Technical Report Documentation Page

1. Report No. FHWA/TX-11/0-6092-2	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle HIGH RAP MIXES DESIGN METHODOLOGY WITH BALANCED PERFORMANCE		5. Report Date August 2011 Published: November 2011
		6. Performing Organization Code
7. Author(s) Fujie Zhou, Sheng Hu, Gautam Das, and Tom Scullion		8. Performing Organization Report No. Report 0-6092-2
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Project 0-6092
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Technical Report: September 2010–August 2011
		14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Performance Evaluation & Mix Design for High RAP Mixtures
URL: http://tti.tamu.edu/documents/0-6092-2.pdf

16. Abstract

The use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) can significantly reduce the increasing cost of hot-mix asphalt paving, conserve energy, and protect the environment. This report presents a comprehensive study focusing on methodologies to improve the performance of high RAP content mixes. Firstly this report addresses one major concern—RAP variability. It was found that in Texas the RAP materials are consistent and have low variability in terms of aggregate gradation and asphalt content, within individual stockpiles. The authors evaluated the impact of RAP on optimum asphalt content (OAC), rutting/moisture resistance, and cracking resistance. OAC generally increases with more RAP (and RAS) usage, but the increase in OAC is small when the RAP content is below 20 percent; increasing RAP content always improves rutting/moisture resistance as measured in the Hamburg wheel tracking test (HWTT). However, in the laboratory cracking resistance always reduces with increasing RAP content, especially when RAP content is 30 percent and above and also when RAP/RAS combinations are used. Additionally, the use of 10–15 percent RAP, without lowering virgin binder PG grade has a small impact on rutting/moisture and cracking resistance, but the influence, especially on cracking resistance, is much more significant when higher levels area used.

A balanced RAP mix design approach is proposed in this study. In the proposed balanced mix design approach the final asphalt content is selected after optimizing the mix density, HWTT, and Overlay Test (OT) requirements. RAP handling in the process of mix design is critical, especially the mixing and compaction temperatures for high RAP mixes. It was recommended that the mixing and compaction temperatures used for the virgin binder be used for the RAP mix as well. Finally, the balanced RAP mix design procedure is demonstrated and validated through the construction of field test sections containing different levels of RAP. One of the interesting findings is that cracking requirement in terms of OT cycles should vary, depending at least on climate (cold vs. hot), traffic (heavy vs. light), and existing pavement condition (overlay over cracked pavements vs. new construction). For asphalt overlays over severely cracked pavements, a minimum OT requirement of 300 cycles previously proposed was further validated with performance data from the RAP sections on IH40 near Amarillo, Texas. More work is needed to develop criteria for different climatic zone and different pavement conditions.

17. Key Words RAP, Mix Design, Overlay Tester, Rutting, Cracking	18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia 22312 http://www.ntis.gov

19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 46	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

HIGH RAP MIXES DESIGN METHODOLOGY WITH BALANCED PERFORMANCE

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Report 0-6092-2
Project 0-6092
Project Title: Performance Evaluation & Mix Design for High RAP Mixtures

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

August 2011
Published: November 2011

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There is no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

ACKNOWLEDGMENTS

This project was made possible by the Texas Department of Transportation in cooperation with the Federal Highway Administration. The authors thank the many personnel who contributed to the coordination and accomplishment of the work presented herein. Recognitions are due to all McNew lab staff of TTI. Special thanks are extended to Robert Lee, P.E., for serving as the project director. Many people volunteered their time to serve as project advisors, including:

- Dar-Hao Chen, Ph.D., P. E.
- Feng Hong, Ph.D., P. E.

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CHAPTER 1. INTRODUCTION

The asphalt paving industry has always advocated recycling, including reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), tires, etc. The earliest recycling asphalt pavement dates back to 1915 (*1*). However, significant use of RAP in hot-mix asphalt (HMA) really started in the mid-1970s due to extremely high asphalt binder prices as the result of the oil embargo. In addition to conserving energy and protecting the environment, the use of RAP can significantly reduce the cost of HMA paving. Many studies (*1, 2, 3, 4, 5, 6, 7, 8*) have been made to use more RAP in HMA mixes. Furthermore, historical data (*9*) showed that the RAP mixes, when properly designed and constructed, could have the same or similar performance as well as virgin HMA mixes. A fine example is the RAP asphalt overlay sections on US175 near Dallas, Texas, which was part of long-term pavement performance (LTPP) test sections. Acceptable performance of the four overlay sections with 35 percent RAP was reported even after 17 years of service (*10*). Additionally, RAP processing equipment and procedures have significantly advanced in the past several years. RAP is typically processed into smaller pieces through RAP crushing and fractionating the material into two or three fractions. The fractionated material is more uniform and can potentially be used in higher percentages in HMA without compromising its quality. Also, hot-mix plants are better able to handle higher amounts of RAP without detrimental effects. As a result, it is now possible to produce quality HMA containing 25 percent RAP or more.

However, a recent survey indicates that the average RAP usage in new asphalt mixes is 12 to 15 percent (*11*). Many states including Texas have upper limits on use of RAP in asphalt mixes due to different concerns: RAP variability, impact of RAP on performance (especially cracking resistance), and the lack of a rational RAP mix design method, etc. To address these concerns, in 2008 the Texas Department of Transportation (TxDOT) initiated a research study at the Texas Transportation Institute (TTI) with an overall objective of improving the design methodologies and construction specifications for high RAP content mixes. To achieve these objectives the following steps were undertaken by the researchers:

- Investigate RAP variability in both TxDOT and contractor stockpiles in Texas.
- Evaluate the impact of RAP content on mix performance in terms of both rutting/moisture and cracking resistance.
- Develop a RAP mix design methodology with balanced rutting/moisture and cracking resistance requirements.
- Demonstrate and validate the balanced RAP mix design methodology through field test sections.

Details of each of these are presented in the following chapters of this report. Chapter 2 presents the RAP variability of Texas RAP stockpiles. Chapter 3 discusses the impact of RAP usage on optimum asphalt content, rutting/moisture resistance, and cracking resistance. A RAP mix design methodology is proposed in Chapter 4. In the proposed RAP mix design methodology the final asphalt content is selected after optimizing the mix density, rutting/moisture resistance, and cracking resistance requirements. Chapter 4 also recommends the mixing and compaction temperatures used for designing RAP mixes. To validate the proposed RAP mix design methodology, field test sections containing different levels of RAP were constructed in completely different climate zones, which are described in Chapter 5. Finally, Chapter 6 presents a summary and conclusions from this project.

CHAPTER 2. RAP VARIABILITY IN TEXAS

RAP variability has always been a cause for concern to many pavement/material engineers. To investigate this issue, the authors visited and surveyed three RAP stockpiles owned by TxDOT and eight RAP stockpiles owned by contractors around Texas. One observation during the visits was that both TxDOT and contractors generally kept different stockpiles for RAP taken from different sources. During each visit, RAP samples were collected when visiting each individual RAP stockpile. A front-end loader was used to make the sampling platform and then the bag samples were collected. In most cases, seven RAP samples were collected around the RAP stockpile and then brought back to TTI for laboratory evaluation. A series of laboratory tests were conducted, and due to space limitations, only part of the laboratory test results are presented here. Tables 1 to 6 show the ignition oven test results of RAP owned by TxDOT and contractors, respectively.

It can be seen from Tables 1–6 that there is little variability in the RAP materials collected during the field visits, in terms of aggregate gradation and asphalt content. For example, the largest standard deviation on passing #8 sieve size for all RAP samples is 5.0 percent and most of them are below 4.0 percent, which is better than the national survey results (average=4.32 percent and ranging from 0.78 to 9.0 percent) reported by West (*7*). The standard deviations of passing #200 sieve size in this study range from 0.5 to 2.3 percent, which is a little better than the national survey results ranging from 0.3 to 3.0 percent (*7*); as for the asphalt content, the standard deviations ranging from 0.1 to 0.5 percent are much smaller than the national results, which are between 0.1 to 1.5 percent (*7*). Apparently, these laboratory test results show that both TxDOT and contractors' RAP materials, in terms of aggregate gradation and asphalt content, are consistent. Therefore it is reasonable to expect that produced RAP mixes will be consistent as well. However, as discussed below consistent RAP mixes does not always equal good performing mixes.

Table 1. TxDOT Owned Stockpile #1: Unfractionated RAP.

Sieve Size	Cumulative % Passing of RAP Samples							Average	Standard Deviation
	#1	#2	#3	#4	#5	#6	#7		
¾	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
½	97.9	99.6	99.8	98.4	99.4	99.1	100.0	99.2	0.8
3/8	88.7	90.2	94.2	89.7	91.4	94.2	95.3	92.0	2.6
#4	59.4	63.2	69.8	61.6	62.6	69.1	69.8	65.1	4.4
#8	40.6	43.7	49.2	41.7	40.6	48.4	50.6	45.0	4.3
#16	31.8	33.8	38.2	32.7	31.3	37.1	40.4	35.0	3.5
#30	26.0	26.6	30.5	26.3	25.5	29.7	32.4	28.1	2.7
#50	17.9	19.0	21.0	17.7	17.8	21.0	21.8	19.4	1.8
#100	11.0	11.1	13.1	10.5	11.2	13.5	13.7	12.0	1.4
#200	6.9	7.0	8.2	6.3	7.1	8.6	9.1	7.6	1.1
AC (%)	5.3	5.4	5.6	5.4	5.2	5.8	5.3	5.4	0.2

Table 2. TxDOT Owned Stockpile #2: Unfractionated RAP.

Sieve Size	Cumulative % Passing of RAP Samples							Average	Standard Deviation
	#1	#2	#3	#4	#5	#6	#7		
¾	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
½	95.9	97.9	99.0	98.7	98.3	97.0	97.0	97.7	1.1
3/8	89.7	94.7	90.3	90.8	92.9	90.7	90.7	91.4	1.8
#4	73.1	81.6	67.1	67.8	68.3	73.8	73.8	72.2	5.1
#8	43.5	53.4	43.9	47.7	46.4	46.5	46.5	46.8	3.3
#16	29.3	36.5	31.6	35.3	33.9	31.9	31.9	32.9	2.5
#30	21.6	26.2	24.3	27.4	25.6	23.4	23.4	24.6	2.0
#50	15.5	18.7	18.5	20.8	18.6	17.1	17.1	18.0	1.7
#100	10.0	12.0	12.4	13.7	12.1	11.2	11.2	11.8	1.2
#200	6.4	7.6	8.0	8.8	7.5	7.2	7.2	7.5	0.7
AC (%)	7.5	8.1	7.7	8.6	8.2	8.0	7.4	7.9	0.4

Table 3. Contractor A Owned Stockpile: Crushed RAP.

Sieve Size	Cumulative % Passing of RAP Samples							Average	Standard Deviation
	#1	#2	#3	#4	#5	#6	#7		
¾	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
½	99.1	99.3	99.1	95.4	99.7	97.8	98.4	98.4	1.5
3/8	93.6	93.7	95.5	86.8	96.1	90.6	92.5	92.7	3.2
#4	76.3	74.4	77.9	69.9	77.2	71.2	74.5	74.5	3.0
#8	57.5	54.4	58.1	55.7	60.0	52.0	56.3	56.3	2.6
#16	45.7	41.8	44.7	45.6	47.5	40.0	45.1	44.3	2.5
#30	36.5	32.2	33.6	35.3	35.5	31.1	35.5	34.2	2.0
#50	27.4	23.1	23.0	23.6	23.1	22.6	25.5	24.0	1.8
#100	18.7	15.3	14.8	14.7	14.7	15.4	17.0	15.8	1.5
#200	13.8	11.3	11.0	10.6	10.8	11.5	12.4	11.6	1.1
AC (%)	5.5	5.0	5.1	5.1	5.0	4.6	5.5	5.1	0.3

Table 4. Contractor B Owned Stockpile: Crushed RAP.

