Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-15/0-6738-2		

4. Title and Subtitle	5. Report Date
PERFORMANCE STUDIES AND FUTURE DIRECTIONS FOR MIXES CONTAINING RAP/RAS: TECHNICAL REPORT	Published: February 2016
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Soohyok Im, Sheng Hu, and Fujie Zhou	Report 0-6738-2
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Texas A&M Transportation Institute College Station, Texas 77843-3135	11. Contract or Grant No. Project 0-6738
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Implementation Office 125 E. 11th Street Austin, Texas 78701-2483	Technical Report: September 2012–August 2015
	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 Studies and Future Directions for Mixes Containing RAP and RAS

URL: http://tti.tamu.edu/documents/0-6738-2.pdf

16. Abstract

In the last several years reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) have been widely used in asphalt mixes in Texas. The use of RAP/RAS can significantly reduce the initial cost of asphalt mixtures, conserve energy, and protect the environment. There are always two main concerns: variability of RAP/RAS and durability (or cracking) of RAP/RAS mixes. Past studies in Texas have clearly indicated that both RAP and RAS have acceptable variability following the best practices for handling RAP/RAS.

This study focused on the durability problems of RAP/RAS asphalt mixes. First, extensive laboratory tests were performed to investigate the impacts of RAP/RAS on the durability of RAP/RAS blended binders and asphalt mixes. Second, a field survey on test sections with RAP/RAS mixes was conducted to identify how significant RAP/RAS are and which approach to improve the durability problems of mixes. Third, a pavement life cycling cost analysis on RAP/RAS mixes was conducted to investigate the financial benefits of them. Finally, the findings, conclusions, and recommendations for RAP/RAS mixes are made.

17. Key Words	18. Distribution Statement
Reclaimed Asphalt Pavement, Recycled Asphalt Shingles, Asphalt Mix Design, Field Performance	No restrictions. This document is available to the public through NTIS: National Technical Information Service Alexandria, Virginia http://www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	124	

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

PERFORMANCE STUDIES AND FUTURE DIRECTIONS FOR MIXES CONTAINING RAP AND RAS: TECHNICAL REPORT

by

Soohyok Im
Assistant Transportation Researcher
Texas A&M Transportation Institute

Sheng Hu
Associate Research Engineer
Texas A&M Transportation Institute

and

Fujie Zhou
Research Engineer
Texas A&M Transportation Institute

Report 0-6738-2
Project 0-6738
Project Title: Performance Studies and Future Directions for Mixes Containing RAP and RAS

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

Published: February 2016

TEXAS A&M TRANSPORTATION INSTITUTE
College Station, Texas 77843-3135

DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Dr. Fujie Zhou, P.E. (Texas, #95969).

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 State of America or any foreign country.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The authors thank the many personnel who contributed to the coordination and accomplishment of the work presented herein. Special thanks are extended to Mr. Darrin Jensen for serving the project manager and Mr. Robert Lee, P.E., for serving the technical point person. Many people volunteered their time to serve as project advisors, including:

- Larry Coyle, P.E.
- Jason Duncan, P.E.
- Tom Hunter, P.E.
- Chad Ingram, P.E.
- Scot Reaves, P.E.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

CHAPTER 1
INTRODUCTION

The asphalt paving industry has always advocated recycling, including reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), tires, etc. In addition to conserving energy and protecting the environment, the use of recycled material can significantly reduce the asphalt paving cost. The earliest recycling of asphalt pavement dates back to 1915, as noted by Kandhal and Mallick (*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 a result of the oil embargo. Many recent studies (*2–7*) have been made to better use RAP in HMA and warm-mix asphalt (WMA). Furthermore, historical data (*6*) showed that the RAP mixes, when properly designed and constructed, could have the same or similar performance as virgin HMA mixes. A fine example is the RAP asphalt overlay sections on US175 near Dallas, Texas, which were part of the 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 (*8*). In addition to RAP, RAS including both tear-off (TOAS) and manufacture waste asphalt shingles (MWAS) have also been used in asphalt pavement construction in recent years (*9–16*).

Additionally, RAP/RAS 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. Similarly, RAS is being grinded finer and finer. Also, asphalt mix plants are better able to handle higher amounts of RAP/RAS without detrimental effects. As a result, it is now possible to produce quality asphalt mixes containing higher RAP/RAS.

