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# Significance of Restricted Zone in Superpave Aggregate Gradation Specification

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## Significance of Restricted Zone in Superpave Aggregate Gradation Specification

COMMITTEE ON GENERAL ISSUES IN ASPHALT TECHNOLOGY (A2D05)

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### Foreword

A sphalt technologists recognized it for many years prior to Superpave® (Superior Performing Asphalt Pavements)—a characteristic hump in a mix gradation within the intermediate sieve sizes which could cause a hot-mix asphalt (HMA) mix to be prone to tenderness and rut susceptibility. The Strategic Highway Research Program (SHRP) gave it a name—the restricted zone—and included it in Superpave as a recommended guideline. Some transportation agencies interpreted it as a requirement. However, based on experiences with mixes violating the restricted zone, many asphalt technologists did not agree with its inclusion in Superpave.

The authors of this Circular present the historical basis of the restricted zone in HMA mixes and summarize the published research conducted on the restricted zone to determine its significance within the Superpave gradation specification.

The Transportation Research Board (TRB) Committee on General Issues in Asphalt Technology (A2D05)was asked to review the information presented by the authors. The committee agreed that it should be of interest to materials and pavement engineers and others responsible for designing HMA pavements.

## Contents

Introduction	3
Historical Background	4
Origin of Restricted Zone	4
Research Related to the Restricted Zone	6
Significance of the Restricted Zone	
References	19

### Significance of Restricted Zone in Superpave Aggregate Gradation Specification

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#### **INTRODUCTION**

SHRP's asphalt research was primarily aimed at the properties of asphalt binders and paving mixes and their effect on asphalt pavement performance. The SHRP study of aggregate particles (including gradation) was intentionally excluded from the asphalt program, yet SHRP had to recommend a set of aggregate properties and an aggregate gradation specification for use in mix design without any experimentation.

In order to recommend aggregate properties and gradations, SHRP formed an Aggregate Expert Task Group (ETG) consisting of 14 acknowledged experts. In lieu of formal experimentation, 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. The modified Delphi process used five rounds of questionnaires to narrow a wide list of aggregate properties and criteria to those recommended in Superpave. The final recommended aggregate gradation criteria included control points through which gradations must fall between and a restricted zone that lies along the maximum density line (MDL) between the intermediate sieve sizes [either 4.75 or 2.36 mm depending upon the nominal maximum aggregate size (NMAS) of the gradation] and the 0.3-mm sieve size.

The restricted zone was not a new concept. For many years, asphalt technologists have recognized that mixes having gradations with a characteristic "hump" within the intermediate sieve sizes have been susceptible to tenderness and rut in the field. However, not until the SHRP recommendations did the "zone" get a name and become a formal guideline.

Although the restricted zone was included in Superpave as a recommended guideline and not a required specification, some agencies interpreted it as a requirement. Based upon past experience with mixes having gradations violating the restricted zone, many asphalt technologists believe that compliance with the restricted zone may not be desirable or necessary in every case to produce mixes with good performance. This Circular presents an evaluation of the historical basis of the restricted zone and published research conducted on the restricted zone to determine its significance within the Superpave gradation specification.

#### **HISTORICAL BACKGROUND**

From a historical perspective, the restricted zone is something new. Not until Superpave was there a formal guideline for aggregate gradation called the restricted zone. However, the industry has been aware of potential performance problems with gradations that pass through the Superpave-defined restricted zone region. In 1940, Hveem (1) described a number of hot-mix asphalt (HMA) gradations that showed a hump between the 0.6- and 0.15-mm sieve sizes. Hveem indicated that the hump was caused by an excessive amount of sand in this size fraction. He said that the hump is indicative of wind-blown sand (smooth-textured, rounded sand) within the aggregate blend and that based upon his experience resulted in HMA mixes with low stability.

The initial concept of a restricted zone around the MDL can probably be indirectly traced back to Goode and Lufsey (2). Based upon some work by Nijboer (3) to identify a MDL, Goode and Lufsey presented a 0.45 power grading chart for plotting aggregate gradations. This grading chart utilized the sieve size (in microns) raised to the 0.45 power as the horizontal axis and the percent passing (by mass) on an arithmetical scale as the vertical axis.

To utilize the newly developed gradation chart, Goode and Lufsey evaluated 24 gradations to observe the effect of sand content on the stability of HMA mixes. What prompted their study were some reported cases where tender mixes were encountered with gradation humps between the 0.6- and 0.3-mm sieve sizes. Based upon their work, Goode and Lufsey found that, in general, gradations that show appreciable humps above the MDL at about 0.6-mm sieve produced higher voids in mineral aggregate (VMA) and lower Marshall stability than gradations that plot as a more dense gradation.