Sieve Size	Cumulative % Passing of RAP Samples							Average	Standard Deviation
	#1	#2	#3	#4	#5	#6	#7		
¾	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
½	98.0	99.2	98.1	98.5	95.7	98.9	98.8	98.1	1.1
3/8	90.6	95.2	92.7	94.0	84.0	91.5	91.9	91.4	3.6
#4	67.8	74.3	69.1	69.5	53.9	68.1	69.8	67.5	6.4
#8	46.1	52.3	47.8	47.4	36.0	46.9	48.6	46.5	5.0
#16	34.5	39.7	36.0	35.6	28.1	34.5	36.3	35.0	3.5
#30	27.6	31.8	28.9	28.9	23.8	27.2	29.6	28.3	2.5
#50	21.8	25.1	22.6	22.7	19.8	20.6	23.4	22.3	1.8
#100	12.9	15.1	13.4	13.1	12.4	11.5	13.5	13.1	1.1
#200	7.9	9.5	8.3	7.9	7.8	6.8	8.2	8.1	0.8
AC (%)	4.5	4.7	4.4	4.3	4.2	4.2	4.6	4.4	0.2

Table 5. Contractor C Owned Stockpile: Crushed Fine RAP.

Sieve Size	Cumulative % Passing of RAP Samples							Average	Standard Deviation
	#1	#2	#3	#4	#5	#6	#7		
¾	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
½	99.5	100.0	100.0	99.5	100.0	100.0	100.0	99.8	0.3
3/8	98.6	98.8	99.1	97.5	99.1	99.5	99.0	98.8	0.6
#4	83.2	84.6	84.9	84.5	85.6	87.6	85.7	85.2	1.4
#8	57.0	58.0	56.2	57.2	59.2	63.2	60.1	58.7	2.4
#16	43.9	45.2	42.5	43.4	45.6	49.2	46.9	45.2	2.3
#30	36.8	38.7	35.7	36.4	38.1	40.8	39.4	38.0	1.8
#50	27.7	29.5	26.4	26.2	27.5	29.7	29.5	28.1	1.5
#100	15.8	16.3	14.2	13.7	14.1	15.5	15.9	15.1	1.0
#200	8.0	8.2	6.8	6.6	6.8	7.9	8.3	7.5	0.7
AC (%)	5.6	5.1	5.1	5.3	5.6	5.3	5.3	5.3	0.2

Table 6. Contractor D Owned Stockpile: Crushed Coarse RAP.

Sieve Size	Cumulative % Passing of RAP Samples							Average	Standard Deviation
	#1	#2	#3	#4	#5	#6	#7		
¾	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
½	96.3	98.2	99.5	97.7	99.1	96.6	95.3	97.5	1.5
3/8	79.4	88.0	86.9	86.0	84.0	86.9	80.3	84.5	3.4
#4	51.6	56.1	56.8	57.5	55.0	58.7	45.7	54.5	4.5
#8	36.0	38.2	39.3	38.7	38.0	40.2	28.4	37.0	4.0
#16	25.8	26.9	28.0	27.6	27.0	28.9	18.9	26.2	3.3
#30	19.9	20.2	20.9	20.9	20.4	22.2	14.1	19.8	2.6
#50	15.1	14.6	14.9	15.1	14.7	16.6	10.4	14.5	1.9
#100	8.1	7.3	7.5	7.7	7.3	8.8	5.6	7.5	1.0
#200	4.0	3.3	3.5	3.7	3.2	4.2	3.0	3.6	0.5
AC (%)	3.0	2.9	3.0	2.9	2.9	3.1	2.2	2.8	0.3

CHAPTER 3. IMPACT OF RAP CONTENT ON LABORATORY MIX PERFORMANCE

Low variability of RAP material itself provides contractors some confidence to produce consistent RAP mixes. However, the consistence of RAP mixes does not always guarantee good field performance, although it is one important requirement. The inclusion of RAP materials into asphalt mixes often improves the resistance to rutting, but it may greatly jeopardize the resistance to cracking. Therefore, it is necessary to thoroughly investigate the impact of RAP content on mix performance in terms of both rutting and cracking. In this study a variety of RAP, virgin aggregates, and virgin asphalt binders were used in three case studies. The following steps were followed for each case study:

- Step 1: Fix the RAP content (i.e., 20 percent) and adjust virgin aggregates percentage to make the total aggregates gradation for each RAP mix within each case study as close to each other as possible. For example, the gradations of the four mixes used in Case Study 1 described below are very close to each other with varying RAP content from 0 percent to 40 percent.
- Step 2: Design the RAP mixes and select an optimum asphalt content (OAC) for each following TxDOT's standard mix design procedure (Tex-204-F) for dense graded mixes that are widely used in Texas (75 percent of all the HMA used in Texas).
- Step 3: Evaluate the rutting/moisture and cracking resistance of mixes with varying RAP content at OAC. The rutting/moisture resistance of RAP mixes was characterized using the Hamburg Wheel Tracking Test (HWTT) (Tex-242-F). The specimen size of the HWTT is 6 in. (150 mm) diameter by 2.5 in. (62 mm) height and its target air voids content is 7±1 percent. The HWTT is conducted in a water bath at a constant temperature of 122°F (50°C). The specimens are tested under a rolling 1.85 in. (47 mm) wide steel wheel using a 158 lb (705 N) force. An average rut depth measured at several locations including the center of the wheel travel path is reported at end of the test.

The cracking resistance of RAP mixes was determined using Texas Overlay Tester (Tex-248-F). The standard specimen size of Overlay Test (OT) is 6 in. (150 mm) long by 3 in. (75 mm) wide by 1.5 in. (38 mm) high and its target air voids content is 7±1 percent after cutting. The OT is run in a displacement controlled mode with a maximum opening displacement of 0.025 in. (0.63 mm) at test temperature of 77°F (25°C). The number of cycles to failure (93 percent reduction of the cyclic maximum load from the one measured at the first load cycle) is reported at end of the test. The correlation between the OT result and field cracking performance has been well documented (*12, 13*), and the OT has been used for evaluating both reflective and fatigue cracking by different researchers (*14, 15, 16, 17*). A total of three different RAP materials were used in this study: designated as RAP1, RAP2, and RAP3.

Case 1: Granite Aggregates/Virgin PG70-22/RAP1

The first case study was a dense-graded Type D mix with granite aggregates, a PG70-22 virgin binder with four RAP contents (0, 20, 30, and 40 percent). Since the focus here was on the influence of the amount of RAP usage on mix performance, the aggregates gradations for the four RAP mixes were adjusted very close to each other, as shown in Figure 1. For each RAP mix, a design was performed separately using Texas Gyratory Compactor (TGC), and the OAC was selected corresponding to 96.5 percent density, following TxDOT's mix design procedure (Tex-204-F). Figure 2 shows the determined OAC for each RAP mix. The mixing and compaction temperatures were kept the same for all four RAP mixes. Furthermore, the rutting/moisture and cracking resistances of these four RAP mixes at OAC were evaluated under the HWTT and OT, and test results are presented at Figures 3 and 4, respectively.

It can be seen from Figure 2 that increasing RAP content generally leads to higher OAC if the target design density and mixing and compaction temperatures are the kept the same for all mixes. The reason for this is that the increasing RAP content increases the composite PG grade of the blended RAP/virgin binder. Therefore with the higher composite PG grade the mixing and compaction temperatures should be increased for high RAP mixes. When the mixing and compaction temperatures are kept the same for each RAP mix, it will need more asphalt binder for higher RAP mixes to achieve the same density. The mixing and compaction temperatures issue for RAP mixes will be discussed further in Chapter 4.

Figure 3 clearly indicates that increasing RAP content always improves laboratory rutting/moisture resistance. Inversely, cracking resistance worsens with use of more RAP, especially when RAP content is 30 percent and above, as illustrated in Figure 4. There are two potential reasons for the observations in Figures 3 and 4. One is related to higher temperature grade of the overall binder after blending, although it is difficult to know exactly how much the blending between virgin binder and RAP binder truly is. Generally speaking, higher temperature PG grade leads to better rutting/moisture resistance but worse cracking resistance. The other potential reason is due to partial blending between virgin binder and RAP binder, and consequently less effective asphalt binder in RAP mixes, although some RAP mixes even have higher total OAC, compared to the 0 percent RAP mix. To achieve both acceptable rutting/moisture and cracking performance, one has to either establish an upper limit for RAP usage if preferring to keep the same virgin binder PG grade, drop the virgin binder PG grade to use higher RAP content or change the target density requirements so that the total binder content will be increased. More discussion on the upper RAP limit is offered at the end of this section.

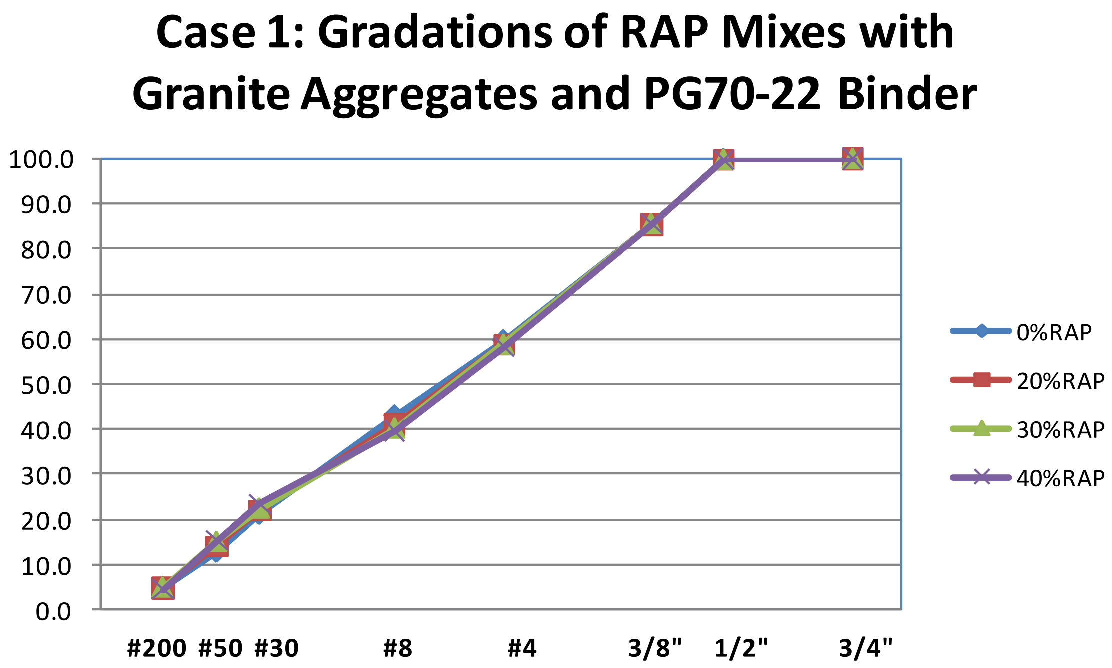

Figure 1. Case 1: Aggregates Gradations of Four RAP Mixes.

