor can be determined.

ANOVA for Voids in Mineral Aggregate

Table 5 presents the results of the analysis of variance (ANOVA) to determine the impact of the mixes and gradation types corresponding to the restricted zone on the VMA. The larger F-statistics for gradation type means it had a greater impact on VMA than mix type.

Table 5: Results of ANOVA for VMA Analysis

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F-statistic
Mix	2.589	3	0.863	2.081
Gradation	4.472	2	2.236	5.391
Error	2.488	6	0.415	-

Figure 8 illustrates the effect of gradation type on VMA. Each bar on this Figure represents the average VMA for four mixes having the same gradation type.

This figure shows that the BRZ gradation provided much higher VMA then did the TRZ and ARZ. On average, mixes below the restricted zone had approximately 1.5 percent higher VMA than mixes through the restricted zone, and 0.9 percent higher VMA than mixes above the restricted zone. The TRZ gradation provided the lowest VMA, because it is closer to the maximum density line. It was not expected that mixes having gradation above the restricted zone would have lower VMA than the BRZ mixes. However, in the recently completed National Cooperative Highway Research Program project - NCHRP 9-14: "The Restricted Zone in the Superpave Aggregate gradation

Specification" ($\underline{2}$), this phenomenon (VMA for ARZ less than VMA for BRZ) was also observed for the 25.0 mm MAS mixes.

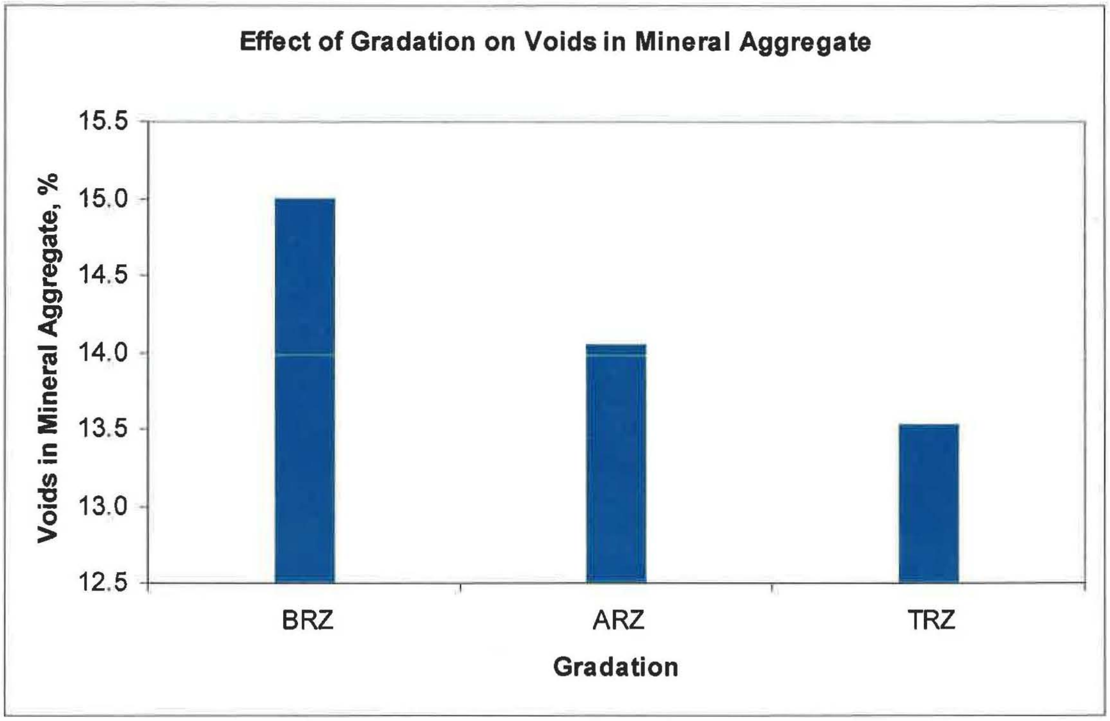

Figure 8: Effect of Gradations on Voids in Mineral Aggregate

ANOVA for Optimum Binder Content

Table 6 presents the results of the ANOVA to evaluate the impact of mix and gradation type on optimum binder content. This table shows the gradation type had a larger impact on optimum binder content.

Table 6: Results of ANOVA for Optimum Binder Content Analysis

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F-statistic
Mix	0.876	3	0.292	5.446
Gradation	0.945	2	0.472	8.813
Error	0.322	6	0.054	

The effect of gradation on optimum binder content is shown in Figure 9. The average optimum binder content for the BRZ mixes was approximately 0.7 percent higher than the TRZ mixes and 0.5 higher than the ARZ mixes. The reason that the BRZ mixes had higher optimum binder contents than the TRZ and ARZ mixes was that the BRZ mixes produced averages of 1.5 and 0.9 percent more VMA than did the TRZ and ARZ mixes respectively.