#### **ORIGIN OF RESTRICTED ZONE**

The origin of the Superpave-defined restricted zone is documented in a SHRP report (SHRP-A-408) (4). This report summarizes the research devoted to the key aspects of the Superpave volumetric mix design system developed under SHRP. The first chapter documents the development of mix design criteria for both aggregates and mixtures through a process called a modified Delphi method. The modified Delphi method consists of a group of members through which a series of questionnaires are presented. The process is evolutionary in that the first questionnaire discusses general issues and each subsequent questionnaire becomes more specific. Under normal Delphi methods, the group members do not meet face-to-face; however, for the SHRP research the experts were allowed to meet during the process as part of a modified Delphi method.

The first questionnaire sent to the group members contained two sets of questions pertaining to aggregate characteristics and asphalt–aggregate characteristics. This Circular focuses on the aggregate characteristics. The members were asked to rate their degree of agreement or disagreement for including the following seven characteristics in Superpave:

- 1. Gradation limits (6.18, 6.15),
- 2. Crushed faces (6.04, 5.77),
- 3. Natural sand content (4.54, 4.92),
- 4. Los Angeles abrasion (4.67, 4.65),
- 5. Aggregate soundness (5.45, 4.85),
- 6. Deleterious materials (5.33, 5.31), and
- 7. Sand equivalent (4.17, 4.23).

Average ratios for each characteristic during the first and second round questionnaires are provided in parentheses, respectively. A rating of 1 represents "very strongly disagree," and a rating of 7 represents "very strongly agree."

Based on the first questionnaire, ETG members indicated the highest degree of agreement for gradation limits. This also occurred for the second and third questionnaires. The third questionnaire contained a few additional characteristics that were subsets of the original seven aggregate characteristics. Within gradation limits, three additional characteristics were added: minimum/maximum aggregate sizes, control points/restricted zone, and control points only. Based on the ratings (Table 1), control points only had the highest degree of agreement with control points/restricted zone having the lowest.

After the third round of questionnaires, researchers believed it was reasonably clear which characteristics should be included in the specifications. However, specification values were less clear. Therefore, the fourth questionnaire required the group members to rank each characteristic assuming each would be included as a specification. Gradation limits were ranked second highest in the fourth questionnaire behind coarse aggregate angularity. No mention of the restricted zone was made in the report for the fourth questionnaire.

The fifth and final round of questionnaires aimed to determine specification limits and to assess the impact of external factors on the selected limits. The fifth questionnaire also asked the group members for restrictions on aggregate gradation. The majority of experts specified aggregate gradations either above the restricted zone (ARZ) or below the restricted zone (BRZ), although about half of the recommended gradations BRZ for high-traffic conditions. This was interesting because the fourth-round questionnaire did not mention the restricted zone.

At the conclusion of the fifth round of questionnaires, the SHRP researchers developed criteria and specifications. For gradation controls, a 0.45 power chart was selected for plotting gradations. Definitions associated with gradation control were provided for NMAS, maximum aggregate size, restricted zone, and MDL. The restricted zone was defined as

a zone lying on the maximum density line extending from the 300  $\mu$ m (No. 50) sieve to the 2.36 mm (No. 8) sieve through which it is undesirable for the gradation to pass.

Based on this discussion of how the restricted zone was selected as a Superpave specification, it is unclear why the restricted zone was specified as it had the lowest degree of agreement for gradation controls during the third round of questionnaires and was not mentioned specifically again within the report until the fifth round. Additionally, this report suggests that gradations passing through the restricted zone (TRZ) are only "undesirable." No mention is made that gradations should be required to pass outside the restricted zone.

TABLE T Average Ratings fro	m the Inird Question	naire
Aggregate Characteristic	Average Rating	Standard Deviation
Gradation Limits:	6.57	0.76
a) Minimum/Maximum Aggregate Size	4.50	1.95
b) Control Points/Restricted Zone	4.14	1.79
c) Control Points Only	5.29	1.68

### 

The origin of the requirement for gradations to pass outside the restricted zone can be directly traced to a FHWA training manual on the Superpave mix design system (5). Along with asphalt binder and mixture criteria for the Superpave mix design system, this manual details how gradations are specified under Superpave and provides definitions for terms relating to gradation controls such as NMAS, maximum aggregate size, MDL, and control points.

The manual states that the restricted zone resides along the MDL between intermediate sieve sizes (either the 4.75 or 2.36 mm) and the 0.3-mm sieve size. It also states that the restricted zone forms a band through which gradations are not permitted to pass. This contradicts the SHRP-A-408 report (4) which states, "Gradations that pass through the restricted zone are undesirable" but does not prevent them from passing through this zone.