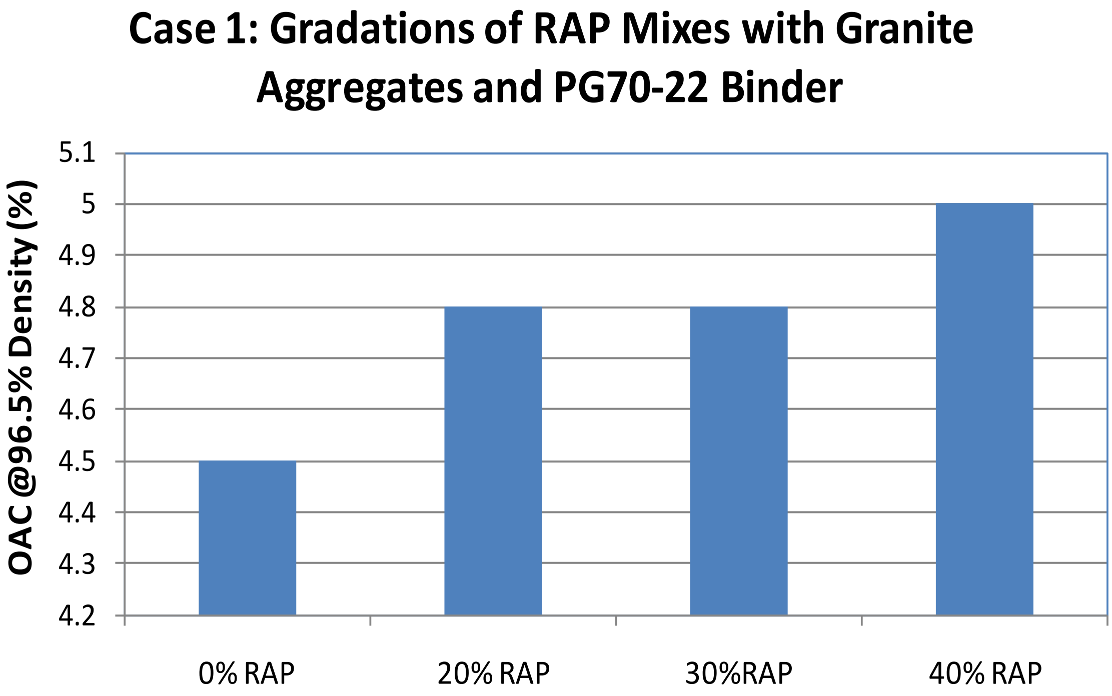

Figure 2. Case 1: OAC of Each RAP Mix.

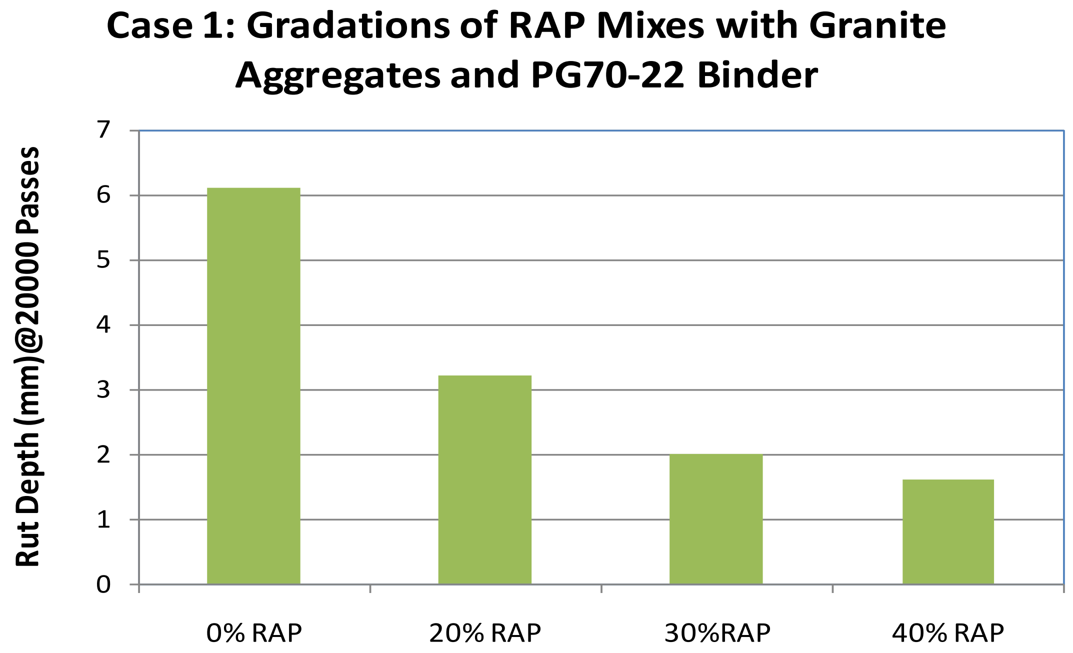

Figure 3. Case 1: HWTT Results of the Four RAP Mixes.

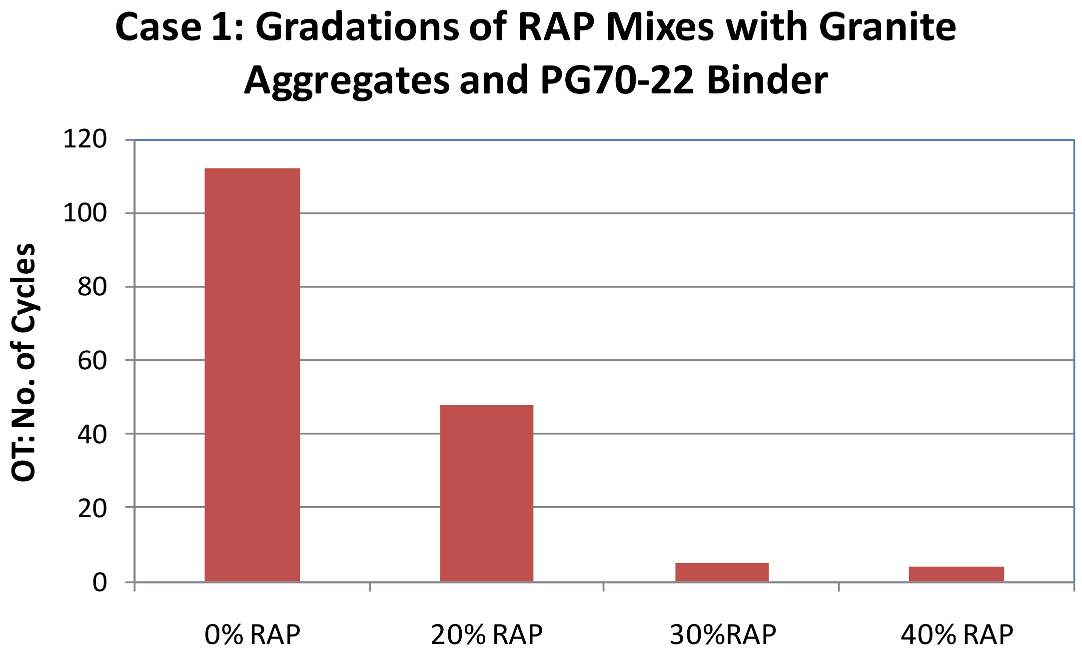

Figure 4. Case 1: OT Results of the Four RAP Mixes.

Case 2: Gravel Aggregates/Virgin PG64-22/RAP2

The second case study was a dense-graded Type C mix with gravel aggregates, a PG64-22 virgin binder, and four RAP contents (0, 10, 20, and 35 percent). Again, the aggregates gradations for the four RAP mixes were adjusted to be very close to each other, as indicated in Figure 5. Similarly, each RAP mix was designed using the TGC following TxDOT's mix design procedures (Tex-204-F), and Figure 6 shows the OAC selected at 96.5 percent density for each RAP mix. Also Figures 7 and 8 present the HWTT and OT test results of four RAP mixes at OAC, respectively.

The results shown in Figures 6, 7, and 8 are very similar to those of Case 1 (see Figures 2, 3, and 4). Again, increasing RAP content generally leads to higher OAC, better rutting/moisture resistance but worse cracking resistance. In this case, the 20 percent RAP mix only lasts 9 cycles under the OT, which is significantly lower than the 178 cycles for the 0 percent RAP mix. Therefore, it is critical to evaluate the cracking resistance of RAP mixes in the design process to ensure that the designed RAP mixes has an acceptable balance of both rutting/moisture and cracking resistance.

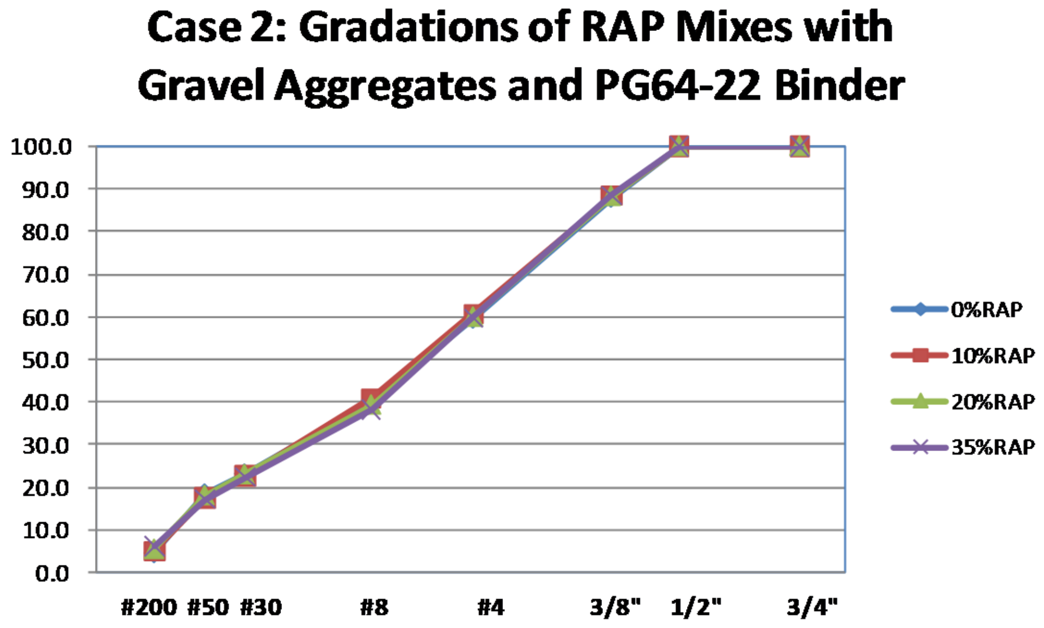

Figure 5. Case 2: Aggregates Gradations of Four RAP Mixes.

