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Restricted-Zone Requirements for Superpave Mixes Made with Local Aggregate Sources

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NDOR Research Project Number P556

FINAL REPORT

Restricted-Zone Requirements for Superpave Mixes Made with Local Aggregate Sources

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16. Abstract

The fine aggregate specification for Superpave hot mix asphalt (HMA) mixtures includes a restricted zone (RZ) that forms a band through which gradations were recommended not to pass, since mixtures passing through the RZ are believed to be rut-susceptible. However, the RZ requirement has long been a contentious issue, leading to many research efforts to investigate the effects of RZ on HMA performance. A generally agreed upon conclusion from the national research is that the RZ criterion is redundant and should be eliminated from the Superpave specification. Although the elimination of the RZ requirement is suggested today, it still remains questionable, since the research conclusion has often been made for a premium mix designed with high-quality aggregates, which is not the case for low volume Nebraska pavements. Therefore, this research was undertaken to evaluate the RZ effects on rutting-associated performance particularly for low volume local-road mixes (called SP2 mix in Nebraska). In addition, mechanical impact due to fine aggregate angularity (FAA) on HMA performance was also evaluated. Five mixes (one above-RZ mix, two through-RZ mixes with different gradations, and two below-RZ mixes with different FAA values) were designed and tested by using a simple performance testing device, the asphalt pavement analyzer (APA). Based on APA performance testing results, it can be concluded that finer-graded mixes are generally similar to or better than coarser-graded mixes. Consequently, the Superpave RZ requirements may not be a factor governing HMA mix design and performance. One more interesting fact observed from this study is that insufficient FAA in coarse-graded mixes might cause more severe rut-damage in HMA. Preliminary findings from this study can be strengthened with more laboratory data and additional work. Suggested follow-up studies conclude this report.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

TABLE Page

CHAPTER 1
INTRODUCTION

The Hot Mix Asphalt (HMA) is widely used in the United States. To improve performance, durability, safety, and the efficiency of the HMA pavements, the U.S. Congress founded the Strategic Highway Research Program (SHRP) in 1987. Seven-year (1987 to 1993) SHRP study produced a great success named "Superpave" (Superior Performing Asphalt Pavements) resulting in significant advancements in testing devices, protocols, and specifications for HMA materials and mixtures. However, the SHRP has primarily targeted the properties of asphalt binders and HMA and their effects on pavement performance. The study of aggregates and their impact on pavement behavior was excluded and/or ignored more or less from the research program. Since there was a need to produce reasonable specifications associated with aggregate properties and gradation, SHRP formed a group of aggregate expert to develop recommendations and/or refinements of aggregate properties and gradations that should be used in the HMA mixtures and pavements. One of these recommendations was the implementation of the restricted zone (RZ) which lies along the maximum density line between the intermediate aggregate size (2.36- or 4.75-mm, depending on the nominal maximum size of the aggregate blend) and the 0.3-mm size and form a band through which it usually was considered undesirable for a gradation to pass.

The restricted zone was established in the initial Superpave guidelines to limit the amount of rounded, natural sand in the Superpave mix, which contributed to the mix instability and premature rutting. The original intention of including the restricted zone was based on two reasons: first, if a mixture gradation is close to the maximum density line, the voids in mineral aggregate (generally called VMA) can be minimized, not allowing sufficient asphalt content and air voids for a durable HMA mixture that would resist rutting and surface flushing under summer traffic. Second, it had been demonstrated that HMA mixtures with a high content of natural rounded sands with a hump in the No. 30 to 100 size fraction (0.60- to 0.15-mm) exhibited tenderness during rolling and compaction.

These hump grading tends to go through the restricted zone because of the scarcity of sizes No.16 to 30 (1.18- to 0.60-mm) and an excess of in the No. 30 to 100 range.

The concept of restricted zone however, remains many questions, because the restricted zone requirement was not developed based on any scientific rigor: it has been developed without the benefit of experimentation to support or verify the needs of restricted zone in Superpave HMA mixes. In fact, historically, prior to Superpave, most of the states in the United States have designed mixes with gradations above or somewhat through the restricted zone. Some researchers have shown that good performing mixtures could go through the restricted zone if the other qualities of the aggregates in the HMA such as fine aggregate angularity (FAA), and coarse aggregate angularity (CAA) meet the Superpave requirements. Nebraska has also allowed HMA mixes that pass through the restricted zone if a minimum fine aggregate angularity (FAA) requirement is satisfied (generally 45 or higher).

Even though the elimination of the restricted zone requirement in Superpave mix design is suggested today, it still remains questions, since the research conclusion supporting elimination of the restricted zone criteria has often been made for mixes with CAA of about 100 (inferring 100% crushed coarse aggregates). The applicability of such research conclusions on local mixes used in Nebraska needs to be verified because the CAA for low volume local mixes used in Nebraska is not close to 100 but typically between 65 and 85. It has also been reported that several mix design variables such as a nominal maximum aggregate size, voids in mineral aggregate (VMA), and the number of compacting gyrations affect mix performance. Consequently, there is a need to study and analyze the effects of mix design variables including the restricted zone on performance of Superpave mixes used in Nebraska.

1.1. RESEARCH OBJECTIVES

The primary objective of this research is to evaluate the need of the restricted zone (RZ) as a required design criterion for low volume local roads paved in Nebraska.

Furthermore, this study also investigates the effects of fine aggregate angularity (FAA) on pavement performance particularly focusing on rutting-associated distress. In order to satisfy the research objectives, several SP2 mixes (Superpave mix designated in Nebraska for low volume local roads) with different aggregate gradations (above-, through-, and below-RZ) and FAA were designed, and the Asphalt Pavement Analyzer (APA) testing was conducted to estimate the rutting-based performance of the mixes.

1.2. RESEARCH SCOPE

To accomplish the objectives, this study has been performed with two phases. Phase 1 consists of literature review, material selection, and volumetric mix design of each SP2 mix used in this study. In phase 2, specimens for APA performance testing are fabricated, and resulting performance data are analyzed. Based on the volumetric characteristics and APA testing results of each mix, the effects of the RZ and FAA on HMA performance is concluded and summarized in the final report including meaningful findings and recommended future work.

1.3. ORGANIZATION OF THE REPORT

This report is composed of 5 chapters. Following this introduction, Chapter 2 presents a literature review associated with the effects of aggregate gradations especially RZ requirements in the Superpave mix and HMA performance. In Chapter 3, detailed descriptions of material selection and research methodology employed for this study are presented. Chapter 4 shows laboratory test results such as fundamental properties of selected materials (an asphalt binder: PG64-22, aggregates, and a filler: hydrated lime), mix design results of all SP2 mixes and the APA testing results. Laboratory testing results are also discussed in this chapter. Finally, Chapter 5 provides a summary of findings and conclusions of the study. Recommendations for future research are also presented in the chapter.