#### **RESEARCH RELATED TO RESTRICTED ZONE**

In 1997, Watson et al. (6) reported that four of the conventional Georgia Department of Transportation (GDOT) dense-graded mixtures that were most commonly used in Georgia had gradation specification bands that encompassed all or part of the Superpave restricted zone and that they had historically provided good performance. These high-performance mixtures incorporated 100% crushed good-quality aggregate and no natural sand. GDOT B– (19.0-mm NMAS) and F– (9.5-mm NMAS) mixture gradation specifications were such that the restricted zone lay totally within them (Figure 1). GDOT E– (12.5-mm NMAS) and Base– (25-mm NMAS) mixture



FIGURE 1 Typical GDOT gradations encompassing the Superpave restricted zone.

gradation specifications also included portions of the restricted zone. The GDOT B– mixture was reported to have exhibited exceptional resistance to permanent deformation in both rutting susceptibility tests and under actual field conditions.

The 1989 GDOT gradation specifications for Interstate pavements were developed based on cooperative research between GDOT and the Georgia Institute of Technology using the Georgia Loaded Wheel Tester (GLWT). A comparison of numerous GLWT mean rut depths for the different mixture types revealed that mixes having gradations passing TRZ performed as well as, or in some cases better, than mixes with gradations passing outside the restricted zone. Based upon the historical laboratory and field performance of these mixes passing TRZ zone, GDOT did not change gradation specifications to the Superpave-defined control points.

At the same time as the analysis of GDOT mixtures, Anderson and Bahia (7) analyzed the Asphalt Institute's extensive database of Superpave mixture design data (128 trial blends) in an effort to provide mix designers with guidelines for the selection of aggregate gradations when designing these types of mixtures. As part of their work, three 19-mm NMAS aggregate blends were developed to cover a range of gradation shapes allowable in Superpave using a single crushed granite aggregate source. These three gradations passed ARZ, TRZ, and BRZ. A fourth blend was developed with the same granite, but it incorporated 20% rounded natural sand and had a gradation passing BRZ.

For each of the mixes, samples were prepared for Superpave analysis testing. Both frequency sweep at constant height (FSCH) and repeated shear at constant height (RSCH) tests were performed to evaluate rutting potential. FSCH tests were conducted at 20°C and 40°C while RSCH tests were conducted at 54°C. From the FSCH tests (m<sub>FS</sub> values, slope of the curve of G\* versus frequency on a log-log graph) the authors concluded that the ARZ blend provided the lowest rutting potential and the BRZ blend provided the highest rutting potential. The mix having a gradation passing TRZ performed better than the BRZ mix but not as well as the ARZ mix. The RSCH tests provided similar results.

At the 1997 8th International Conference on Asphalt Pavements (ICAP) Van de Ven et al. (8) reported on a cooperative research effort focusing on initial validation of Superpave gradation (restricted zone) and fine aggregate angularity (FAA) specifications. A single 100% crushed aggregate source was used to produce three 9.5-mm NMAS blends that passed ARZ, TRZ, and BRZ. The 9.5-mm TRZ blend was actually a 12.5-mm NMAS ARZ gradation by Superpave standards because slightly less than 90% passed the 9.5-mm sieve. The 9.5-mm ARZ and BRZ South African blends met the 9.5-mm Superpave ARZ and BRZ specifications.

The mixtures were designed in the spirit of the Superpave volumetric mix design procedures using a Superpave gyratory compactor (SGC), however, some of the mixtures violated one or more Superpave criteria. This was primarily due to gradations passing TRZ and an effort to compare South African and Superpave specifications. In addition to volumetric mixture designs, indirect tensile stiffness and strength, dynamic creep, and Superpave Shear Tester (SST), mechanical tests were performed. Model Mobile Load Simulator (MMLS) tests were also conducted to evaluate rutting performance of the mixtures.

For the MMLS testing, the mix having a gradation TRZ performed the best. The other mechanical performance tests did not consistently provide the same ranking as the MMLS. In some cases, the mechanical tests did not provide the same ranking among themselves either. The authors emphasized that the conclusions drawn were based on limited data, but blends with TRZ gradations can provide good rutting performance and the significance of the Superpave restricted zone should be reconsidered.

Roque et al. (9) also reported at the 1997 8th ICAP on a study including, but not limited to, the following objectives:

• Evaluating the effects of gradation on shear resistance and volumetric properties of asphalt mixtures;

• Providing insight for establishment of a mixture design process that optimized aggregate gradation to maximize shear resistance; and

• Determining whether it was possible to produce dense gradations that provided shear resistances equal to or greater than those of stone matrix asphalt (SMA) mixtures, such that the use of polymers and/or fibers would not be necessary.

Eighteen 12.5-mm NMAS mixtures were considered. Aggregates typical of Florida limestone were blended to produce coarse aggregate gradations ranging from SMA to close to the MDL. In other words, gradations were representative of TRZ, BRZ, and SMA gradations. A Gyratory Test Machine was used to compact and evaluate all mixtures. Shear resistance appeared to be most strongly related to the gradation characteristics of the coarse aggregate fraction of the mixture. Mixtures could be produced with gradations denser than SMA gradations that had shear resistances equal to or greater than that of SMAs. Finally, good shear resistance could be achieved with a broad range of aggregate structures ranging from TRZ to SMA gradations.