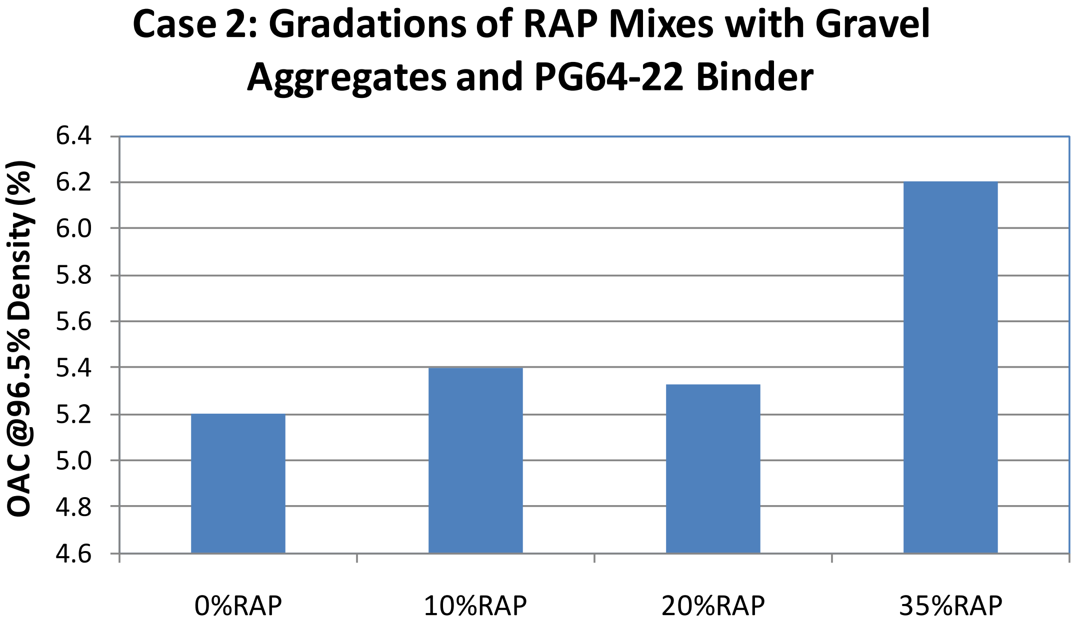

Figure 6. Case 2: OAC of Each RAP Mix.

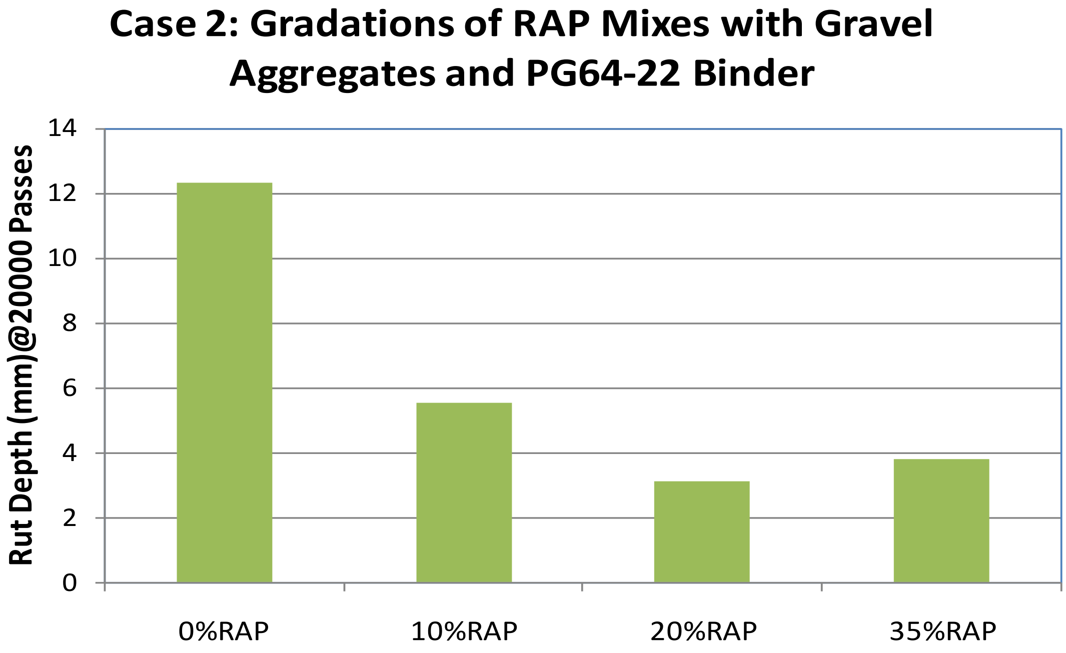

Figure 7. Case 2: HWTT Results of the Four RAP Mixes.

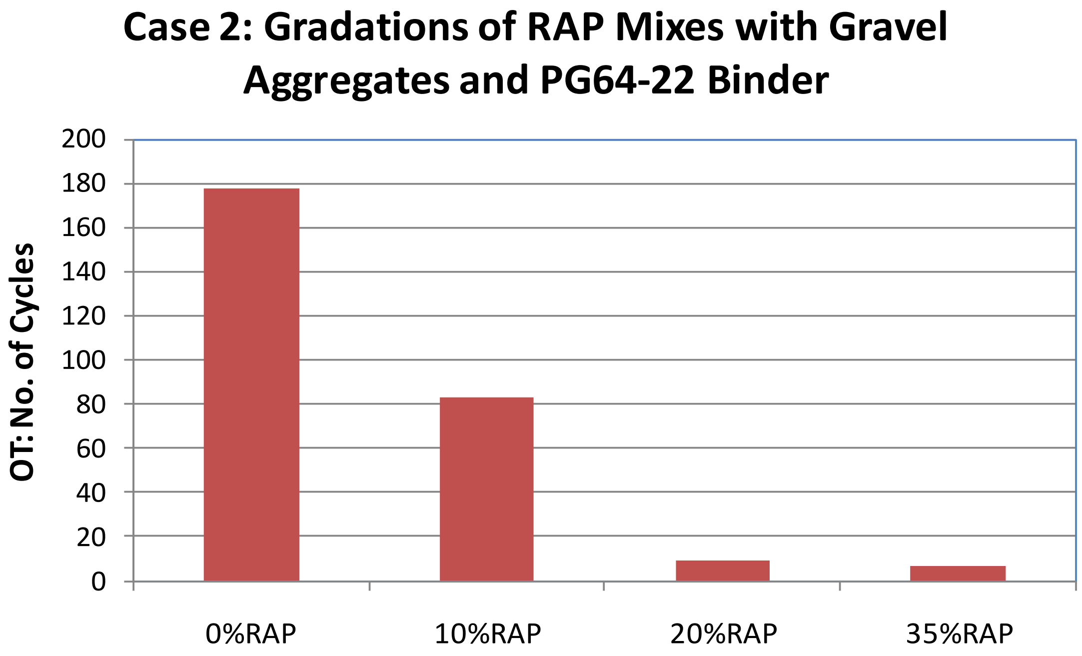

Figure 8. Case 2: OT Results of the Four RAP Mixes.

Case 3: Sandstone Aggregates/Virgin PG64-22/RAP3/RAS

The third case study was another dense-graded Type D mix with sandstone aggregates and a PG64-22 virgin binder. Note that the sandstone aggregates used are very absorptive and have a 2 percent water absorption. Specifically this case study used both RAP and RAS: 0 percent RAP, 15 percent RAP, 20 percent RAP, and 15%RAP/5%RAS. Figure 9 presents the aggregates gradations for this case study. Similarly, the OAC for each RAP/RAS mix was determined at 96.5 percent density following TxDOT's mix design procedure (Tex-204-F), and Figure 10 illustrates the results. The HWTT and OT test results of four RAP/RAS mixes are displayed in Figures 11 and 12, respectively.

The overall results for this case are similar to those of Cases 1 and 2, except that rutting resistances of the four RAP/RAS mixes are almost the same (see Figure 11). Normally, a virgin mix with a PG64-22 binder will have worse HWTT performance. Current TxDOT pass/fail criterion for asphalt mixes with PG64-22 binders is 0.5 in. (12.5 mm) after 10,000 passes. This sandstone mix with PG64-22 binder and 0 percent RAP performed very well under the HWTT and had only 0.16 in. (4.1 mm) rutting after 20,000 passes, which indicates that this sandstone virgin mix is already very rut resistant. Adding more RAP/RAS did not show much improvement in terms of rutting/moisture resistance. As has been found in earlier studies, achieving good cracking and rutting requirements with highly absorptive aggregates is very difficult.

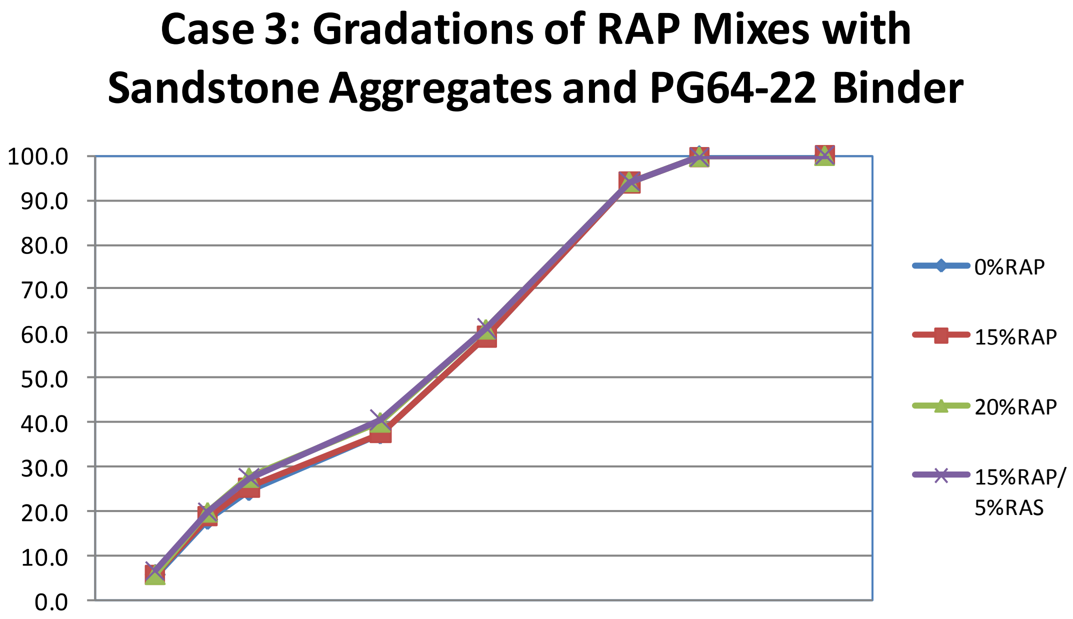

Figure 9. Case 3: Aggregates Gradations of Four RAP/RAS Mixes.

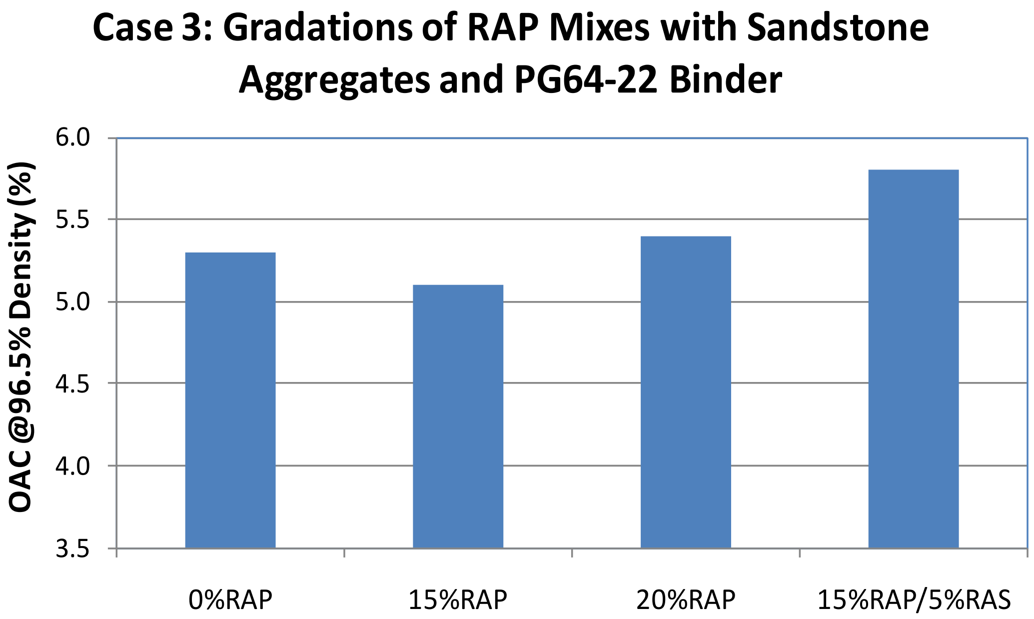

Figure 10. Case 3: OAC of Each RAP/RAS Mix.