CHAPTER 2

LITERATURE REVIEW

The debate about the need of the restricted zone has raged since the adoption of the Superpave grading criteria in Federal Highway Administration (FHWA) recommendations and, later, in American Association of State Highway Transportation Officials (AASHTO) standards. The controversial Superpave restricted zone has been studied and discussed by many asphalt researchers and practitioners. This chapter presents a literature review regarding the effects of aggregate gradations especially restricted zone requirements in the Superpave mix design. The literature survey herein briefly summarizes review of study objectives, employed experimental plans, and resulting laboratory data determining validity of the restricted zone concept based on various studies performed by many researchers.

- In order to determine if restricted zone was required for Superpave, a major research was funded through the National Cooperative Highway Research Program (NCHRP). The research was conducted at the National Center for Asphalt Technology (NCAT) at Auburn University, and was published in NCHRP Report 464 (2001). The primary objective of this project was to determine conditions under which restricted zone is necessary when asphalt paving mix meets all other Superpave requirements. This study concluded that HMA aggregate gradations going through the restricted zone performed similar to or better than mixtures with gradations entirely outside the restricted zone, as long as the aggregate and mix meet the FAA and other Superpave requirements. This conclusion was drawn from the results of experiments with 3/8-in. (9.5-mm) and 3/4-in. (19-mm) nominal maximum aggregate size gradations. NCAT researchers found that for the both nominal maximum size gradations (3/8-in. and 3/4-in.), the restricted zone appears to be a redundant requirement.

- Kandhal and Mallick (2001) conducted a study to check the effect of gradation and the aggregate shape and texture on rutting potential of dense-graded HMA. Mixes with different aggregates (gravel, limestone, and granite) and different gradations (above-RZ, through-RZ, and below-RZ) were evaluated using the Asphalt Pavement Analyzer (APA) and the Superpave Shear Tester (SST). From the APA testing, they found that below-RZ mixes using granite and limestone are most susceptible to rutting than through- and above-RZ mixes. Below-RZ mixes using gravel, in most cases, showed the lowest amount of rutting. Considering the gradation effect using granite and limestone, they concluded that below-RZ mixes presented higher rutting compared to those of above- and through-RZ. For those mixes using gravel, the gradation effect was not significant. From the SST results, Kandhal and Mallick found out no significant difference between the above-, through-, and below-RZ mixes using granite as aggregate. However, mixes using limestone presented similar behavior as stated from APA results, with below-RZ having the highest peak strain. Through-RZ showed the lowest potential of rutting.

- Hand et al. (2001) evaluated the impact of gradation and nominal maximum aggregate size on rutting performance of HMA. Total 21 mixes were subjected to triaxial test, PURWheel laboratory-scale wheel-tracking tests, and the Indiana Department of Transportation (INDOT)/Purdue University prototype-scale accelerated pavement test (APT) facility. They found that nominal maximum aggregate size did not significantly affect HMA performance. The laboratory test results for gradations passing above and through the restricted zone had a better permanent deformation resistance than below the restricted zone gradations.

- Hand and Epps (2001) made a synopsis of recent research related to the impact of gradation with respect to the Superpave RZ on HMA performance. They reviewed 13 journal papers and research reports that investigated the RZ-related gradation effects based on a variety of experiments such as static and dynamic creep tests, triaxial tests, laboratory wheel tracking tests, flexural fatigue tests, prototype-scale accelerated load tests, and even full-scale test track monitoring. A general finding from the study was that fine-graded (above-RZ and through-RZ) mixtures usually provided better performance than below-RZ gradation mixtures, and technically speaking, adequate HMA performance could always be obtained with gradations ranging from above-RZ to below-RZ: indicating no significant relationship between the Superpave RZ and HMA rutting or fatigue performance.

- Sebaaly et al. (2004) analyzed results gathered from field test sections and the laboratory performance data. The test sections were designed using a series of mixtures for a range of traffic and environmental conditions typically encountered in Nevada. The field performance was monitored for up to 5 years after construction. Their findings concerning to the Superpave RZ requirement showed that mixtures passing through the restricted zone performed better than coarse-graded mixtures (generally below-RZ mixes). They also found that through-RZ mixtures had greater stiffness than below-RZ mixtures made of same materials.

- Zhang et al. (2004) reported the effect of Superpave defined restricted zone on HMA rutting performance. They evaluated the rutting performance of aggregate gradations passing above-RZ, through-RZ, and below-RZ using the APA, rotary-loaded wheel tester and Marshall test. Based on laboratory rutting tests, they found that gradations violating the Superpave RZ requirement performed similar to or better than mixtures passing above-RZ or below-RZ. Besides, they found that rutting performance of below-RZ mixtures was more sensitive to aggregate properties than rutting performance of through-RZ and above-RZ mixtures.

- Watson et al. (1997) analyzed mixes from Georgia Department of Transportation (GDOT) using the Georgia loaded wheel tester (GLWT) to determine the rut susceptibility of mixes and concluded that good performing mixtures could go through the restricted zone. They suggested the use of GLWT or other special proof-testing equipment during the design process to accept mixes.

- Nukunya et al. (2002) evaluated the Superpave RZ as a guideline for mixture design using either angular or non-angular aggregates and concluded that, in opposite to what is stated by Superpave, below the restricted zone mixes are not rutting resistant because of the higher amount of asphalt cement that causes potential problems to achieve the minimum VMA specified.

- Kandhal and Cooley (2002) compared coarse-graded Superpave mixtures (below the restricted zone) to fine-graded Superpave mixtures (above the restricted zone) in terms of resistance to rutting. In order to determine whether restrictions on gradation type (either coarse- or fine-graded mixtures) are necessary or not, three laboratory performance tests (APA, SST and RLCC: Repeated Load Confined Creep) were performed. Testing results indicated no significant performance difference among mixes analyzed.

- Chowdhury et al. (2001a, 2001b) performed comprehensive investigation of the RZ effect on HMA rutting-based performance. They took into account for the effect of RZ with respect to aggregate types (crushed granite, crushed limestone, crushed river gravel, and a mixture of crushed river gravel as coarse aggregate with natural fines) and gradations (above-, through-, and below-RZ). In order to evaluate the permanent deformation potential of each different mix, they conducted various laboratory tests including SST, simple shear test at constant height (SSCH), frequency sweep test at constant height (FSCH), repeated shear test at constant stress ratio (RSCSR), repeated shear test at constant height (RSCH), and APA tests. The research concluded that there is no relationship between the restricted zone and permanent deformation when crushed aggregates are used in the mixture design. They also concluded that Superpave mixtures with gradations below the restricted zone were generally most susceptible to permanent deformation, while mixtures above the restricted zone were least susceptible to permanent deformation. Recommendations include elimination of the restricted zone from HMA design specifications.

CHAPTER 3
RESEARCH METHODOLOGY

This chapter describes materials used in this research (aggregates, hydrated lime, and asphalt binder). It also illustrates mix design method to obtain five mixes (one above-, two through-, and two below-RZ) satisfying NDOR (Nebraska Department of Roads) SP2 mix design specifications. At the end of this chapter, a brief description of APA testing is addressed.