McGennis (10) presented results of a laboratory study to evaluate materials with known performance using Superpave mix design technology. The study was conducted because of problems encountered in asphalt overlays using crushed gravel. Aggregate types used in this study included two coarse crushed gravels and a fine aggregate from the same source. Additionally, two locally available unprocessed fine aggregates (Bagley and CXI), called field sands, which were characterized as marginal in quality, were utilized along with a fine aggregate (TF) of higher quality. The asphalt binder was a Performance Grade (PG) 64-22. Various combinations of the materials were evaluated using Superpave mix design tests.

For the mixture gradations the coarse aggregate percentages were fixed, and the percentages of the different fine aggregates were varied to obtain different blends having a 19.0-mm NMAS. Each of the fine aggregates, not including the one from the same source as the two coarse aggregates, were blended at both 10% and 20% of the total aggregate mass. The resulting gradations showed that the blends with 20% passed ARZ and the blends with 10% passed TRZ. For comparison purposes, the researcher blended two gradations using the two gravel coarse aggregates and the fine aggregate from the same source [Gradation Blend 1 (GB1) and GB2]. These two were used as a baseline to compare the other mixtures. Additionally, three blends were made using a University of Texas (UT) laboratory standard fine aggregate (limestone) with the two coarse, crushed gravels (UT Scrn 1, UT Scrn 2, and UT Sand).

Properties used to evaluate the 11 mixtures are provided in Table 2. Based on this table, none of the 11 mixtures met all Superpave criteria (aggregate consensus properties and/or mixture volumetrics). FAA precluded all of the field sands (Bagley, CXI, and TF). Interestingly though, percent theoretical maximum density at the initial number of gyrations ( $G_{mm}@N_{ini}$ ) would not have precluded two of the field sand mixtures that passed TRZ. Moreover, the combination of the FAA and  $G_{mm}@N_{ini}$  requirement of less than 89% precluded all of the mixtures that were shown to have poor performance independent of the restricted zone guideline. Therefore, based on the results of this study, the restricted zone was not needed to identify poor mixture performance.

	Mix Meets Superpave Requirements* for								
Mix	Gradation	Coarse Aggr. Angularity	FAA	Flat/ Elon Particles	Sand Equivalent	%G <sub>mm</sub> @ N <sub>initial</sub>	VMA %	VFA %	Dust Proportion
Bagley 10%	N	Y	N	Y	N	Y	Y	Y	Y
Bagley 20%	N	Y	N	Y	N	Y	Y	N	Y
CXI 10%	Y	N	N	Y	Y	N	Y	Y	N
CXI 20%	N	Y	N	Y	N	Y	Y	N	N
TF 10%	Y	Y	N	Y	Y	Y	Y	N	Y
TF 20%	N	Y	N	Y	N	Y	Y	Y	Y
GB 1	Y	Y	Y	Y	Y	Y	N	N	Y
GB 2	Y	Y	Y	Y	Y	Y	N	N	Y
UT Scrn 1 UT Scrn 2 UT Sand	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	Y Y Y	N Y N	N N N	Y Y Y

 TABLE 2 Summary of Mix Properties Compared with Superpave

 Mix Design Requirements (10)

\* Based on traffic level > 3.0 million equivalent single-axle loads (ESALs).

Sebaaly et al. (11) evaluated several mixtures with aggregates from different sources and different grades of asphalt binder for the purpose of selecting the most desirable HMA mixtures. The materials included four aggregate sources commonly used in Nevada and five types of asphalt binder. For each of the aggregate sources, four different gradations were used. Of these, one gradation (G1) passed TRZ, one (G2) passed ARZ, and the remaining two (G3 and G4) passed BRZ. Table 3 provides the results of the Superpave consensus aggregate property tests performed on the different aggregate source–gradation combinations. All Superpave consensus properties were met except for the LV materials that failed the coarse aggregate angularity requirement.

Five asphalt binders used in this study included an AC-20, two polymer-modified AC-20s, an AC-30, and a polymer-modified AC-30. Each of these binders was graded based on the Superpave PG system. Results of these gradings were:

Binder	Grade
AC-20	PG 64-22
AC-20P <sub>1</sub>	PG 64-28
AC-20P <sub>2</sub>	PG 58-22
AC-30	PG 64-22
AC-30P	PG 70-22

Mix designs using the Hveem mix design system were conducted for 50 combinations of aggregate source–gradation–asphalt binder to determine optimum asphalt binder contents. Ten of