However, a recent survey indicates that the average RAP usage in new asphalt mixes is 12 to 15 percent (*17*), and in most cases the maximum allowable RAS usage is 5 percent. Many states, including Texas, have upper limits on use of RAP/RAS in asphalt mixes mainly due to two major concerns:

- RAP/RAS variability.
- Premature cracking of RAP/RAS mixes (as a result of the stiff RAP/RAS binder and the lack of a rational RAP mix design method).

To address these concerns, in 2008, the Texas Department of Transportation (TxDOT) initiated research studies at the Texas A&M Transportation Institute (TTI) on RAP and later another study on RAS:

- Project 0-6092: Performance Evaluation and Mix Design for High RAP Mixtures.
- Project 0-6614: Use of Recycled Asphalt Shingles in HMA.

These two studies clearly showed that the processed RAP and RAS materials have low variability in terms of asphalt binder content and aggregate gradation (*18, 19*). This study focuses on the durability problems of RAP/RAS asphalt mixes. This report presents laboratory test results of RAP/RAS blended binders and asphalt mixes, field performance of test sections, life cycle cost analysis (LCCA) on RAP/RAS mixes, and recommendations for RAP/RAS mixes.

Following the current introduction, Chapter 2 presents a review of the field performance of RAP/RAS mixes in Texas and other states, which strongly supports the necessity of establishing a mix design and performance evaluation system for project-specific service conditions. Chapter 3 documents laboratory test results of RAP/RAS blended binders and asphalt mixes. Chapter 4 describes developed laboratory aging protocols for RAP/RAS mixes. Chapter 5 presents the field performance results of various test sections, including a forensic study. Chapter 6 shows a pavement LCCA of each approach improving durability of RAS/RAP mixes based on laboratory test results. Chapter 7 recommends effective approaches for improving RAP/RAS mixes. Finally, Chapter 8 summarizes the findings and conclusions.

CHAPTER 2
LITERATURE REVIEW

In the last few years, TxDOT districts have widely used RAP and RAS in asphalt mixes since they can significantly reduce the initial cost of asphalt mixtures, conserve energy, and protect the environment. However, there is substantial speculation that the recent introduction of higher RAP and RAS contents to TxDOT's Item 341 mixes has had a negative impact on the life of HMA overlays. The Houston District commented that the average overlay life now appears to be less than 5 years, whereas in the past they counted on at least 8 years for a new overlay. No hard data are available to substantiate these claims. As TxDOT moves into more and more RAP/RAS usage with different mix types (i.e., stone matrix asphalt [SMA], fine PFC, Superpave), it is necessary to learn from the experiences of the past 3 to 4 years and then define new directions to best use the black gold in the mixes for pavement construction. The following sections will discuss several aspects of RAP/RAS mixes that will help define future directions.

- Characterization of RAP/RAS properties and binder blending.
- Field performance of RAP/RAS mixes.
- Approaches to improving durability of RAP/RAS mixes in terms of mix design.

CHARACTERIZATION OF RAP/RAS PROPERTIES AND BINDER BLENDING

Characterization of RAP/RAS Properties

Extensive studies have been conducted under Projects 0-6092 and 0-6614 to characterize RAP/RAS properties, including RAP/RAS variability. RAP/RAS stockpiles have been sampled around the state, and the laboratory test results showed that both fractionated RAP and the processed RAS are consistent in terms of aggregate gradation and asphalt binder content. Additionally, the binder was extracted and recovered from RAP/RAS. The main concern is the stiffness of the RAP/RAS binder, which is very variable. The high end of performance grade (PG) of RAP binders ranges from 82 to 115°C. The biggest concern is the RAS binder (Figure 1). Apparently, it is very challenging to design mixes with such stiff RAS materials. Either softening agents or rejuvenators should be considered to lower the PG of RAS binder.