3.1. MATERIAL SELECTION

To meet the research objective "evaluation of the RZ requirements as a design criterion for low volume local roads in Nebraska", widely-used local paving materials (asphalt binder and aggregates) were selected. In addition, an anti-stripping agent, hydrated lime was used in this project, since hydrated lime has been accepted as an active anti-stripping agent to be used for pavements constructed in Nebraska due to its unique chemical and mechanical characteristics.

3.1.1 Aggregates

Total six local aggregates (5/8-in. limestone, 1/4-in. limestone, several crushed gravels (such as 2A, 3ACR, and 47B), and Screenings) were used in this project. These aggregates were selected because they are most widely used by Nebraska pavement contractors.

Coarse Aggregates

Four coarse aggregates (5/8-in. limestone, 1/4-in. limestone, 2A, and 3ACR) were selected and blended. Selection criteria for the coarse aggregates were that they should come from different mineralogical sources and have different angularities and surface textures so that the coarse aggregate blends gave a range of properties such as gradation, mineralogy, and angularity. Each coarse aggregate was sieved and stored in separate buckets to be blended with other aggregates for better control and efficiency in mix design. Since this study primarily takes into account the effects of restricted zone where is located within fine aggregate fraction, coarse aggregates for all five mixes (one above-, two through-, and two below-RZ) were blended with exactly same amount of each size and each source of aggregates, so that all five mixes present same gradation, aggregate angularity, and mineralogy at coarse aggregate fraction. Fundamental properties of each aggregate were measured and are described in following chapter, Testing Results and Discussion.

Fine Aggregates

Because the restricted zone is within fine aggregate fraction, selection of fine aggregates was conducted with care. Similar to coarse aggregates, selection criteria for the fine aggregates were also based on the angularities and mineralogical characteristics of each aggregate. Three fine aggregates (Screenings, 3ACR, and 47B) were finally selected. They were sieved and stored in each separate bucket for blending. As mentioned, each blend differs near the RZ (above, through, and below-RZ) to investigate RZ-associated pavement performance. Fundamental fine aggregate properties were measured and are presented in Chapter 4.

3.1.2 Asphalt binder

The asphalt binder used in this study is a Superpave performance-graded binder PG 64-22, which has been used in the state of Nebraska. The asphalt was provided from KOCH Materials Company, located in Omaha. Mechanical properties of this asphalt binder were measured and are presented in Table 4.2 in Chapter 4.

3.1.3 Hydrated lime

In this project, hydrated lime was used as an anti-stripping agent for HMA mixes, since hydrated lime has been known as a promising potential material to improve HMA performance due to its unique physical/chemical/mechanical characteristics. Use of hydrated lime has been accepted in many states including Nebraska where HMA pavements are susceptible to moisture-related stripping. Based on this fact, hydrated lime was used in this project.

3.2. MIX DESIGN METHOD

Mix design was the most time consuming activity in this project. In order to complete mix designs of all five HMA mixes (one above-, two through-, and two below-RZ), the following elaborated steps described in Figure 3.1 were performed.

As noticed in Figure 3.1, one fine aggregate, Screenings passing No. 16 sieve was washed and dried before blending with other aggregates because the Screenings through dry sieving contained too much extra dust (particles passing No.200 sieve: generally less than 75 micron). The fact that actual amount of dust from dry-sieved Screenings is much more than target amount of dust infers that some amount of dust stick to fine particles and this dust can not be appropriately separated from dry sieving. Uncontrolled dust content significantly affects HMA volumetric properties such as voids in mineral aggregates (VMA). Many problematic mixtures are associated with inappropriate dust control. In an attempt to minimize problems associated with dust, extra dust from dry sieving of two suspicious fine aggregates, Screenings and 3ACR was monitored by washing aggregates retained on No.30 sieve to No.200 sieve. Dust analysis results are demonstrated in Table 3.1. As shown in the table, Screenings needs dust control, while 3ACR does not significantly affect total amount of dust in an actual mix. Figure 3.2 clearly demonstrate the extra dust placed in fine aggregates.

