

NCHRP

REPORT 464

**NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM**

The Restricted Zone in the Superpave Aggregate Gradation Specification

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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**The Restricted Zone in the
Superpave Aggregate
Gradation Specification**

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SUBJECT AREAS

Materials and Construction

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

*By Staff
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This report presents the findings of a research project to determine whether the restricted zone requirement is necessary for aggregate gradations designed in accordance with AASHTO MP2 and PP28 if mix volumetric and fine aggregate angularity criteria are met. Its main finding is that, based on an evaluation of the performance properties of hot mix asphalt, the restricted zone requirement is redundant in these circumstances. The report will be of particular interest to materials engineers in state highway agencies, as well as to materials suppliers and paving contractor personnel responsible for the specification and production of hot mix asphalt.

In developing the Superpave mix design method, the Asphalt Research Program (1987–1993) of the Strategic Highway Research Program (SHRP) primarily targeted the properties of asphalt binders and hot mix asphalt (HMA) and their effects on pavement performance. Other than asphalt-aggregate adhesion and its consequences to moisture damage, the study of the aggregate's contribution to pavement performance was purposefully excluded from the program. Yet, SHRP researchers were required to produce an aggregate gradation specification without the benefit of experimentation to support or verify its formulation.

In lieu of a formal research program, a group of acknowledged experts in the areas of aggregate production and behavior and HMA mix design developed, through the use of a modified Delphi approach, the set of recommended aggregate properties and criteria that appeared in the original Superpave mix design method. These criteria included a restricted zone in the gradation; the zone lies along the maximum density line between the intermediate size (either 4.75 or 2.36 mm, depending on the nominal maximum size of the aggregate) and the 300- μ m size and forms a band through which it usually was considered undesirable for a gradation to pass. The original intention of including a restricted zone, which particularly affects (1) the use of natural sands that may be rounded or have a limited size distribution and (2) the allowable ratio of the fine sand fraction (150 to 600 μ m) to the total sand (passing 2.36 mm), was to help reduce the incidence of tender or rutting-prone HMA. Although the restricted zone was presented in the Superpave mix design method as a guideline, it often has been implemented by specifying agencies as a requirement for the design of acceptable HMA.

In the experience of many agency engineers and materials suppliers, however, it has been found that compliance with the restricted zone criterion was neither desirable nor necessary in every instance to produce well-performing HMA mix designs. For example, when aggregate particles in the size range of the restricted zone are highly angular (i.e., have high fine aggregate angularity [FAA] values), it is likely that high-quality, rut-resistant, nontender paving mixes can be produced regardless of whether the gradation passes through the restricted zone. Furthermore, there are many known examples of aggregate gradations passing through the restricted zone that produce well-performing HMA.

Under NCHRP Project 9-14, “Investigation of the Restricted Zone in the Superpave Aggregate Gradation Specification,” the National Center for Asphalt Technology at Auburn University was assigned the task of determining under what conditions, if any, compliance with the restricted zone requirement is necessary when an HMA mix design meets all other Superpave mix volumetric and FAA criteria for a paving project. The research team (1) conducted a literature search and critical review of the use and effectiveness of the restricted zone and (2) carried out a program of laboratory testing to determine the impact of the restricted zone requirement on HMA performance.

The three-part laboratory testing program compared the performance of HMA mix designs measured with three independent mechanical property tests: the Asphalt Pavement Analyzer, a laboratory wheel-tracking device; the repeated load confined creep test; and the repeated shear at constant height test. The testing program included the following experimental factors:

- A PG 64-22 asphalt binder;
- Two coarse aggregates—a crushed granite and a crushed gravel;
- Ten fine aggregates with FAA values between 38 and 50;
- Nominal maximum aggregate sizes of 9.5 and 19 mm;
- Compaction levels of 75, 100, and 125 gyrations; and
- Five gradation types—above, below, and through the restricted zone (ARZ, BRZ, and TRZ); humped through the restricted zone (HRZ); and crossover through the restricted zone (CRZ).

With a few exceptions requested by the project panel and described in the report, performance testing was only conducted on HMA mix designs that met all Superpave mix design criteria, except the restricted zone requirement.

The research team found that HMA mixes meeting Superpave mix volumetric and FAA requirements with gradations passing through the restricted zone performed similarly to or better than mixes with gradations passing outside the restricted zone. The team concluded that the restricted zone requirement is not necessary to ensure satisfactory performance when all other relevant Superpave design requirements are met, and it recommended changes to AASHTO MP2 to implement this finding.

This final report includes a detailed description of the experimental program, a discussion of the research results, and five supporting appendixes:

- Appendix A: Review of Literature Relevant to the Restricted Zone;
- Appendix B: Compacted Aggregate Resistance Test;
- Appendix C: Volumetric Mix Design and Performance Data for Part 1;
- Appendix D: Volumetric Mix Design and Performance Data for Part 2; and
- Appendix E: Volumetric Mix Design and Performance Data for Part 3.

The entire final report will also be distributed as a CD-ROM (*CRP-CD-10*) along with task and final reports for NCHRP Projects 9-10 and 9-19. The research results have been referred to the TRB Mixtures and Aggregate Expert Task Group for its review and possible recommendation to the AASHTO Highway Subcommittee on Materials for revision of the applicable specifications and recommended practices.

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carried out under the direction of Prithvi S. Kandhal, associate director of NCAT and member of the graduate faculty of Civil Engineering, Auburn University, who served as the principal investigator. L. Allen Cooley, Jr., served as the research engineer for this project.

THE RESTRICTED ZONE IN THE SUPERPAVE AGGREGATE GRADATION SPECIFICATION

SUMMARY

The aggregate specification for Superpave[®] hot-mix asphalt (HMA) mixtures includes a restricted zone that lies along the maximum density gradation between the intermediate size (i.e., either 4.75 or 2.36 mm, depending on the nominal maximum size of the aggregate) and the 0.3-mm size. The restricted zone forms a band through which gradations were recommended not to pass. The restricted zone requirement was adopted in Superpave to reduce the incidence of tender or rut-prone HMA mixes. Although the restricted zone was included in Superpave as a recommended guideline and not as a required specification, some highway agencies interpret it as a requirement.

According to many asphalt paving technologists, compliance with the restricted zone criteria may not be desirable or necessary to produce paving mixes that give good performance in terms of rutting. Some highway agencies and suppliers can provide examples of aggregate gradations that pass through the restricted zone, but produce paving mixes that have performed well.

This research project was undertaken to evaluate the effect of the Superpave restricted zone on permanent deformation of dense-graded HMA mixtures on the basis of a statistically planned and properly controlled laboratory experiment. The project's primary objective was to determine under what conditions, if any, compliance with the restricted zone requirement is necessary when HMA meets all other Superpave requirements such as fine aggregate angularity (FAA) and volumetric mix criteria for the specific project.

The following factors were evaluated: two coarse aggregates, ten fine aggregates, two nominal maximum size mixes (i.e., 9.5 and 19.0 mm), five aggregate gradations, and three compactive efforts (i.e., $N_{\text{design}} = 75, 100, \text{ and } 125$). Of the five gradations used, three pass through the restricted zone and two (i.e., the control group) fall outside of the restricted zone. Permanent deformation characteristics of mixes meeting Superpave volumetric requirements were evaluated by two different types of tests: empirical and fundamental. For the empirical test, the Asphalt Pavement Analyzer was used. The Superpave shear tester and a repeated load confined creep test were used as fundamental tests. Test results from the three mechanical tests were analyzed statistically to evaluate the effect of the five gradations on permanent deformation of the HMA mixtures.

Mixes meeting Superpave and FAA requirements with gradations that violated the restricted zone performed similarly to or better than the mixes having gradations passing outside the restricted zone; therefore, the restricted zone requirement is redundant for mixes meeting all Superpave volumetric parameters and the required FAA. It has been recommended to delete references to the restricted zone as either a requirement or a guideline from the AASHTO specification (AASHTO MP2) and practice (AASHTO PP28) for Superpave volumetric mix design.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

PROBLEM STATEMENT AND RESEARCH OBJECTIVE

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 gradation) was intentionally excluded from the asphalt research program. Yet, the SHRP researchers had to recommend a set of aggregate properties and an aggregate gradation specification without the benefit of experimentation so that a comprehensive Superpave mix design system could be formulated.

SHRP formed an Aggregate Expert Task Group (ETG) consisting of 14 acknowledged aggregate experts. In lieu of a formal aggregate research program, the Aggregate ETG used a modified Delphi approach to develop a set of *recommended* aggregate properties and criteria that are now included in the Superpave volumetric mix design method (AASHTO MP2 and PP28). The Delphi process was conducted with five rounds of questionnaires. The final recommended aggregate gradation criteria included control points between which the gradation must fall, as well as a restricted zone that lies along the maximum density line (MDL) between the intermediate size (i.e., either 4.75 or 2.36 mm, depending on the nominal maximum size of the aggregate in the mix) and the 0.3-mm size.

Although the restricted zone was included in Superpave as a recommended guideline and not as a required specification, some highway agencies have interpreted it as a requirement. Many asphalt technologists believe that compliance with the restricted zone criteria may not be desirable or necessary in every case to produce asphalt mixes with good performance. If highly angular aggregates are used in the mix, it is likely that the mix will not exhibit any tenderness during construction and will be rut-resistant under traffic regardless of whether its gradation passes through the restricted zone. The Georgia Department of Transportation (DOT) has used such mixes successfully for many years. Some asphalt technologists also question the need for the restricted zone when the mix has to meet volumetric properties such as minimum voids in the mineral aggregate (VMA) and specified air void contents at N_{initial} , N_{design} , and N_{maximum} gyrations.

This research was carried out to evaluate the effect of restricted zone on mix performance on the basis of a sta-

tistically planned and properly controlled experiment. The research's primary objective was to determine under what conditions, if any, compliance with the restricted zone requirement is necessary when the hot-mix asphalt (HMA) meets all other Superpave requirements such as fine aggregate angularity (FAA) and volumetric mix criteria for the specific project.

SCOPE OF STUDY

The following tasks were conducted in two phases to accomplish the objective of this study.

Phase I

The tasks in Phase I were as follows:

- **Task 1:** Conduct a literature search and review of information relevant to the basis, use, and effect of the restricted zone.
- **Task 2:** Select materials (i.e., coarse aggregates, fine aggregates, and asphalt binder) for use in this study. A wide range of material properties should be evaluated.
- **Task 3:** Develop a research plan that utilizes a laboratory investigation to determine under what conditions, if any, the restricted zone requirement is necessary to ensure satisfactory HMA performance.
- **Task 4:** Prepare an interim report that documents the work accomplished in Tasks 1 through 3 and provides the detailed work plan for Phase II.

Phase II

The tasks in Phase II were as follows:

- **Task 5:** Execute the research plan approved in Phase I. Analyze data and draw conclusions based on test results.
- **Task 6:** Develop a recommended experimental plan and budget for a separate project to extend the analysis to other traffic levels and mixture types. (This additional work has been accomplished and is part of this final report.)

- **Task 7:** Submit a final report that documents the entire research effort. The report will include a plan for extending the results of this study and an implementation plan for moving the research results into practice.

RESEARCH APPROACH

The research approach for this project included reviewing literature relevant to the restricted zone (see Appendix A),

selecting a variety of coarse and fine aggregates of different mineralogical compositions and angularities, conducting Superpave volumetric mix designs using gradations both conforming to and violating the restricted zone, conducting performance tests on mixtures meeting Superpave volumetric and FAA criteria, and analyzing the relative performance of mixes to determine whether the restricted zone requirement is necessary in Superpave for ensuring better performance.

CHAPTER 2

EXPERIMENTAL PLAN

SELECTION OF MATERIALS

Materials needed for this study consisted of coarse aggregates, fine aggregates, and an asphalt binder. Two coarse aggregates, ten fine aggregates, and one asphalt binder were selected. The descriptions of the materials selected for this study along with properties of the selected materials follows.

Coarse Aggregates

Two coarse aggregates were used. Selection criteria for these two coarse aggregates were that they should come from different mineralogical types and have different angularities and surface textures. These criteria were selected to ensure that the coarse aggregates gave a range of properties. Selected coarse aggregates were a crushed granite and a crushed gravel. The crushed gravel is predominately composed of quartz. Both of these sources were used in NCHRP Project 4-19, "Aggregate Tests Related to Asphalt Concrete Performance in Pavements." Properties of these two coarse aggregates are provided in Table 1.

Fine Aggregates

Because the restricted zone is applied within the fine aggregate sieve sizes, the shape and texture of the fine aggregates are the most important factors affecting the performance of HMA mixtures; therefore, the approach taken in identifying and selecting fine aggregates for use in this study was to select aggregates with varying values of FAA. Also included within the selection criteria were mineralogical composition of the fine aggregates and type of crusher. Maximization of these three criteria ensured using fine aggregates with a wide range of properties.

During the identification process, aggregates that have been or are being used in controlled field pavement performance studies were included. Field studies considered included FHWA WesTrack, ICAR (at the International Center for Aggregate Research), Pooled Fund Study No. 176 at Purdue, and MnRoad.

A large database of FAA values was compiled to select the nine fine aggregates for this study. This database included fine aggregates from Mississippi, Alabama, Georgia, Illinois, Min-

nesota, Virginia, Tennessee, Nevada, California, Louisiana, North Carolina, Indiana, and Iowa. FAA values within this database ranged from a low of 38 to a high of 52.

The 10 selected fine aggregates, along with their mineralogical type and FAA value (AASHTO T304), are provided in Table 2. Six different mineralogical types were selected and include natural sands, sandstone, dolomite, limestone, granite, and diabase (i.e., traprock). FAA values of the ten fine aggregates ranged from 38.6 to 50.3.

FA-10 was included in this study based upon recommendations from the project panel. This fine aggregate purposely had a FAA value below 40 (i.e., FAA = 38.6). FA-10 was included to provide a "worst-case" reference point for comparing the response variables described later in this report.

As can be seen from Table 2, a wide range of FAA values was selected. As indicated in the approved work plan, three compactive efforts were used during this study. These three compactive efforts included medium, high, and very high. The Superpave FAA requirement for the high and very high compactive efforts is 45 percent voids. For the medium compactive effort, the FAA requirement is 40 percent voids. Because two of the three compactive efforts used in this study require a minimum FAA value of 45, approximately two-thirds (i.e., six) of the fine aggregates shown in Table 2 meet a FAA value of 45.

Additional testing on each fine aggregate is presented in Table 3. This table presents the results of specific gravity (AASHTO T84), sand equivalency (AASHTO T176), and adherent fines testing. The procedure used to measure the percent of adherent fines was a modified version of ASTM D5711. This procedure calls for testing of aggregates larger than 4.75 mm. Since the fine aggregates were the materials in question for this study, ASTM D5711 was followed except testing was conducted on aggregates passing the 4.75-mm (No. 4) sieve and retained on the 0.075-mm (No. 200) sieve.

Table 3 shows that a wide range of physical properties was selected. Apparent specific gravities ranged from 2.614 to 2.973 while bulk specific gravities ranged from 2.568 to 2.909. All but three fine aggregates had water absorption values less than 1.0 percent. The highest absorption value was 1.7 percent for FA-8. An interesting observation from Table 3 is that the sand equivalency and percent adherent fines values appear to be related. Generally, as the adherent fines values increased, sand equivalency values decreased.

TABLE 1 Coarse-aggregate properties

Test	Procedure	Crushed Gravel	Granite
Flat or Elongated 2:1	ASTM D4791	20	57
Flat or Elongated 3:1	ASTM D4791	2	11
Flat or Elongated 5:1	ASTM D4791	0	1
Flat and Elongated 2:1	ASTM D4791	40.1	64.3
Flat and Elongated 5:1	ASTM D4791	0	1.0
Uncompacted Voids (Method A)	AASHTO TP56	41.7	47.0
Apparent Specific Gravity	AASHTO T84	2.642	2.724
Bulk Specific Gravity	AASHTO T85	2.591	2.675
Water Absorption, %	AASHTO T85	0.7	0.6
Los Angeles Abrasion, % loss	AASHTO T96	28	41
Coarse Aggregate Angularity % 1 Fractured Face, % 2 Fractured Faces	ASTM D5821	100/92	100/100

TABLE 2 Fine aggregates selected for study

Fine Aggregate	FAA Value	Mineralogical Type	Comments
FA-1	40.7	River Sand	Washed, uncrushed, river deposit comprised of predominantly quartz, from Kentucky
FA-2	42.6	Quartz Sand	No processing, natural quartz river deposit with some chert, from Tennessee
FA-3	44.1	Natural Sand	Uncrushed, natural quartz sand with some chert, from Alabama
FA-4	49.7	Sandstone	Mined, cone crusher, from Alabama
FA-5	50.3	Dolomite	Mined from Alabama
FA-6	46.9	Limestone	Mined, same source as FA-8 but crushed by impact crusher, from Alabama
FA-7	48.9	Granite	Mined, cone crusher, from Minnesota, used on MnRoad
FA-8	48.3	Limestone	Mined, same source as FA-6 but crushed by cone crusher, from Alabama
FA-9	50.1	Diabase	Mined, impact crusher, from Virginia
FA-10	38.6	Natural Sand	Dredged stream deposit from Mississippi

TABLE 3 Physical properties of fine aggregates

Fine Aggregate	Apparent Specific Gravity	Bulk Specific Gravity	% Absorption	Sand Equivalency, %	Adherent Fines, %
FA-1	2.614	2.610	0.2	100	0.1
FA-2	2.665	2.568	1.4	98	0.3
FA-3	2.664	2.638	0.4	95	0.2
FA-4	2.789	2.731	0.8	29	10.4
FA-5	2.856	2.822	0.5	61	3.2
FA-6	2.737	2.661	1.0	91	2.4
FA-7	2.742	2.711	0.4	94	0.6
FA-8	2.777	2.648	1.7	100	2.1
FA-9	2.973	2.909	0.8	59	7.5
FA-10	2.653	2.636	0.3	100	0.1

In addition to the testing outlined in Tables 2 and 3, the compacted aggregate resistance (CAR) test was also conducted. This test involves compacting the fine aggregate sample in Marshall mold, testing its shear resistance by penetrating a 1.5-in. (38-mm) diameter round bar with the Marshall stability machine, and reading the peak load. The CAR test is not a standard test, so the method is provided in Appendix B. Figures 1 and 2 present the CAR results.

Results of the CAR test appear to relate with the FAA results. Generally, as FAA values increased, the peak loads from the CAR test also increased. It is interesting to note that the four uncrushed natural sands (i.e., FA-1, FA-2, FA-3, and FA-10) all had the lowest peak loads in the CAR test. However, FA-7, with an FAA value of 48.9, also gave relatively lower peak load in the CAR test.

Asphalt Binder

The asphalt binder selected was a Superpave performance-based PG 64-22, which is one of the most commonly used grades in the United States. This binder is one of the National Center for Asphalt Technology (NCAT) labstock asphalt binders and has been used successfully on numerous research projects. Properties of this asphalt binder are provided in Table 4.