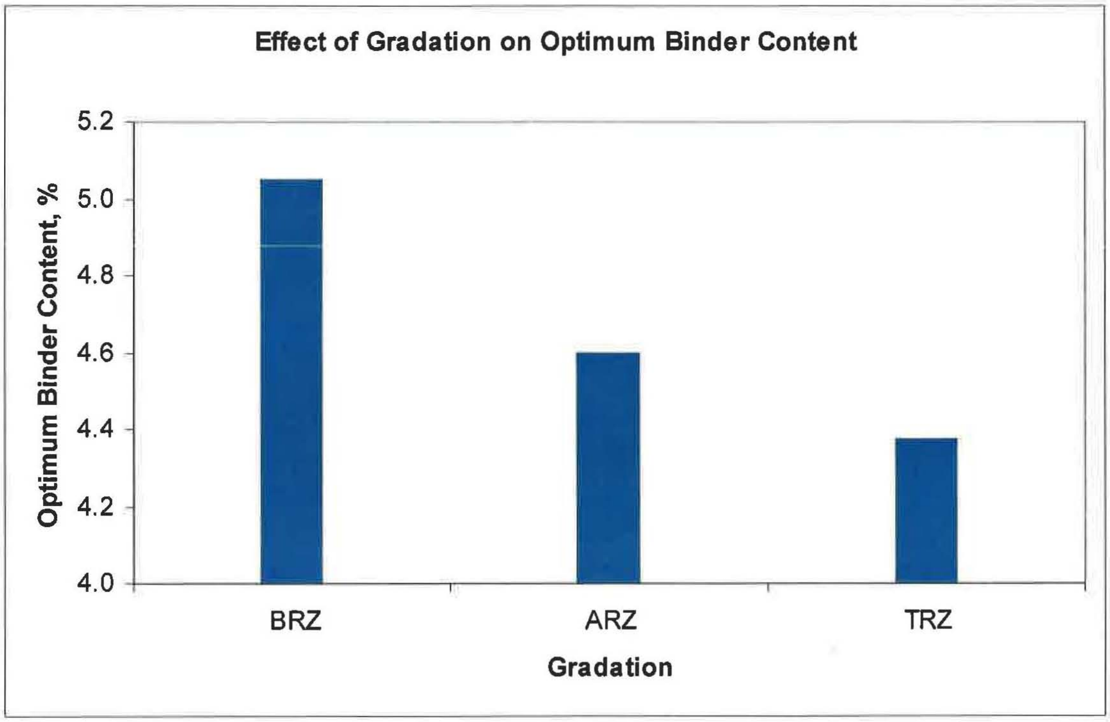

Figure 9: Effect of Gradations on Optimum Binder Content

ANOVA for %G_{mm}@$N_{initial}$

Table 7 presents the results of the two-factor ANOVA to evaluate the impact of mix and gradation type on %G_{mm}@$N_{initial}$. This table shows that both the mix and the gradation impacted %G_{mm}@$N_{initial}$.

Table 7: Results of ANOVA for %G_{mm}@$N_{initial}$ Analysis

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Squares	F-statistic
Mix	5.556	3	1.852	9.324
Gradation	6.755	2	3.378	17.006
Error	1.192	6	0.199	

Figure 10 illustrates the effect of gradation on $\%G_{mm}@N_{initial}$. The ARZ gradations provided the highest $\%G_{mm}@N_{initial}$ values. On average, the BRZ gradations had approximately 1.8 percent lower $\%G_{mm}@N_{initial}$ values than the ARZ gradations and the TRZ gradations had approximately 1.1 percent lower $\%G_{mm}@N_{initial}$ (87.5 versus 89.3 and 88.6). The ARZ mixes were finer than the TRZ and BRZ mixes, and finer gradations tend to yield higher $\%G_{mm}@N_{initial}$ values.

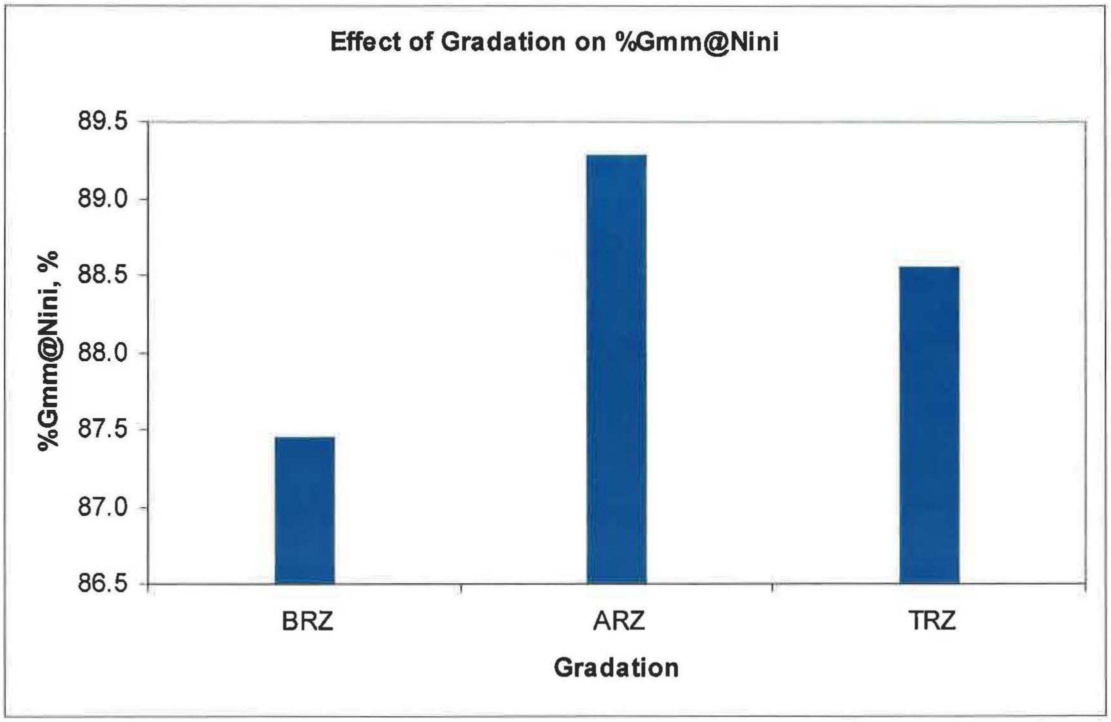

Figure 10: Effect of Gradations on $\%G_{mm}@N_{initial}$

Results of Asphalt Pavement Analyzer Rut Testing

Results of APA rut testing conducted on the mixes are presented in Table 8. A critical rut depth of 8.2-mm to separate potentially rutting susceptible from non rutting susceptibility mixes was determined based upon a rutting study by Zhang, et. al. (3). This value was verified using a temperature-effect model (4) that converted the Georgia Department of Transportation critical rut depth of 5-mm at 50°C to the test temperature of 64°C. The 8.2 mm was used as the critical rut depth in this study for comparison purposes.