Aggregate Source	Credation	Coarse Aggrega (%)	ate Angularity )	FAA	Flat and Elongated Particles (%)	
	Gradation	2 Fractured Faces	1 Fractured Face	(%)		
Specification*		90 min.	95 min.	45 min.	10 max.	
FS	G1	93.1	93.1 99.5		0.0	
	G2	93.2	99.6	49.2	0.0	
	G3	93.5	99.6	49.8	0.0	
	G4	93.1	99.5	50.8	0.0	
AP	G1	97.1	99.0	49.2	0.9	
	G2	97.3	99.0	50.4	1.0	
	G3	97.1	99.0	51.4	0.9	
	G4	96.9	99.0	52.8	0.9	
LV	G1	84.9	93.2	51.0	0.1	
	G2	85.5	93.5	50.1	0.1	
	G4	87.9	94.5	51.1	0.1	

 TABLE 3 Comparison of Aggregate Properties with Superpave Specifications for

 All Aggregate Sources (11)

\* Specifications based on less than 30 million ESALs and less than 100 mm of depth from surface.

the combinations were omitted from further testing because they did not meet VMA or Hveem stability requirements.

Next, the authors went through a process designed to select the most desirable mixture(s). The selection process consisted of the following steps:

1. Select mixtures based on criteria for resilient modulus, tensile strength, and retained strength ratios.

2. Evaluate the mixtures that passed the criteria from Step 1 with a repeated load triaxial permanent deformation test. Based on these results, select the best mixtures for low-temperature cracking test.

3. Evaluate the low-temperature properties of the selected mixtures from Step 2 using the thermal stress-retained specimen test (TSRST).

The authors found that gradation affected the results of the first two steps while the asphalt binder type strongly influenced the TSRST results. Based on the results of the resilient modulus, tensile strength, retained strength ratios, and permanent deformation testing, the authors concluded that the mixtures with gradations passing TRZ were the most favorable for all aggregate sources. Gradations passing ARZ were concluded to be the least favorable.

Sousa et al. (12) studied the effect of gradation on HMA fatigue life using the SHRP-M009 four-point bending fatigue test. ARZ, TRZ, and BRZ gradations ranging in NMAS from 12.5 to 25.0 mm were considered. Six aggregate sources and two PG binder grades were used to produce nine mixtures. All aggregate was 100% crushed granite. The distribution of gradations considered was four ARZ, three TRZ, and two BRZ. The BRZ mixtures were designed using the Superpave volumetric method ( $N_{design}$  = 143). Five of the others were designed using the Marshall method, one using a roller wheel compactor, and one using the Quebec LC mixture design method.

Gradations passing TRZ or ARZ appeared to have better fatigue performance than gradations passing BRZ. The researchers indicated that higher ACs associated with the ARZ and TRZ gradations probably assisted in improved fatigue resistance.

The effect of aggregate gradation on HMA mixture performance was one of the parameters considered in Phase I of National Pooled Fund Study No. 176 (13). Performance tests used in this study were the Indiana Department of Transportation (INDOT)/Purdue University prototype scale accelerated pavement tester (APT), the PURWheel laboratory scale wheel-tracking test, and a triaxial test. HMA mixtures evaluated were prepared using a PG 64-22 asphalt binder, one coarse limestone aggregate, and one limestone sand (with an FAA value of 44%). The effect of gradations passing ARZ, BRZ, and TRZ on rutting performance was investigated.

INDOT/Purdue APT test results indicated that mixtures comprised of all three gradations performed similarly. Rut depths measured in PURWheel tests also indicated that the mixtures with TRZ gradations performed better than the BRZ mixtures under both wet- and dry-test conditions. Results of triaxial testing indicated that mixes with ARZ gradations performed better than TRZ and BRZ mixes. The authors concluded that the use of gradations violating the restricted zone alone did not necessarily ensure poor performance.

El-Basyouny and Mamlouk (14) conducted an investigation of the effects of aggregate gradation, NMAS, and asphalt content on rutting potential and volumetrics of laboratory compacted specimens. ARZ, TRZ, and BRZ gradations for 19.0- and 37.5-mm NMAS were considered. A PG 70-10 binder was used to prepare specimens over a range of asphalt contents using an SGC ( $N_{design} = 113$ ).

Volumetric determinations included bulk specific gravity, air voids, VMA, and voids filled with asphalt (VFA). Creep properties obtained from uniaxial creep tests were used in the VESYS-3AM software to predict mixture rutting potential. Analysis of variance (ANOVA) was conducted to examine the effects of factors considered in the study. The researchers concluded that NMAS, aggregate gradation, asphalt content, and the interaction between asphalt content and NMAS significantly affected mixture properties. Mixtures with TRZ gradations exhibited higher bulk specific gravities than ARZ and BRZ mixtures, thus TRZ gradations exhibited the lowest air voids. The VMA of mixtures with ARZ and BRZ gradations was slightly higher than those with TRZ gradations. Mixtures with TRZ gradations exhibited the highest VFA, and the mean values of VFA for ARZ and BRZ mixtures were approximately equal. The researchers also found that the VESYS-3AM software predicted that an average of 10 mm of rutting would develop in mixtures with TRZ gradations.