EXPERIMENTAL PLAN

Based on the review of literature (see Appendix A) and properties of the selected materials, a statistically based, con-

trolled laboratory experimental plan was developed with the objective of determining under what conditions, if any, the restricted zone requirement is necessary to ensure satisfactory HMA performance when the FAA and the Superpave mixture volumetric criteria are met.

The literature review identified a number of variables with potential for inclusion in the experimental plan: crushed versus uncrushed fine aggregates, compactive efforts during mix design, volumetric properties, FAA values, and nominal maximum aggregate size for gradations.

To achieve the primary objective of this study, a number of gradations using different aggregate types (i.e., coarse and fine aggregates) were tried for mix design. These consisted of gradations that both met and did not meet the restricted zone criteria. These mixes were prepared at optimum asphalt content and tested by performance-related, mechanical test methods. Also, because the literature review suggested that the effect of the restricted zone on mix performance is different for aggregates with different particle shape, angularity, and surface texture, the experiment included a set of aggregates with a significant range of shape and texture properties (i.e., FAA values).

The overall research approach is shown in Figure 3. This figure illustrates that the research effort was broken into three parts to maximize the information obtained. During Part 1, variables included within the research were two coarse aggregates, ten fine aggregates, one nominal maximum aggregate size (NMAS), five gradations, one asphalt binder, and one compactive effort with the Superpave gyratory compactor (SGC). Based on the results of Part 1, Part 2 involved a

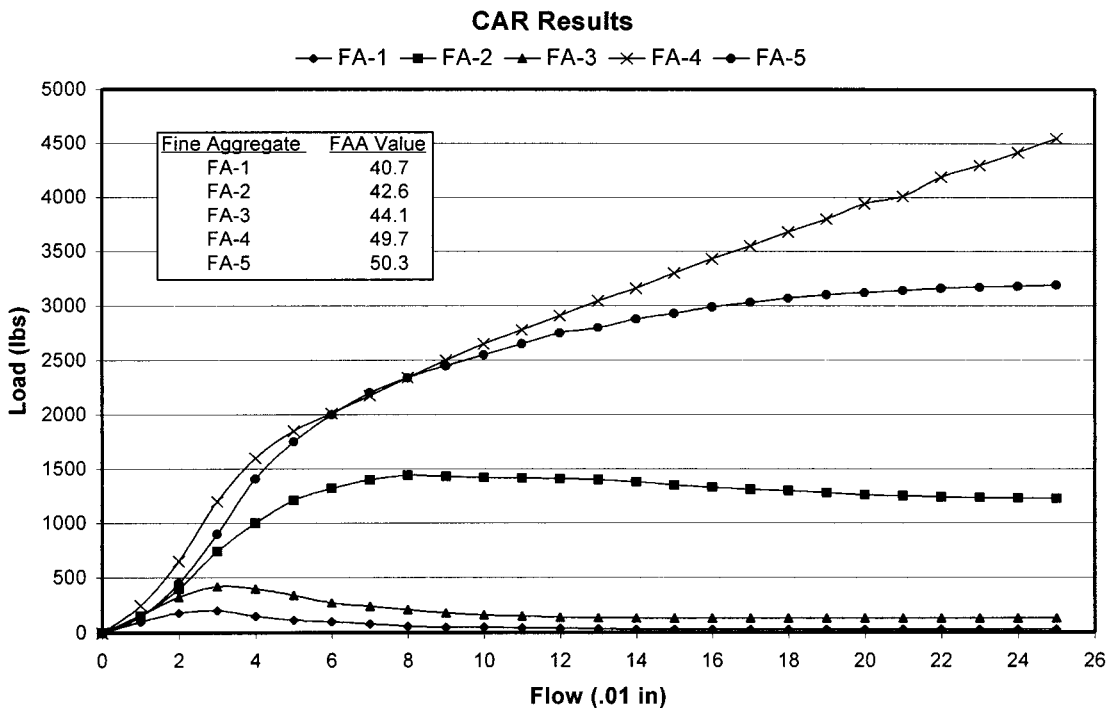


Figure 1. Results of CAR test for fine aggregates FA-1 through FA-5.

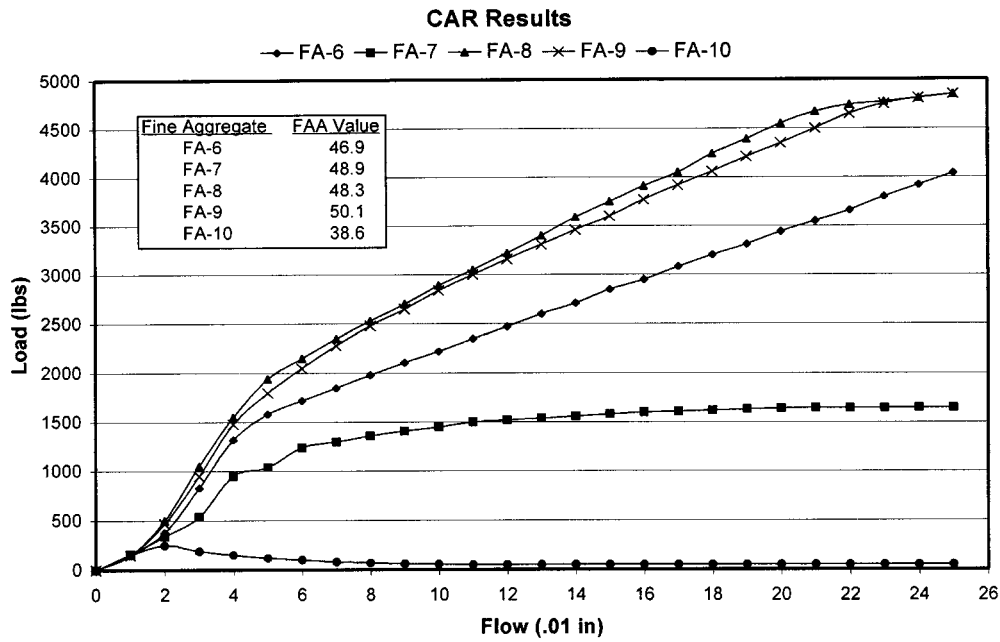


Figure 2. Results of CAR test for fine aggregates FA-6 through FA-10.

TABLE 4 Properties of asphalt binder

Test	Temperature (°C)	Test Result	Requirement
Unaged DSR, $G^*/\sin\delta$ (kPa)	64	1.85	1.00 min
RTFO-Aged DSR, $G^*/\sin\delta$ (kPa)	64	3.83	2.20 min
PAV-Aged DSR, $G^*\sin\delta$ (kPa)	25	4063	5000 max
PAV-Aged BBR, Stiffness (MPa)	-12	244	300 max
PAV-Aged BBR, m -value	-12	0.301	0.300 min

NOTE: DSR = dynamic shear rheometer;
 RTFO = rolling thin film oven;
 PAV = pressure aging vessel;
 BBR = bending beam rheometer.

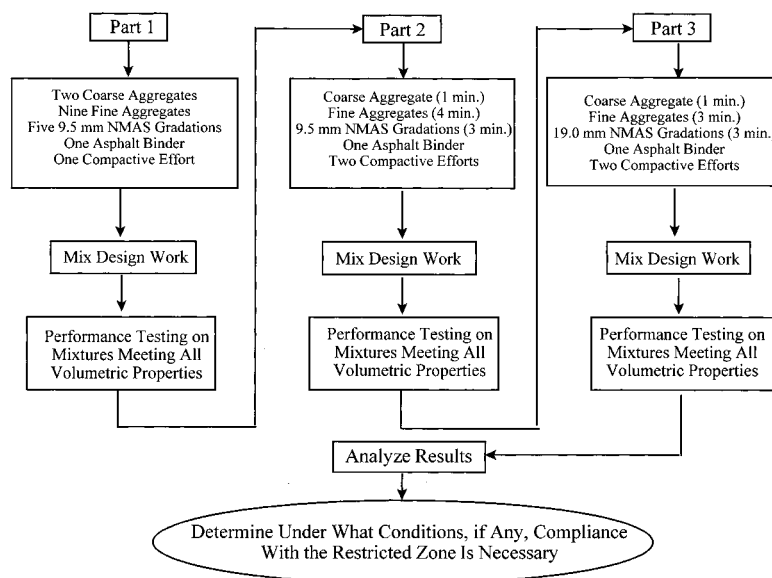


Figure 3. Overall research approach.

critical coarse aggregate (sensitive to the effect of different fine aggregates on HMA performance properties), critical fine aggregates (sensitive to the effect of different gradations on HMA performance properties), and critical gradations for the same NMAS (showing the most significant effect on HMA performance properties) combined with the same asphalt binder and designed using two different compactive efforts with the SGC. In Part 3, the coarse aggregate, fine aggregates, gradations (different NMAS), and compactive effort were based on results from Parts 1 and 2. The detailed work plans for the three parts are described as follows.

Part 1 Work Plan

The work plan for Part 1 is illustrated in Figure 4. Factor-level combinations included in Part 1 consisted of two coarse aggregates, ten fine aggregates, five 9.5-mm NMAS gradations, and one compactive effort. Of the five gradations used in Part 1, three violated the restricted zone (VRZ) while two resided outside the restricted zone (i.e., the control group). These five gradations are given in Table 5 and illustrated in Figure 5. The compactive effort used during Part 1 was that for a 20-year design traffic level of 3 to 30 million equivalent single axle loads (ESALs). The initial, design, and maximum

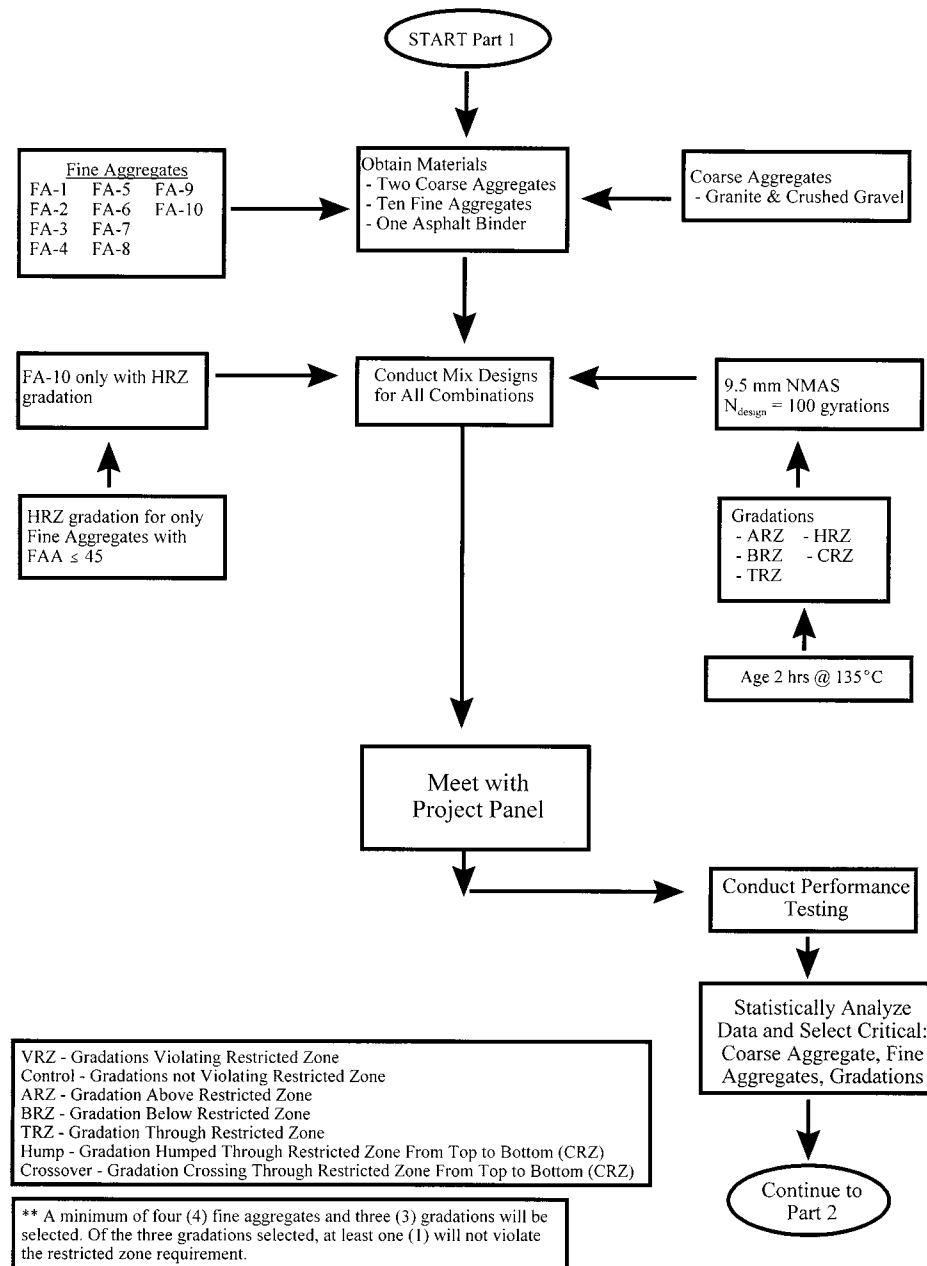


Figure 4. Research approach for Part 1.

TABLE 5 9.5-smm NMA5 gradations used in Parts 1 and 2

Sieve, mm	BRZ	ARZ	TRZ	HRZ	CRZ
12.5	100	100	100	100	100
9.5	95	95	95	95	95
4.75	60	60	60	60	60
2.36	42	50	46	46	52
1.18	28	42	34	34	34
0.60	18	32	24	30	20
0.30	14	22	18	24	14
0.15	10	10	10	10	10
0.075	5	5	5	5	5

number of gyrations for this design traffic level are 8, 100, and 160, respectively (see Table 6).

As seen in Figure 5, all five gradations follow the same trend from the 12.5-mm sieve down to the 4.75-mm sieve. From the 4.75-mm sieve, the BRZ (below the restricted zone) gradation passes below the restricted zone and above the lower control points. The ARZ (above the restricted zone) gradation passes above the restricted zone and below the upper control points. These two gradations are designated the control gradations because they do not violate the Superpave restricted zone. Figure 5 shows that the remaining three gradations do violate the restricted zone. From the 4.75-mm sieve, the TRZ (through the restricted zone) gradation passes almost directly along the MDL. The HRZ (humped through the restricted zone) gradation follows a similar gra-

duction as the TRZ gradation down to the 1.18-mm sieve where it humps on the 0.6- and 0.3-mm sieves and represents gradations generally containing a large percentage of natural, windblown sands. From the 4.75-mm sieve, the CRZ (crossover through the restricted zone) gradation begins above the restricted zone on the 2.36-mm sieve but then crosses through the restricted zone between the 0.6- and 0.3-mm sieves. The CRZ gradation represents gradations that are not continuously graded between 2.36-mm and 0.60-mm sizes and generally exhibit low mix stability. All five of the gradations then meet at the 0.15-mm sieve and follow the same trend down to the 0.075-mm sieve. A common material passing the 0.075-mm sieve (No. 200) sieve (P200) was used in all HMA mixtures to eliminate P200 as a variable. Different P200 materials stiffen the asphalt binder and HMA mix-

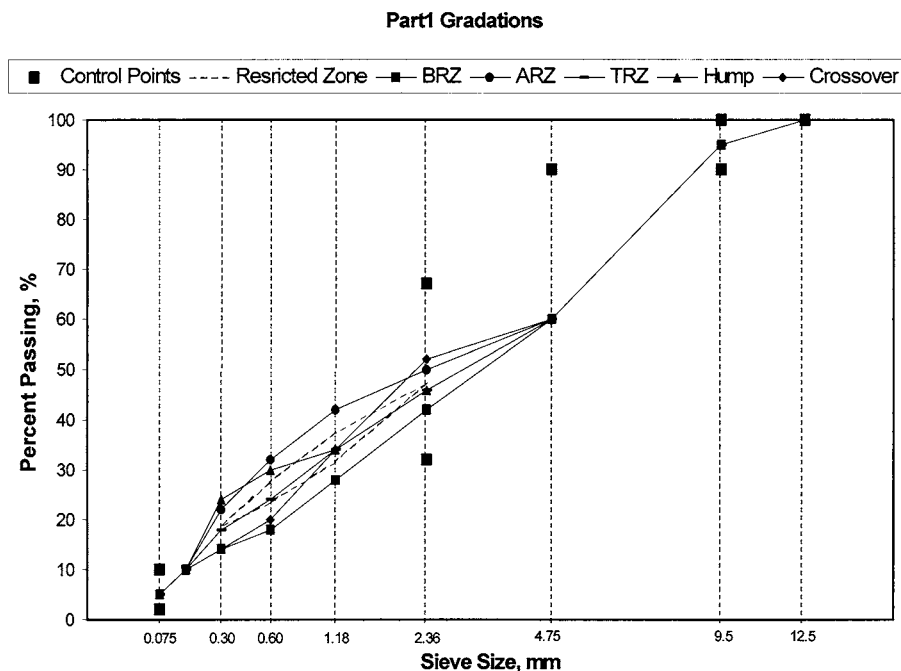


Figure 5. Part 1 gradations.

TABLE 6 Superpave design compactive effort and aggregate consensus property requirements

Estimated Design Traffic Level (Million ESALs) ¹	Superpave Compaction Parameters ²			%G _{mm} N _{initial} Requirement	Aggregate Consensus Properties					
	N _{initial}	N _{design} ⁷	N _{maximum}		Coarse Aggregate Angularity ³		Fine Aggregate Angularity ⁴		Sand Equivalent Value ⁵	Flat and Elongated ⁶
					≤ 100 mm	> 100 mm	≤ 100 mm	> 100 mm	All Mixtures	All Mixtures
< 0.3	6	50	75	≤ 91.5	55/-	-/- ⁹	- ⁹	- ⁹	40	- ⁹
0.3 – 3	7	75	115	≤ 90.5	75/-	50/-	40	40	40	< 10 %
3 – 10	8	100 ⁸	160	≤ 89.0	85/80	60/-	45	40	45	< 10 %
10 – 30	8	100 ⁸	160	≤ 89.0	95/90 ³	80/75	45	40	45	< 10 %
>30.0	9	125	212	≤ 89.0	100/100	100/100	45	45	50	< 10 %

¹ Values shown are based upon 20-year equivalent single axle loads (ESALs). For roadways designed for more or less than 20 years, determine the estimated ESALs for 20 years and choose the appropriate N_{design} level.

² It is recommended that Superpave mixtures be compacted to N_{design} gyrations.

³ "85/80" denotes that 85% of the coarse aggregate has one fractured face and 80% has two or more fractured faces.

⁴ Criteria are minimum presented as percent air voids in loosely compacted fine aggregate. Test is to be run in accordance with AASHTO TP-33.

⁵ No distinction is made between depth from surface. Test is to be run in accordance with AASHTO T176.

⁶ Criterion based upon a 5:1 maximum-to-minimum ratio.