Table 8: APA Rutting Test Results for Mixes

Mix	Gradation	Asphalt Content (%)	Rut Depth (mm)
1	BRZ	5.2	7.38
	ARZ	4.5	6.73
	TRZ	4.5	3.00
2	BRZ	4.5	4.69
	ARZ	4.5	5.25
	TRZ	3.7	4.90
3	BRZ	5.2	8.16
	ARZ	4.9	8.54
	TRZ	4.8	7.60
4	BRZ	5.3	11.82
	ARZ	4.5	6.43
	TRZ	4.5	6.90

The rut depth data in Table 8 indicate that two mixes of the total twelve exceeded the critical rut depth of 8.2 mm: Mix 3-ARZ gradation, and Mix 4-BRZ gradation. Mix 3-BRZ barely passed the criteria. Based on the discussion of volumetric properties presented earlier, the high VMA, and thus high asphalt contents for BRZ and Mix 3 (Table 4) is the likely reason for the high rut depths. It should be noted that none of the four TRZ mixes had rut depths higher than the 8.2-mm criteria.

Analysis of the rut depth data consisted of conducting an ANOVA. Due to lack of aggregate materials for some mixes, instead of six (3 pairs) gyratory samples, four (2 pairs) samples were tested for some mixes with the Asphalt Pavement Analyzer (APA). Therefore, for this analysis, three or two replicate observations were included for each factor-level combination. Because there were two or three replicate observations, a measure of experimental error was available evaluating the significance of the factors.

Table 9 presents the results of the ANOVA conducted on the APA rut testing data. Based on the results of the ANOVA shown in Table 9, the two main factors (gradation and mix) and two-way interaction were significant.

Table 9: Results of ANOVA for APA Rut Depth Data

Source of Variation	Degrees of Freedom	Sequential sums of squares	Adjusted sums of squares	Adjusted Mean Squares	F-statistic	P-Value	Significant at 95%
Mix	3	58.164	64.288	21.429	13.17	0.000	Yes
Gradation	2	21.721	27.92	13.96	8.58	0.002	Yes
Mix*Grad	6	42.388	42.388	7.065	4.34	0.007	Yes
Error	18	29.299	29.299	1.628			
Total	29	151.572					

Based upon Table 9, mix had the most significant effect on rut depth. Variable "mix" combines aggregate sources and properties, design gyration levels, and Maximum Aggregate Size. Therefore, it is difficult to draw a conclusion from the data for these four mixes since all factors affected rut performance. The effects of aggregate properties, design gyration levels, and MAS on rut depths were beyond the scope of this study.

Figure 11 shows the effect of gradation on rut depth. The BRZ gradation had slightly higher rut depths than the ARZ and TRZ gradations. On average, mixes having gradations below the restricted zone rutted about 2.4 mm and 1.3 mm more than did mixes having TRZ gradation and ARZ gradation, respectively. This was also as expected. Recall that the design mixes (BRZ gradations) had higher VMA and thus higher optimum binder contents than did the TRZ and ARZ mixes (average difference of 1.5 and 0.9 percent VMA, and 0.7 and 0.5 percent binder). The increased binder contents likely caused the higher rut depths. This indicates that the mixes having gradations through the restricted zone performed slightly better than did the mixes having gradations below and above the restricted zone. However, long-term durability might be a problem for some the TRZ mixes since all did not meet the minimum VMA requirements (Table 4).