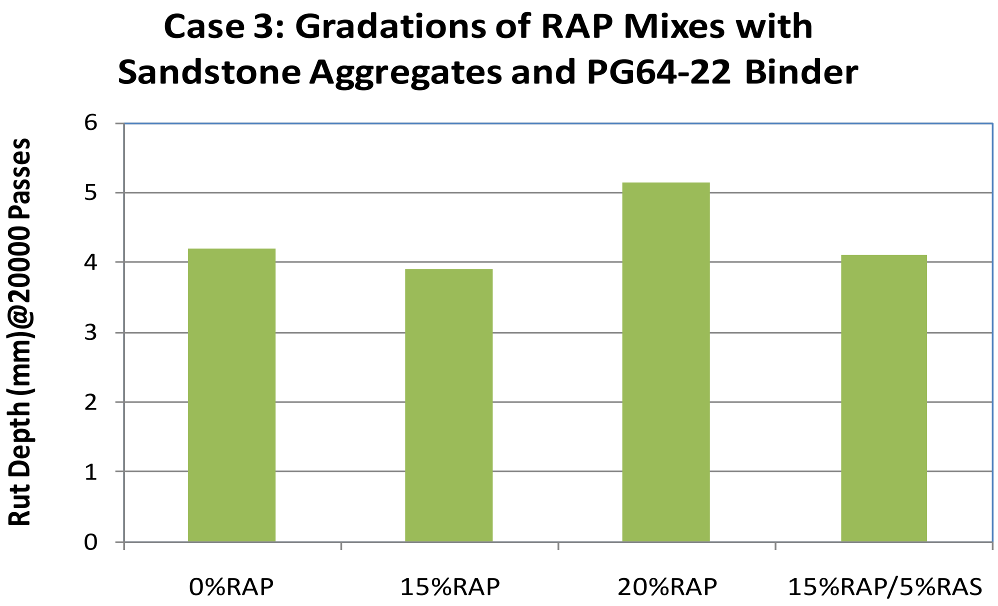

Figure 11. Case 3: HWTT Results of the Four RAP/RAS Mixes.

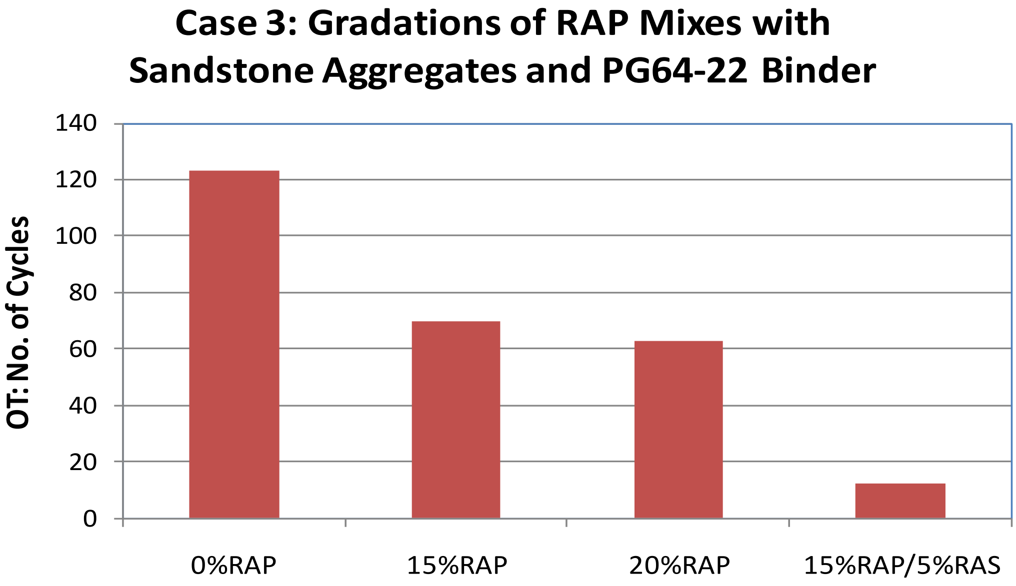

Figure 12. Case 3: OT Results of the Four RAP Mixes.

DISCUSSION

Reviewing all three case studies presented above, it can be seen that the general trend for OAC is increasing with higher RAP (/RAS) contents (see Figures 2, 6, and 10), although the increase in OAC is small when the RAP content is below 20 percent. There is always a significant increase in OAC when more than 20 percent RAP (or 15% RAP/5% RAS) is used. The use of 10–15 percent RAP, without lowering virgin binder PG grade, has some minor impact on rutting/moisture and cracking resistance (see Figures 3, 4, 7, 8, 11, 12), but the influence (especially on cracking resistance) is not as much as the 20 percent RAP (see Figure 8) and beyond (see Figures 4, 8, and 12) for which lower PG virgin binder or specific design is necessary. Basically, the findings are consistent with the three-tier virgin binder selection concept recommended in AASHTO M 323 (*18*). Specifically for asphalt mixes with higher RAP content (i.e., more than 25 percent) or RAP/RAS combinations, the virgin binder selection, according to AASHTO M 323, is based on blending chart and the assumption that there is always 100 percent blending between the virgin and RAP binders, regardless of how stiff the RAP (or RAS) binder is. Apparently, the assumption of 100 percent blending between the virgin and RAP binders is debatable. Based on the limitations of the blending chart approach, this report presents a balanced RAP mix design methodology in the next chapter.

CHAPTER 4. RAP MIX DESIGN METHODOLOGY WITH BALANCING RUTTING/MOISTURE AND CRACKING RESISTANCE

Although there is no significant difference between RAP mixes and virgin mixes in terms of production in the plant, designing RAP mixes is more complicated than virgin asphalt mixes. Not only does the virgin aggregates and virgin binder information have to be obtained, but RAP binder content and RAP aggregate gradation also needs to be determined through the ignition oven or asphalt binder extraction test. In addition asphalt binder recovery tests may be needed to grade the RAP binder in order to use the blending chart. (Note that Bahia and his associates [*21*] recently developed a test protocol to estimate RAP binder low-temperature property without extraction.) Additionally, there are at least four more challenges when designing RAP mixes in the laboratory, especially for high RAP mixes (i.e., more than 25 percent):

1. *Virgin and RAP binder blending*: AASHTO M 323 and other mix design methods that are used by different states assume that the RAP binder is 100 percent active and complete blending between the virgin and RAP binders is achieved. Although some approaches such as dynamic modulus-based approaches (*19, 20*), have been proposed, how much active RAP binder and how the RAP binder blend with the virgin binder is very difficult, if not impossible, to determine accurately.
2. *Bulk specific gravity of RAP aggregates*: AASHTO M 323 and other volumetric design methods heavily rely on the voids in mineral aggregate (VMA) requirement to control durability (or cracking resistance) of the designed asphalt mix. In order to calculate VMA of any RAP mix, one has to know the bulk specific gravity of the RAP aggregates. Although different approaches for measuring or backcalculating bulk specific gravity of RAP aggregates have been proposed, there is no method that is currently widely accepted.
3. *RAP handling*: RAP needs to be heated up to make it workable and RAP binder active. There are many methods available for handling RAP in the lab during mix design process, but none of them can truly simulate the production process in the plant.
4. *Mixing and compaction temperatures*: It is well known that the mixing and compaction temperatures are important and have influence on compaction, volumetrics (air voids, VMA, etc.), and consequently on OAC. For any virgin asphalt mix, the mixing and compaction temperatures are selected based on virgin binder properties (i.e., viscosity). When RAP is added, one has to consider both virgin binder and RAP binder. Guidelines are needed for selecting the mixing and compaction temperatures, especially when designing high RAP mixes

There are no acceptable solutions for the first two challenges, but alternative approaches exist. One of them is to use balanced mix design approach proposed by Zhou et al. (*22*) in which the OAC is selected based on target air voids (or density), rutting/moisture, and cracking resistances determined using the HWTT and OT, respectively. The balanced mix design approach addresses challenges 1 and 2 through employing the OT to directly measure the cracking resistance of RAP mixes. Regarding the last two challenges, some ideas were explored in this study and are described below.

RAP HANDLING

Proper RAP handling is one of the critical steps in the RAP mix design process. It is import to heat up RAP materials to make sure binder transfers from the RAP to the virgin aggregates. Basically there are two issues with RAP heating (or handling) in the laboratory: heating time and temperature. Different methods are available. Some designers preheat RAP materials at the target mixing temperature for a period of time before mixing with virgin aggregates. Others superheat the virgin aggregate and mix the RAP in at room temperature. Additionally NCHRP Report 452 (*2*) recommends a preheating temperature of 230°F (110°C) for RAP and the 10°C above mixing temperature for virgin aggregates. Recently, the National Center for Asphalt Technology (NCAT) investigated different approaches of handling RAP in the laboratory, as reported by Kvasnak (*23*). After evaluating the four popular methods, Kvasnak (*23*) recommended that RAP be preheated at the same target mixing temperature as that of virgin aggregates, but with a timeframe of no less than 30 min. and no longer than 3 hr, depending on RAP amount. Therefore, one target mixing temperature for both RAP and virgin aggregates is more practical for mix designers to implement. Therefore the authors adopted the single temperature approach for this study. Regarding the pre-heating time, after many trials and consulting several contractors' mix designers, a two-step preheating process is recommended: 1) warm up the RAP materials overnight (12–15 hr) at 140°F (60°C), which is the most used temperature to dry materials, and 2) preheating the RAP at the mixing target temperature for 2 hr, which is often the time for preheating virgin binder. This two-step preheating process combines NCAT's recommendations on one temperature for all and meanwhile fixes the preheating time. This RAP handling process as verified by contractors in Texas provides consistent results between laboratory mix design and plant produced QC job formula.

Mixing and Compaction Temperatures

The mixing and compaction temperatures for high RAP mixes have not been well addressed in the literature, because this is not an issue when RAP contents are relatively low. As shown in Figures 2, 6, and 10, OAC of RAP mixes are not significantly different from those of virgin mixes when RAP contents are less than 20 percent. However, it becomes an issue for higher RAP mixes, because OAC for high RAP mixes is much higher than that of the virgin mix. As discussed previously, Kvasnak (*23*) recommended the same target mixing temperature for RAP materials and virgin aggregates, but the target mixing temperature was not clearly defined in that paper. Normally the virgin binder PG grade controls the mixing and compaction temperatures for virgin mixes. But for RAP mixes, there are at least three options for selecting the laboratory mixing and compaction temperatures:

1. The mixing and compaction temperatures corresponding to the virgin binder.
2. The mixing and compaction temperatures corresponding to the blended virgin/RAP binder.
3. The mixing and compaction temperatures corresponding to the RAP binder.