⁷ (a) N_{design} compactive effort is for typical traffic speeds. For slow/standing traffic, increase N_{design} by one (1) traffic level or increase high-temperature binder grade by one. (No changes in aggregate properties with increased compactive effort and do not exceed N_{design} of 125 gyrations.)
(b) For pavement layers where the top of the design layer is more than 100-mm below the surface, decrease the compactive effort by one level, but not less than N_{design} of 50 gyrations.

⁸ Use for stone matrix asphalt (SMA). However, when the L.A. abrasion value for the aggregate used in SMA exceeds 30, consider dropping to the next lower compaction level (75 gyrations).

⁹ Dash means no requirement.

tures to a different degree and, therefore, affect the mix performance test results. A limestone filler (which has a Rigden voids value of 33.5 percent) was utilized as the P200.

Based on Figure 4, factor-level combinations were designed using an SGC (N_{design} = 100 gyrations). In accordance with recommendations by the project panel, FA-10 was combined with the two coarse aggregates only for the HRZ gradation. The project panel also recommended not combining fine aggregates having an FAA value greater than 45 with the HRZ gradation because the HRZ gradation is indicative of gradations having a large percentage of natural rounded sand. Natural rounded sands very rarely have FAA values greater than 45. It was therefore deemed unnecessary to evaluate HRZ gradations with fine aggregates having FAA values greater than 45.

Part 2 Work Plan

The work plan for Part 2 was very similar to that of Part 1, with two major differences: (1) fewer factor-level combinations and (2) two different compactive efforts. The factor-level combinations included were one critical coarse aggregate (i.e., granite), three 9.5-mm NMAS gradations (i.e., BRZ, TRZ, and CRZ), and two compactive efforts. The BRZ gradation was included as the control gradation. For Part 2, the two compactive efforts were equal to the medium and very high traffic levels from Table 6 (i.e., N_{design} = 75 and 125 gyrations, respectively). Based upon the Part 1 mix design data and guidance

from the project panel, seven fine aggregates were investigated in Part 2. For the lower compactive effort (i.e., N_{design} = 75), mix designs were conducted for FA-2, FA-3, FA-4, FA-6, FA-7, and FA-10. For the higher compactive effort (i.e., N_{design} = 125), mix designs were conducted for FA-4, FA-7, FA-9, and FA-10. Similar to Part 1, FA-10 was only used with the HRZ gradation.

Mix designs were conducted for all combinations of fine aggregate, gradation, and compactive effort. Performance testing was then accomplished on those mixtures meeting all volumetric requirements.

For the lower compactive effort experiment (i.e., N_{design} = 75), humped gradations (i.e., HRZ) were included for the fine aggregates having a FAA value less than 45.0 (FA-2 and FA-3). Realistically, the potential for using natural sands (which have low FAA values) is greatest for low-volume roadways. Additionally, when natural sands are incorporated into an aggregate gradation, there is a higher potential for humped gradations.

Similar to the Part 1 work, a mix design and performance testing using FA-10, granite coarse aggregate, HRZ gradation, and 75-gyraton design level were conducted. This information was used as a baseline against which to compare other results.

Part 3 Work Plan

The primary objective of Part 3 was to extend the Part 1 and Part 2 research results to 19.0-mm NMAS gradations. During Parts 1 and 2, only 9.5-mm NMAS gradations were used.

Figure 6 presents the experimental plan for Part 3. This figure shows that two compactive efforts were used: 75 and 100 gyrations. Within the lower compactive effort experiment (i.e., $N_{design} = 75$), a gravel coarse aggregate was used because preliminary testing indicated that mixes containing the gravel coarse aggregate should prevent mixtures with excessive VMA (as seen at $N_{design} = 75$ during Part 2). Five fine aggregates were used including FA-2, FA-3, FA-4, FA-6, and FA-7. These fine aggregates are identical to those used during the Part 2 work at $N_{design} = 75$. As suggested by the project panel, three gradations were included: BRZ, TRZ, and ARZ. These gradations are illustrated in Figure 7 and presented in Table 7. The same asphalt binder was used in Part 3 as in Parts 1 and 2. Mix designs were conducted for the HRZ for FA-2 and FA-3 (which have FAA values less than 45.0).

Within the higher compactive effort experiment (i.e., $N_{design} = 100$), a granite coarse aggregate was used with five

fine aggregates: FA-2, FA-4, FA-6, FA-7, and FA-9. Again, the BRZ, TRZ, and ARZ gradations were investigated.

For both compactive effort experiments, mix designs and performance testing using FA-10 and the HRZ gradation were conducted. Similar to Parts 1 and 2, this information should provide a “worst-case” baseline.

Figure 6 shows the flow of work in Part 3. For a given factor-level combination, mix designs were first conducted for the gradation(s) violating the restricted zone. If the mixture(s) met all Superpave volumetric requirements, then mix designs were conducted for the two control gradations (i.e., BRZ and ARZ). However, if none of the mixes violating the restricted zone met all volumetric criteria, testing was stopped for that factor-level combination. Mixtures meeting all volumetric criteria were used for performance testing. For Part 3, only the Asphalt Pavement Analyzer (APA) was used as a performance test.

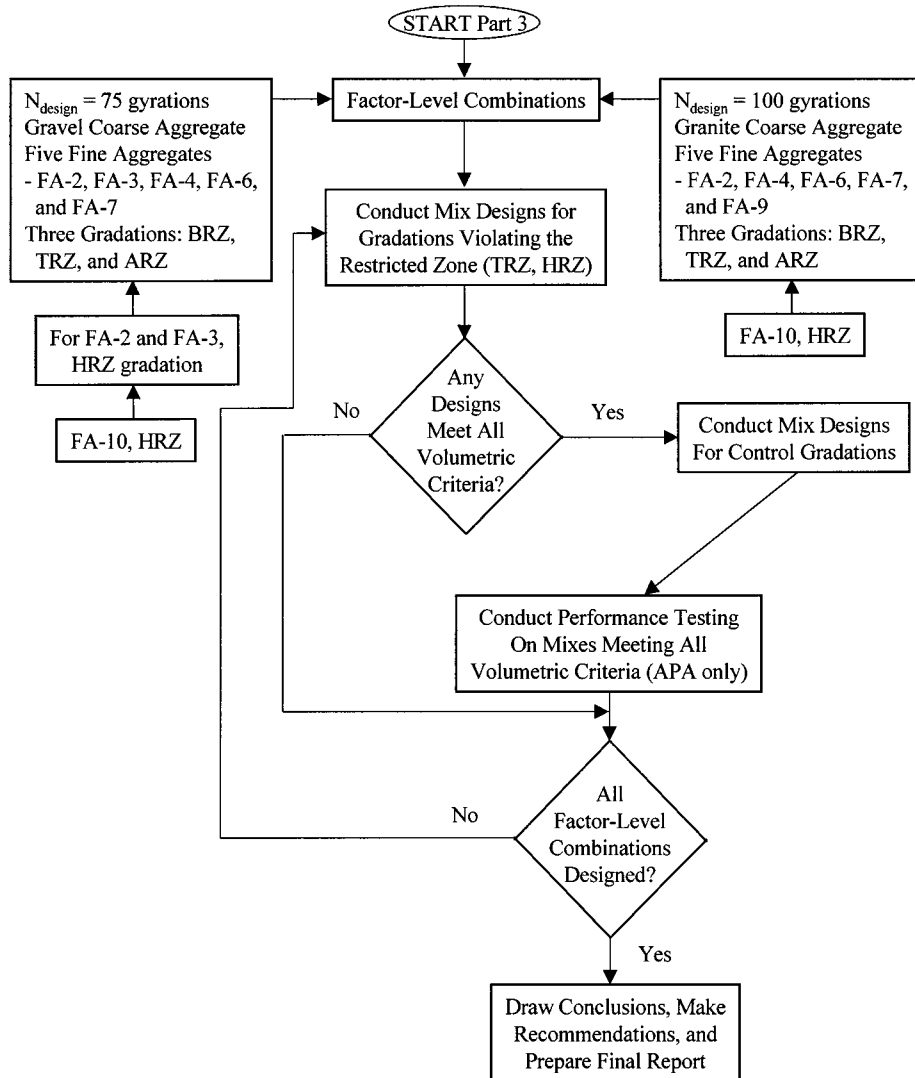


Figure 6. Flow diagram showing work for Part 3.

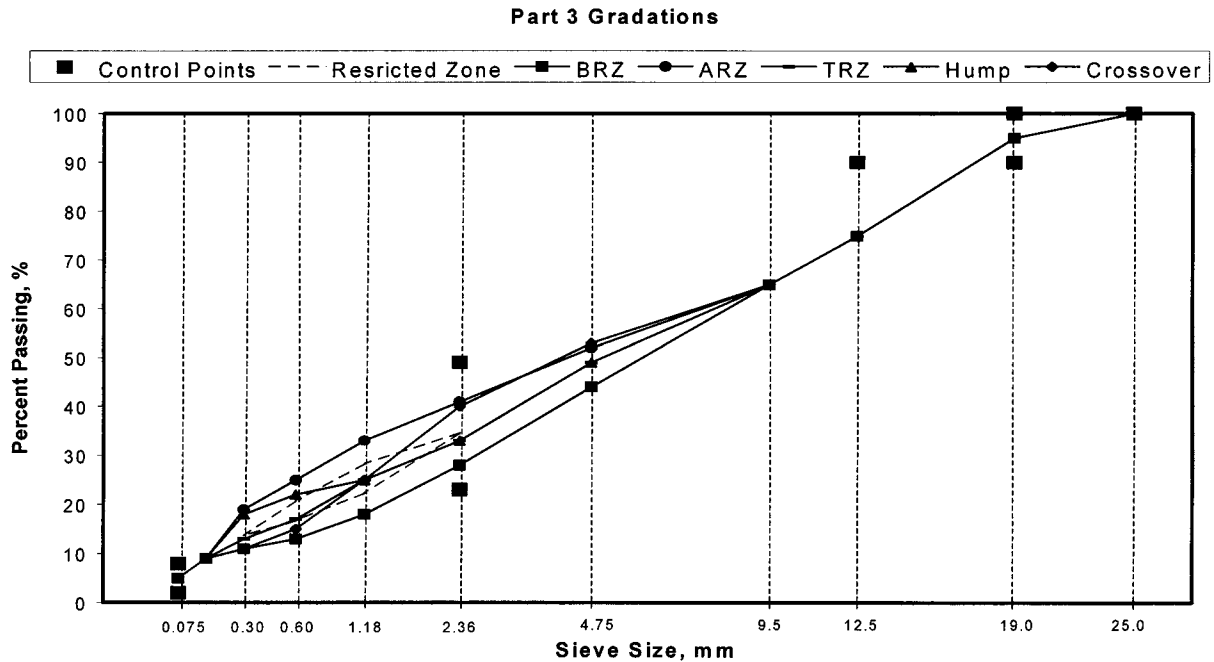


Figure 7. Part 3 gradations.

Response Variables

The performance of mixes with various factor-level combinations meeting Superpave volumetric requirements were evaluated on the basis of performance-related mechanical tests. Because the primary purpose of the restricted zone is to avoid rut-prone mixes, the mixes in this study were evaluated for their rutting potential. This was accomplished by two different types of tests: empirical and fundamental. For the empirical test, the APA was used. The Superpave shear tester and the repeated load confined creep (RLCC) test were used as fundamental tests.

Three tests were included to ensure a satisfactory conclusion of this study. It was not expected that all three permanent deformation tests (i.e., one empirical and two fundamental) will provide exactly similar results. If they did, one mix validation test would be sufficient. However, all three tests might not be equally sensitive to changes in gradation and FAA values. Their relative sensitivity to changes in gradation and FAA values would be evident from the test data. The test that is most sensitive to these two important factors of this research project will be considered the most relevant and significant.

TABLE 7 19.0-mm NMA5 gradations used in Part 3

Sieve, mm	BRZ	ARZ	TRZ	HRZ
25.0	100	100	100	100
19.0	95	95	95	95
12.5	75	75	75	75
9.5	65	65	65	65
4.75	44	52	49	49
2.36	28	41	33	33
1.18	18	33	25	25
0.60	13	25	17	22
0.30	11	19	13	18
0.15	9	9	9	9
0.075	5	5	5	5

Asphalt Pavement Analyzer

The APA is an automated, new generation of Georgia Load Wheel Tester (GLWT). The APA (see Figure 8) features controllable wheel load and contact pressure, adjustable temperature inside the test chamber, and the capability to test the samples while they are either dry or submerged in water. This enhanced version of the GLWT gives rutting and moisture susceptibility test environments that are more representative of actual field conditions than were previously provided by the GLWT. The APA test was conducted dry to 8,000 cycles, and rut depths were measured continuously. The APA can test three pairs of gyratory-compacted specimens of 75-mm height. Testing with the APA was conducted at 64°C. The air void content of the different mixtures was 6.0 ± 0.5 percent. The mixture was aged 2 h at the compaction temperature prior to compacting. Hose pressure and wheel load were 690 kPa and 445 N (100 psi and 100 lb), respectively.

Superpave Shear Tester (AASHTO TP7-94)

The Superpave shear tester, shown in Figure 9, is a closed-loop feedback, servohydraulic system that consists of four major components: a testing apparatus, a test control unit, an



Figure 8. Asphalt Pavement Analyzer.



Figure 9. Superpave shear tester.

environmental control chamber, and a hydraulic system. The ability of a pavement structure to resist permanent deformation and fatigue cracking is estimated through the use of the Superpave shear tester. The Superpave shear tester simulates, among other things, the comparatively high shear stresses that exist near the pavement surface at the edge of vehicle tires—stresses that lead to the lateral and vertical deformations associated with permanent deformation in surface layers.

The repeated shear at constant height (RSCH) test (AASHTO TP7, Procedure F) was selected to assess the permanent deformation response characteristics of the mixtures. The RSCH test is performed to estimate rut depth. This test operates by applying repeated shear load pulses to an asphalt mixture specimen. As the specimen is being sheared, the constant height prevents specimen dilation, thereby promoting the accumulation of permanent shear strain. The test can be used for comparatively analyzing shear response characteristics of mixtures subjected to similar loading and temperature conditions.

The literature review indicated that this Superpave shear tester has been used successfully by researchers to evaluate

the relative rutting potential of HMA mixtures. All specimens for Superpave shear testing were fabricated at 3.0 ± 0.5 percent air voids and tested at 50°C . This test temperature was selected because it is representative of effective temperature for permanent deformation ($T_{\text{eff}}[PD]$) as used in Superpave shear test protocol for the southeastern United States and is believed to be critical for inducing rutting in HMA pavements. Prior to compaction, the mixture was aged for 4 h at 135°C .

Repeated Load Confined Creep Test

The RLCC test is considered a fundamental experimental method to characterize the rutting potential of HMA because

fundamental creep principles can be applied to deformation of viscoelastic mixes. A material testing system (MTS) was used to conduct this test. A deviator stress, along with a confining stress, is repetitively applied on a HMA sample for 1 h, with a 0.1-s load duration and a 0.9-s rest period. After the 1-h test, the load is removed, and the rebound measured for 15 min. The strain observed at the end of this period is reported as the permanent strain. The permanent strain indicates the rutting potential of the mix. The target air void content for mixtures tested by the RLCC test was 4.0 ± 0.5 percent. Prior to compaction, the mixture was aged for 4 h at 135°C . The test temperature was 60°C . Test loadings consisted of an 138 kPa (20 psi) confining pressure and an 827 kPa (120 psi) normal pressure.

CHAPTER 3

LABORATORY TEST RESULTS AND ANALYSIS

This chapter presents the test results and analysis of the laboratory experiment. The experimental plan was divided into three parts. Experiments in Parts 2 and 3 were guided by the results of Part 1. This chapter is divided into three sections, each providing test results, analysis, and decisions made for subsequent parts.

PART 1 TEST RESULTS AND ANALYSIS

Mix designs for 9.5-mm NMA mixes were conducted for 80 factor-level combinations during Part 1. As mentioned earlier, the compactive effort used in Part 1 corresponded to a design traffic level of 3 to 30 million ESALs. The initial, design, and maximum number of gyrations were 8, 100, and 160, respectively. The results of these mix designs are presented in Appendix C.

Of the 80 mixes designed, only 9 mixes met all volumetric (i.e., VMA, VFA [voids filled with asphalt], and $\%G_{mm}@N_{initial}$ [the percent of maximum specific gravity at the initial number of gyrations]) and FAA criteria. Of the mixes not meeting criteria, 22 did not meet VMA, 13 did not meet VFA, 6 did not meet $\%G_{mm}@N_{initial}$, 28 did not meet VMA and $\%G_{mm}@N_{initial}$, 1 did not meet $\%G_{mm}@N_{initial}$ and VFA, and 1 did not meet VMA and VFA.

A secondary goal of this research was to evaluate the effect of mix constituent properties on the volumetrics of the 80 designed mixes. Volumetric properties considered included air voids, VMA, VFA, $\%G_{mm}@N_{initial}$, and $\%G_{mm}@N_{maximum}$. Air voids were kept constant at 4 percent as this void level defines optimum asphalt content, so air voids were not analyzed. VFA is a function of VMA and air voids and no mix failed $\%G_{mm}@N_{maximum}$, so neither were included. Therefore, only VMA and $\%G_{mm}@N_{initial}$ were analyzed.

The first step in this analysis was to conduct an analysis of variance (ANOVA) to determine the effect of coarse aggregate, fine aggregate, and gradation on VMA and $\%G_{mm}@N_{initial}$. For these ANOVAs, the calculation of the F -statistics had to be modified. This was because only one response was obtained for each factor-level combination (e.g., there was only one VMA for each mix). To calculate the F -statistic, the degrees of freedom associated with the interactions among the experiment factors were sacrificed. This sacrifice of degrees of freedom for the interactions provided the necessary mean

squares of error to calculate the F -statistic without sacrificing the results of the ANOVA.

Results of the ANOVA conducted to evaluate the significance of the experiment's main factors is presented in Table 8. This table shows that all three main factors significantly affect VMA. Based upon the F -statistics, it is seen that the coarse aggregate had the greatest effect on VMA (i.e., it had the largest F -statistic) followed by fine aggregate and gradation, respectively.

Figure 10 illustrates the relative effect of coarse aggregate and gradation on VMA. Each bar on this figure represents the average VMA for mixes having the same coarse aggregate and gradation type—therefore, each bar is the average VMA for all fine aggregates. This figure suggests that mixes containing the more angular coarse aggregate yielded collectively higher VMA values than did mixes containing the crushed gravel fine aggregate. This was true for each gradation. Figure 10 shows that the ARZ and CRZ gradations tended to provide higher VMA values and that the HRZ and TRZ provided the lowest VMA values. Recall that the HRZ gradation was only combined with fine aggregates having an FAA of 45 or lower. Evaluation of the FA-1, FA-2, and FA-3 mix design data indicated that the HRZ gradation provided higher VMA values (an average of 14.4 percent for granite and 13.3 percent for gravel coarse aggregates, respectively) than did the TRZ gradation (an average of 13.8 percent for granite and 12.9 percent for gravel coarse aggregate, respectively). Because the TRZ gradation generally provided the lowest VMA values, it appears that the MDL defined within the Superpave mix design system for 9.5-mm NMA gradations relatively is in the correct location.