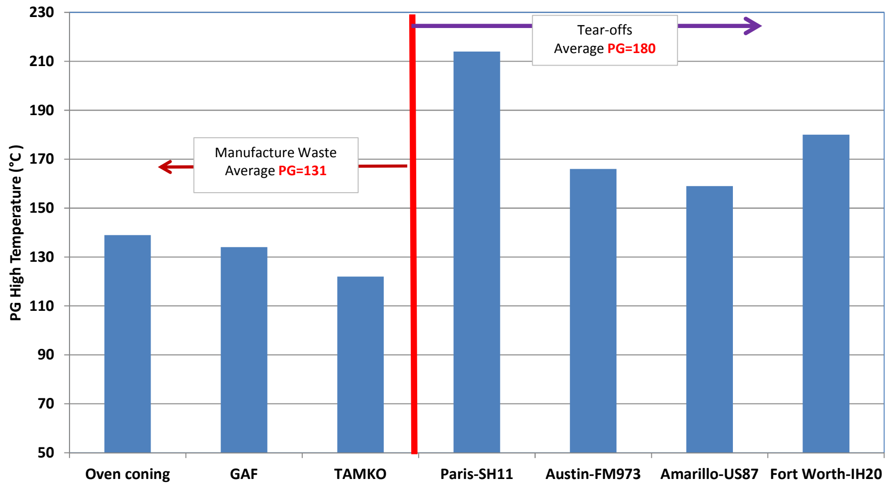


Figure 1. Dynamic Shear Rheometer Test Results of RAS Binders.

RAP/RAS and Virgin Binder Blending

One of the concerns with using RAP/RAS mixes is the effect of the RAP/RAS binder on the PG of the total combined binder. One of the approaches to addressing this concern is to develop a blending chart between RAP/RAS binder and the virgin binder. Although the blending chart will not represent what is happening between RAP/RAS binder and virgin binder during plant production, it does provide some guidelines for determining maximum allowable RAP/RAS binder in the mix. McDaniel and Anderson (*4*) proposed a linear blending chart for RAP binder and virgin binder under the National Cooperative Highway Research Program 9-12. Recently, Zhou et al. under Project 0-6092 verified the linear blending chart using Texas RAP and virgin binders. Figure 2 shows an example of blending between a RAP binder (PG115-3) and a virgin PG64-22 binder. In this case, the lower PG end will not meet PGXX-22 requirement if 20 percent RAP binder is blended with a PG64-22 binder. To keep −22°C as the lower end, there are at least three options: 1) use less RAP binder (say 15 percent), 2) select softer virgin binder (say PGXX-28), and 3) increase design density and indirectly increase the virgin binder content/reduce RAP binder. Note that the case shown in Figure 2 will be the worst scenario because normally the RAP binder is much softer than RAP binder PG115-3.

The study on RAS, compared to RAP, is very limited. There is no published study on the blending between RAS binder and virgin binder. TxDOT's Project 0-6614 is the first project to investigate the RAS/virgin binder blending. One of the difficulties in this area is to grade the extracted RAS binder. RAS binder is so stiff that regular dynamic shear rheometer (DSR) and the bending beam rheometer (BBR) cannot grade it. TTI specifically purchased a high-temperature DSR for characterizing RAS binder and evaluating the blending between the RAS binder and virgin binder and is in the process of buying a new asphalt binder cracking device. So far the results clearly indicated that the blending between RAS binder and virgin binder is not linear blending (Figure 3). Again, 20 percent RAS binder will disqualify the combined binder from meeting the PGXX-22.

Current study on binder blending under Projects 0-6092 and 0-6614 needs to consider the impact of WMA technologies. The WMA technologies will lead to more challenges for blending due to the lower temperature, which should be investigated. Also, the investigation should focus on plant mixes.

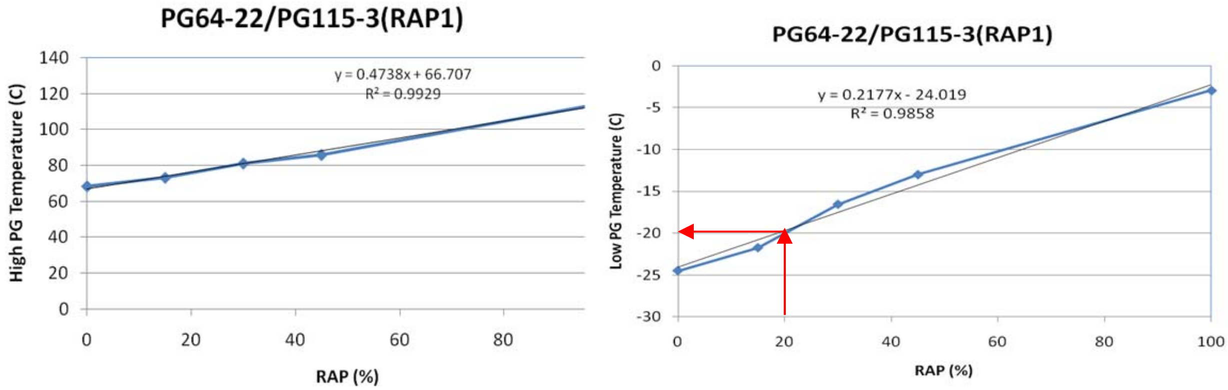


Figure 2. Linear Blending Chart between RAP Binder and Virgin Binder.