Generally RAP binder is stiffer than virgin binder. The virgin binder will be over heated and consequently over aged if Option 3—the mixing and compaction temperatures corresponding to the RAP binder—is chosen. So it is not a good option. Therefore, only Options 1 and 2 were evaluated under this study.

Cases 2 and 3 were used here to evaluate the influence of the mixing and compaction temperatures on OAC and associated cracking resistance of the mixes. Note that only cracking resistance of RAP mixes was considered here, because rutting resistance of RAP mixes is generally not a concern. Two sources of PG64-22 virgin binders were used in Cases 2 and 3. Three mixing and compaction temperatures corresponding to PG64-22 (virgin binder), PG70-22, and PG76-22, respectively, were chosen for each high RAP mix in Cases 2 and 3 (see Table 7). Figure 13 shows the OACs of Cases 2 and 3 at 3 mixing and compaction temperatures, respectively. Increasing the mixing and compaction temperatures significantly lowers the OAC, and there is a significant OAC drop when increasing the mixing and compaction temperatures to those corresponding to PG70-22. Consequently, cracking resistance of RAP mixes at the higher mixing and compaction temperatures becomes worse due to lower OAC and aging at high temperatures, as shown in Figure 14. Therefore, from the conservative point of view, it is proposed to use the mixing and compaction temperatures corresponding to virgin binder for RAP mixes design so that RAP mixes can have higher OAC, enough virgin asphalt binder, and better cracking resistance.

Table 7. Mixing and Compaction Temperatures by PG Grade.

Binder PG	**Mixing Temperature**	**Compaction Temperature**
PG64-22	290°F (143°C)	250°F (121°C)
PG70-22	300°F (149°C)	275°F (135°C)
PG76-22	325°F (163°C)	300°F (149°C)

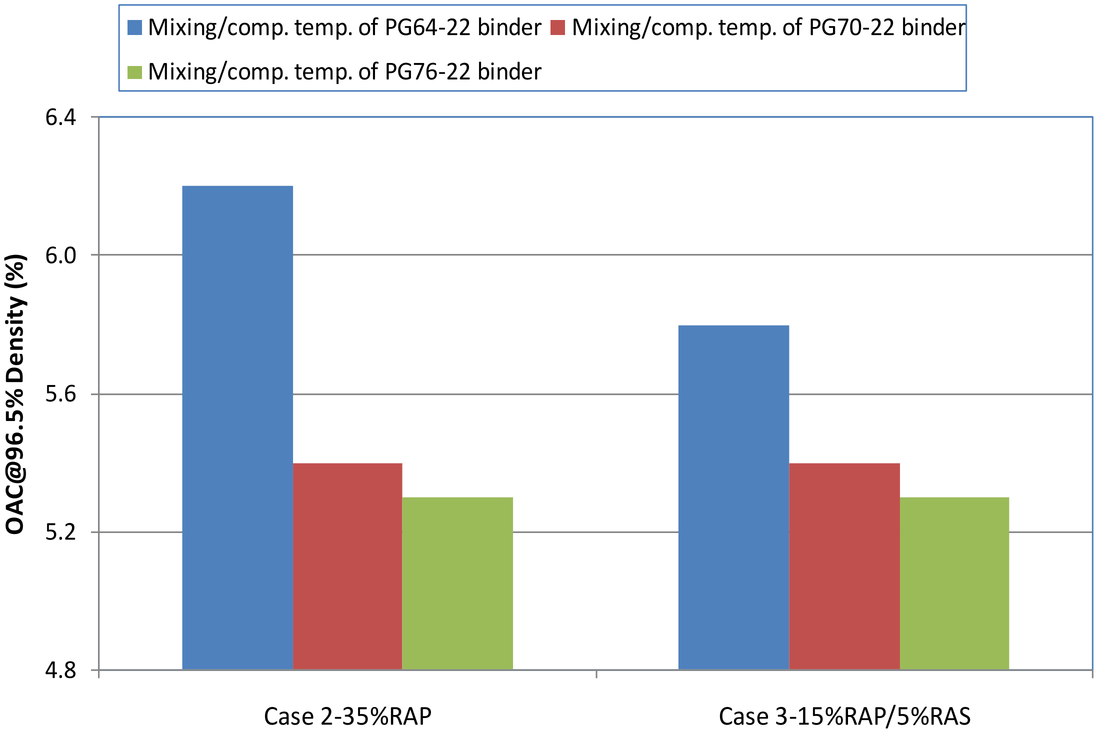

Figure 13. Influence of Mixing and Compaction Temperatures on OAC.

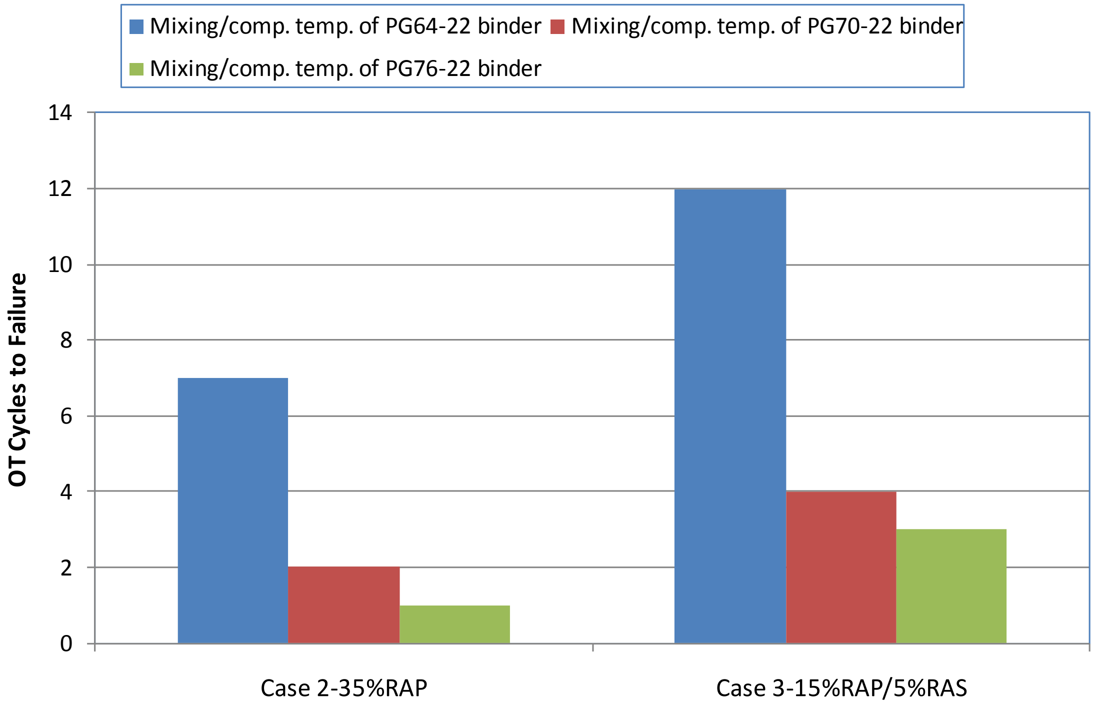

Figure 14. Influence of Mixing and Compaction Temperatures on Cracking Resistance.

Proposed RAP Mix Design Approach with Balanced Rutting and Cracking Requirements

Based on the discussion above and the previous work (*12, 13, 22*), a balanced RAP mix design approach is proposed, as presented in Figure 15. Basically it consists of 11 steps as described below:

1. Evaluate RAP materials to determine RAP binder content and RAP aggregates gradation.
2. Select virgin binder, virgin aggregates, and total aggregates gradation.
3. Weigh up virgin aggregates and preheat the aggregates in an oven to the preselected mixing temperature based on virgin binder property.
4. Weigh up RAP and warm up RAP at 140°F (60°C) over night (load the RAP materials in a dry oven or room just before the end of the day/office hours).
5. Manually mix the preheated RAP with hot virgin aggregates (in morning of the second day).
6. Load virgin binder into the oven and wait around 2 hr to melt the virgin binder.
7. Mix virgin binder with the RAP/virgin aggregates blended in Step 5.
8. Lower the oven to compaction temperature for short-term aging.
9. Compact the RAP mix samples by either TGC or Superpave gyratory compactor (SGC) for volumetric evaluation.
10. Meanwhile compact the RAP mix samples by SGC for performance evaluation under HWTT and OT testing.
11. Select a balanced asphalt content meeting volumetric, rutting/moisture damage, and cracking requirements. Note that volumetric requirement refers to maximum density that is used to control potential bleeding. VMA is not considered here for two reasons: 1) without accurate RAP aggregate specific gravity and unknown amount of blending between RAP binder and virgin binder, it is difficult to calculate accurate VMA of the RAP mix, and 2) OT, instead of VMA, is used to directly evaluate cracking resistance of RAP mixes.

Field validation of this balanced RAP mix design approach and detailed examples are presented in next section.

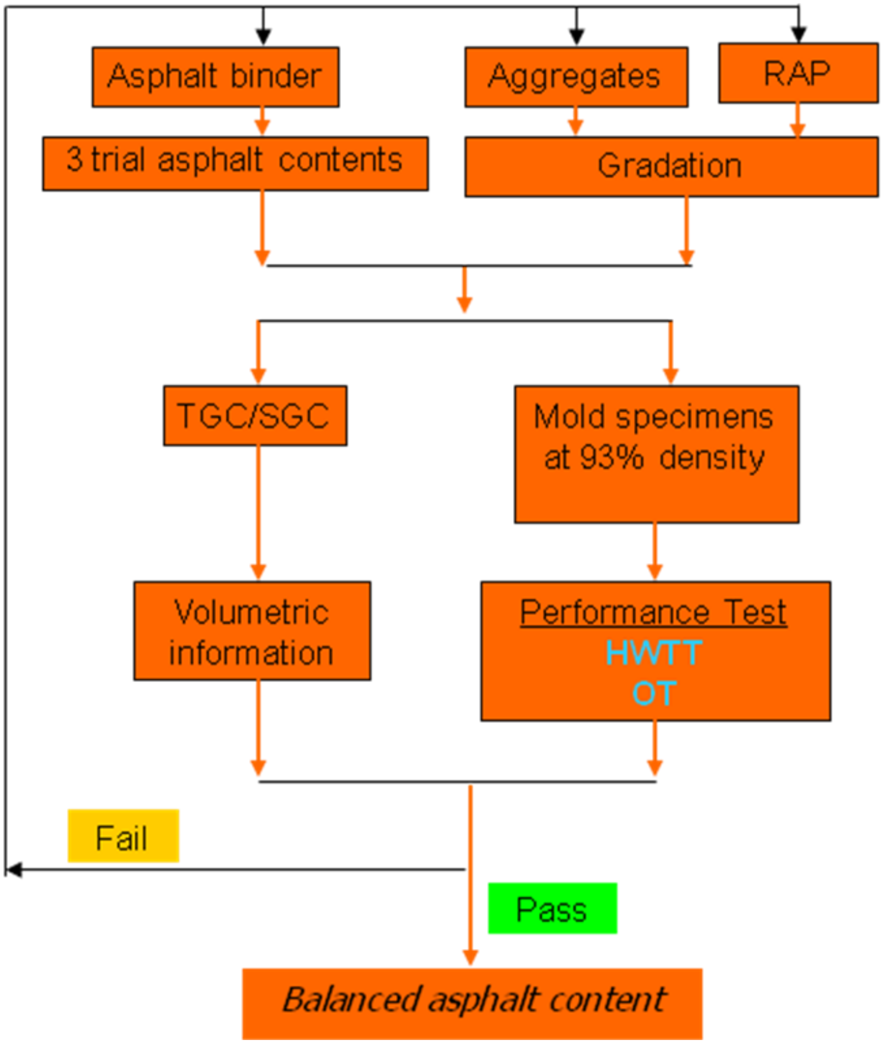

Figure 15. Balanced RAP Mix Design Flowchart.