The effect of fine aggregate on the VMA values was evaluated by correlating VMA to FAA. Figures 11 and 12 illustrate the relationship between FAA and VMA for mixes containing granite and gravel coarse aggregates, respectively. Within these figures, the relationship between FAA and VMA is shown for each gradation. Coefficients of determination (R^2) are also shown for each relationship. Table 9 presents the F -statistic and p -value for each regression. Figures 11 and 12 indicate that the relationship between VMA and FAA is poor as R^2 values are typically below 0.25. In fact, the F -statistic and probability values indicate that the relationships are not significant. Although there is no significance to the relationships, there does appear to be a trend that is common to

TABLE 8 Results of ANOVA to determine significance of main factors on VMA

Source	Degrees of Freedom	F-Statistic	P-Value
Coarse Aggregate	1	156.40	0.000
Fine Aggregate	8	110.85	0.000
Gradation	4	13.99	0.000

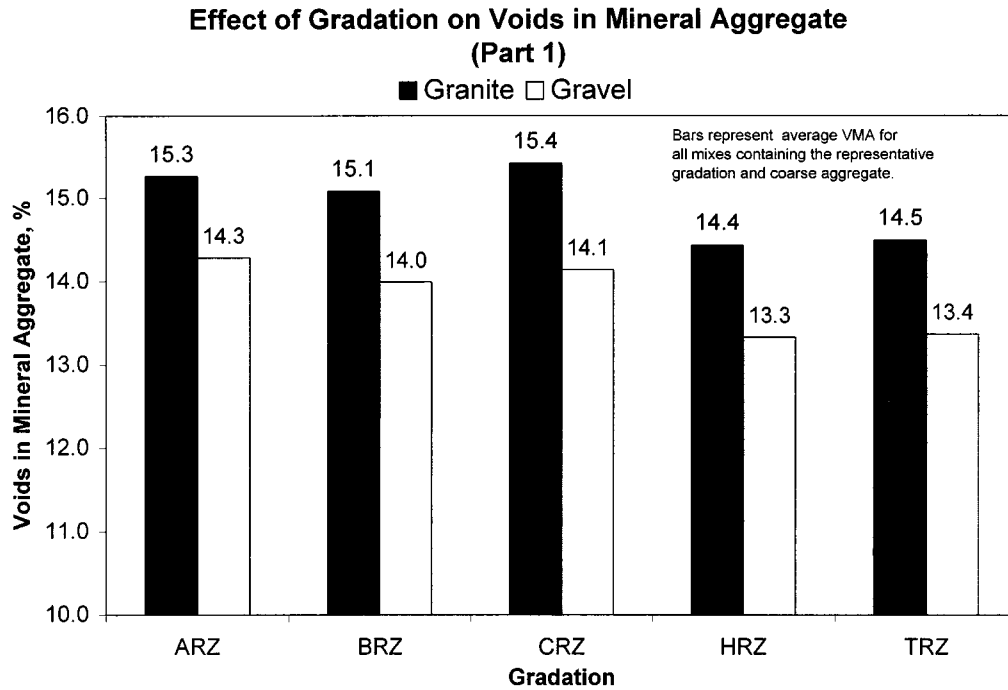


Figure 10. Effect of gradation on VMA.

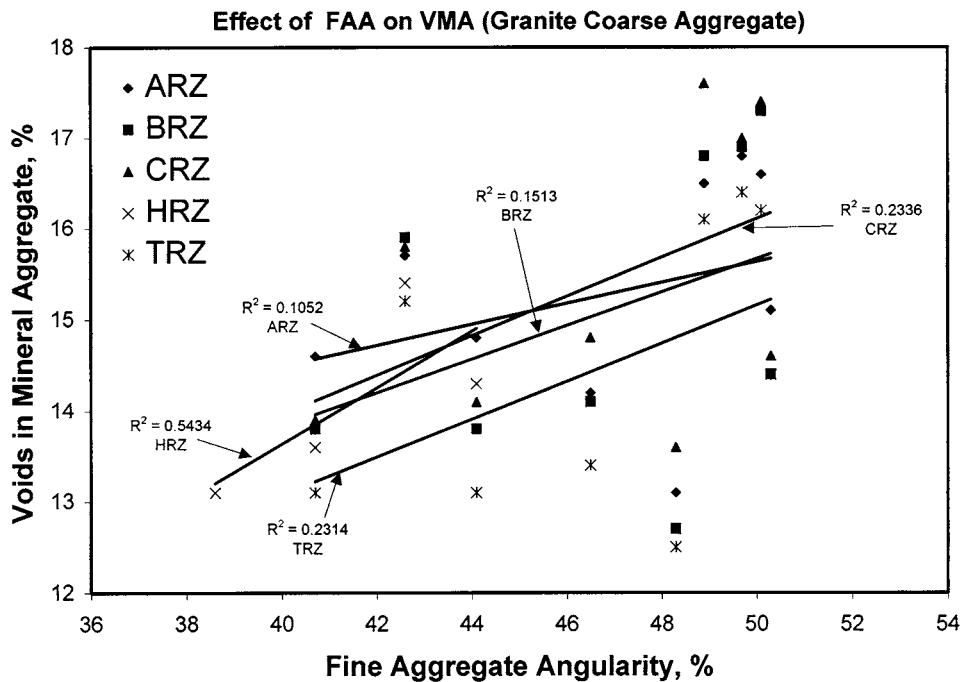


Figure 11. Effect of FAA on VMA (granite coarse aggregate).

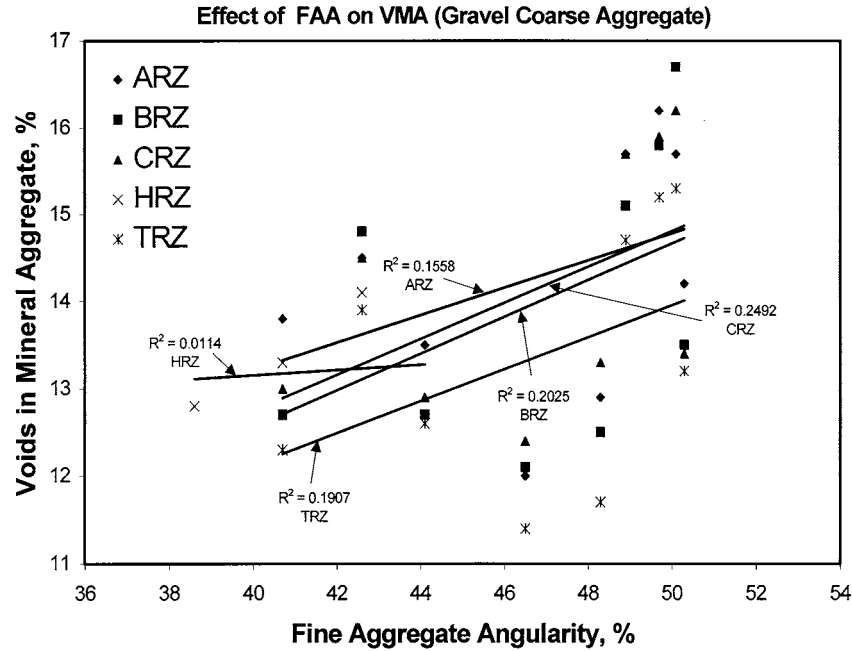


Figure 12. Effect of FAA on VMA (crushed gravel coarse aggregate).

all relationships: increasing VMA values with increasing FAA values. The relative locations of the regression lines are similar for both the granite and gravel coarse aggregate data sets.

Results of the ANOVA conducted to evaluate the significance of coarse aggregate, fine aggregate, and gradation on $%G_{mm}@N_{initial}$ is presented in Table 10. This table shows that all three main factors significantly affect $%G_{mm}@N_{initial}$, similar to the VMA analysis. Based upon the *F*-statistics, the fine aggregate had the greatest effect, followed by gradation and coarse aggregate, respectively.

Figure 13 illustrates the effect of coarse aggregate and gradation on $%G_{mm}@N_{initial}$. As shown by the ANOVA, the effect of coarse-aggregate type seems to be minimal (although significant). This figure suggests that the BRZ gradation provided the lowest $%G_{mm}@N_{initial}$ values. The CRZ gradation had similar but slightly higher $%G_{mm}@N_{initial}$ values. Figure 13 suggests that the HRZ gradation provided the highest $%G_{mm}@N_{initial}$ values. However, similar to the VMA analysis, this conclusion would be misleading. For the three fine aggregates in which both gradations were used, the $%G_{mm}@N_{initial}$ averaged 91.0 percent for the HRZ gradation and 90.7 percent for the TRZ gradation;

TABLE 9 Regression statistics for FAA versus VMA regressions

Gradation	Granite		Gravel	
	<i>F</i> -statistic	<i>p</i> -value	<i>F</i> -statistic	<i>p</i> -value
ARZ	0.82	0.394	1.29	0.293
BRZ	1.25	0.301	1.78	0.224
CRZ	2.13	0.187	2.32	0.171
HRZ	2.38	0.263	0.02	0.893
TRZ	2.11	0.190	1.65	0.240

TABLE 10 Results of ANOVA to determine significance of main factors on $%G_{mm}@N_{initial}$

Source	Degrees of Freedom	<i>F</i> -Statistic	<i>P</i> -Value
Coarse Aggregate	1	7.89	0.007
Fine Aggregate	8	101.85	0.000
Gradation	4	38.31	0.000

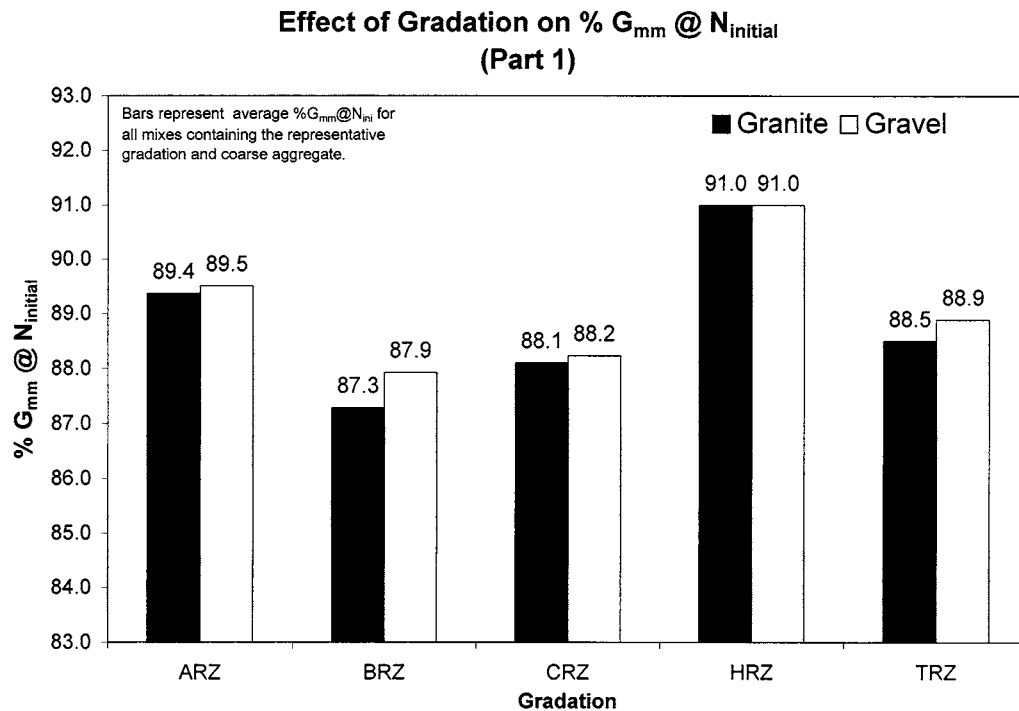


Figure 13. Effect of gradation on % G_{mm} @ $N_{initial}$ (Part 1).

therefore, both appear similar and suggest that the ARZ gradation actually provided the highest % G_{mm} @ $N_{initial}$ values.

The effect of fine aggregate on % G_{mm} @ $N_{initial}$ is illustrated in Figures 14 and 15 for mixes containing granite and gravel coarse aggregate, respectively. These figures illustrate the relationship between FAA and % G_{mm} @ $N_{initial}$. R^2 values are also shown for each relationship. The R^2 values indicate a stronger relationship between FAA and % G_{mm} @ $N_{initial}$ than for FAA and VMA (see Figures 11 and 12). Table 11 presents the F -statistics and probabilities for each regression shown in Figures 14 and 15.

The regression statistics in Table 11 suggest a significant relationship between FAA and % G_{mm} @ $N_{initial}$. The relationships show increasing values of FAA led to decreasing values of % G_{mm} @ $N_{initial}$. Furthermore, none of the mixes having an FAA value of 45 or lower met the % G_{mm} @ $N_{initial}$ requirement of 89 percent maximum. This was true for both coarse aggregates. Overall, it appears that higher FAA values contribute to a stronger aggregate skeleton (in terms of more resistance to compaction) at initial compaction levels.

Another interesting observation from the Part 1 mix design data was that none of the mixes failed the % G_{mm} @ $N_{maximum}$ requirement of 98 percent maximum. This was true even for the worst-case FA-10 mixes with a humped gradation. This observation raises the question of whether the $N_{maximum}$ requirement is necessary or whether the limit of 98 percent needs to be changed.

After completion of all mix designs, performance testing was conducted. Performance testing included the APA, RSCH test with the Superpave shear tester, and the RLCC test as

described in Chapter 2. The project statement for this study called for performance testing on mixes that met all volumetric criteria. However, with the concurrence of the project panel, some mixes not meeting VFA requirements were performance tested. This VFA exception was made because of current Superpave VMA requirements for 9.5-mm NMAS mixtures. Optimum asphalt content is defined as the asphalt content that provides 4.0 percent air voids. For 9.5-mm NMAS mixes, the minimum VMA allowed is 15.0 percent. At a VMA of 15.0 percent and an air void content of 4.0 percent, VFA is equal to 73.3 percent. The Superpave requirements for VFA range from 65.0 to 75.0 percent. This VFA range effectively limits VMA to a maximum of 16.0 percent as air voids are set at 4.0 percent at mix design. Only a 1.0-percent range of VMA, therefore, is allowed by the Superpave mix design requirements.

The exception used in this study was based on the findings of the WesTrack Forensic Team (1). This report recommended that VMA be restricted to no more than 2.0 percent above the minimum value; therefore, besides mixes meeting all volumetric requirements, performance testing was also conducted on mixtures that failed VFA but that had VMA values below or equal to 17.0 percent. This provided an allowable VFA range in this study of 73.3 to 76.5 percent.

Another exception approved by the project panel was to conduct performance testing on mixtures containing FA-6 (a limestone fine aggregate) and granite coarse aggregate (all gradations) even though these combinations did not meet VMA. The project panel recommended the inclusion

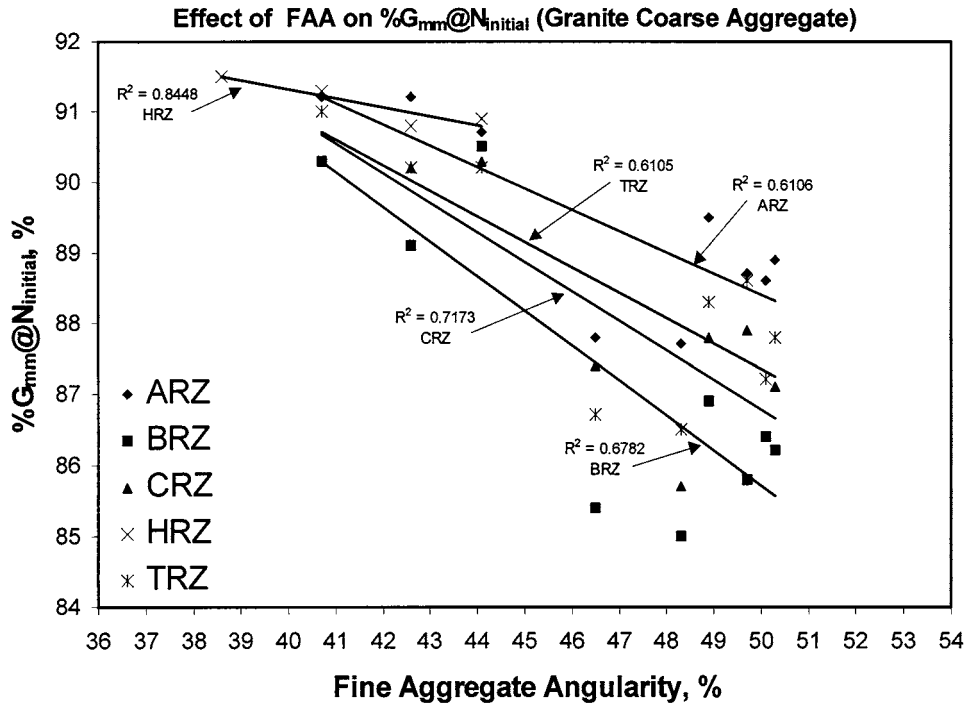


Figure 14. Effect of FAA on $\%G_{mm}@N_{initial}$ (granite coarse aggregate).

of these mixes because none of the mixtures meeting all volumetric criteria (and those included with the VFA exception) contained a limestone fine aggregate, which is one of the most common aggregates in the United States. The FA-6/granite mixes were included for informational purposes only.

The fine aggregate FA-10, which had a very low FAA value of 38.6, was used with both granite and gravel coarse

aggregates to provide a humped gradation violating the restricted zone (i.e., HRZ). These two mixes did not meet the Superpave requirements for FAA, VMA, or $N_{initial}$. However, these mixes were performance tested to obtain a baseline, worst-case scenario.

Results of Part 1 performance testing for mixes containing FA-10, FA-6, FA-7, FA-4, and FA-9 are presented in

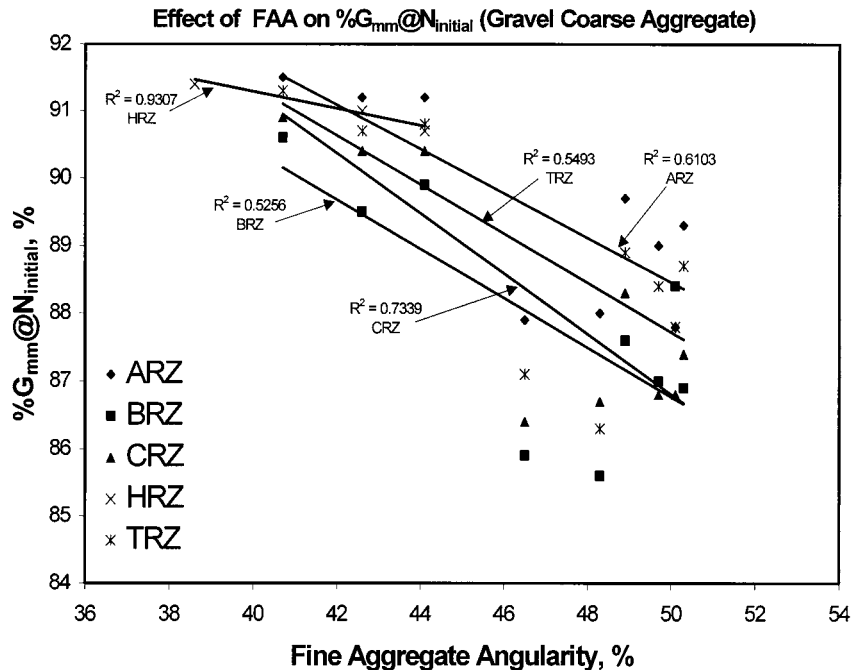


Figure 15. Effect of FAA on $\%G_{mm}@N_{initial}$ (crushed gravel coarse aggregate).