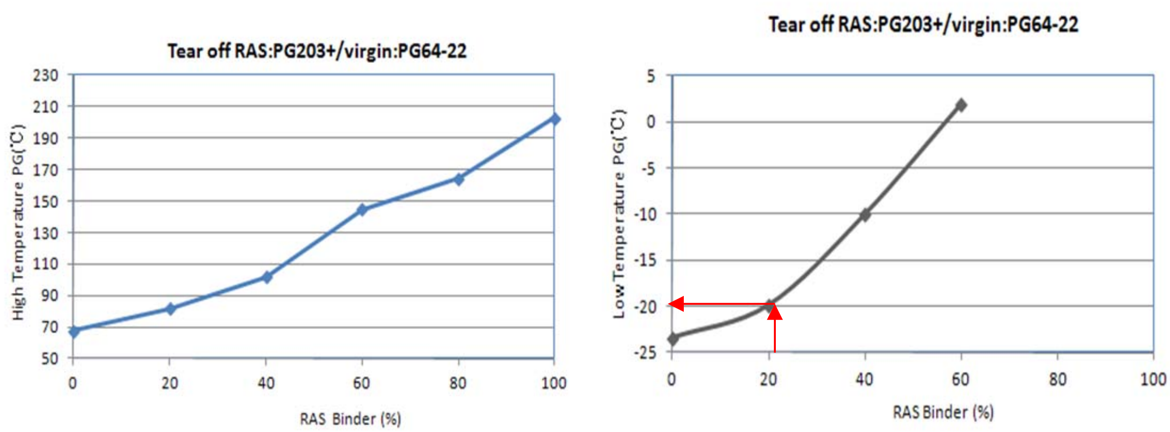


Figure 3. Blending Chart between a Tear-off RAS Binder and a PG64-22 Virgin Binder.

FIELD PERFORMANCE OF RAP/RAS MIXES

Field performance is what pavement engineers and users really care about, regardless of the use of RAP/RAS/WMA or not. It is critical to identify the real field performance of RAP/RAS/WMA mixes. Detailed information on field performance is described below.

Field Performance of RAS Test Sections under the National Pooled Fund Study TPF-5(213): "Performance of Recycled Asphalt Shingles (RAS) in Hot Mix Asphalt"

In the last several years, there has been an ongoing national pooled fund study, TPF-5(213): "Performance of Recycled Asphalt Shingles (RAS) in Hot Mix Asphalt" conducted by Chris Williams at the Iowa State University. The primary goal of TPF-5(213) is to determine the best practices for the use of RAS in asphalt applications. One of the tasks is to construct demonstration projects in the participating states. The available performance data of a portion of the demonstration projects are described as follows.

Minnesota Department of Transportation (DOT) Demonstration Project (20)

The Minnesota demonstration project is located at the MnRoad Cold Weather Road Research Facility in Albertville, Minnesota. The project is 3.5-miles long with 18 test sections on the passing and driving shoulders of the westbound IH94 mainline. Figure 4 shows a plan view of test cells. Mix laid down in Cell 20 contains 30 percent RAP and serves as the control section. Mixes of Cells 5, 6, 13, and 14 contain 5 percent manufacture waste RAS. Mixes of Cells 15 to 23 contain 5 percent post-consumer (or tear-off) RAS. Each cell is 500 ft long including a 50-ft transition area. All cells are 3-in. thick with a granular base, except Cell 5 is paved on top of an HMA base. Construction of test sections was completed in September 2008.

The Minnesota demonstration project used a 12.5 mm (0.5 in.) nominal maximum aggregate size (NMAS) aggregate gradation for all test mixes. The gradations of mixes containing 5 percent RAS are similar to each other. The control mix gradation contains more coarse aggregates than the mixes containing RAS. The asphalt content is 17.1 percent for the manufactured RAS and 23 percent for the tear-off RAS. The RAP used in the control section has an asphalt content of 6 percent. The total design asphalt content for all mixes is 5 percent. The same PG58-28 virgin binder was used for all 34 test sections. Table 1 shows more mix design information.