CHAPTER 5. DEMONSTRATION AND VALIDATION OF THE BALANCED RAP MIX DESIGN METHODOLOGY THROUGH FIELD RAP TEST SECTIONS

This section focuses on constructing field test sections to demonstrate and validate the balanced RAP mix design methodology. In order to do so, two sets of field test sections with different RAP contents were built in two completely different environmental zones of Texas. The first set of test sections were on a mill and overlay rehabilitation project on Interstate Highway (IH) 40 in the Amarillo District with very cold weather and extremely heavy traffic. Another set of test sections with three RAP contents were built in new construction site located at Pharr, Texas, on FM1017 with hot weather and very light traffic. These two sets of test sections are in sharp contrast to each other in terms of climate, traffic, and construction conditions (milling/overlay vs. new construction). More detailed information about these test sections and field performance observed so far are presented below.

RAP TEST SECTIONS ON IH40 AND OBSERVED FIELD PERFORMANCE

As noted previously, the main objective of constructing field sections is to demonstrate and validate the balanced RAP mix design procedure. The four RAP test sections shown in Figure 16 were constructed on IH40 near Amarillo, Texas, on August 11, 2009. The existing pavement has a total of 8 in. of existing HMA with severe thermal related transverse cracking which extends full depth of the HMA. The reason for choosing these four sections is to permit the rapid determination of field performance of sections designed by both the current mix design method and the balanced RAP mix design method. The pavement design called for a 4 in. (100 mm) milling and 4 in. (100 mm) overlay section. Amarillo's climate is a temperate semi-arid climate characterized by numerous freeze-thaw cycles and occasional blizzards during the winter season. Average daily high temperatures of Amarillo range from 48°F (9°C) in January to 92°F (33°C) in July. Furthermore, the traffic on IH40 is extremely heavy with over 50 percent heavy loaded trucks in the traffic stream. The cold weather, heavy traffic loading, and severe existing pavement cracking makes this a good case study to rapidly evaluate the impact of different RAP layers on pavement performance.

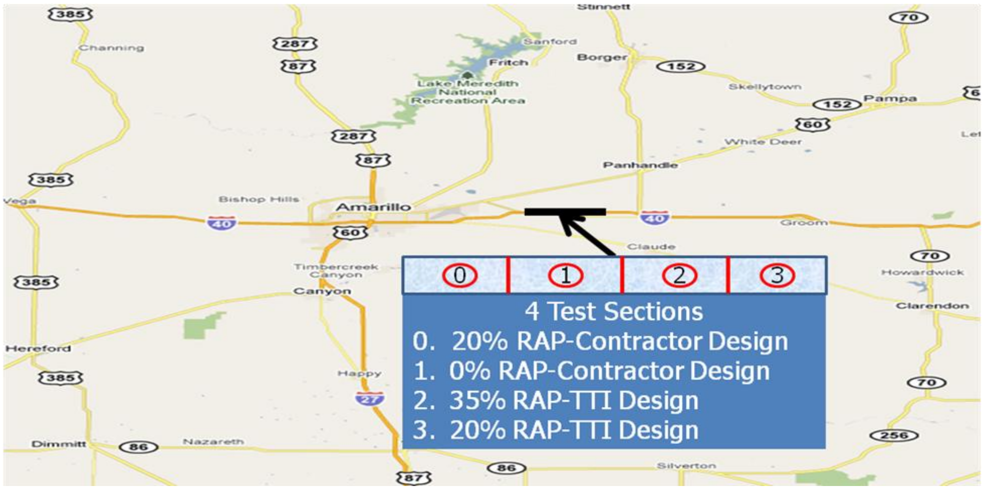

Figure 16. Four RAP Test Sections on IH40 near Amarillo, Texas.

severe transverse cracks even after 4 inch milling

Figure 17. Existing Pavement Conditions of IH40 after Milling.

RAP Mix Design Information of the Four Test Sections

The four RAP mixes used on IH40 are all dense-graded Type C mixes. As indicated in Figure 16, the 20 percent RAP mix and 0 percent RAP mix used in Sections #0 and #1, respectively, were designed by the contractor who followed TxDOT's standard mix design procedure (Tex-204-F) in which the OAC was selected based on a target 96.5 percent density and then checked to ensure the mix meets the HWTT 0.5 in. (12.5 mm) rutting requirement. Detailed mix design information about these two mixes and associated HWTT and OT results are tabulated in Table 8.

The 35 percent RAP and 20 percent RAP mixes used in Sections #2 and #3 were designed by TTI following the balanced RAP mix design method (see the flow chart in Figure 15). As discussed previously, the final balanced asphalt content is determined by optimizing the maximum density, HWTT rut depth, and OT cycles. Based on past TxDOT experience with the TGC, a maximum density of 98 percent was chosen in this study. Figure 18 illustrates the asphalt content for the 98 percent maximum density line, rut depth (left vertical axis) and OT cycles (right axis) at different asphalt contents for the 35 percent RAP mix designed for Section #2. Section #2 is different from the other three sections as it used a softer PG58-28 virgin binder: to compensate the high RAP content. (Also because the initial trial mixes at 35 percent RAP with the PG 64-22 virgin binder yielded very poor OT results.) It can be seen from Figure 18 that based on the 98 percent max density requirement the maximum asphalt content is 5.6 percent. As long as the asphalt content is below 5.6 percent, rutting/moisture requirement are automatically met. Therefore, the real control factor is the cracking requirement. Currently, there is no official cracking criteria in Texas for dense graded mixes. Past experience with dense-graded asphalt mixes used on the LTPP sections on US175 near Dallas, Texas, showed that the good performance overlay mixes often have a minimum of 300 cycles (*12*). Apparently, the 35 percent RAP mix cannot meet such criteria. However, with these test sections the 300-cycle criteria can be further evaluated. For a factor of safety, 5.5 percent asphalt content was selected for 35 percent RAP test section, which is 0.1 percent less than the maximum asphalt content (5.6 percent) for 98 percent density. The corresponding OT cycles to 5.5 percent asphalt content is 200 cycles for the 35 percent RAP mix. More information on the 35 percent RAP mix is provided in Table 8.

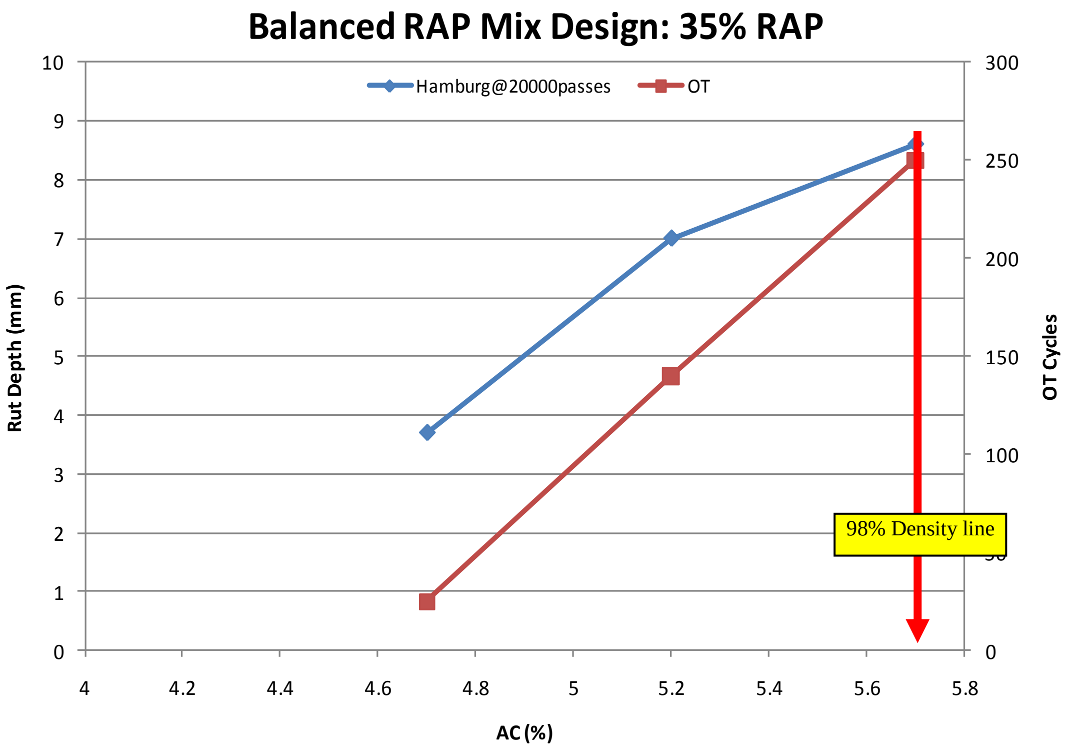

Figure 18. Balanced RAP Design for 20 Percent RAP Mix of Section #2.

Similarly, the 20 percent RAP mix used in Section #3 was designed, as illustrated in Figure 19. Again rutting/moisture resistance is not a problem as long as asphalt content is below 5.4 percent, which corresponds to 98 percent density. But cracking resistance is not ideal.

Similar to the 35 percent RAP mix, asphalt content of 5.3 percent was recommended for 20 percent RAP mix, which is 0.1 percent less than the maximum asphalt content (5.4 percent) for 98 percent density. The corresponding OT cycles to 5.3 percent asphalt content is 125 cycles. Again, Table 8 details the 20 percent RAP mix design information.

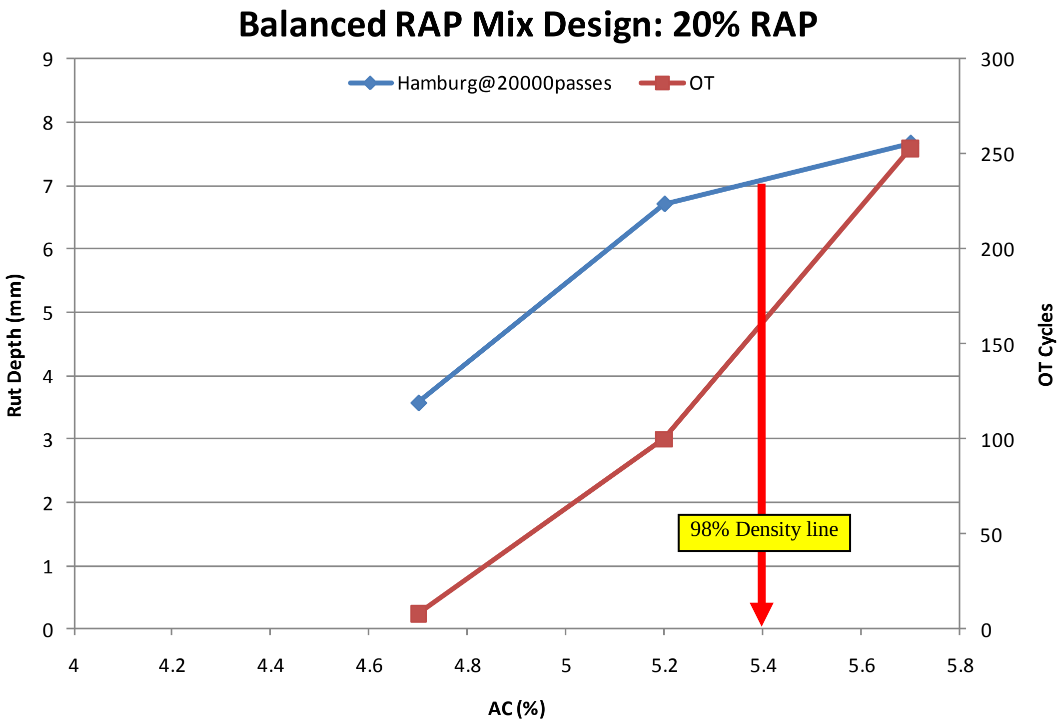

Figure 19. Balanced RAP Design for 20 Percent RAP Mix of Section #3.