TABLE 11 Regression statistics for FAA versus % G_{mm} @ $N_{initial}$ relationships

Gradation	Granite		Gravel	
	F-statistic	p-value	F-statistic	p-value
ARZ	10.98	0.013	10.96	0.013
BRZ	14.76	0.006	7.75	0.027
CRZ	17.76	0.004	19.31	0.003
HRZ	10.89	0.081	26.88	0.035
TRZ	10.97	0.013	8.53	0.022

Appendix C. Results for the APA are presented as the manually measured rut depth after 8,000 cycles. For the RSCH test, results are presented as the plastic strain after 5,000 cycles, expressed as a percentage. Results for the RLCC test are presented as the permanent strain measured after 3,600 load repetitions (applied in 1 h) and a 15-min rebound time, again expressed as a percentage.

Figure 16 illustrates the results of APA testing in the form of a bar chart. Results are shown for the 24 mixes that (1) met all volumetric criteria, (2) met the VFA exception, (3) were recommended by the project panel (e.g., containing FA-6), or (4) was a worst-case scenario (e.g., containing FA-10).

Data within Figure 16 are classified by whether the mixture has a gradation that violates the restricted zone. Solid black bars depict mixes having gradations violating the restricted zone; unshaded bars represent mixes having gradations that do not violate the restricted zone. As can be seen from the figure, the same combination of coarse aggregate and gradation was not tested for all fine aggregates—therefore, performing an analysis of variance was not possible. Duncan’s multiple range tests (DMRT) were used to rank the performance of

mixes having identical coarse aggregate and fine aggregate (e.g., granite/FA-4). This analysis provided a comparison among gradations for a given coarse aggregate/fine aggregate combination to determine whether gradations violating the restricted zone performed differently than gradations residing outside the restricted zone. Figure 16 shows the results of the DMRT rankings as A, AB, and B. There is no statistically significant difference (at a significance level $\alpha = 0.05$) in performance if two gradations within a coarse aggregate/fine aggregate combination have the same letter ranking.

Figure 16 shows that all three main factors (i.e., coarse aggregate, fine aggregate, and gradation shape) appear to affect the measured APA rut depths. Collectively, where comparisons are possible, mixes containing the more angular granite coarse aggregate tended to have lower rut depths.

The fine aggregate type also affected the measured rut depths. The FA-10 mixes containing gravel coarse aggregate were the least rut resistant. Also as expected, mixes containing FA-6 were rut resistant. Recall that these four FA-6 mixes were included for informational purposes only because all failed VMA requirements. Because each mix had low VMA,

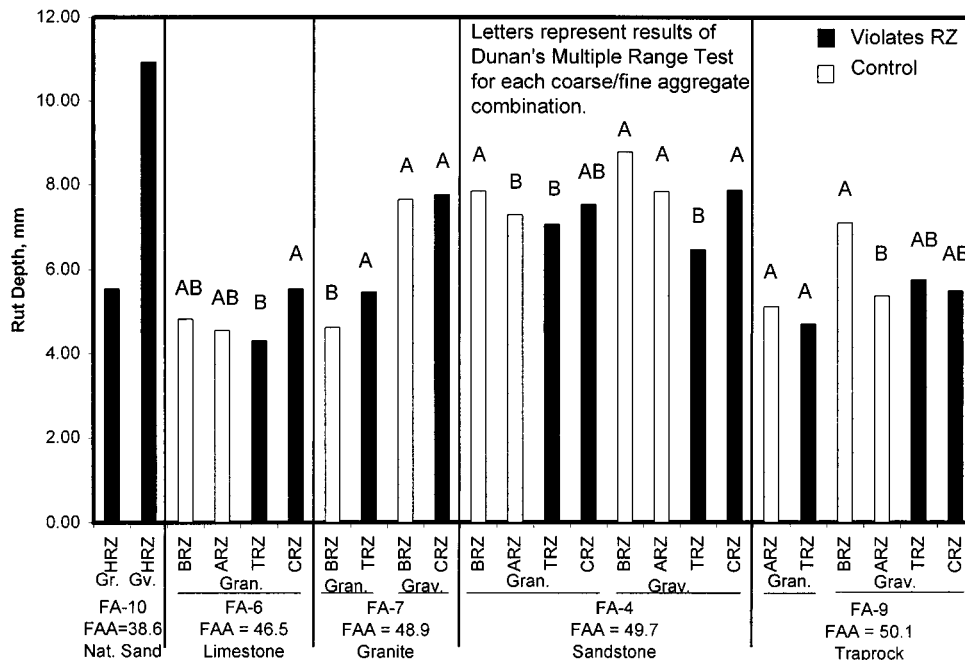


Figure 16. APA rut test data (Part 1).

all four mixes were under-asphalted and, as a result, were rut resistant. However, the FA-6 mixes that violated the restricted zone criteria (i.e., TRZ and CRZ) did perform similarly to the mixes not violating the restricted zone (i.e., BRZ and ARZ).

In all but one case (FA-7/granite mixes) of the seven coarse aggregate/fine aggregate combinations tested, the mixes having gradations that violate the restricted zone performed similarly or better than did the mixes having gradations that did not violate the restricted zone. In this one case, the rut depths for both FA-7/granite/BRZ and FA-7/granite/TRZ were both less than 6 mm. Based upon these Part 1 APA data, it appears that the restricted zone is practically redundant as a requirement to ensure adequate rut resistance if the mix meets all Superpave volumetric and FAA criteria.

No meaningful relationship between FAA values and APA rut depth was obtained, probably because the FAA values of the mixes (which met volumetric requirements) only ranged from 48.9 to 50.1.

Figure 17 illustrates the results of the RLCC test. Results are presented as permanent strain as a percentage. Similar to the APA results, the results show the mixes containing FA-10 had the least resistance to permanent deformation. These FA-10 mixes had considerably higher permanent strain values when compared with the other mixes. The FA-6 limestone mixes collectively had the lowest permanent strain values, similar to the APA rut depths. Again, this was likely due to the low asphalt contents in these mixes (i.e., low VMA).

Similar to the APA analysis, DMRT rankings were conducted on each combination of coarse aggregate/fine aggregate

to isolate the effect of gradation. In all but one case (i.e., FA-9/granite) of the seven coarse aggregate/fine aggregate combinations tested, the mixes having gradations violating the restricted zone performed as well or better than did the mixes having gradations complying with the restricted zone requirement. Close inspection of the one exception (i.e., FA-9/granite) shows that both mixes ARZ and TRZ have very low permanent strain values and, therefore, can be considered rut resistant. The RLCC data appears to confirm the APA conclusion that the restricted zone requirement is not needed when the Superpave volumetric and FAA criteria are met.

Figure 18 presents the RSCH test data. Results in this figure are shown as plastic strain expressed as a percentage. Initial observation of Figure 18 indicates little variation in the test results: even the worst-case FA-10 mixes did not have high plastic strain values. All test results were below 2.5 percent plastic strain, which historically suggests adequate rut resistance. Similar to the APA and RLCC test data, DMRT rankings were determined for each fine aggregate/coarse aggregate combination. These rankings also show that not much variation in test results was exhibited. Except for the FA-9/gravel combination, all combinations had similar DMRT rankings. This suggests that the RSCH test was not sensitive enough to identify small changes in gradation or asphalt content, possibly because of test variability. Three replicates were used in this study. Recent research (2) has suggested the use of five replicates, discarding the minimum and maximum values and averaging the middle three values to improve the reliability of the RSCH test.

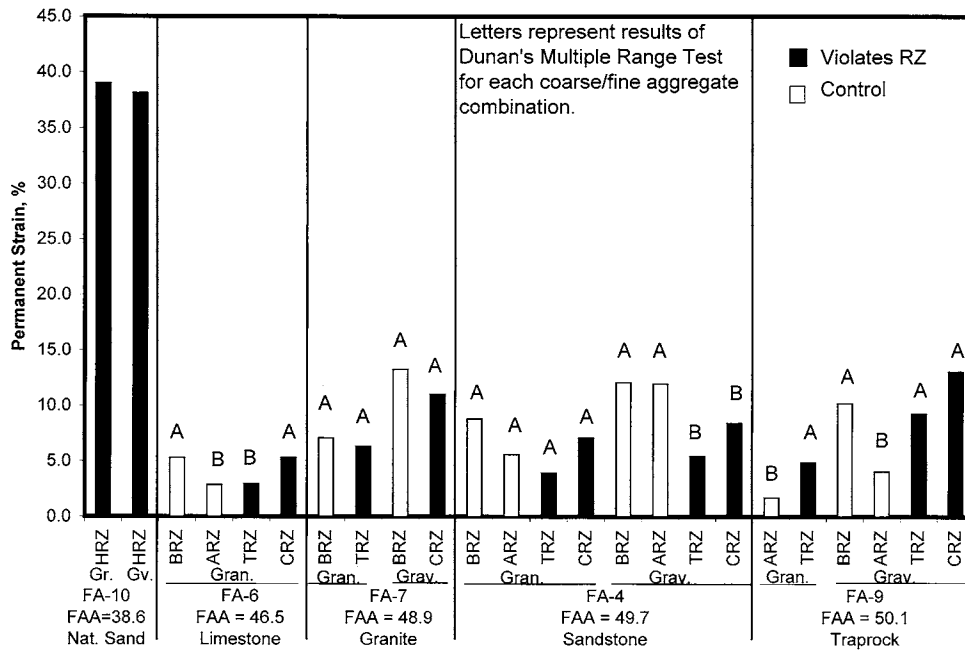


Figure 17. RLCC test data (Part 1).

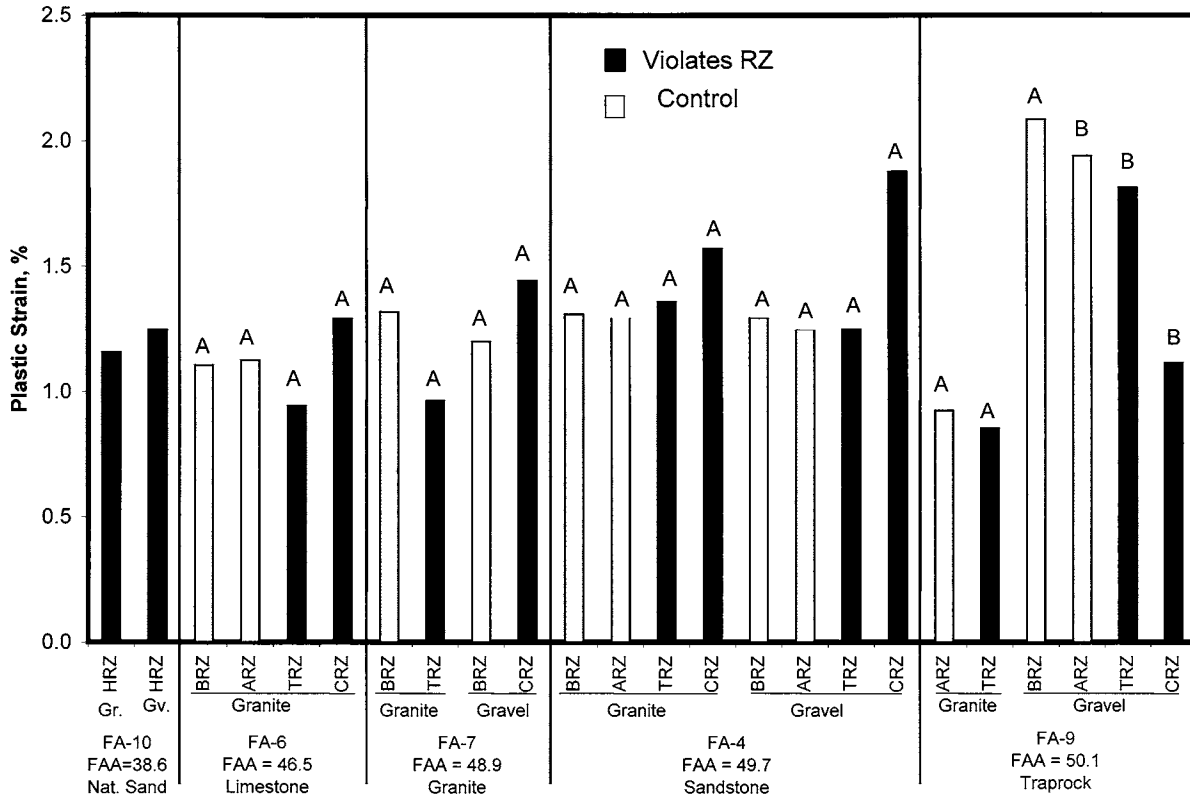


Figure 18. RSCH test data (Part 1).

PART 2 TEST RESULTS AND ANALYSIS

Similar to Part 1, Part 2 involved 9.5-mm NMAS gradations, but included two compactive efforts different than those used in Part 1. The two compactive efforts corresponded to 0.3 to 3 million ESALs (i.e., $N_{\text{design}} = 75$ gyrations) and more than 30.0 million ESALs (i.e., $N_{\text{design}} = 125$ gyrations). Only three gradations were used in all mixes: BRZ, TRZ, and CRZ. Only the granite coarse aggregate was used in Part 2. During Part 1, gravel coarse aggregate produced mixes with low VMA values.

Six fine aggregates—FA-10, FA-2, FA-3, FA-6, FA-7, and FA-4 (in increasing order of FAA values)—were used in mixes designed with an N_{design} of 75 gyrations. Appendix D gives optimum mix design data for mixes with these fine aggregates. Four fine aggregates—FA-10, FA-7, FA-4 and FA-9—were used in mixes compacted with an N_{design} of 125 gyrations. Appendix D also gives optimum mix design data for these fine aggregates. Fine aggregates that had high potential of meeting the minimum VMA requirements (based on mix design data obtained in Part 1) were selected for Part 2. A limestone fine aggregate (i.e., FA-6) was included because limestone is widely used in the United States.

Because each of the mixes studied in Part 2 contained the same coarse aggregate, the factors evaluated were design

compactive effort, fine aggregate type (i.e., FAA), and gradation shape. Similar to the analyses conducted in Part 1, the mix design data were analyzed to determine the effect of each factor on volumetric properties. Figures 19 and 20 present the effect of gradation on VMA and $\%G_{\text{mm}}@N_{\text{initial}}$ for both compactive efforts, respectively. Similar to Part 1, Figure 19 shows that the CRZ gradation produced the highest VMA values for both compactive efforts. This effect is probably caused by the CRZ gradation being somewhat gap-graded. The TRZ and HRZ provided low VMA values. Similar to the Part 1 analyses, in which the TRZ and HRZ gradations were designed for the same fine aggregate (i.e., FA-2 and FA-3 for Part 2), the HRZ gradation provided a slightly higher VMA than did the TRZ gradation. Because the TRZ generally provided the lowest VMA values, these Part 2 data support the finding that for 9.5-mm NMAS gradations, the MDL can be used as a guideline for increasing or decreasing VMA in continuously graded HMA mixes. As expected, the mixes using the CRZ and BRZ gradations had lower VMA values for the higher compactive effort (i.e., N_{design} of 125) although the difference was not as large as would be expected.

Figure 20 illustrates the effect of mix gradation on $\%G_{\text{mm}}@N_{\text{initial}}$. The effect of design compactive effort is also evident in this figure. Mixes compacted at 125 gyrations had

Effect of Gradation on Voids in Mineral Aggregate (Part2)

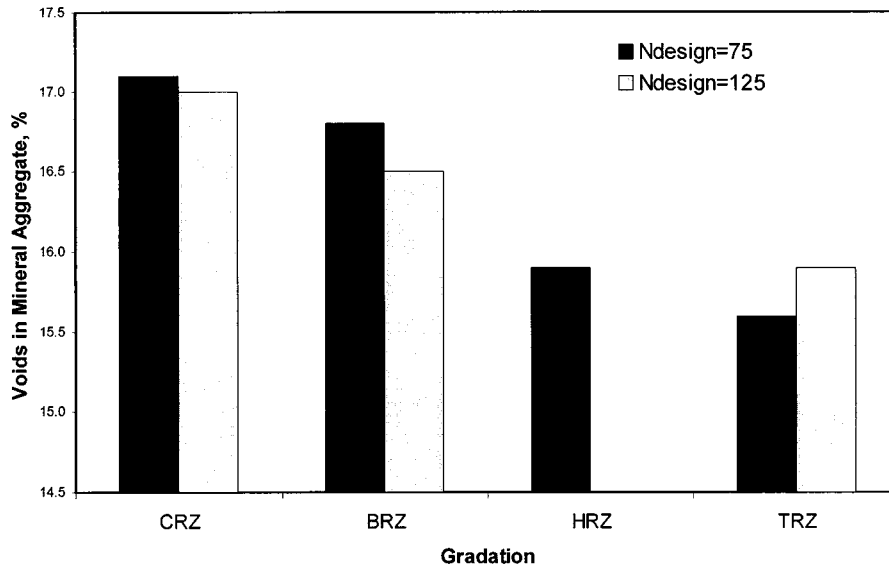


Figure 19. Effect of gradation on VMA for Part 2.

lower $\%G_{mm}@N_{initial}$ values although the initial number of gyrations for the 125 gyration compactive effort was 8 gyrations and the $N_{initial}$ for the 75 gyration compactive effort was 7 gyrations. This is probably due to relatively higher FAA values and lower asphalt contents in high compactive effort mixes compared with low compactive effort mixes, which provided increased initial resistance to compaction. The data also shows a similar effect of gradation on $\%G_{mm}@N_{initial}$ as in Part 1; the mixes using the BRZ and CRZ gradations had similar

$\%G_{mm}@N_{initial}$ values and were slightly lower than the values for the TRZ gradation.