Figure 5 shows field performance of these RAP/RAS mixes on MnRoad. Several interesting observations are made:

- The 30 percent RAP mix, compared with mixes with RAS, has the best performance in terms of transverse cracking, although it has the highest binder replacement (33.4 percent).
- The existing pavement structure (before asphalt overlay) has significant influence on cracking performance. Cell 15 with jointed plain concrete pavement has the longest transverse cracking.

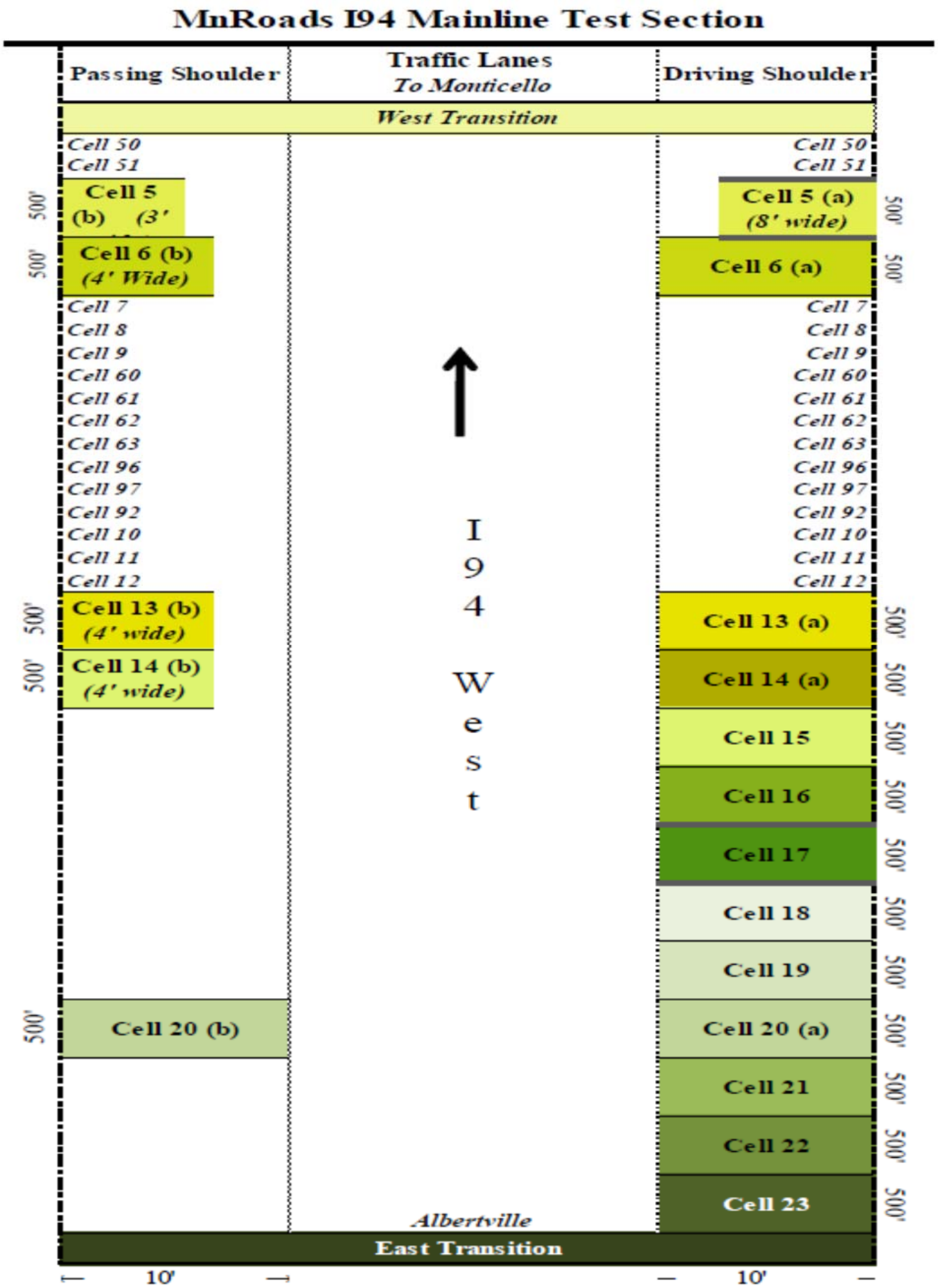


Figure 4. Plan View of MnRoad Test Cells (*20*).