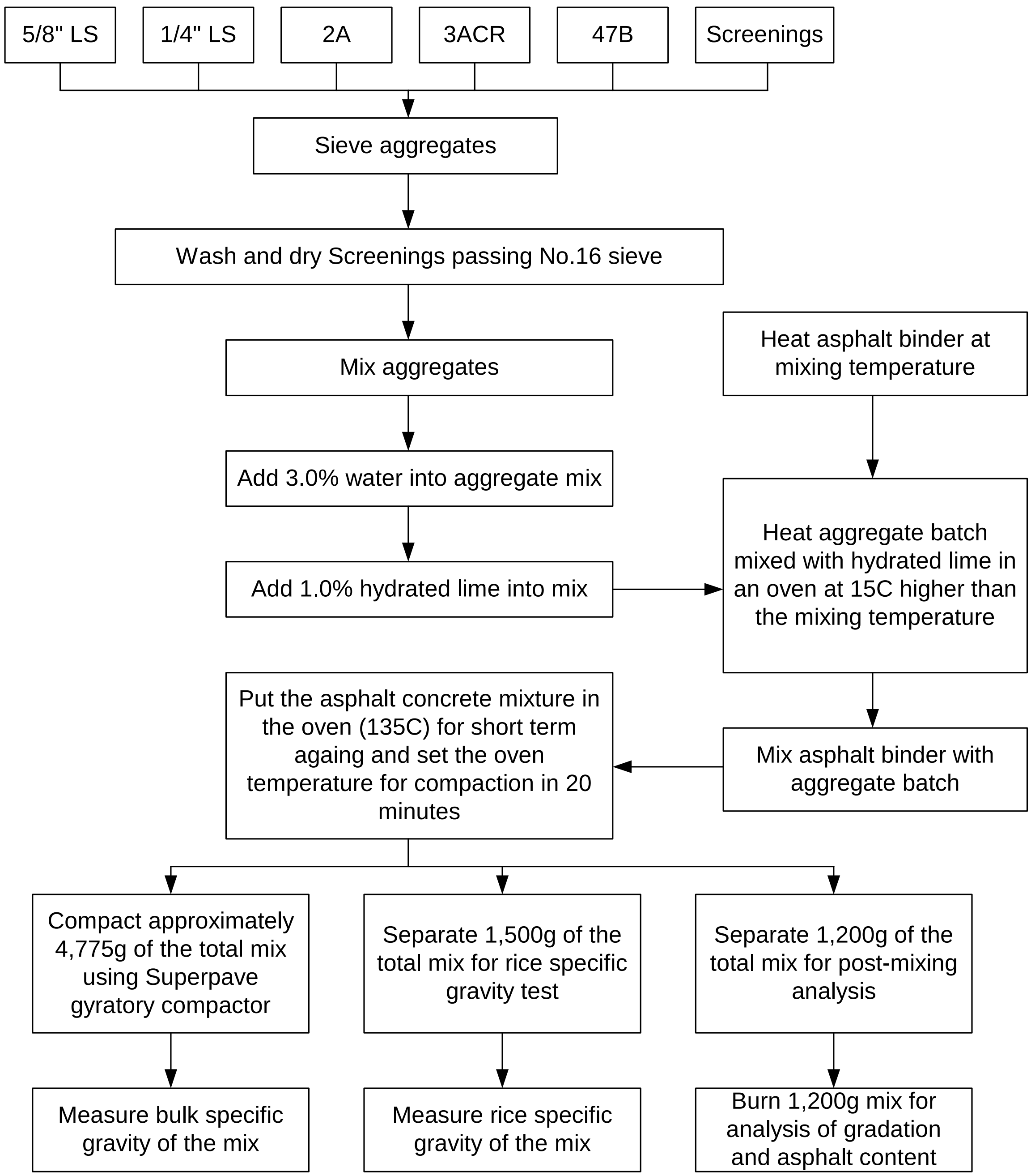

Figure 3.1 Mix Design Procedure.

Table 3.1 Dust Analysis Results of Two Aggregates: Screenings and 3ACR.

Screenings				**3ACR**		
Sieve No.	#30	#100	#200	Sieve No.	#100	#200
Sample (g)	300	300	300	Sample (g)	250	100
Remaining #30 (g)	263.8	0	0	Remaining #30 (g)	0	0
Remaining #50 (g)	0	0	0	Remaining #50 (g)	0	0
Remaining #100 (g)	0	215.8	0	Remaining #100 (g)	243.30	0
Remaining #200 (g)	0.5	5.4	106.7	Remaining #200 (g)	0.00	92.80
Remaining (%)	88	73.73	35.57	Remaining (%)	97.32	92.80
Dust (%)	12	26.27	64.43	Dust (%)	2.68	7.20
In an actual mix				In an actual mix		
Sieve	#30	#100	#200	Sieve	#100	#200
Amount (g)	420.00	360.00	440.00	Amount (g)	480.00	110.00
Dust (g)	49.98	94.56	283.51	Dust (g)	12.86	7.92
Dust in the mix (%)	0.50	0.95	2.84	Dust in the mix (%)	0.13	0.08
Total amount of extra dust (%)	4.29			Total amount of extra dust (%)	0.21	
Total weight of mix. (g)	10,000			Total weight of mix. (g)	10,000	

(a) before washing

(b) after washing

Figure 3.2 Demonstration of Extra Dust in Fine Aggregates: (a) Before Washing; (b) After Washing.

As mentioned earlier, gradation effects regarding RZ were primarily investigated in this study. Therefore, other aggregate properties such as angularity, specific gravity, and mineralogy should be controlled in an appropriate way among different mixes. In order to account for this issue, an Excel Worksheet that can automatically control overall mix specific gravity, aggregate angularities (CAA and FAA), and corresponding required amount of each aggregate in a trial blend was developed. Figure 3.3 presents a part of the Worksheet. The Worksheet allows one to determine individual amount of aggregates blended at each sieve size with given target angularity value and gradation of any arbitrary trial mix. For example, as illustrated in Figure 3.3, 230g (passing 19-mm and retained on 12.5-mm) and 248.4g (passing 12.5-mm and retained on 9.5-mm) of 5/8-in. limestone, 27.6g (passing 12.5-mm and retained on 9.5-mm) and 117.3g (passing 9.5-mm and retained on 4.75-mm) of aggregate 2A, 312.8g (passing 9.5-mm and retained on 4.75-mm) of 3ACR, and 351.9g (passing 9.5-mm and retained on 4.75-mm) of 1/4-in. limestone produce overall CAA value of 84.6 at the given aggregate gradation. By adjusting proportion of different aggregate source at each sieve size, a target angularity specified by user can be easily obtained. Similarly, bulk specific gravity of aggregate blend (G_{sb}) can also be controlled based on individual specific gravities of each aggregate as demonstrated in the figure.

Using the Worksheet (Figure 3.3), several trial blends with different gradation, angularity, and proportion of each aggregate type were constructed and modified to meet SP2 mix design requirements. Total 38 trial mix designs (17 for above-RZ mix, 11 for first through-RZ mix, 5 for first below-RZ mix, 3 for second through-RZ mix, and 2 for second below-RZ mix) were necessary to meet all the volumetric parameters described in the Nebraska Department of Roads (NDOR) SP2 volumetric design specifications. Resulting five mix gradations are shown in Table 3.2 and Figure 3.4. As presented, the gradations are similar except near the restricted zone. All five gradations follow the same trend from the 12.5-mm sieve down to the 4.75-mm sieve: no difference in coarse aggregate part among mixes. From the 4.75-mm sieve, the above-RZ gradation passes above the restricted zone and below the upper control points. As shown in the figure, two crossover through-RZ gradations were tried in this study. One is closer to above-RZ gradation (inferring finer mix), and the other is closer to below-RZ mix (inferring coarser mix). By comparing the two different through-RZ mixes, any effects of mix coarseness (or fineness) on mechanical performance can be drawn, if any significant effects appear. Remaining two more mixes are located below restricted zone and above the lower control points. Second below-RZ mix slightly differs from first below-RZ mix in gradation and consists of much less angular fine aggregates. FAA of second below-RZ mix was set close to 40, while 43 was the FAA value for other four mixes including first below-RZ mix. Any mechanical effects of fine aggregate angularity (FAA) on rutting-associated HMA performance can be successfully evaluated by investigating those two below-RZ mixes designed with different FAA values.

Sieve Size (mm)	above_P	above_R		% of each	CAA or FAA	aggregate (Wt)	Gsb
19	100	0					
12.5	95.0	5.0			100		2.631
			5/8" LS	100.0	100	230	2.631
			2A	0.0	28	0	2.586
			SCREENINGS	0.0	N/A	0	
			FINE SAND	0.0	N/A	0	
			47B	0.0	35	0	2.575
			3ACR	0.0	70	0	2.576
			1/4" LS	0.0	100	0	2.606
			MAN SAND	0.0	N/A	0	
9.5	89.0	6.0			92.8		2.626
			5/8" LS	90.0	100	248.4	2.631
			2A	10.0	28	27.6	2.586
			SCREENINGS	0.0	N/A	0	
			FINE SAND	0.0	N/A	0	
			47B	0.0	35	0	2.575
			3ACR	0.0	70	0	2.576
			1/4" LS	0.0	100	0	2.606
			MAN SAND	0.0	N/A	0	
4.75	72.0	17.0			77.2		2.591
			5/8" LS	0.0	100	0	2.631
			2A	15.0	28	117.3	2.586
			SCREENINGS	0.0	N/A	0	
			FINE SAND	0.0	N/A	0	
			47B	0.0	35	0	2.575
			3ACR	40.0	70	312.8	2.576
			1/4" LS	45.0	100	351.9	2.606
			MAN SAND	0.0	N/A	0	
				overall	84.61428571		2.606

Figure 3.3 Excel Worksheet Developed.