Table 8. Mix Design Information of the Four RAP Test Sections on IH40 near Amarillo, Texas.

Section	RAP (%)	Virgin binder	Designer	Mix design method	OAC (%)	HWTT rut depth@ 20,000 passes	OT cycles
0	20	PG64-28	Contractor	TxDOT's Tex-204-F	5.0	3.72	10
1	0	PG64-28	Contractor	TxDOT's Tex-204-F	4.8	4.38	50
2	35	AC-10 (PG58-28)	TTI	Balanced mix design	5.5	8 mm	200
3	20	PG64-28	TTI	Balanced mix design	5.3	7.4 mm	125

Observed Field Performance

These four test sections were constructed on August 11, 2009. Since then three field surveys have been conducted on April 22, 2010, September 8, 2010, and April 5, 2011, respectively. So far no rutting has been observed, but reflective cracking was observed on all four test sections on the third survey. Detailed reflective cracking observations for each section are tabulated in Table 9. Prior to placing the overlay the number of pre-existing cracks in each section was documented and mapped. The reflective cracking rate is therefore defined as the ratio of the number of reflective cracks to the original number of cracks before the 4 in. (100 mm) overlay. For the purpose of comparison, OT cycles of each mix are also added in Table 9. It is clear that the higher the lab OT cycles of the RAP mix, the lower reflective cracking rate, which further validates the effectiveness of OT for reflective cracking. It also clearly indicates that the 35 percent RAP test section with 200 OT cycles performed the best among the four sections. The overall conclusion from these four sections is that high RAP mix can have better or similar performance to the virgin mix, but it must be well designed following appropriate mix design methods, such as the balanced RAP mix design methodology.

Additionally, these data provide a chance to check the tentative cracking criteria of 300 OT cycles. The reflective cracking rate versus the OT cycles of each test section is plotted in Figure 20. A simple linear line is used to fit the data. As shown in Figure 20, a min. 300 OT cycles is probably a reasonable number in order to have lower cracking rate for asphalt overlay mixes. Certainly, more field validations are needed.

Table 9. Field Performance Survey: Reflective Cracking Rate (%).

Sections	8/11/2009	4/22/2010	9/8/2010	4/5/2011	OT cycles (from Table 8)
20% RAP-contractor	0	0	34	87	10
0% RAP-contractor	0	0	18	55	50
35% RAP-TTI	0	0	0	27	200
20% RAP-TTI	0	0	4	54	125

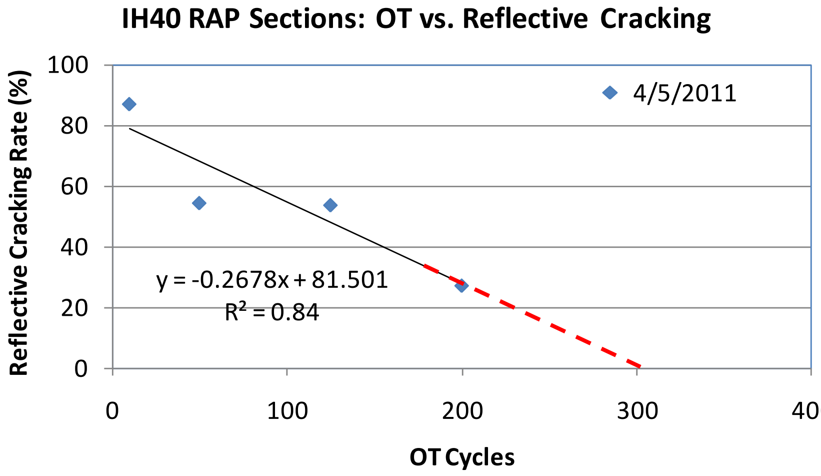

Figure 20. Relationship between OT Cycles and Observed Reflective Cracking Rate.

RAP Test Sections at Pharr, Texas, on FM1017

Three RAP sections were constructed in south Texas on FM1017 near Pharr on April 6, 2010. It was a new construction with a 1.5 in. (37 mm) surface asphalt layer. The three RAP mixes are all dense-graded, fine Type D mixes. Again, two RAP mixes were designed by the contractor using TxDOT's standard mix design procedure, and one mix with 35 percent RAP was designed at TTI following the balanced mix design method. Table 10 presents the mix design information of these three RAP test sections and associated engineering properties. Since the completion of construction, two field surveys have been conducted. Figure 21 shows the pavement conditions of the three RAP sections surveyed on April 12, 2011. So far rutting and cracking has not occurred yet. After reviewing the low OT cycles of these three RAP mixes and comparing with those RAP mixes on IH40, one would wonder why these sections lasted one year without cracking. These three RAP test sections are in complete contrast to those on IH40 described previously, as noted in Table 11. It must also be recalled that a) FM1017 is new construction with a stiff base, b) there is no pre-existing cracks to initiate reflection cracks, c) the traffic is very light on this highway, d) the climate is very mild with no cold weather, and e) this area has received very little rainfall since construction. It is too early to make a conclusion on these three RAP sections on FM1017 because of short period of performance data, and monitoring will continue. However, this section will permit the researchers to evaluate the impact of climate (cold vs. hot), traffic (heavy vs. light), and existing pavement conditions (overlay over cracked pavement vs. new construction) on section performance. It will also provide information on how to establish practical OT criteria for different pavement design conditions.

Table 10. Mix Design Information of the Three RAP Test Sections on FM1017 near Pharr, Texas.

Section	RAP (%)	Virgin binder	Designer	Mix design method	OAC (%)	HWTT rut depth@ 20,000 passes	OT cycles
1	20	PG64-22	Contractor	TxDOT's Tex-204-F	5.0	3.4 mm	2
2	35	PG64-22	TTI	Balanced mix design	6.4	9.3 mm	16
3	0	PG76-22	Contractor	TxDOT's Tex-204-F	4.9	2.2 mm	4

Figure 21. RAP Test Sections on FM1017: None of Rutting and Cracking on April 12, 2011.

Table 11. RAP Sections on FM1017 vs. IH40.

Test section	Climate	Traffic	Construction
RAP sections on FM1017	Very hot	Very light	New construction No existing crack before laying RAP mixes
RAP sections on IH40	Very cold	Extremely heavy	Milling and overlay Severe transverse cracks before the inlay

DISCUSSION

The two series of RAP test sections represent two extremes in terms of climate (cold vs. hot), traffic (heavy vs. light), and applications (overlay vs. new construction). The overall performance of these RAP test sections indicates that high RAP mixes (i.e., 35 percent) can have better or similar performance to virgin mixes as long as they are well designed following a mix design method that has a performance related cracking test. This study proposes the balanced mix design methodology using the Texas Overlay Tester. Additionally, it is important to consider climate, traffic, and applications together when defining acceptable cracking criteria for asphalt mixes. Specifically, asphalt overlay mixes over cracked pavement should have better cracking resistance to retard early reflective cracking and this may not be a major concern for new pavements. This conclusion has also been observed in the NCAT 2006 test track performance results on seven RAP sections were built in 2006, as reported by Kvasnak at the RAP ETG meeting in October 2008 (*24*). The mixes used on the NCAT sections were 1) virgin control mix with PG 67-22, 2) 20 percent RAP with PG 67-22 virgin binder, 3) 20 percent RAP with PG 76-22 virgin binder, 4) 45 percent RAP with PG 52-28 virgin binder, 5) 45 percent RAP with PG 67-22 virgin binder, 6) 45 percent RAP with PG 76-22 virgin binder, and 7) 45 percent RAP with PG 76-22 virgin binder + Sasobit. After two years, 10 million ESALs traffic, only the section with 45 percent RAP mix with PG 76-22 + Sasobit had cracks and all other 6 sections have almost no cracks at all. Further investigation found that the cracks observed were reflective cracking. The RAP test sections under this study and those at NCAT 2006 test track clearly indicate the importance of varying cracking requirement for overlay mixes on cracked pavements and the mixes used for new construction.

CHAPTER 6. SUMMARY AND CONCLUSIONS

This report presents a comprehensive study on high RAP mixes including RAP variability, impact of RAP content on OAC and engineering properties of RAP mixes, and balanced RAP mix design methodology. Two sets of RAP field test sections were constructed to demonstrate and validate the proposed RAP mix design methodology balancing rutting/moisture and cracking requirements. Based on the research presented in this report, the following conclusions are offered.

1. Both TxDOT and contractors' RAP materials, in terms of aggregate gradation and asphalt content, are consistent and have low variability. The standard deviation of the RAP in Texas is lower than the national survey results reported by West (*7*). Therefore it is reasonable to expect that produced RAP mixes will be consistent as well.

2. All three case studies presented in this report clearly indicate that RAP content influences the OAC, rutting/moisture resistance, and cracking resistance. OAC generally increase with more RAP (/RAS) usage, but the increase in OAC is small when RAP content is below 20 percent. Furthermore, increasing RAP content always improves rutting/moisture resistance. Inversely, cracking resistance worsens with use of more RAP, especially when RAP content is 30 percent and above or when RAP/RAS combinations are used.

3. It is also found that there is always a significant increase in OAC when more than 20 percent RAP (or 15% RAP/5% RAS) is used. Meanwhile, use of 10–15 percent RAP, without lowering virgin binder PG grade, has some impact on rutting/moisture and cracking resistance, but the influence is minor compared to RAP contents of 20 percent and above (see Figures 4, 8, and 12). These findings are based on mix rutting/moisture and cracking resistance evaluation and are consistent with the three-tier virgin binder selection concept recommended in AASHTO M 323 (*18*).

4. A balanced RAP mix design methodology is proposed in this study. Recognizing the challenges of calculating accurate VMA of the RAP mix, the authors recommend the use of the OT to directly measure cracking resistance of RAP mixes. The HWTT test is used for evaluating rutting/moisture resistance. Additionally a maximum density of 98 percent is included to avoid over-compaction and possible bleeding. The final balanced asphalt content is selected after optimizing the mix density, HWTT, and OT requirements.

5. Specifically, RAP handling in the lab and the mixing and compaction temperatures for high RAP mixes are also discussed in this report. It is proposed that in the laboratory all mix designs be performed at the temperature specified for the virgin binder. From this study this will provide a higher OAC and hopefully mitigate some of the potential cracking problems.

6. The balanced RAP mix design methodology is demonstrated and validated through the construction of field RAP test sections. One of the interesting findings is that cracking requirement in terms of OT cycles should vary, depending at least on climate (cold vs. hot), traffic level (high vs. low), and existing pavement condition (overlay over cracked pavements vs. new construction). For asphalt overlays over severely cracked pavements, a minimum OT requirement of 300 cycles previously proposed was further validated with performance data from the RAP sections on IH40 near Amarillo, Texas. More work is needed to develop criteria for different climatic zone and different pavement conditions.

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