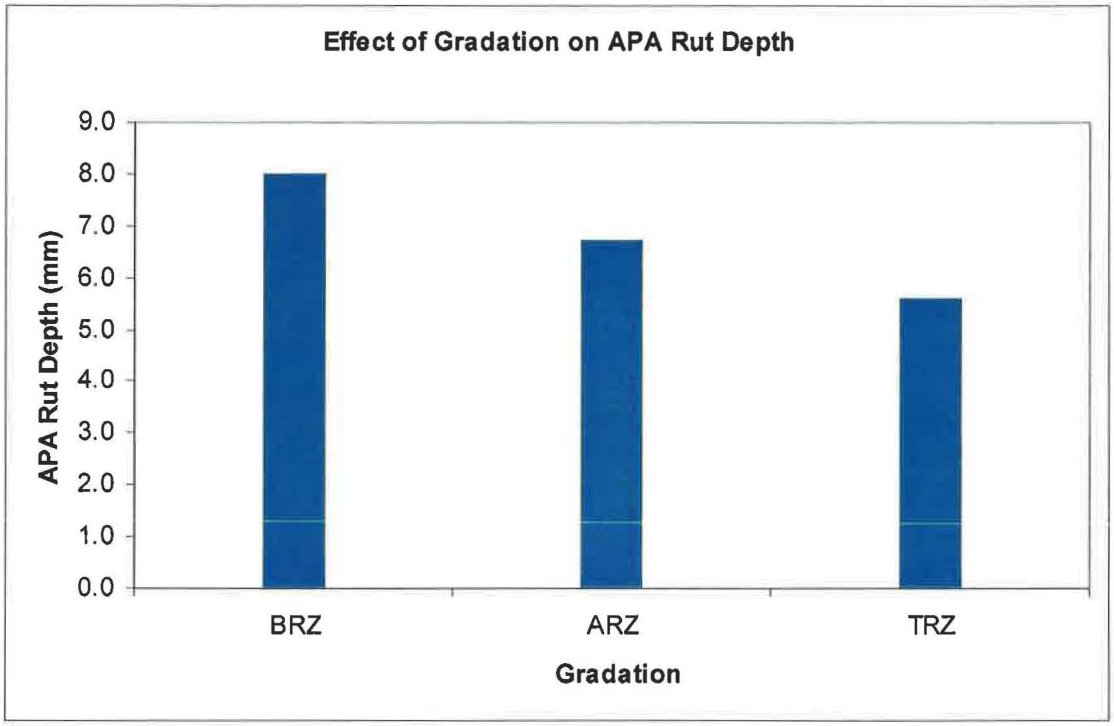

Figure 11: Effect of Gradation on APA Rut Depth

The interaction between mix and gradation was also shown to be significant. This interaction on rut depths is shown in Figure 12. Based on this figure, there was a greater difference in rut depths for the BRZ gradations than for the ARZ and TRZ gradations. Considering it was a pass-fail situation for the BRZ gradation mixes, this interaction suggests that aggregate properties are more critical for gradations below the restricted zone. It also shows that mixes having gradations below the restricted zone do not guarantee sufficient rut resistant performance.

This figure also shows that the rut depth difference for mixes is greater than it is for gradations. This strengthens the role an aggregate plays in a mix for rutting performance. Some aggregate sources can be designed rut-resistant by having gradations below, above, or through the restricted zone.

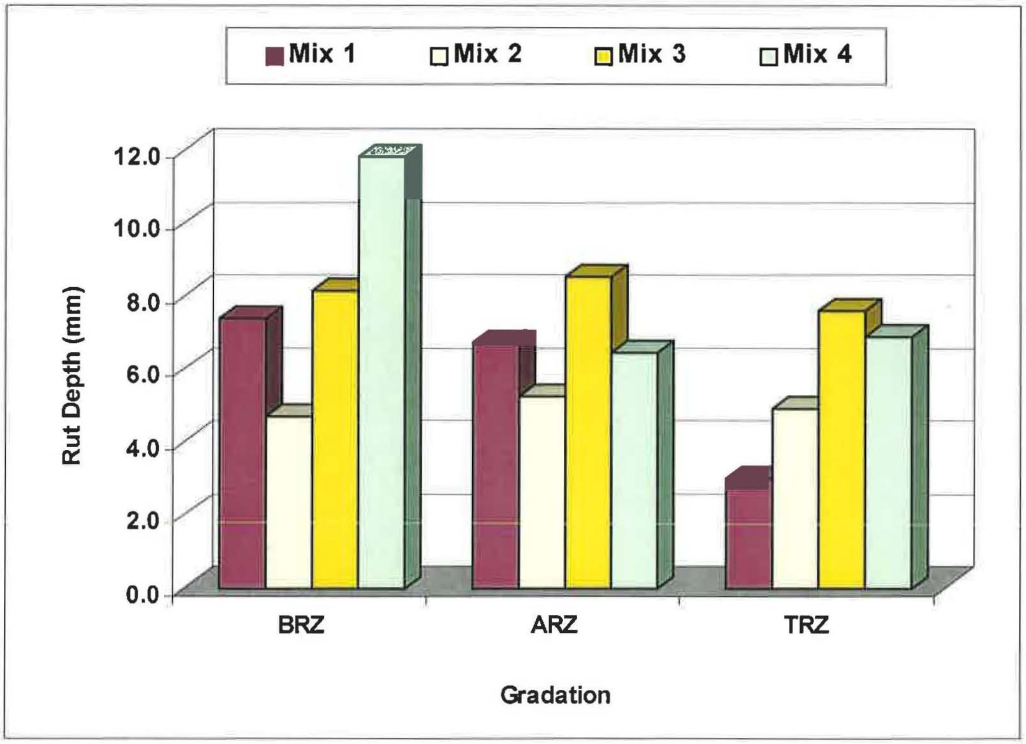

Figure 12: Asphalt Pavement Analyzer Rutting Results for Mixtures

Results of CPN RutMeter Testing

Results of Rutmeter testing conducted on the mixes are presented in Table 10.

Table 10: CPN RutMeter Rutting Test Results for Mixes

Mix	Gradation	Asphalt Content (%)	Rut Depth (mm)
1	BRZ	5.2	14.57
	ARZ	4.5	16.64
	TRZ	4.5	2.48
2	BRZ	4.5	3.51
	ARZ	4.5	5.04
	TRZ	3.7	2.59
3	BRZ	5.2	13.48
	ARZ	4.9	6.83
	TRZ	4.8	5.13
4	BRZ	5.3	13.60
	ARZ	4.5	3.34
	TRZ	4.5	5.45

During the tests, several samples could not be tested to 16,000 load applications because the device stops at 0.25 inches (6.35 mm) of deformation. In that case, rut depth was extrapolated using the rut slope and intercept from the last half loading period. Figure 13 shows an example of the extrapolation and the method of calculation.