Table 3.2 Gradation (% Passing) of Each Mix and Restricted Zone Specified.

Sieve		Above-RZ	First Through-RZ	First Below-RZ	Second Through-RZ	Second Below-RZ	RZ limits	
19.0 mm	3/4"	100	100	100	100	100	-	-
12.5 mm	1/2"	95	95	95	95	95	-	-
9.5 mm	3/8"	89	89	89	89	89	-	-
4.75 mm	#4	72	72	72	72	72	-	-
2.36 mm	# 8	57	55	36	55	32	39.1	39.1
1.18 mm	# 16	42	24	21	35	19	25.6	31.6
0.60 mm	# 30	30	15	14	19	13	19.1	23.1
0.30 mm	# 50	19	11	10	11	9	15.5	15.5
0.15 mm	# 100	7	7	7	7	7	-	-
0.075 mm	# 200	1.5	3.5	3.5	3	3.5	-	-

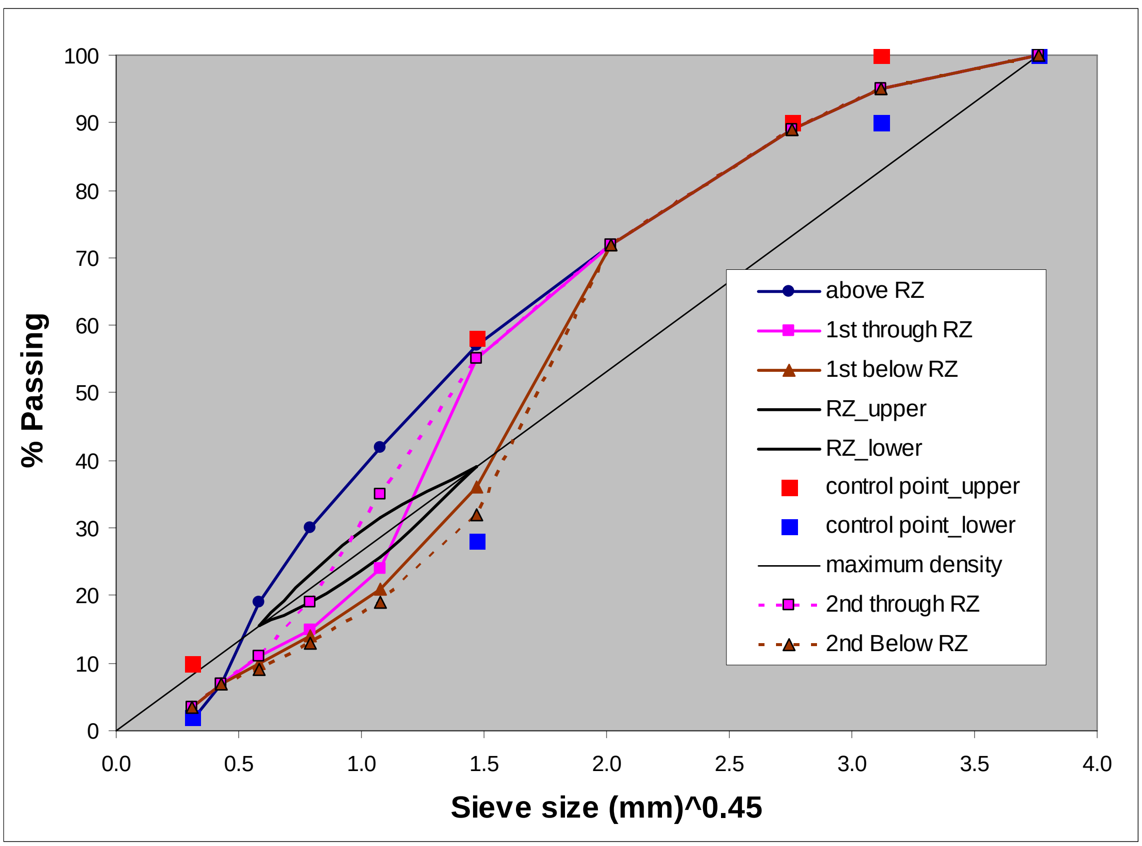

Figure 3.4 Gradation Curves of All Five SP2 Mixes.

All the mixes for this project are SP2 type, a low quality weak mix used mostly for low volume local road pavements. The compaction effort used for the SP2 mix is the one for a traffic volume around 0.3 to 1 million Equivalent Single Axle Loads (ESALs). Table 3.3 summarizes NDOR specification requirements of aggregate properties, volumetric mix design parameters, and laboratory compaction effort for the SP2 mix. Compaction effort was estimated based on average value of high air temperature in Omaha, Nebraska: 98ºF (36.67ºC).

All five mixes designed in asphalt/concrete laboratory at the University of Nebraska-Lincoln (UNL) were submitted to NDOR asphalt/aggregate laboratories for validation of material properties (aggregates, asphalt, and hydrated lime) and volumetric mix design parameters. UNL design values and NDOR validations are presented and compared in following chapter, Chapter 4 Testing Results and Discussion.

3.3. PERFORMANCE TEST - ASPHALT PAVEMENT ANALYZER (APA)

The mechanical test to evaluate the resistance of mixes depending on aggregate gradation (RZ-associated) and fine aggregate angularity was performed by using Asphalt Pavement Analyzer (APA) shown in Figure 3.5. The APA is an automated, new generation of Georgia Load Wheel Tester (GLWT) used to evaluate rutting, fatigue, and moisture resistance of HMA mixtures. During the APA test, the rutting susceptibility of compacted specimens is tested by applying repetitive linear loads through three pressurized hoses via wheels. Even though it has been reported that APA testing results are not very well matched with actual field performance, APA testing is relatively simple to do and produces rutting potential of mixes by simply measuring sample rut depth with an electronic dial indicator. Due to its simplicity and availability, APA was employed in this project to estimate effects of RZ and FAA on rutting-based HMA pavement performance. Testing results are presented and discussed in Chapter 4.

Table 3.3 Required Volumetric Parameters and Aggregate Properties for SP2 Mix.

	NDOR Specification (SP2 Mix)
Compaction Effort	
N_{ini}: the number of gyration at initial	7
N_{des}: the number of gyration at design	76
N_{max}: the number of gyration at maximum	117
Aggregate Properties	
CAA (%): coarse aggregate angularity	> 65
FAA (%): fine aggregate angularity	> 43
SE (%): sand equivalency	> 40
F&E (%): flat and elongated aggregates	< 10
Volumetric Parameters	
$\%V_a$: air voids	4 ± 1
%VMA: voids in mineral aggregates	> 14
%VFA: voids filled with asphalt	65 - 78
$\%P_b$: asphalt content	-
D/B (ratio): dust-binder ratio	0.7 - 1.7

Figure 3.5 APA Testing Facility in NDOR.