As stated previously, during Part 2 the design compactive effort was a factor in the experiment. Figures 21 and 22 present the effect of FAA values on VMA for the $N_{design} = 75$ and $N_{design} = 125$ compactive efforts, respectively. Based upon the regression lines presented in Figure 21, the relationship between FAA and VMA is not significant (i.e., p -values are greater than 0.5). Coefficients of determination ranged from

Effect of Gradation on $\%G_{mm}@N_{initial}$ (Part2)

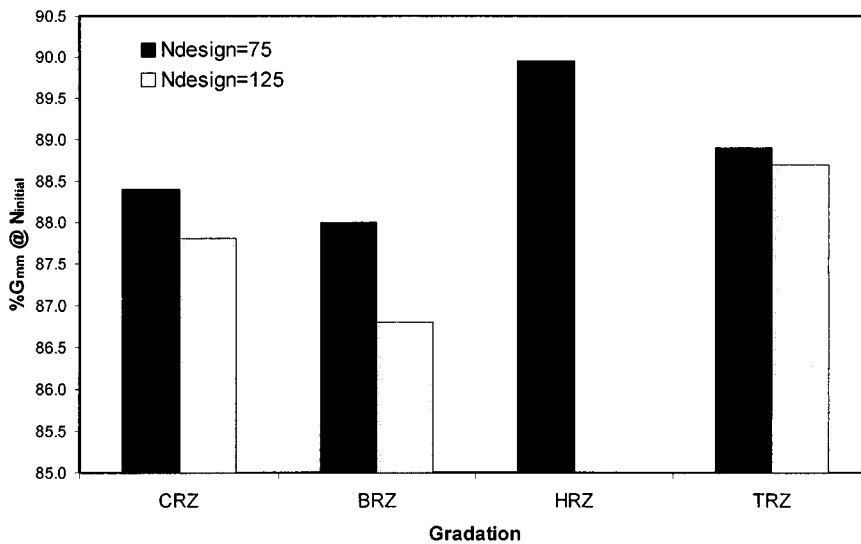


Figure 20. Effect of gradation on $\%G_{mm}@N_{initial}$ for Part 2.

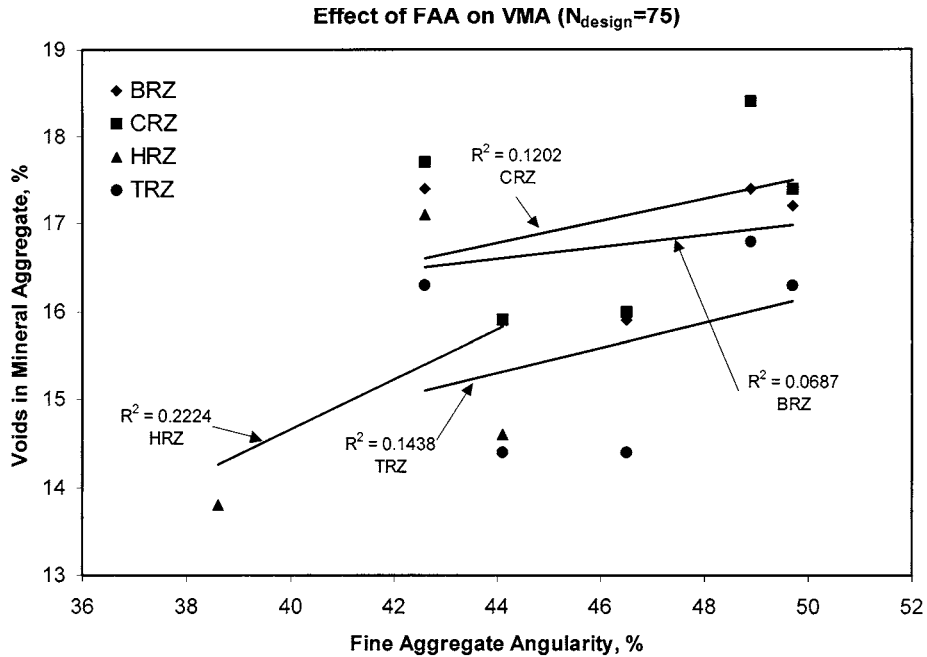


Figure 21. Effect of FAA on VMA for $N_{design} = 75$, Part 2.

0.06 to 0.22. However, the trend lines do show increasing VMA values with increasing FAA values. This is similar to results in Part 1. Although the results for the $N_{design} = 125$ mixes did show some higher R^2 values (see Figure 22), the range in FAA values for the $N_{design} = 125$ mixes was very small (i.e., 48.7 to 50.1). The small range in both FAA and VMA likely resulted in the higher R^2 values for the CRZ and BRZ gradations. The TRZ gradation still had a low R^2 value of 0.01.

Figures 23 and 24 present the relationships between the FAA and $\%G_{mm}@N_{initial}$ for the $N_{design} = 75$ and 125 mixes, respectively. As shown in the similar Part 1 analyses, the FAA values increase as the $\%G_{mm}@N_{initial}$ values decrease. This relationship suggests that the more angular fine aggregates (i.e., those having higher FAAs) tend to resist early compaction more so than the lower FAA aggregates. For both compactive efforts, the R^2 values were higher than those observed for

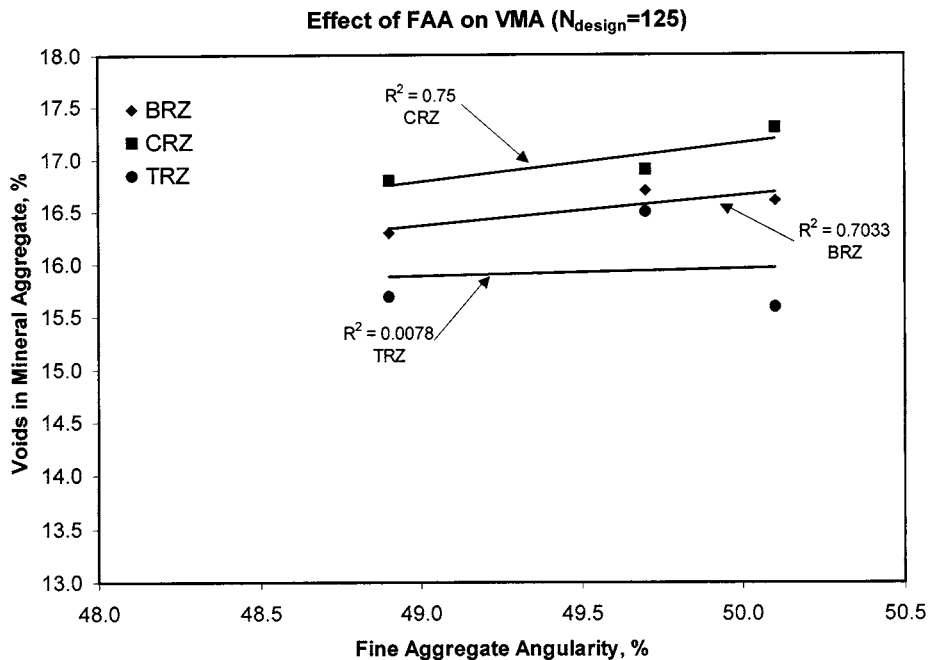


Figure 22. Effect of FAA on VMA for $N_{design} = 125$ mixes, Part 2.

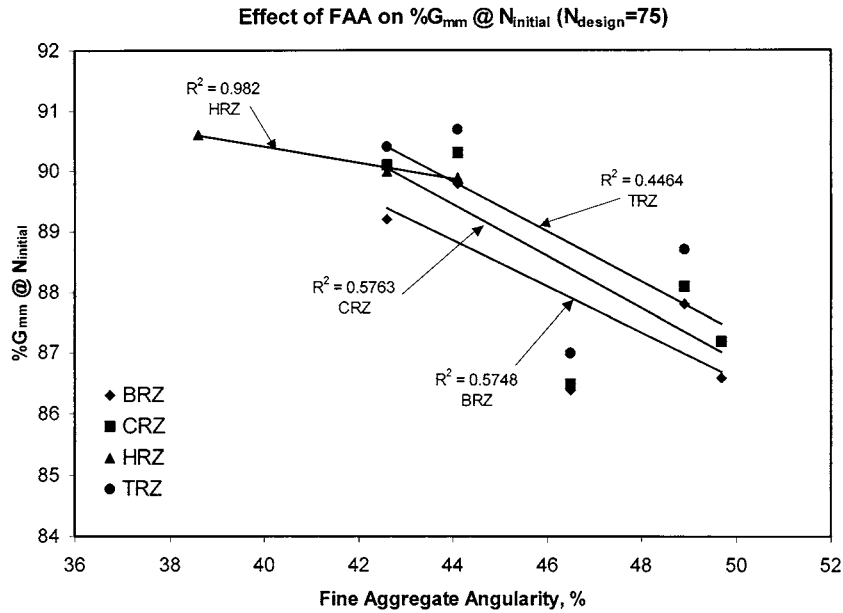


Figure 23. Effect of FAA on %G_{mm}@N_{initial} for N_{design} = 75 mixes, Part 2.

the FAA–VMA relationships, but the relationships were not significant. However, there was one exception: the TRZ gradation for N_{design} = 125 mixes (see Figure 24). This relationship had an R² value of almost zero. The likely reason for this low R² value is that the slope of the trend line was basically zero.

Another definite trend can be observed about the relationship between FAA and %G_{mm}@N_{initial} for the five gradations used in Parts 1, 2, and 3 (see Figures 14, 15, 23, and 24). HRZ and CRZ have the highest correlation in all cases. Also, the order of lines remains the same. That is, the short line of HRZ

is followed by ARZ, TRZ, CRZ, and, finally, BRZ. These trends should be helpful to the mix designer to ensure the mix meets the maximum requirement for %G_{mm}@N_{initial}. Thus, it appears that %G_{mm}@N_{initial} is predominantly controlled by FAA and the fine aggregate content.

After completion of all mix designs, performance testing was conducted. Similar to Part 1, performance testing included testing with the APA, RSCH test with the Superpave shear tester, and RLCC tests. Results of performance testing for both compactive efforts are provided in Appendix D.

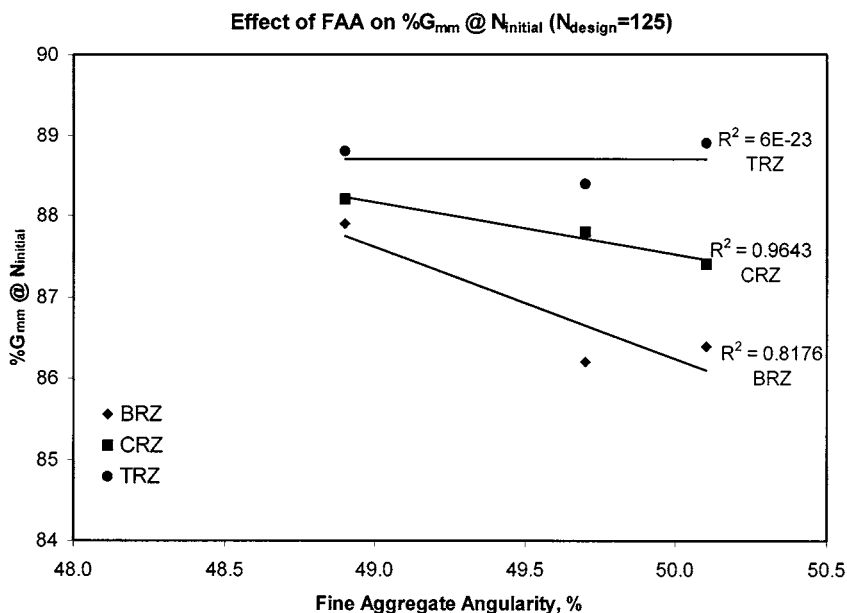


Figure 24. Effect of FAA on %G_{mm}@N_{initial} for N_{design} = 125 Mixes, Part 2.

A number of mixes in Part 2 failed the VFA requirement with values in excess of the upper limit of 75.0 percent. The VFA exception used in Part 1 was also used in Part 2. This exception called for the performance testing of mixes that failed the upper limit of VFA, but had a VMA value that was no more than 2.0 percent higher than the minimum value (i.e., 17.0 percent or less).

Again, FA-10 was performance tested even though the mixes did not meet volumetric criteria. This was done to provide a baseline of poor performance in the laboratory.

Figure 25 illustrates the results of the APA testing conducted on Part 2 mixes designed at 75 gyrations. Initial observation of this figure suggests that angularity and surface texture of the fine aggregate (i.e., FAA) has a significant effect on measured rut depths. Those mixes containing fine aggregates with FAA values above 46 (i.e., FA-4, FA-6, and FA-7) all had significantly lower rut depths than did the mixes with fine aggregates having FAA values below 46 (i.e., FA-10, FA-2, and FA-3). Also upon initial observation, it is seen that the two FA-3 gradations (i.e., BRZ and CRZ) that met volumetric requirements had rut depths that were slightly higher than did the worst-case baseline FA-10 mix. From a restricted zone standpoint, there was no statistical difference based on DMRT rankings in rut depths between the FA-3 mix that violated the restricted zone (i.e., CRZ) and the control gradation (i.e., BRZ). The only other combination in which a comparison could be made between a gradation violating the restricted zone and a control gradation was FA-6. Again, there was no statistical difference, based on DMRT rankings, in rut depths between the two mixes (i.e., BRZ and CRZ). FA-2,

FA-4, and FA-7 had only one gradation that met volumetric requirements (including the VFA exception). Other gradations for these fine aggregates had VMA values in excess of 17.0 percent.

Within the Superpave mix design system, fine aggregates used in mixes designed at 75 gyrations have a requirement for FAA of 40 percent minimum. The data illustrated in Figure 25 suggests that mixes having fine aggregates with FAA values below 46 tend to have more potential for rutting. However, from the standpoint of the restricted zone, there does not seem to be an interaction between the effect of FAA and gradations passing through the restricted zone. This is shown by the data for FA-3 in which the BRZ and CRZ gradations both have similar rut depths. It can be surmised, therefore, that even for this lower compactive effort, the restricted zone is not needed to ensure a rut-resistant mixture. In fact, the data appears to indicate the need for a laboratory “proof” test to be used on designed mixes.

Figure 26 illustrates the APA results of Part 2 mixes designed with 125 gyrations. This figure shows little difference in rut depths among any of the experimental mixes (i.e., FA-4, FA-7, and FA-9 mixes). FA-10 had the highest rut depth, as expected, at approximately 11 mm. The remaining mixes all had rut depths of approximately 8 mm. For each of the fine aggregates (except FA-10), sufficient gradations were available to conduct DMRT rankings to compare the gradations violating the restricted zone (i.e., TRZ and CRZ) and the control gradation (i.e., BRZ). For all three fine aggregates (i.e., FA-4, FA-7, and FA-9), there was no statistical difference among the different gradations. Similar to the Part 1

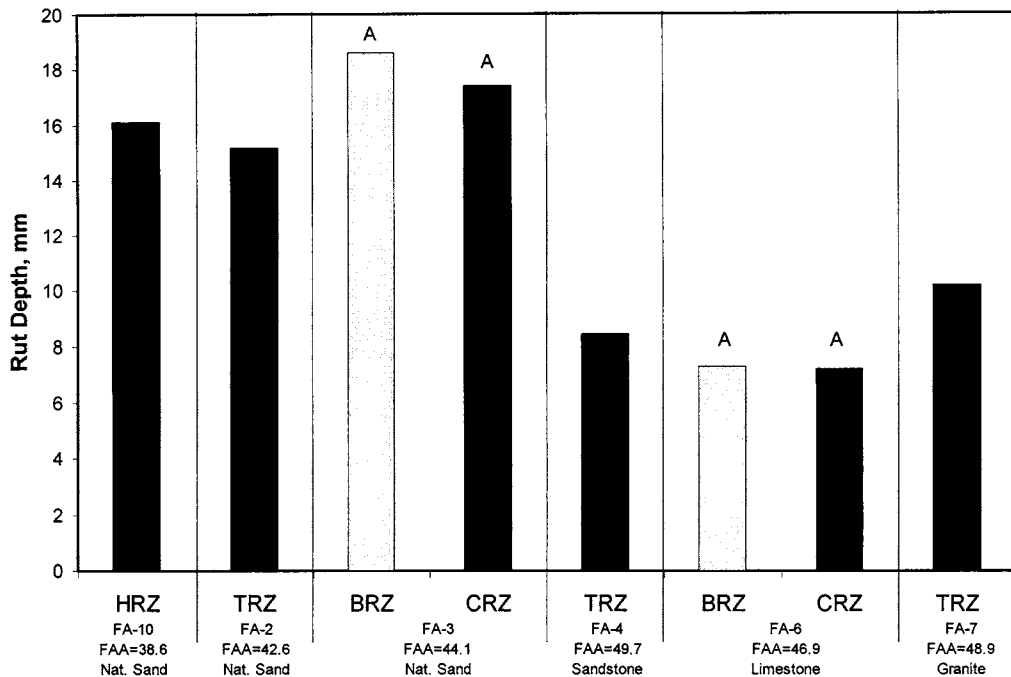


Figure 25. Results of APA testing on mixes designed with 75 gyrations for Part 2.

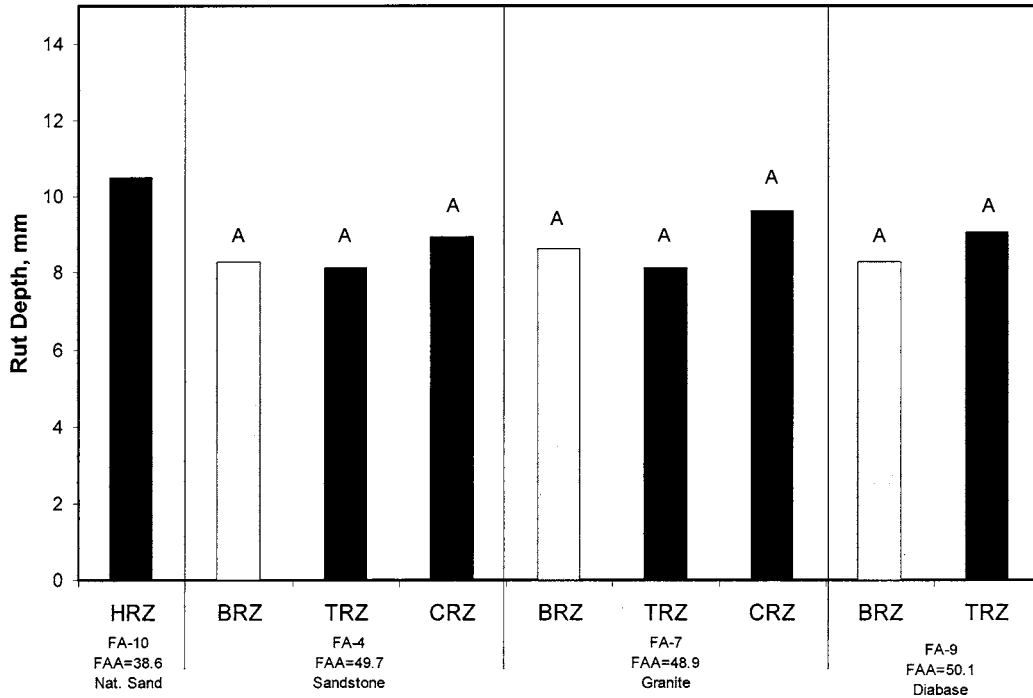


Figure 26. Results of APA testing on mixes designed with 125 gyrations for Part 2.

APA data, Figure 26 suggests that the restricted zone is practically redundant as a requirement to ensure adequate rut resistance if the mix meets all Superpave volumetric and FAA criteria.