Kandhal and Mallick (15) evaluated the effect of mixture gradation on the rutting potential of dense-graded HMA. The performance of 18 mixtures was evaluated based on Asphalt Pavement Analyzer (APA) and SST tests. Two NMAS (12.5 and 19.0 mm), three aggregate types (granite, limestone, and partially crushed gravel), and three gradation types (ARZ, TRZ, and BRZ) were considered. The coarse fraction of the gradation curve (+4.75 mm) was held constant while the fine fraction of the gradation was adjusted to produce the ARZ, TRZ, and BRZ blends. A single PG 64-22 binder was used, and mixtures were designed in

accordance with the Superpave volumetric method ( $N_{design} = 76$ ). Both APA and SST performance test specimens were compacted to 4.0% air voids with an SGC. APA tests were conducted at 64°C, and RSCH tests were conducted in accordance with AASHTO TP7 at 50°C.

Statistical analysis (ANOVA) of APA rut depths indicated aggregate type, gradation, and NMAS, as well as the interaction between aggregate type and gradation, were significant. A significant difference between rut depths of ARZ, TRZ, and BRZ mixtures was observed. For granite and limestone mixtures performance ranked from best to worst for TRZ, ARZ, then BRZ gradations. For the partially crushed gravel mixtures performance ranked from best to worst for BRZ, TRZ, then ARZ gradations. An unsuccessful attempt was made to relate VMA to rutting performance and gradation type. It was reported that the effect of VMA on rutting performance appeared to be associated with binder film thickness.

Based on RSCH tests significant differences were not observed between ARZ, TRZ, and BRZ gradations for granite mixtures of either NMAS. Both NMAS limestone mixtures with BRZ gradations exhibited the poorest performance. For gravel mixtures of both NMAS, performance ranked from best to worst for TRZ, BRZ, then ARZ gradations. The RSCH test did not appear to be as sensitive to differences in gradation as the APA, but it did provide similar results. These findings suggest that there is no clear relationship between performance and gradation relative to the restricted zone.

Kandhal et al. (16) states that minimum VMA requirements were included in the Superpave mix design system to ensure that the minimum binder content needed to protect HMA mixtures against durability problems was incorporated. However, studies have shown that HMA mixture durability is directly related to binder film thickness and that minimum required binder film thickness is dependent on gradation. Therefore, he suggested that minimum VMA requirements should be determined based on minimum binder film thickness. It was recognized that particle size affected film thickness and that it decreased as aggregate surface area increased. On the basis of previous studies the authors used an average binder film thickness of 8 mm to illustrate the effect of aggregate gradation and NMAS aggregate on mixture VMA.

Mixtures with 19.0- and 12.5-mm NMAS and ARZ, TRZ, and BRZ gradations were used for illustration. The VMA of these mixtures was computed for film thicknesses of 6, 7, and 8 mm and 4% air voids. Calculations showed that for a constant film thickness, VMA of ARZ mixtures were highest while VMA of BRZ mixtures were lowest.

To validate this illustration, six 12.5-mm NMAS Superpave mixtures were prepared. Three contained 100% crushed granite and three contained 80% crushed granite plus 20% natural sand. The aggregates were mixed with a PG 64-22 asphalt binder and compacted in an SGC ( $N_{design} = 96$ ). ARZ, TRZ, and BRZ gradations were evaluated. The gradations were different only relative to the restricted zone. In other words, the coarse fraction of the gradation curves (+4.75 mm) was held constant.

The mixtures with 20% natural sand consistently had lower VMA values than those with 100% crushed granite. Both TRZ and BRZ mixtures with natural sands failed to meet the 14% minimum VMA requirement. However, based on the minimum binder film thickness of 8 mm, the BRZ with natural sand mixture would meet the durability requirement (film thickness = 9.5 mm). It was concluded that the current Superpave minimum VMA requirement could lead to rejection of durable HMA mixtures, especially BRZ mixtures, despite adequate binder film thickness. It was recommended that minimum average asphalt film thickness be used instead of minimum VMA to ensure mixture durability.

Chowdhury et al. (17) summarized an investigation of the effect of the Superpave restricted zone on HMA rutting performance in which aggregate particle shape and surface texture were kept constant while gradation was varied around and TRZ. Crushed granite, crushed limestone, and crushed river gravel were used. Three different 19.0-mm NMAS gradations (ARZ, TRZ, and BRZ) were studied for each aggregate source. The coarse fraction of the gradation curve (+4.75 mm) was held essentially constant while the fine fraction of the gradation was adjusted to produce the ARZ, TRZ, and BRZ gradations. A single PG 64-22 binder was used.

The nine mixtures were designed for performance testing with the SST to evaluate their resistance to permanent deformation. Tests conducted using the SST included the simple shear at constant height (SSCH), FSCH, repeated shear at constant stress ratio (RSCSR), and RSCH tests. SSCH, FSCH, and RSCSR tests were performed on all mixtures, whereas the RSCH was performed on the river gravel mixtures only. Permanent deformation resistance of the individual mixtures tested at 46°C is summarized in Table 4.