CHAPTER 4
TESTING RESULTS AND DISCUSSION

In this chapter, fundamental properties of each HMA mixture constituent (aggregates, asphalt binder, and additional filler: hydrated lime) selected for this study are presented. Physical and geometrical properties of aggregates (5/8-in limestone, 1/4-in limestone, 2A, 3ACR, 47B, and Screenings) and mechanical properties of an asphalt binder PG64-22 were measured and discussed in this chapter. Basic physical and chemical properties of hydrated lime have been obtained from a lime supplier, Mississippi Lime Company, and are presented here, too. Superpave mix designs for all five SP2 mixes (one above-, two through-, and two below-RZ) accomplished at UNL were validated from NDOR asphalt/aggregate laboratories, and mix design results from both UNL and NDOR laboratories are presented in this chapter. Finally, laboratory testing results from the asphalt pavement analyzer (APA) are also discussed in detail in this chapter.

4.1. MATERIAL PROPERTIES

Table 4.1 illustrates laboratory-measured physical properties such as bulk specific gravity and absorption capacity of six aggregates used in this study. In addition, important Superpave aggregate consensus properties, coarse aggregate angularity (CAA), fine aggregate angularity (FAA), and sand equivalency (SE) are also presented in the table. As can be seen, each aggregate demonstrates very different characteristics, so that a wide range of aggregate blends meeting target specific gravity and angularity can be obtained via appropriate aggregate mixing.

Fundamental mechanical properties of asphalt binder were characterized by performing dynamic shear rheometer (DSR) tests and bending beam rheometer (BBR) tests that have been designated in the Superpave binder specification as fundamentally-required testing to identify performance grade and viscoelastic properties of asphalt binder. Table 4.2 presents testing results. The asphalt binder satisfies all PG grade (64-22) requirements.

Table 4.1 Fundamental Properties of Aggregates.

	Aggregate Property						
	Fine Aggregate			Coarse Aggregate			
Aggregate	G_{sb}	**Absorption Capacity (%)**	**FAA (%)**	G_{sb}	**Absorption Capacity (%)**	**CAA (%)**	**Sand Equivalency (%)**
2A	2.580	0.76	37.6	2.589	0.68	28	100.0
1/4" LS	N/A	N/A	N/A	2.607	1.54	100	N/A
Screening	2.478	3.66	46.7	N/A	N/A	N/A	26.0
5/8" LS	N/A	N/A	N/A	2.624	1.25	100	N/A
3ACR	2.556	1.13	43.7	2.588	0.75	70	84.0
47B	2.605	0.49	37.3	2.594	0.65	35	98.0

Table 4.2 Mechanical Properties of Asphalt Binder PG64-22.

Test	Temperature (°C)	Test Result	Required Value
Unaged DSR, G*/sinδ (kPa)	64	1.48	Min. 1.00
RTFO - Aged DSR, G*/sinδ (kPa)	64	3.499	Min. 2.20
PAV - Aged DSR, G*sinδ (kPa)	25	4,576	Max. 5,000
PAV - Aged BBR, Stiffness(MPa)	-12	203.97	Max. 300
PAV - Aged BBR, m-value	-12	0.312	Min. 0.30

Table 4.3 describes physical and chemical properties of hydrated lime used in this study. The properties were obtained from the lime manufacturer, Mississippi Lime Company.

4.1. MIX DESIGN RESULTS

Volumetric parameters and aggregate properties of each mix are shown in Table 4.4. All five SP2 mixes were designed at UNL, and representative batches of each mix were sent to NDOR laboratories for validation. As can be seen in the table, mix volumetric properties and aggregate characteristics obtained from UNL laboratory matched well with NDOR measurements and met NDOR SP2 mix specifications. Based on NDOR validation study, it can be inferred that UNL mix designs have been conducted successfully. However, one thing to be noted from the table is that CAA estimated from UNL is somewhat different from NDOR measurements. All SP2 mixes were designed with a target value of CAA around 85, however CAA values measured from each batch delivered to NDOR were approximately 80 to 90. This is not so surprising since the CAA testing protocol in the Superpave specification is not quite repeatable in nature, because CAA value is substantially influenced by aggregate sampling. Furthermore, CAA testing results are generally dependent on person who performs the testing. Some researchers have recommended new testing methods such as the one based on image analysis for better characterizing aggregate angularity in a more appropriate way. In fact, as shown in Table 4.4, NDOR CAA results demonstrated testing variability: 82 for the second below-RZ mix vs. 91 for the above-RZ mix, even though exactly same types and amount of aggregate were blended for all five mixes. Except the difference in CAA, no significant discrepancy in design parameters was observed between UNL and NDOR.

Table 4.3 Physical and Chemical Properties of Hydrated Lime.

Physical Properties	
Specific Gravity	2.343
Dry Brightness, G.E.	92.0
Median Particle Size - Sedigraph	2 micron
pH	12.4
BET Surface Area	22 m^2/g
-100 Mesh (150 μm)	100.0%
-200 Mesh (75 μm)	99.0%
-325 Mesh (45 μm)	94.0%
Apparent Dry Bulk Density - Loose	22lbs./ft^3
Apparent Dry Bulk Density - Packed	35lbs./ft^3
Chemical Properties	
$Ca(OH)_2$ - Total	98.00%
$Ca(OH)_2$ - Available	96.80%
CO_2	0.50%
H_2O	0.70%
$CaSO_4$	0.10%
Sulfur - Equivalent	0.024%
Crystalline Silica	<0.1%
SiO_2	0.50%
Al_2O_3	0.20%
Fe_2O_3	0.06%
MgO	0.40%
P_2O_5	0.010%
MnO	0.0025%

Table 4.4 Volumetric Mix Properties and Aggregate Properties - Results and Limits.