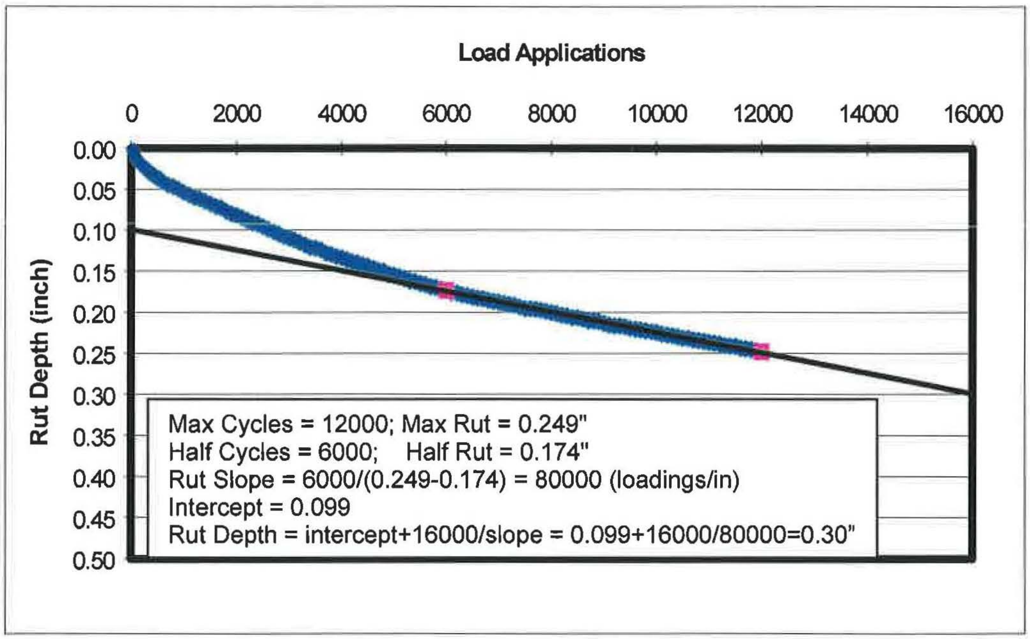

Figure 13: Extrapolation of Rut Depth at 16,000 Load Applications

Similar to the analysis for APA rut depth, analysis of the CPN Rutmeter data consisted of conducting an ANOVA. It was intended to conduct Rutmeter tests on three replicates for each mix, however, due to the limited availability of aggregates, some mixes only had two replicates for rut testing. Because there were two or three replicate observations, a measure of experimental error was available for calculating the F-statistics during the ANOVA analysis.

Table 11 presents the results of the ANOVA conducted on the Rutmeter testing data. Based on the results of the ANOVA shown in Table 11, the two main factors (gradation and mix) and the two-way interaction were significant.

Table 11: Results of ANOVA for RutMeter Rut Depth Data

Source of Variation	Degrees of Freedom	Sequential sums of squares	Adjusted sums of squares	Adjusted Mean Squares	F-statistic	P-Value	Significant at 95%
Mix	3	208.192	224.47	74.823	22.49	0.000	Yes
Gradation	2	294.204	291.012	145.506	43.74	0.000	Yes
Mix*Grad	6	265.042	265.042	44.174	13.28	0.000	Yes
Error	19	63.212	63.212	3.327			
Total	30	830.65					

Gradation had a greater effect on RutMeter rut depths than did mix type. Figure 14 illustrates the effect of gradation on rut depth. Again, the BRZ gradation had the highest rut depth, followed by mixes having ARZ and TRZ gradations. On average, the design mixes (BRZ gradations) had approximately 7.4 and 3.3 mm higher rut depth in RutMeter testing than did mixes having TRZ gradation and ARZ gradation, respectively.

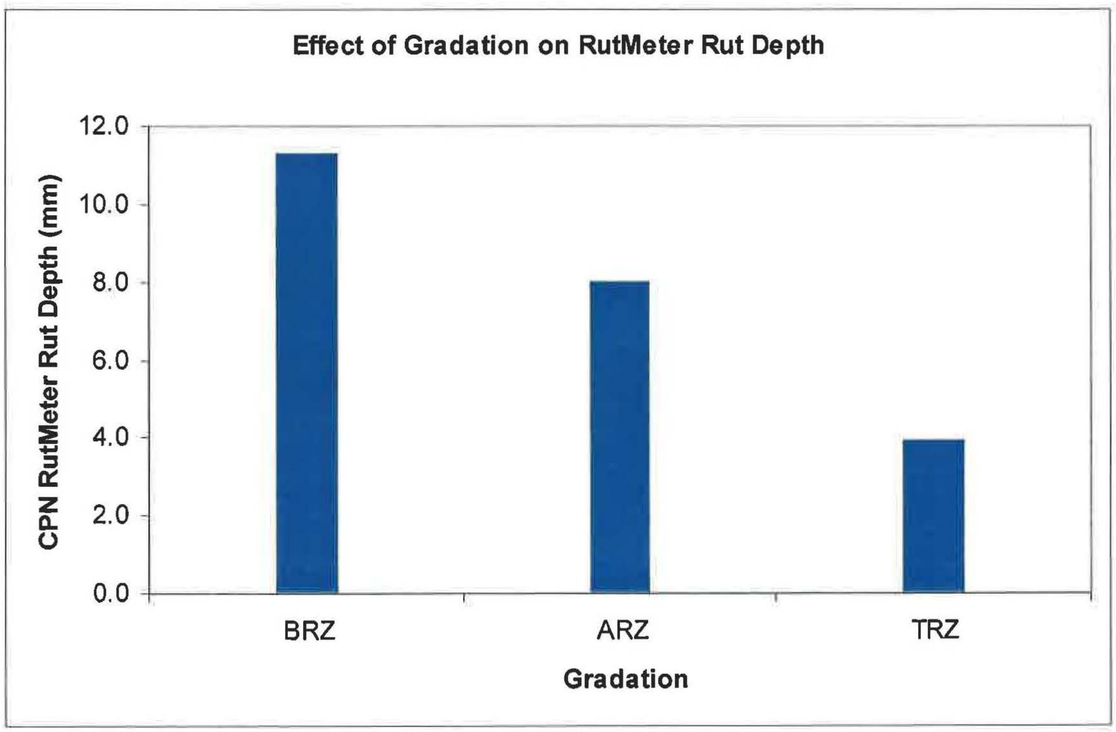

Figure 14: Effect of Gradation on CPN RutMeter Rut Depth

These results indicate that the mixes having gradations through the restricted zone performed better than did the mixes having gradations below and above the restricted zone. This confirms the conclusion from the APA data that the restricted zone is not needed to ensure a rut-resistant mixture.