Based on maximum shear strains observed in SSCH tests, the more susceptible mixtures were the river gravel and limestone mixtures with BRZ gradations and the granite mixture with an ARZ gradation. The most rut-resistant mixtures were the river gravel and limestone mixtures with ARZ gradations and the granite mixture with the TRZ gradation. River gravel mixtures exhibited greater strains than granite or limestone mixtures. RSCSR tests were not significantly affected by different gradations regardless of aggregate type. However, they did show that river gravel mixtures exhibited greater rutting susceptibility than limestone or granite mixtures.

The ratio between complex shear modulus and shear phase angle (G\*/sin $\delta$ ) from FSCH tests was used to assess rutting resistance. Mixtures with greater rutting resistance were the granite mixture with a TRZ gradation and the river gravel mixtures with ARZ and TRZ gradations. The river gravel mixture with a BRZ gradation was most susceptible to rutting. For limestone mixtures, there was no clear trend observed among gradations. RSCH test results on river gravel mixtures were used to predict cumulative permanent strains after the application of  $10x10^6$  ESALs using a model developed at Texas A&M University. The model predicted that

Test Type	Measured Property	River Gravel	Granite	Limestone	Natural Sand
FSCH	G*	$A\congT>B$	T > A > B	$A\congB>T$	$A > T \cong B$
	G*/sinδ	$A\congT>B$	T > A > B	$A\congB>T$	$A > T \cong B$
SSCH	Maximum Shear Strain	A > T > B	$A\congT>B$	A > T > B	A > T > B
	Permanent Shear Strain	A > T > B	T > A > B	A > T > B	A > T > B
	Elastic Shear Strain	A > T > B	A > T > B	$A\congT>B$	$A\congB>T$
	Permanent Shear Strain @ N = 1	A > T > B	T > B > A	A > T > B	N/A
RSCSR	Permanent Deformation	A > T > B	T > A ≅ B	A > T ≅ B	A > T > B
RSCH	Permanent Deformation	A > T > B	N/A	N/A	N/A

TABLE 4 Resistance to Permanent Deformation Ranking<br/>(at 46°C and Design Asphalt Content) (17).

Note: A = Above, T = Through, B = Below; A > B = A is better than B.

permanent strains in ARZ mixtures would be less than those in TRZ mixtures, which in turn would be less than those in BRZ mixtures.

All 12 mixtures were also tested for rutting with the APA. From the APA results there is no indication that mixtures passing TRZ would produce the most rutting (Figure 2).

The natural sand mixture yielded the highest and the river gravel mixture yielded the second highest rut depth. Rut depth for natural sand and crushed river gravel mixtures were similar. This phenomenon was attributed to the fact that the design ACs for natural sand mixtures were much lower than that of crushed river gravel mixtures. Again, in both cases, the mixtures passing BRZ produced the largest rut depth.

The results showed that the restricted zone does not have a significant impact on rutting PG and fine-graded (ARZ and TRZ) mixtures typically provided better performance. Partially crushed river gravel mixtures were more sensitive to permanent deformation than 100% crushed limestone and granite mixtures. Finally, the authors suggested that the restricted zone could be omitted from the Superpave mixture design specifications.

In Phase I of the previously described National Pooled Fund Study 176 testing was limited to six mixtures designed from one coarse limestone and one limestone sand with a FAA value of 44. The mixtures evaluated in Phase II of the project were expanded to include at total of 21 mixtures developed from two coarse aggregate types (granite and limestone) and three fine aggregate types (granite, limestone, and natural sand) with FAA values of 50, 44, and 39, respectively (*18*). Similar to Phase I, 9.5- and 19-mm NMAS mixtures with ARZ, TRZ, and BRZ gradations were used.



FIGURE 2 Rut depth measured with APA for all mixtures after 8,000 cycles (17).

The overall study objective was to validate various HMA aggregate specifications and volumetric relationships established by Superpave, specifically the effects of gradation type, FAA, and volumetric properties on rutting performance. INDOT/Purdue APT, PURWheel, triaxial, and SST tests were used to evaluate rutting performance.

FSCH and RSCH tests indicated that ARZ mixtures were slightly more shear resistant than BRZ mixtures. Triaxial test results suggested that ARZ mixtures were slightly more shear resistant than TRZ and BRZ mixtures. PURWheel tests indicated that TRZ mixtures were more rut resistant than ARZ and BRZ mixtures. The INDOT/Purdue full scale APT is more indicative of expected field performance than any of the laboratory performance tests employed. Figure 3 shows the effect of gradation type relative to the restricted zone on rutting performance in these APT tests.