	NDOR LIMITS	Above-RZ		1st Through-RZ		2nd Through-RZ		1st Below-RZ		2nd Below-RZ	
		UNL	NDOR	UNL	NDOR	UNL	NDOR	UNL	NDOR	UNL	NDOR
G_{mm}	-	2.447	2.456	2.421	2.437	2.443	2.447	2.429	2.437	2.418	2.424
G_{sb}	-	2.583	2.583	2.582	2.582	2.582	2.582	2.575	2.575	2.581	2.581
G_{mb}	-	2.336	2.338	2.312	2.336	2.339	2.348	2.331	2.337	2.311	2.313
CAA	> 65	84.6	91	84.6	90	84.6	84	84.6	90	84.6	82
FAA	> 43	42.9	43.8	42.95	42.7	42.89	42.6	42.93	43.8	40.87	41.7
SE	> 40	-	73	-	73	-	73	-	81	-	81
F&E	< 10	-	1	-	0	-	0	-	0	-	0
$\%V_a$	4 ± 1	4.60	4.80	4.50	4.14	4.20	4.05	4.00	4.10	4.40	4.58
VMA	> 14	14.40	14.26	15.50	14.70	14.20	14.04	14.30	14.28	15.50	15.45
VFA	65 - 78	68.40	66.32	71.00	71.78	70.20	71.18	71.70	71.26	71.50	70.36
$\%P_b$	-	5.36	5.28	5.65	5.70	5.29	5.47	5.27	5.55	5.59	5.65
D/B	0.7 - 1.7	1.56	0.77	1.19	1.16	1.46	1.14	1.31	1.32	1.30	1.14
GRADATION (% Passing)											
3/4"	-	100	100.0	100	100	100	100	100.0	100	100	100
1/2"	-	97.4	96.2	93.6	94.3	95.1	95.5	95.5	94.2	96.9	93.5
3/8"	-	91.8	91.1	87	89.4	89.2	89.4	90.6	88.2	87.6	87.9
# 4	-	79	73.9	71.8	72.4	71.8	75.2	72.8	70.6	72.1	71.3
# 8	-	62.7	57.9	53.9	54.7	54.5	56.5	36.8	35	34.3	32.1
# 16	-	46.4	43.2	26	26.1	36.3	36.6	22.4	21.8	21.1	19.8
# 30	-	34	31.0	17.1	16.8	21.2	20.7	15.6	15.4	14.8	14.1
# 50	-	23.3	20.0	12.7	12.8	13.3	12.6	11.5	11.4	11	10.4
# 100	-	11.4	8.1	8.8	8.5	9.4	8.4	8.5	5.7	9	8.3
# 200	-	6.8	3.2	5.8	5.4	6.4	5	5.9	5.9	6.4	5.5

4.2. APA TESTING RESULTS

The APA test was conducted dry to 8,000 cycles, and rut depths were measured continuously. APA testing was conducted on pairs (up to three) at a time using gyratory-compacted HMA cylinders of 75-mm high with 4.0 ± 0.5% air void. In case that APA specimen demonstrates deeper than 12-mm rut depth before the completion of the 8,000 cycles, the testing was manually stopped and the corresponding number of strokes at the 12-mm rut depth was recorded. Testing with the APA was conducted at 64ºC based on the national research by Kandhal and Cooley (NCHRP report-508, 2003). The testing temperature was set to the high temperature of the standard Superpave binder

Performance Grade (PG), 64ºC in this study. The APA specimens needed pre-heating approximately 6 to 24 hours in the APA chamber before testing. The hose pressure and wheel load were 690 kPa and 445 N (100 psi and 100 lb), respectively.

Table 4.5 presents a summary of APA performance testing results of all five mixes. Considering all data, above-RZ and through-RZ mixes generally performed well, and below-RZ mixes demonstrated more susceptible characteristics to rutting than the above- and through-RZ mixes. Another fact to be noted from the table is that second through-RZ mix which is closer to above-RZ mix gradation (inferring finer-graded mix) was more rut-resistant than first through-RZ mix that is closer to below-RZ gradation (coarser-graded mix). Better rut-resisting potential of above mixes and/or finer-graded mixes than coarser-graded mixes has been reported in many other studies including Hand et al. (2001), Hand and Epps (2001), Chowdhury et al. (2001a, 2001b), and Sebaaly et al. (2004). The effects of fine aggregate angularity (FAA) on rutting potential can also be explained from the table. As mentioned earlier, second below-RZ mix was designed with lower FAA value (approximately 41) than the FAA value (approximately 43) for other four mixes to investigate any mechanical impact due to the lower angularity of fine aggregates. No significant relationship between FAA values and APA rut depth was observed from testing data currently obtained, however APA testing results infers that the lower fine angularity is a factor that might cause more rut damage based on a fact that second below-RZ mix (target FAA of 40.5) is similar to or slightly more susceptible to rutting-associated damage compared to first below-RZ mix (target FAA of 42.6). This may be from reduced aggregate interlocking in the mix.

For this study, each APA sample was fabricated from individual 4,600-gram batch with an intention to minimize sample-to-sample variability, but the individual 4,600-gram batch for each APA sample did not always yield a sufficient level of repeatability, which can be noticed from the discrepancy in rut depth between samples (front and back) of several pairs of APA testing such as second pair of first through-RZ mix, first and second pairs of first below-RZ mix, and first pair of second below-RZ mix. It should be also noted that the samples demonstrating differences in rut depth were compacted with somewhat different compaction effort (e.g. the number of gyrations up to 75-mm sample height), and this might cause variations in mechanical behavior, APA rut depth. In an attempt to reduce the APA testing variability, fourth pair of first below-RZ mix was compacted differently by equally dividing a total 10,000-gram batch into two parts (one part for a front sample and the other for a back sample). This attempt can reduce variability in collecting representative HMA mix for an APA sample so that more identical APA samples can be produced. As can be noticed from Table 4.5., APA samples compacted from 10,000-gram batch showed repeatable testing results, e.g. APA rut depth, air void, and specific gravity between front and back sample.

Table 4.5 APA Test Results.

HMA mixes	Sample position	G_{mm}	G_{mb}	$\%V_a$	Strokes	Rut depths (mm)	Pass or Fail (12mm @ 8,000)
Above-RZ	Front1	2.439	2.341	4.0	8000	5.14	Pass
	Back1	2.448	2.350	4.0	8000	4.84	
	Front2	2.442	2.341	4.1	8000	6.12	Pass
	Back2	2.441	2.344	4.0	8000	5.12	
First Through-RZ	Front1	2.432	2.328	4.3	8000	8.13	Pass
	Back1	2.441	2.330	4.5	8000	6.85	
	Front2	2.423	2.332	3.7	5300	12.01	Fail
	Back2	2.428	2.333	3.9	5300	6.15	
Second Through-TZ	Front1	2.443	2.345	4.1	8000	4.60	Pass
	Back1	2.443	2.343	3.9	8000	3.88	
	Front2	2.444	2.343	4.2	8000	6.34	Pass
	Back2	2.442	2.344	4.0	8000	6.92	
First Below-RZ	Front1	2.434	2.336	3.9	4000	6.70	Fail
	Back1	2.434	2.343	3.9	4000	12.60	
	Front2	2.436	2.333	4.2	6000	7.97	Fail
	Back2	2.434	2.337	4.0	6000	12.80	
	Front3	2.429	2.337	3.8	8000	8.85	Pass
	Back3	2.432	2.332	4.1	8000	6.28	
	Front4*	2.441	2.344	4.0	6390	11.71	Fail
	Back4*	2.441	2.345	3.9	6390	12.01	
Second Below-RZ	Front1	2.424	2.328	4.0	5480	6.00	Fail
	Back1	2.426	2.337	3.7	5480	12.00	
	Front2	2.421	2.327	3.9	6324	11.44	Fail
	Back2	2.426	2.334	3.8	6324	12.30	

Note: Front4*, Back4*: 4th pair of the APA samples for first below-RZ mix was compacted by equally dividing a total 10,000-gram batch into two parts (one part for a front sample and the other is for a back sample). Other APA samples except the 4th pair of first below-RZ mix were fabricated from individual compaction of 4,600-gram batch for each APA sample.