The interaction between mix and gradation was also significant. The effect of this interaction on RutMeter rut depths is presented in Figure 15.

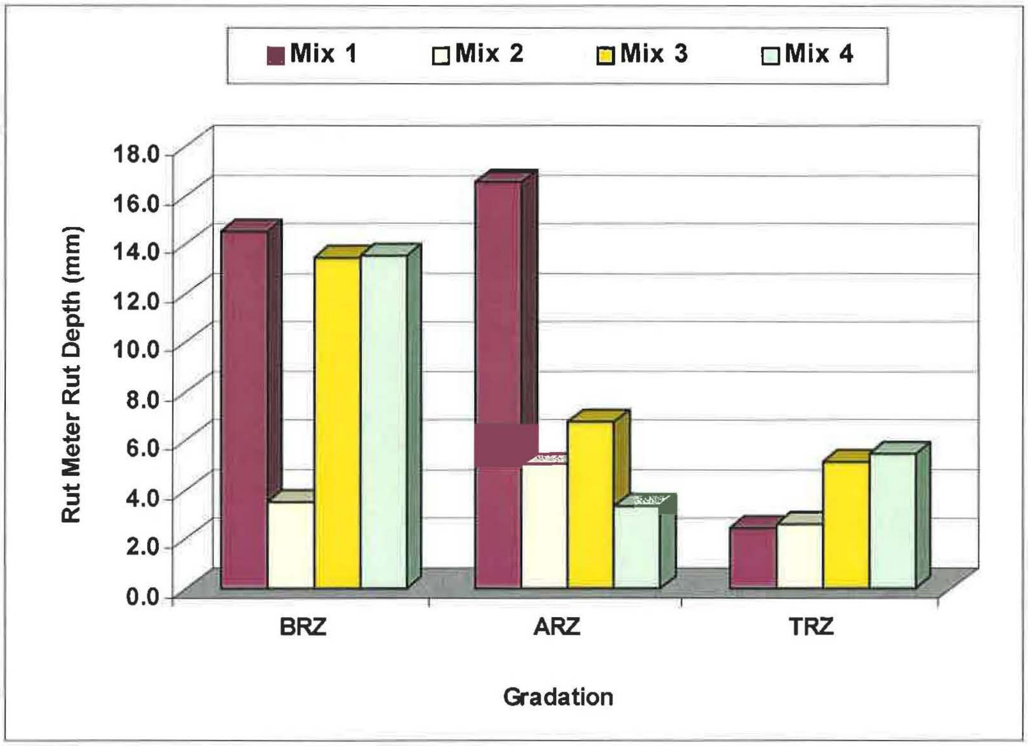

Figure 15: Interaction Between Gradation and Mix on CPN RutMeter Rut Depths

Based on this figure, there was a greater difference in rut depths for the BRZ gradations and ARZ gradation than the TRZ gradations. For the BRZ gradation, three of the four mixes had relatively high rut depths. However, Mix 2 at BRZ gradation performed very well with a rut depth of 3.51 mm. Again, this suggests that aggregate sources and properties become important for the mixes having gradation below the restricted zone. Based upon the RutMeter rut depth in this figure, all four mixes having gradation through the restricted zone performed very well.

Results of Marshall Stability and Flow Testing

Results of Marshall stability and flow testing are presented in Table 12. One more logical property is the Marshall stiffness index which is the Marshall stability divided by flow. This is an empirical stiffness value and is used by some engineers, especially in Europe, to evaluate the strength of asphalt mixture. A higher value of stiffness index indicates a stiffer mixture and, hence, indicates the mixture is likely more resistant to permanent deformation. This data is also included in Table 12.

Table 12: Marshall Stability and Flow Test Results

Mix	Gradation	Asphalt Content (%)	Stability (lbf)	Flow (0.01 inch)	Stiffness Index (lbf/inch)
1	BRZ	5.2	4458	20.8	21487
	ARZ	4.5	2522	17.5	14410
	TRZ	4.5	7310	16.0	49800
2	BRZ	4.5	4088	23.0	17789
	ARZ	4.5	2263	19.3	11789
	TRZ	3.7	3948	22.8	17352
3	BRZ	5.2	2900	21.3	13653
	ARZ	4.9	3217	18.3	17603
	TRZ	4.8	3127	20.3	15431
4	BRZ	5.3	1937	20.6	9401
	ARZ	4.5	2225	17.8	12527
	TRZ	4.5	2015	18.4	10991

The ANOVA results conducted on stability, flow, and stiffness index are presented in Tables 13 through 15, respectively.