There is no clear trend in performance relative to the restricted zone or FAA. This clearly shows the restricted zone alone is inadequate to characterize gradation to ensure acceptable rutting performance. The authors stated that despite the importance of gradation in building aggregate structure, the selection of gradation with respect to the Superpave restricted zone as a requirement for performance was not suggested because equally adequate performance as observed with ARZ, TRZ, and BRZ gradations. They also indicated that it was not possible to identify strong relationships between mixture volumetrics, including VMA, and rutting performance. Binder film thickness correlated better with performance than volumetric properties, and it was suggested that film thickness be included in mixture design procedures.



Gradation with Respect to the Restricted Zone

FIGURE 3 Effect of gradation with respect to the restricted zone on rutting performance (18).

Kandhal and Cooley (19) recently completed a research project: NCHRP Report 464: Investigation of the Restricted Zone in the Superpave Aggregate Specification. The primary objective of the research project was to determine under what conditions, if any, compliance with the restricted zone requirement is necessary when the asphalt paving mix meets all other Superpave requirements such as FAA and volumetric mix criteria for a project.

A total of 80 mixtures having varying 9.5-mm NMAS gradations were designed in Part 1 of the study. The following factor-level combinations were evaluated: two coarse aggregates, ten fine aggregates, five 9.5-mm NMAS gradations, and one compactive effort. Of the five gradations, three violated the restricted zone and two fell outside the restricted zone (control). Mixes meeting all Superpave volumetric criteria were subjected to three different permanent deformation tests [APA, Repeated Load Confined Creep (RLCC), and RSCH]. Results of APA and RLCC performance testing are illustrated in Figures 4 and 5. RSCH results are not presented here because they showed little significant differences in permanent strain between coarse/fine aggregate combinations and therefore were considered not sensitive enough to differentiate between good and poor performing mixtures.

Figure 4 shows a histogram for APA rut test data for mixes containing the following fine aggregates: FA-6, FA-7, FA-4, and FA-9. The Duncan's Multiple Range Test (DMRT) was used to rank the performance of gradations violating the restricted zone [TRZ and cross through the restricted zone (CRZ)] as well as those complying with the restricted zone (BRZ and ARZ). Figure 4 illustrates that all of the mixes (except FA-4/BRZ/Gravel) had rut depths less than 8 mm, the



FIGURE 4 APA rut test results and analysis (19). (NOTE: Letters represent results of Dunan's Multiple Range Test for each coarse/fine aggregate combination.)



FIGURE 5 RLCC results and analysis (19). (NOTE: Letters represent results of Dunan's Multiple Range Test for each coarse/fine aggregate combination.)

maximum rut depth criteria recently established by Zhang et al. (20) at the same test conditions. Based upon APA testing, the authors concluded that the restricted zone appears practically redundant as a requirement to ensure adequate rut resistance if the mix satisfies both Superpave volumetric and FAA criteria.

Similar to the APA analysis, the DMRT was used to rank the performance from the RLCC tests. The RLCC results were consistent with the APA results, indicating that the restricted zone requirement is not needed when the Superpave volumetric and FAA criteria are met.

Findings were successfully extended to different compactive levels ( $N_{design} = 75$ , 100, and 125) and NMASs (9.5 and 19 mm) through performance testing conducted in Parts 2 and 3 of the NCHRP study. From the experimental results with 9.5- and 19-mm NMAS gradation at  $N_{design}$  values of 75, 100, and 125 gyrations, the researchers concluded that 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.

The results of the study demonstrated that the restricted zone is redundant in all conditions (such as NMAS and traffic level) when all other relevant Superpave volumetric mix and FAA requirements are satisfied.

#### SIGNIFICANCE OF RESTRICTED ZONE

The findings of recently completed research relevant to the performance of mixtures with gradations passing ARZ, BRZ, CRZ, and TRZ were presented. A total of 14 papers or reports were summarized. Aggregate types representative of a wide range of physical and mineralogical properties were included. An extensive range of NMAS gradations and mixture gradations types were included in the research reviewed. Performance with respect to rutting, fatigue cracking, and low-temperature cracking properties were evaluated by 11, 1, and 1 researcher(s), respectively. The tests conducted by researchers to evaluate rutting included both fundamental and simulative tests. SHRP four-point bending fatigue test was utilized to assess HMA fatigue potential. As expected, TSRST results showed that low-temperature cracking of HMA was strongly influenced by asphalt binder type rather than gradation.

Independent results from the literature clearly indicate that no relationship exists between the Superpave restricted zone and HMA rutting or fatigue performance. 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. Results from numerous studies show that the restricted zone is redundant in all conditions (such as NMAS and traffic levels) when all other relevant Superpave volumetric mix and FAA requirements are satisfied.

In a recent TRB Superpave Mixture and Aggregate ETG meeting (21), it was recommended by ETG members that "the restricted zone should be removed from the Superpave procedures. In particular, all references to the restricted zone should be deleted from AASHTO MP2 and PP28."

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