In an attempt to compare APA rut depths of all tested mixes better, a bar chart was constructed using averaged rut depths of each pair of mixes as illustrated in Figure 4.1. Figure 4.1 indicates that HMA aggregate gradations going through the restricted zone performed similar to or better than mixtures with gradations entirely outside the restricted zone, as long as the aggregate and mix met other Superpave requirements. From the figure, it can be inferred that mixes below the restricted zone particularly designed with lower FAA (close to 40 or less) will be more rut-prone than the mixes violating Superpave restricted zone concept (such as through-RZ mixes) and/or finer-graded mixes like above-RZ mixes. Figure 4.2 presents the difference in the APA rut depths between good-performing mix (above-RZ mix) and the worst-performing mix (second below-RZ mix).

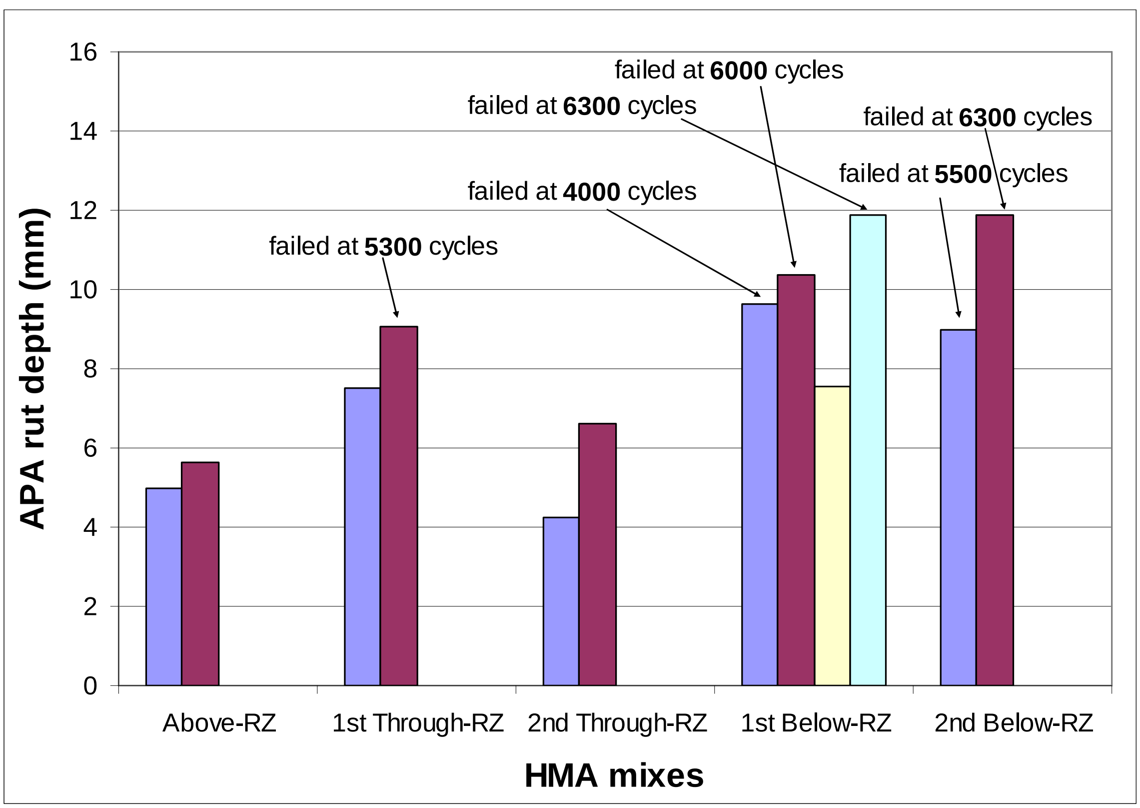

Figure 4.1 APA Rut Test Data in a Form of Bar Chart.

(a) Second Below-RZ Mix (b) Above-RZ Mix

Figure 4.2 APA Rut Depths of (a) Second Below-RZ Mix; (b) Above-RZ Mix.

Even though some meaningful findings can be drawn from this study, the findings herein should be viewed with some cautions as they are based on a single laboratory performance testing, APA, with probably insufficient amount of data. Additional testing and/or more extensive APA testing results can confirm the conclusions to the wide range of cases. Furthermore, variability of APA testing results shown in this study, which is not so surprising based on other pre-published APA-related studies (Choubane et al. 2000, Mohammad et al. 2001, Park and Epps 2003), should be controlled by developing more sophisticated testing protocols and performance criteria. A better-controlled suit of APA testing will result in more acceptable conclusions based on improved accuracy and repeatability with less laboratory effort.

CHAPTER 5
CONCLUDING REMARKS

From the comparison and analysis in this study, the following conclusions and suggested follow-up studies can be drawn:

5.1. CONCLUSIONS

- Research approach employed in this study was successful: a great care to control the amount of dust in the mix and a spreadsheet developed to manage detail aggregate properties such as angularities, specific gravities, and mineralogy improved overall research quality.

- Based on APA performance testing results, good rut-resistant performance can be achieved from finer-graded (above-RZ and first through-RZ that is close to above-RZ gradation) mixtures. Coarser-graded mixes such as below-RZ and second through-RZ mixes were generally more susceptible to rutting. Therefore, the Superpave RZ requirements may not be a factor governing HMA mix design and performance.

- Lower FAA demonstrated somewhat potential impact on reduced HMA rut-resistance. Mixes designed with below-RZ gradation and lower FAA were more rut-prone than a similar mix with higher FAA.

- Research findings obtained from this study generally agreed with other RZ-related studies, even though target mixes for this study were low volume, local-road HMA (SP2) that have typically been designed with low quality aggregates (lower CAA and FAA), while other studies in open literature have been performed for better mixes (premium HMA mixes designed with good quality aggregates).

- Additional testing and/or more number of APA replicates will confirm the research findings to the wide range of cases.

5.2. RECOMMENDATIONS

- The effects of aggregate angularities (CAA and FAA) on HMA performance and mix design should be investigated. The follow-up angularity study combined with research findings from this project will provide more acceptable conclusions based on better understanding of aggregate properties. Angularity and gradation are two most important aggregate properties that have to be controlled for better-performing HMA pavements.

- APA performance testing is advantageous because it is easy to do, relatively fast, and simple to interpret testing data. However, its testing variability should be better controlled. More sophisticated testing protocols, procedures, and performance-based criteria should be developed. A better-controlled APA testing will produce more acceptable and repeatable data with less laboratory effort.

5.3 NDOR IMPLEMENTATION PLAN

- In response to findings from this research projects, NDOR plans to introduce more natural aggregates on zero or low volume roads in Nebraska.

- A research project, intended to evaluate how best to interpret APA results, is being considered for funding in the FY-2007 NDOR Research Work Program.

- A research project, intended to evaluate effects of aggregate angularities, is being considered for funding in the FY-2007 NDOR Research Work Program.

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