Figure 27 illustrates the results of RLCC testing conducted on Part 2 mixes designed with 75 gyrations. This

figure does not show the two FA-3 mixes that failed prior to 3,600 load repetitions (i.e., the BRZ and CRZ gradations). As stated previously, the RLCC test uses a confinement pressure on samples. This necessitates the use of a triaxial cell during testing. The premature failure was defined as the point at which the sample within the triaxial cell

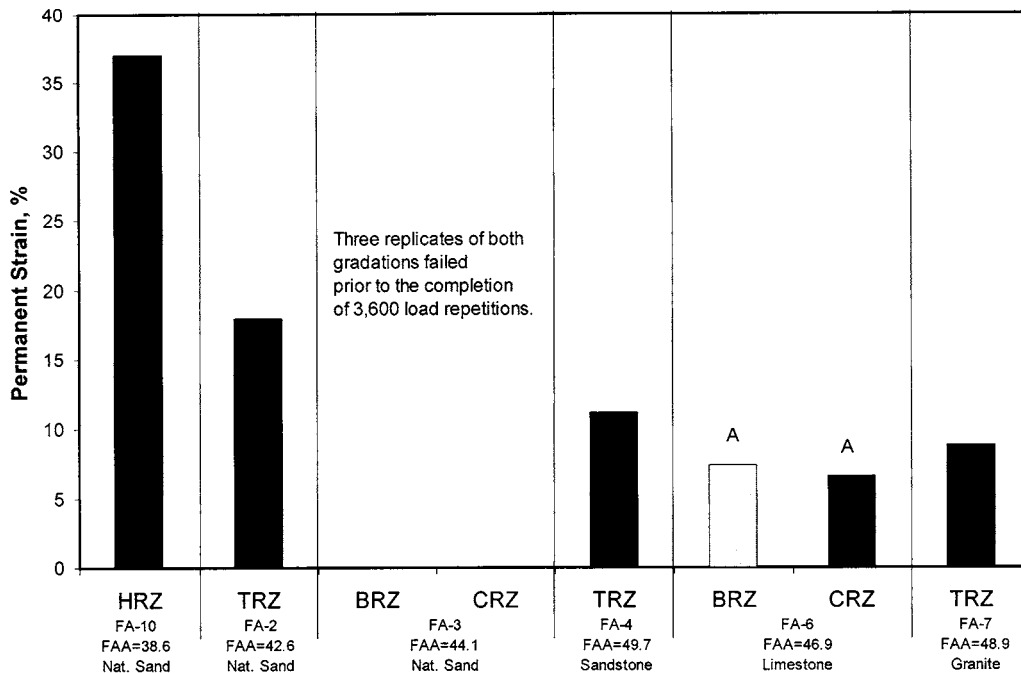


Figure 27. Results of RLCC testing on mixes designed with 75 gyrations for Part 2.

deformed laterally sufficiently to become in contact with the triaxial cell.

The results illustrated in Figure 27 are similar to the APA results shown in Figure 25 in that the mixes containing fine aggregates with FAA values less than 46 (i.e., FA-10, FA-2, and FA-3) all showed significantly less permanent deformation resistance than did the mixes containing fine aggregates with FAA values above 46 (i.e., FA-4, FA-6, and FA-7). Only one fine aggregate had mixes in which gradations violating the restricted zone and a control gradation could be compared (i.e., FA-6). For this fine aggregate, the DMRT rankings indicated that both gradations have similar rut depths.

Based upon both the APA and RLCC performance data for mixes designed with 75 gyrations, it appears that the volumetric and FAA criteria alone do not ensure a rut-resistant mixture. However, gradations passing through the restricted zone do not show more propensity to rut than do gradations residing outside the restricted zone.

Results of RLCC performance testing on Part 2 mixes designed with 125 gyrations are illustrated in Figure 28. Similar to the $N_{design} = 125$ Part 2 APA testing, all of the mixes except the FA-10 mix had similar laboratory performance. The worst-case FA-10 mix had significantly higher strain values than did the other eight mixes tested. Sufficient data was available to conduct a DMRT ranking within the FA-4, FA-7, and FA-9 mixes. Results of the three DMRT rankings indicate the permanent strain values for each gradation (with a given fine aggregate) are not significantly different. Interestingly, the CRZ gradation did show the highest magnitude permanent strain for both the FA-4 and FA-7 data

although it was not significantly different. Based upon these Part 2 $N_{design} = 125$ performance data, it appears that the restricted zone is redundant with the Superpave volumetric and FAA value.

Figure 29 illustrates the results of RSCH testing on Part 2 mixes design with 75 gyrations. Unlike the Part 1 RSCH data (see Figure 18), there is some variation in test data among the mixes tested. Similar to the APA and RLCC testing conducted on mixes designed with 75 gyrations, the mixes containing fine aggregates with FAA values greater than 46 (i.e., FA-4, FA-6, and FA-7) had significantly less plastic strain than did those mixes using fine aggregates with FAA values less than 46 (i.e., FA-10, FA-2, and FA-3). The FA-10/HRZ, FA-2/TRZ, and FA-3/CRZ mixes had plastic strains approaching the limits measurable by the RSCH test (i.e., approximately 8 percent). The other four mixes—FA-4/TRZ, FA-6/BRZ, FA-6/CRZ, and FA-7/TRZ—all had plastic strains less than 3 percent.

There were sufficient FA-3 and FA-6 mixes to evaluate the restricted zone with the DMRT. Of these two, FA-3 had significant differences in plastic strain between the gradation violating the restricted zone (i.e., CRZ) and the gradation residing outside the zone (i.e., BRZ). The plastic strain for the FA-3/BRZ gradation was approximately 4 percent; the plastic strain for the FA-3/CRZ gradation was approximately 7 percent. Both of these mixes would be considered susceptible to permanent deformation based upon previous research. For the FA-6 combinations (i.e., BRZ and CRZ), results of the DMRT rankings suggested that the plastic strain values were similar.

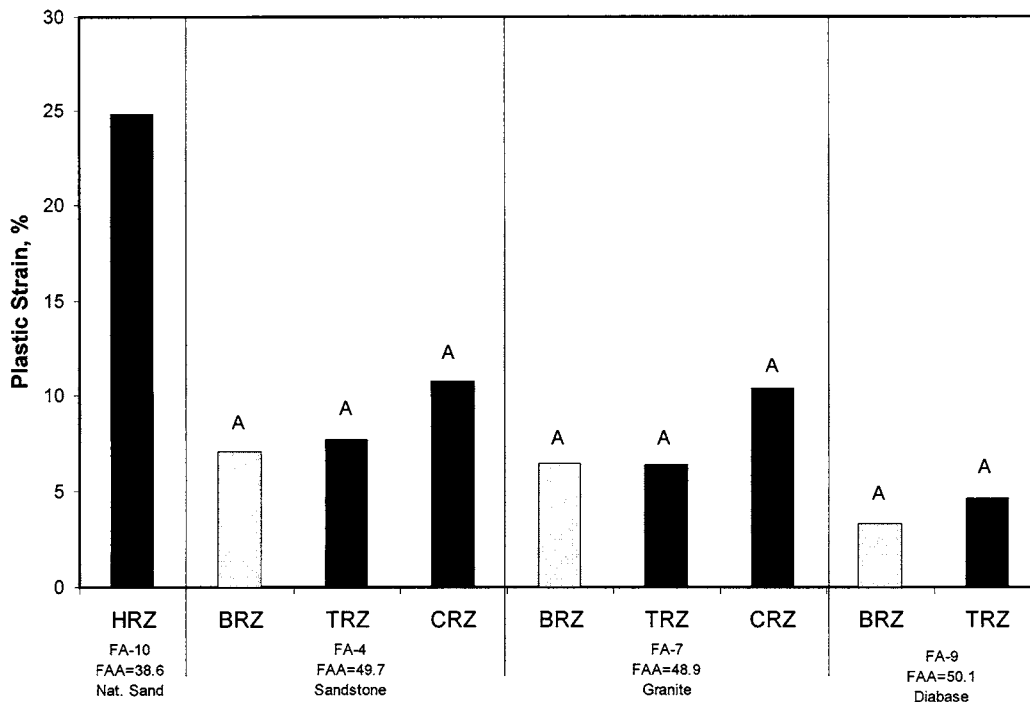


Figure 28. Results of RLCC testing on mixes designed with 125 gyrations for Part 2.

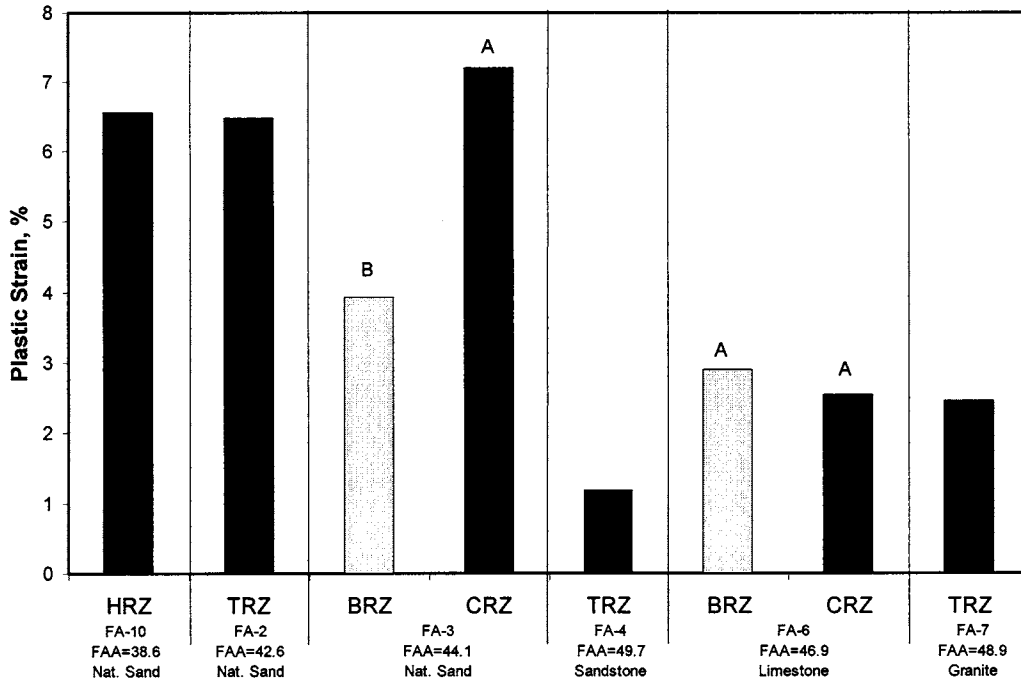


Figure 29. Results of RSCH testing on mixes designed with 75 gyrations for Part 2.

Similar to the APA and RLCC testing, the results shown in Figure 29 suggest that volumetric and FAA criteria are not adequate to ensure rut-resistant mixes when the $N_{design} = 75$ design compactive effort is used. The APA and RLCC test results indicated that the potential for rutting is not enhanced when gradations pass through the restricted zone. However,

based upon the FA-3 RSCH data, the CRZ gradation (which violates the restricted zone) did show significantly higher potential for rutting.

Results of the RSCH testing conducted on Part 2 mixes designed with 125 gyrations are illustrated in Figure 30. The data illustrated in Figure 30 is very similar to that shown for

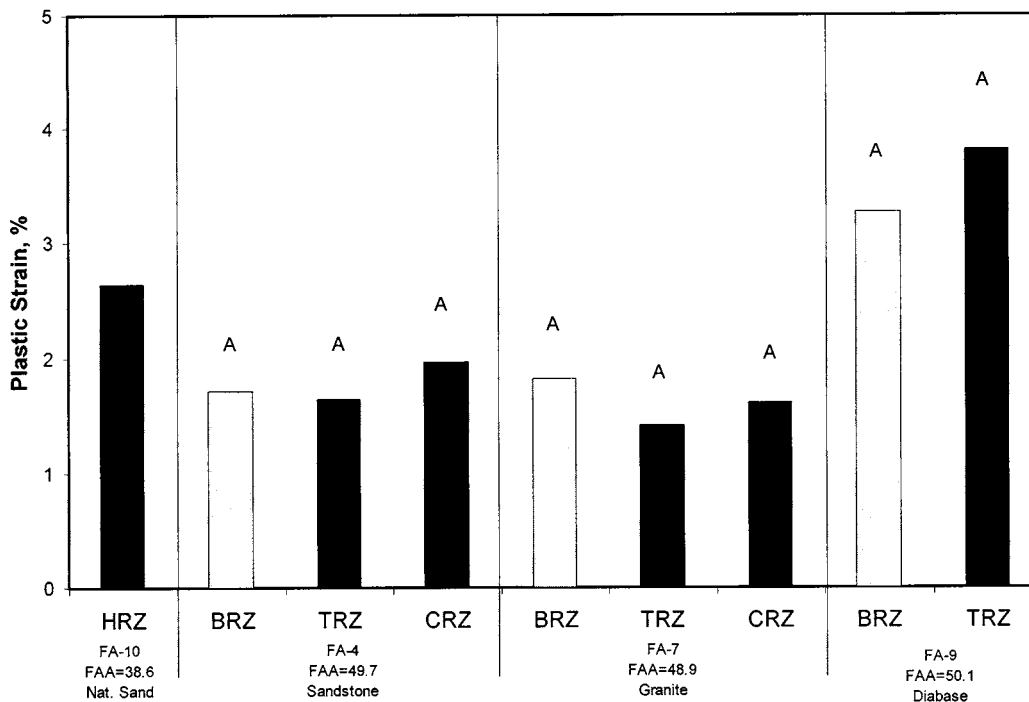


Figure 30. Results of RSCH testing on mixes designed with 125 gyrations for Part 2.

the Part 1 RSCH data (see Figure 18) in that mixes containing FA-9 had higher plastic strain values than did the worst-case FA-10. Besides the FA-9 data, all remaining data appear to be similar (including FA-10). Sufficient mix combinations were available to conduct the DMRT rankings for gradations prepared with FA-4, FA-7, and FA-9. In all instances, no significant differences were shown among the gradations. This suggests that the restricted zone is essentially redundant with the Superpave volumetric and FAA criteria for these high-traffic-volume mixes.

PART 3 TEST RESULTS AND ANALYSIS

As described in Chapter 2, Part 3 was a continuation of Parts 1 and 2, except that 19.0-mm NMA gradations were used instead of 9.5-mm NMA gradations. Four 19.0-mm NMA gradations were included in Part 3: BRZ, TRZ, HRZ, and ARZ. The BRZ, TRZ, and ARZ gradations were used with all fine aggregates; the HRZ gradation was included only with fine aggregates having an FAA value of less than 45 percent. Both the granite and gravel coarse aggregates were included in Part 3. Two design compactive efforts were used, $N_{design} = 75$ and 100. During Parts 1 and 2, a number of mixes had excessive VFA (i.e., above 75 percent because of excessive VMA). In an effort to reduce the number of mixes excluded from performance testing because of excessive VFA, mixes designed with 75 gyrations used the gravel coarse aggregate while mixes designed at 100 gyrations used the granite coarse aggregate. Also different in Part 3 was the method of conducting mix designs. In Parts 1 and 2, mix designs were conducted on all factor-level combinations.

During Part 3, for a given coarse aggregate/fine aggregate combination, mix designs were first conducted for the gradation(s) violating the restricted zone. If these mixes met all volumetric criteria, then mix designs were conducted for the control gradations.

A total of six fine aggregates were investigated for the 75-gyration design compactive effort and included FA-10, FA-2, FA-3, FA-4, FA-6, and FA-7. Results of these mix designs are presented in Appendix E. Six fine aggregates were also investigated for mixes designed with 100 gyrations and included FA-10, FA-2, FA-4, FA-6, FA-7, and FA-9. Results of these mix designs are also presented in Appendix E. Similar to Parts 1 and 2, in Part 3 the FA-10 fine aggregate was included as a worst-case baseline on performance.

Of the five experimental fine aggregates used with the 75-gyration design effort (excluding FA-10), three had gradations violating the restricted zone that met volumetric criteria (i.e., FA-2, FA-4, and FA-7). For the two fine aggregates not meeting volumetric criteria (i.e., FA-3 and FA-6), the VMA values were below the 13-percent minimum. Similar to the analysis in Parts 1 and 2, the effect of gradation on VMA and $\%G_{mm}@N_{initial}$ was evaluated for the 75-gyration design effort mixes. Included in this analysis were the fine aggregates in which all gradations were investigated (i.e., FA-2, FA-4, and FA-7). Because only three fine aggregates were included in this analysis, no comparisons were made between VMA or $\%G_{mm}@N_{initial}$ and FAA values.

Figure 31 illustrates the effect of gradation on VMA. This figure shows that the BRZ gradation provided much higher VMA values than did the TRZ, ARZ, or HRZ gradations. The TRZ and ARZ gradations provided somewhat

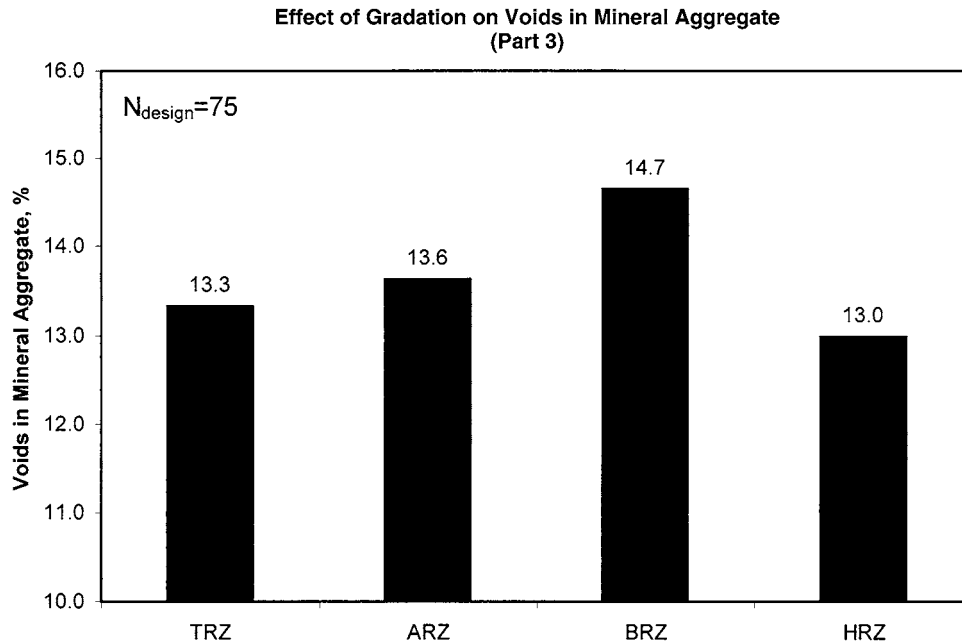


Figure 31. Effect of gradation on VMA ($N_{design} = 75$), Part 3.