Table 13: Results of ANOVA for Marshall Stability Data

Source of Variation	Degrees of Freedom	Sequential sums of squares	Adjusted sums of squares	Adjusted Mean Squares	F-statistic	P-Value	Significant at 95%
Mix	3	20631550	25378881	8459627	128.16	0.000	Yes
Gradation	2	10670711	10906981	5453490	82.62	0.000	Yes
Mix*Grad	6	21231428	21231428	3538571	53.61	0.000	Yes
Error	17	1122167	1122167	66010			
Total	28	53655855					

Table 14: Results of ANOVA for Marshall Flow Data

Source of Variation	Degrees of Freedom	Sequential sums of squares	Adjusted sums of squares	Adjusted Mean Squares	F-statistic	P-Value	Significant at 95%
Mix	3	45.975	45.454	15.151	6.08	0.005	Yes
Gradation	2	48.619	50.786	25.393	10.18	0.001	Yes
Mix*Grad	6	18.346	18.346	3.058	1.23	0.341	No
Error	17	42.385	42.385	2.493			
Total	28	155.326					

Table 15: Results of ANOVA for Marshall Stiffness Index Data

Source of Variation	Degrees of Freedom	Sequential sums of squares	Adjusted sums of squares	Adjusted Mean Squares	F-statistic	P-Value	Significant at 95%
Mix	3	9.41E+08	1.17E+09	3.89E+08	12.10	0.000	Yes
Gradation	2	4.22E+08	4.51E+08	2.25E+08	7.00	0.006	Yes
Mix*Grad	6	1.23E+09	1.23E+09	2.05E+08	6.38	0.001	Yes
Error	17	5.47E+08	5.47E+08	32191401			
Total	28	3.14E+09					

Table 13 presents the results of the ANOVA conducted on the Marshall stability data. Based upon the results, mix, gradation, and the interaction between mix and gradation were significant.

Table 14 presents the results of the ANOVA conducted on the Marshall flow data. Based upon the results, gradation and mix type were significant, but there was no interaction between the two factors.

Table 15 presents the results of the ANOVA conducted on the Marshall stiffness index data. Based upon the results, gradation, mix, and interaction between gradation and mix were all significant.

The effects of the gradation on Marshall stability, flow, and stiffness index are illustrated in Figures 16 through 18.