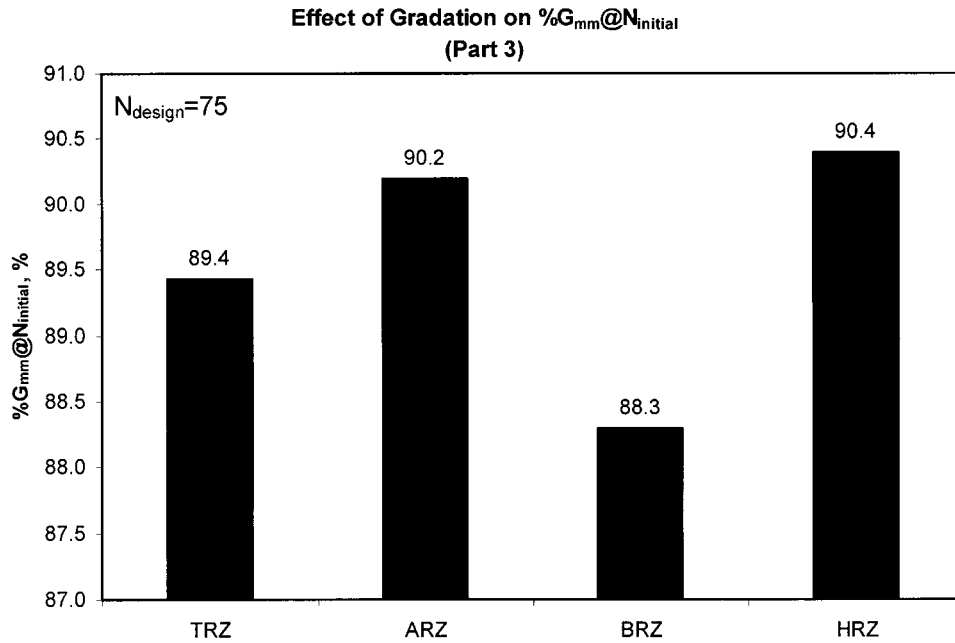


Figure 32. Effect of gradation on % $G_{mm}@N_{initial}$ ($N_{design} = 75$), Part 3.

similar VMAs. Figure 31 suggests that the HRZ gradation provided the lowest VMA value; however, the HRZ gradation was only included with FA-2 (which had an FAA of less than 45 percent). For FA-2, the HRZ gradation provided approximately the same VMA (i.e., 13.0 percent) as the TRZ and ARZ gradations (i.e., 12.9 and 12.8 percent, respectively). These results are similar to those presented in Parts 1 and 2.

The effect of gradation on % $G_{mm}@N_{initial}$ is illustrated in Figure 32. This figure shows that as the gradation becomes coarser, % $G_{mm}@N_{initial}$ values decrease. The BRZ gradation had the lowest % $G_{mm}@N_{initial}$, and the ARZ had the highest. These results are very similar to the results in Parts 1 and 2. The HRZ gradation did have a high % $G_{mm}@N_{initial}$ value; however, a comparison of the FA-2 data suggests that the HRZ gradation had a similar % $G_{mm}@N_{initial}$ value as did the TRZ gradation.

For the experimental fine aggregates designed at 100 gyrations, only two had gradations violating the restricted zone that met volumetric criteria: FA-7 and FA-9. Only the TRZ, ARZ, and BRZ gradations were included with these fine aggregates. The ARZ gradation used with FA-7 failed to meet the % $G_{mm}@N_{initial}$ criteria of 89.0 percent maximum. Trends between VMA and gradation shape were similar for these $N_{design} = 100$ mixes to those for Parts 1 and 2 and the lower compactive effort mixes used in Part 3. The BRZ gradation provided the highest average VMA value at 15.1 percent followed by the ARZ gradation (14.2 percent) and TRZ gradation (13.9 percent). Trends between % $G_{mm}@N_{initial}$ and gradation shape were also similar to pre-

vious analyses in that the coarser the gradation, the lower the % $G_{mm}@N_{initial}$ value. BRZ had the lowest average % $G_{mm}@N_{initial}$ value at 87.1 percent, and ARZ had the highest at 89.1 percent; at 87.6 percent, the TRZ gradation fell between the BRZ and the ARZ.

Results of performance testing conducted in Part 3 are also presented in Appendix E. For Part 3, the APA was used as the only performance test because in Parts 1 and 2 the APA appeared to be more sensitive to changes in gradation. APA results for mixes designed with 75 gyrations in Part 3 are illustrated in Figure 33. Rut depths for gradations that violate the restricted zone are shown with solid black bars; rut depths for control gradations are shown as unshaded bars. As expected, the mix containing FA-10 had a high rut depth. However, the FA-2/BRZ gradation had a slightly higher rut depth. The remaining mixes shown in Figure 33 had similar rut depths. Sufficient data was available for FA-2, FA-4, and FA-7 to conduct DMRT rankings. For FA-4 and FA-7, all of the gradations had similar rankings, which suggests the gradations violating the restricted zone did not result in mixes more susceptible to rutting. The FA-2 mixes did show significantly different rut depths for the two mixes tested. The control gradation (i.e., BRZ) had a significantly higher rut depth than did the gradation violating the restricted zone (i.e., HRZ). Based upon these data for 19.0-mm NMA5 designed with 75 gyrations, it appears that gradations passing through the restricted zone will provide comparable, if not better, rut resistance when compared with gradations passing outside the restricted zone.

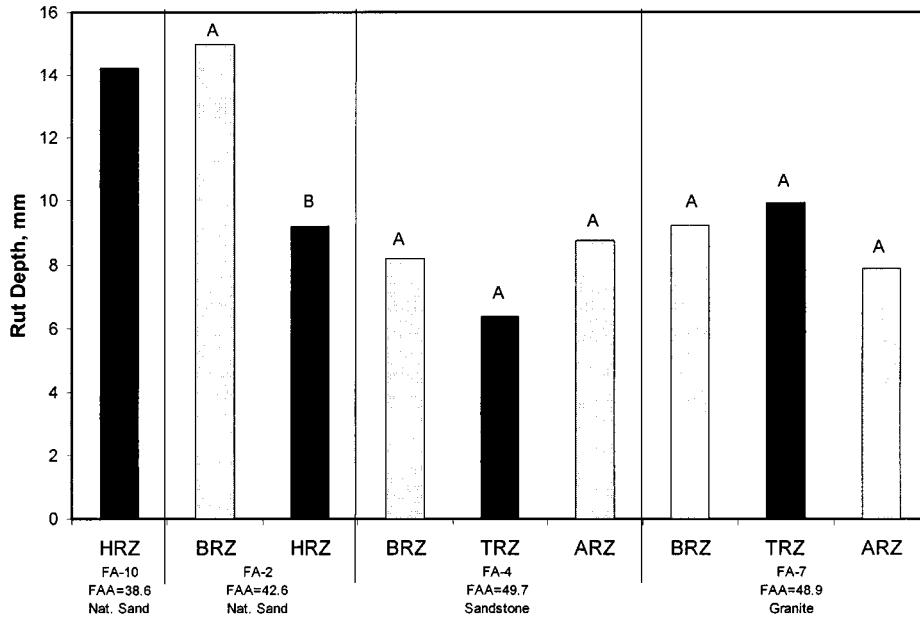


Figure 33. Results of APA testing conducted on mixes designed with 75 gyrations, Part 3.

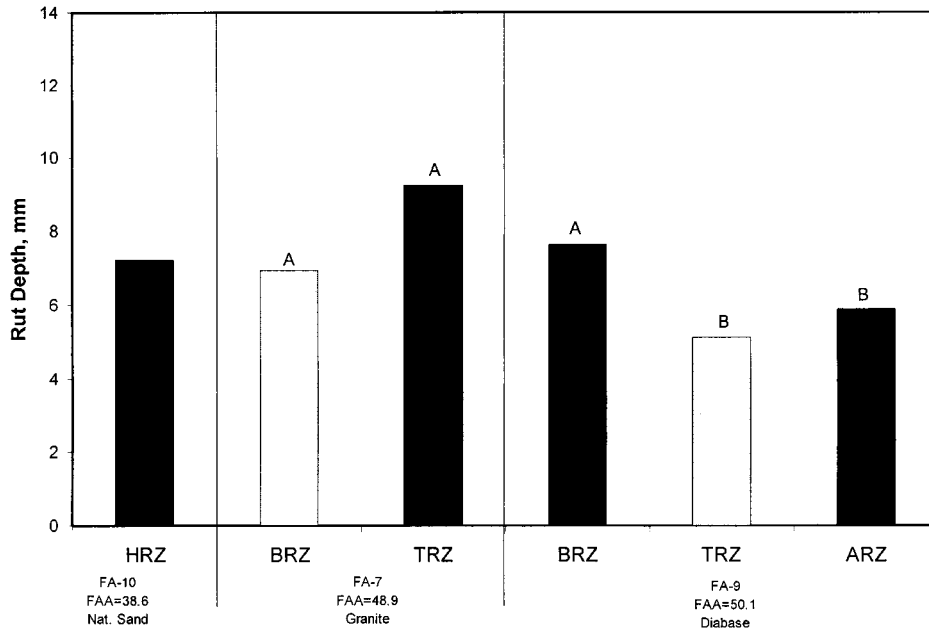


Figure 34. Results of APA testing conducted on mixes designed with 100 gyrations in Part 3.

Results of APA testing conducted on mixes designed with 100 gyrations for Part 3 are illustrated in Figure 34. Sufficient data was available to conduct DMRT rankings for mixes containing FA-7 and FA-9. Mixes containing FA-7 (i.e., BRZ and TRZ) had similar rut depths based upon the DMRT rankings. For the FA-9 mixes, the BRZ gradation (i.e., the control) had

a significantly higher rut depth than did the TRZ and ARZ gradations. This data supports the previous analyses in Parts 1 and 2 and the analysis of the lower design compactive effort work in Part 3. Mixes having gradations passing through the restricted zone perform similarly or better than mixes having gradations passing outside the restricted zone.

CHAPTER 4

CONCLUSIONS, RECOMMENDATIONS, AND SUGGESTED RESEARCH

CONCLUSIONS

The following conclusions are drawn from the analysis of data presented in Chapter 3.

1. Mixes meeting Superpave and FAA requirements with gradations that violated 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 9.5- and 19-mm NMAS gradations at N_{design} values of 75, 100, and 125 gyrations and is supported by extensive, independent results from the literature.
2. The restricted zone requirement is redundant for mixes meeting all Superpave volumetric parameters and the required FAA. References to the restricted zone, as either a requirement or a guideline, should be deleted from the AASHTO specifications and practice for Superpave volumetric design for HMA, regardless of NMAS or traffic level. Some agencies have used the restricted zone to differentiate between coarse- and fine-graded Superpave mixtures. Because the term “restricted zone” will be deleted, research needs to be done to differentiate and define coarse- and fine-gradations, if desired.
3. Although not germane to the primary objective of this project, the following observations were made:
 - Coarse-aggregate type has a significant effect on the VMA of mixes. Coarse, angular granite aggregate generally produced a higher VMA than did the coarse, crushed gravel aggregate.
 - Coarse-aggregate type has a significant effect on $\%G_{\text{mm}}@N_{\text{initial}}$ values. However, fine-aggregate type and gradation appear to have more significant effects.
 - ARZ and CRZ gradations tend to provide higher VMA values; the TRZ gradation provided the lowest VMA values.
 - The TRZ gradations generally provide the lowest VMA values for both the 9.5- and 19.0-mm NMAS mixes. This result suggests that the MDL drawn according to the Superpave guidelines (connecting the origin of the 0.45 power chart to the 100-percent passing the maximum aggregate size) is located reasonably on the gradation chart.
 - Relatively finer gradation mixes (such as ARZ and HRZ) tend to have higher $\%G_{\text{mm}}@N_{\text{initial}}$ values compared with the values of TRZ, CRZ, and BRZ mixes.
 - High FAA values do not necessarily produce high VMA in mixes although there was a general trend of increasing VMA values for increasing FAA.
 - Higher FAA values generally produced lower $\%G_{\text{mm}}@N_{\text{initial}}$ values. None of the mixes having an FAA value lower than 45 met the $\%G_{\text{mm}}@N_{\text{initial}}$ requirements of 89 percent and lower for the mixes prepared at $N_{\text{design}}=100$ and 125. This indicates that high FAA values contribute to a stiffer fine aggregate/asphalt component in HMA at initial compaction levels.
 - None of the mixes failed the $\%G_{\text{mm}}@N_{\text{maximum}}$ requirement of 98 percent maximum. In the future, the validity of this requirement should be examined.
 - Numerous mix designs in this study exceeded the maximum VFA requirement of 75 percent. The Superpave requirement of 65.0 to 75.0 percent for VFA effectively limits the VMA of 9.5-mm NMAS mixes to a narrow range. Both VMA and VFA requirements for 9.5-mm NMAS Superpave mix design need to be evaluated.
 - The potential of mixes failing because of excessive VMA (i.e., more than 2 percent above the minimum specified value) increases with a lower design compactive effort, angular coarse aggregate content, and high FAA values.
 - Both the APA and the RLCC test were reasonably sensitive to the gradation of mixes. The RSCH test conducted with the Superpave shear tester was not found to be as sensitive to changes in gradation.

RECOMMENDATIONS

The primary objective of this research project was to determine under what conditions, if any, compliance with the restricted zone requirement is necessary when an asphalt paving mix meets all other Superpave requirements such as FAA and volumetric mix criteria (such as VMA) for a project. The results of the study demonstrated that the restricted zone is redundant in all conditions (such as NMAS and traf-

fic levels) when all other relevant Superpave volumetric mix and FAA requirements are satisfied. Therefore, all reference to the restricted zone in AASHTO MP2-00 and AASHTO PP28-00 should be deleted thoroughly to avoid any confusion in implementation.

The following specific revisions to AASHTO MP2-00, “Standard Specification for Superpave Volumetric Mix Design,” are recommended:

- Delete Section 6.1.3, which reads: “Gradation Restricted Zones—It is recommended that the selected combined aggregate gradation does not pass through the restricted zones specified in Table 3. See Figure 1 for an example of a graph showing the gradation control points and the restricted zone.”
- Delete Table 3: Boundaries of Aggregate Restricted Zone.
- Renumber Table 4 as Table 3, and Table 5 as Table 4.
- Sections 6.2, 6.3, 6.4, and 6.5: change “Table 4” to “Table 3.”
- Section 7.2: change “Table 5” to “Table 4.”
- Figure 1: delete the words “and Restricted Zone” from the title. Erase or remove the illustration of the restricted zone from the figure.

The following revisions to AASHTO PP28-00, “Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (HMA),” are recommended:

- Section 6.8: revise “confirm that each trial blend meets MP2 gradation control (see Tables 2 and 3 of MP2)” to read as follows: “confirm that each trial blend meets MP2 gradation control (see Table 2 of MP2).”

- Figure 1: remove the illustration of the restricted zone from the figure.

SUGGESTED RESEARCH

Table 3 of AASHTO MP2-00 presents gradation restricted zones for five NMAS mixtures: 9.5-mm, 12.5-mm, 19.0-mm, 25.0-mm, and 37.5-mm. Section 6.1.3 states “It is recommended that the selected combined aggregate gradation does not pass through the restricted zones specified in Table 3.”

AASHTO PP28-00 specifies four design compaction levels (N_{design}) of 50, 75, 100, and 125 gyrations corresponding to four design ESALs of < 0.3 million, 0.3 to < 3 million, 3 to < 30 million, and \geq 30 million, respectively.

Ideally, then, the necessity of the restricted zone for five NMAS and four traffic levels (i.e., $5 \times 4 = 20$ combinations) should be evaluated. This would be a monumental task and is considered unnecessary by the research team. Besides this project (NCHRP Project 9-14), various researchers have already evaluated the restricted zone in NMAS ranging from 9.5 mm to 37.5 mm and N_{design} ranging from 75 to 152 gyrations. Table 12 gives this information; the work is reviewed in detail in Appendix A. This body of research clearly shows the redundancy of the restricted zone for various NMAS and traffic levels listed in Table 12.

There does not appear any need for conducting additional research pertaining to the design compaction level of 50 gyrations because those mixes are used for light-traffic-volume roads. This leaves N_{design} of 75, 100, and 125 gyrations to be researched. Table 13 presents the NMAS mixes that have been evaluated at compactive efforts of 75 gyrations and higher.

TABLE 12 NMAS and compactive efforts evaluated by researchers

Researchers ^a	NMAS	N_{design} (Gyrations)
NCHRP Project 9-14	9.5 mm	75, 100, and 125
	19.0 mm	75 and 100
McGennis (1997)	19.0 mm	96
Anderson and Bahia (1997)	19.0 mm	109
Sebaaly et al. (1997)	19.0 mm	Hveem design
Van de Ven et al. (1997)	9.5 mm	142
	12.5 mm	142
El-Basyouny and Mamlouk (1999)	19.0 mm	113
	37.5 mm	113
Kandhal and Mallick (2001)	12.5 mm	76
	19.0 mm	76
Chowdhury et al. (2001)	19.0 mm	86 and 96
Hand et al. (2001)	9.5 mm	76, 109, and 152
	19.0 mm	76, 109, and 152

^a See Reviews, Appendix A.

TABLE 13 Evaluations by researchers

NMAS	N_{design} Gyration
9.5 mm	75, 76, 100, 109, 125, and 142
12.5 mm	76, 142
19.0 mm	75, 76, 86, 96, 100, 109, 113, and 152
25.0 mm	None
37.5 mm	113

Table 13 shows that all NMAS mixes except 25.0-mm, which is used primarily in HMA base courses, have been evaluated. If the restricted zone is redundant for 19.0-mm and 37.5-mm NMAS mixes, it is probable it will also be redundant for the intervening 25.0-mm NMAS mix as well. The Georgia DOT's 25.0-mm NMAS base mix has gradation that overlaps a small portion of the Superpave restricted zone. According to Watson et al. (3) the average rut depth (measured by the GLWT) obtained on the base mix was 2.6 mm, the lowest of all the mixes used by Georgia DOT; this indicates the redundancy of the restricted zone for 25.0-mm NMAS mixes. The

research team is of the opinion that no further research work on the restricted zone is necessary and that the zone should be considered redundant for all NMAS mixes. However, if it is strongly believed that the research team should fill the research gaps, the following combinations of NMAS and N_{design} are suggested:

NMAS	N_{design} Gyration
12.5 mm	100
25.0 mm	75 and 100

It is recommended to use the APA only for performance testing because it was observed to be the most sensitive to change in gradation of the three test procedures used in NCHRP Project 9-14. At least six fine aggregates covering a wide range of FAA values should be used. It is recommended to use crushed gravel coarse aggregate for an N_{design} of 75 gyrations and granite coarse aggregate for an N_{design} of 100 gyrations similar to the work plan for Part 3. This will increase the potential of obtaining HMA mixes that will meet the minimum VMA requirements. The cost of this additional research work is estimated to be \$200,000.

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1. "Performance of Coarse-Graded Mixes at WesTrack—Premature Rutting" (Final Report). Federal Highway Administration, Washington, DC (1998).
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 3. Watson, D.E., A. Johnson, and D. Jared. "The Superpave Gradation Restricted Zone and Performance Testing with the Georgia Loaded Wheel Tester." *Transportation Research Record No. 1583*, Transportation Research Board, National Research Council, Washington, DC (1997); pp. 106–111.
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