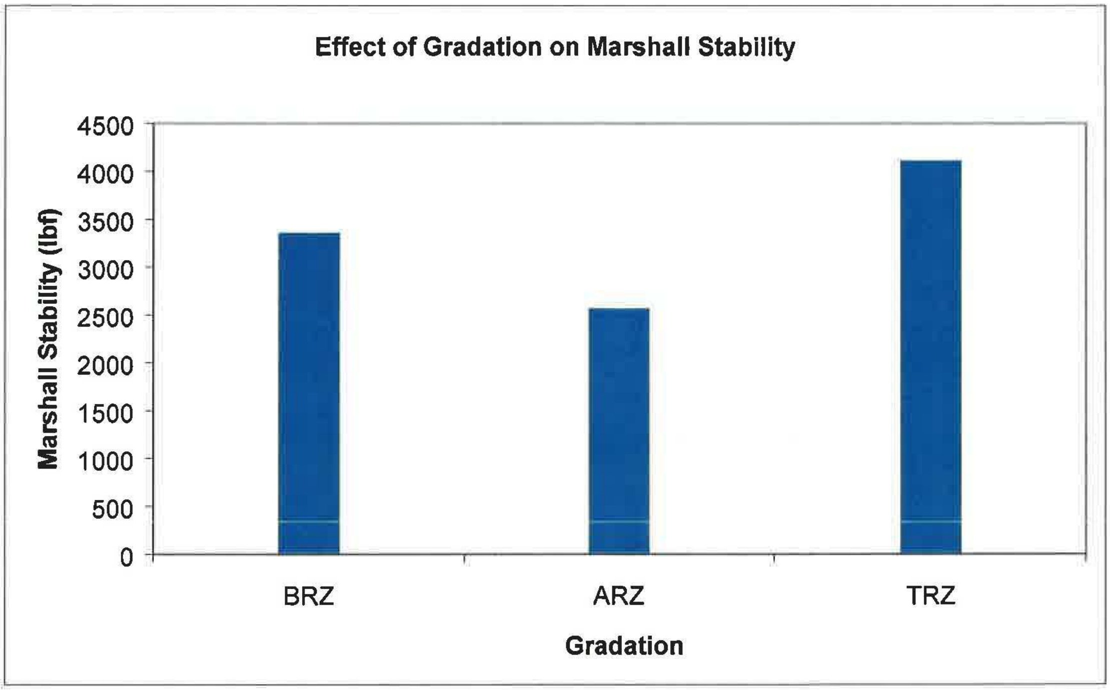

Figure 16: Effect of Gradation on Marshall Stability

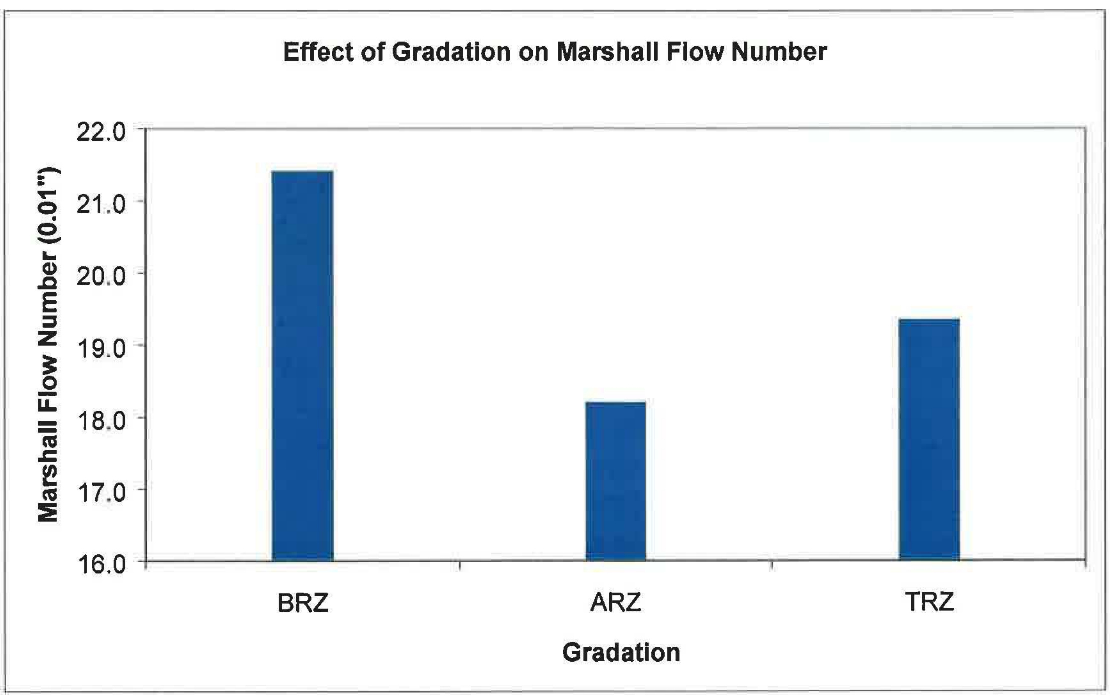

Figure 17: Effect of Gradation on Marshall Flow

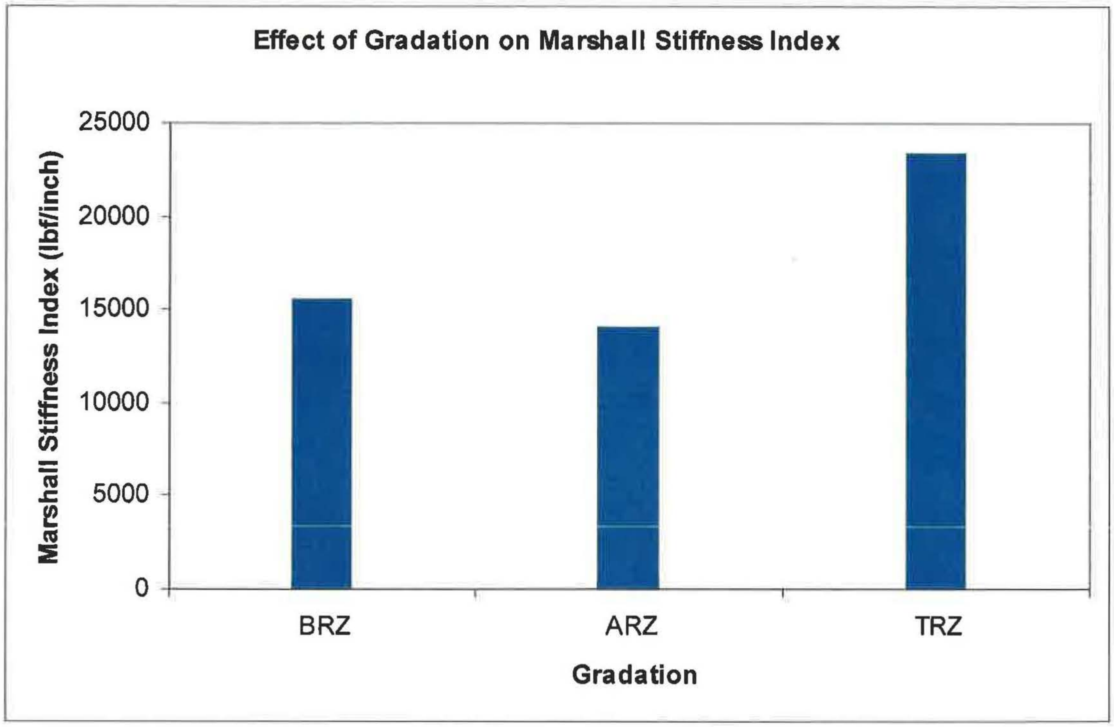

Figure 18: Effect of Gradation on Marshall Stiffness Index

Based upon the results shown in Figures 16 and 18, mixes having TRZ gradations had the highest Marshall stability and the highest stiffness index values. On average, the TRZ gradation had 66 percent higher Marshall stability than did the ARZ mixes (4,100 versus 2,566 lbf) and 23% higher Marshall stability than did the BRZ mixes (4,100 versus 3,345 lbf). Mixes having gradations through the restricted zone had 60% higher stiffness index than did the ARZ mixes and 50% higher than the BRZ mixes. The Marshall stability and stiffness index data appear to confirm the APA and Rutmeter conclusion that the restricted zone requirement is not needed to ensure the rut performance of the mixtures. Flow data from Figure 17 showed that BRZ had much higher flow number than did the ARZ and TRZ mixes. Again, this suggests that mixes having gradations below the restricted did not guarantee good performance.

CONCLUSIONS

The effect of the Superpave defined restricted zone on HMA rutting performance was evaluated in this study. One gradation that violated the restricted zone (TRZ) and two gradations that did not violate the restricted zone (BRZ and ARZ) were evaluated.

Mixes selected for evaluation represented a range of maximum aggregate size of gradation, design traffic level, and aggregate types. Three laboratory tests, Asphalt Pavement Analyzer, CPN Rutmeter, and Marshall test, were used to evaluate the rutting performance.

The following conclusions are drawn from the analysis of the data presented in this study.

1. Mixes having gradations violating the restricted zone performed similarly to or better than the mixes with gradations passing outside the restricted zone. This conclusion is drawn from the results of experiments with 12.5 mm, 19.0 mm and 25.0 mm MAS gradations at N_{design} values of 100, 75, and 50 gyrations. This conclusion is confirmed and supported by a recently completed National Cooperative Highway Research Program project - NCHRP 9-14: "The Restricted Zone in the Superapve Aggregate gradation Specification" (2).
2. Rutting performance of mixes having gradation below the restricted zone, which was commonly recognized to be rut-resistant, appears more sensitive to aggregate properties than do mixes having gradations above or through the restricted zone.

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