Table 1. Mix Design Information on MnRoad RAP/RAS Mixes (*21*).

Mix properties	30% RAP	5% post-manufacture	5% post-consumer
%RAS	0	5	5
%RAP	30	0	0
%Total asphalt content from QC results	5.3	4.9	5.0
%Binder replacement	33.4	14.9	20.5
RAS source	N/A	Manufacture waste	Post-consumer
RAS grind size	N/A	<12.5mm	<9.5mm
N_{design}	90	90	90
NMAS (mm)	12.5	12.5	12.5
Virgin PG	PG58-28	PG58-28	PG58-28

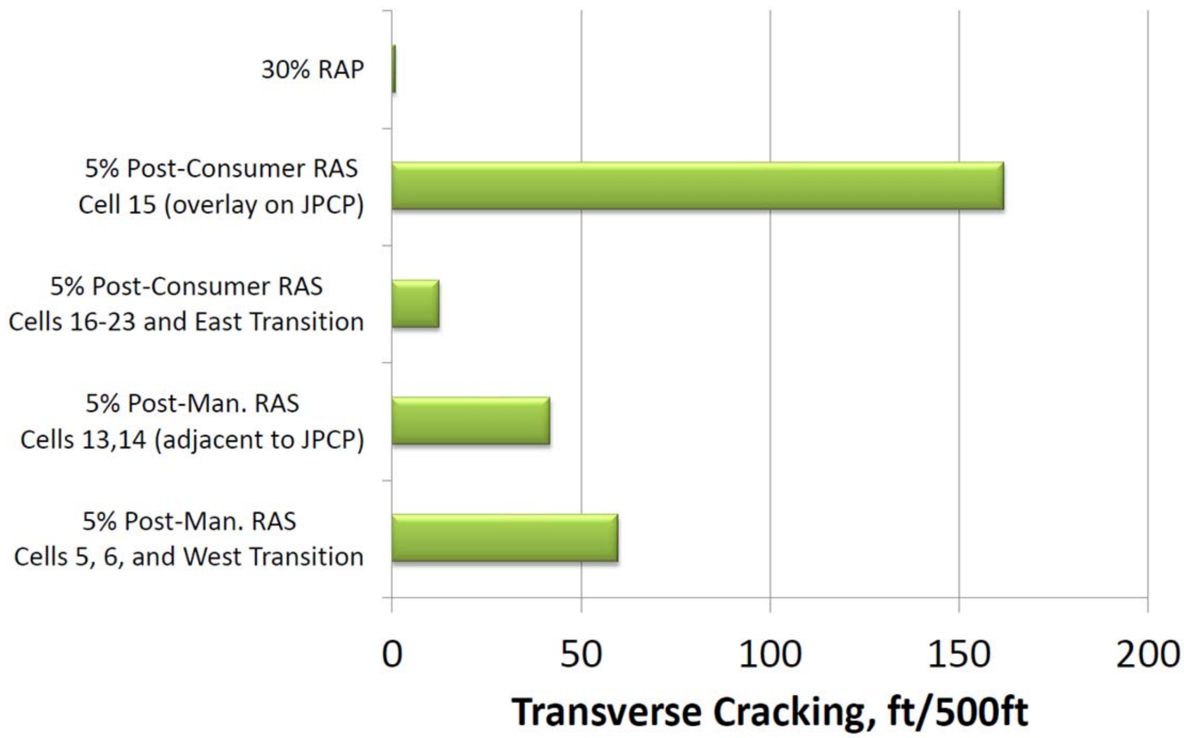


Figure 5. Cracking Performance of RAP/RAS Mixes on MnRoad (*21*).

RAS Test Sections of Iowa DOT Demonstration Project

The Iowa DOT demonstration project is located on Highway 10 west of Paullina, Iowa. The project was constructed in June and July 2010. The total project is 32.5 lane miles including four test sections. Every test section has a 2-in. thick surface course with an underlying granular base. Figure 6 shows a plan view of the RAS test sections. The mixes were designed with the same aggregate gradations and virgin binders, but different RAS contents ranging from 0 percent to 6 percent. Table 2 lists detailed mix design information. Figure 7 shows the observed transverse cracking data. There is no difference among these four test sections in terms of transverse cracking.

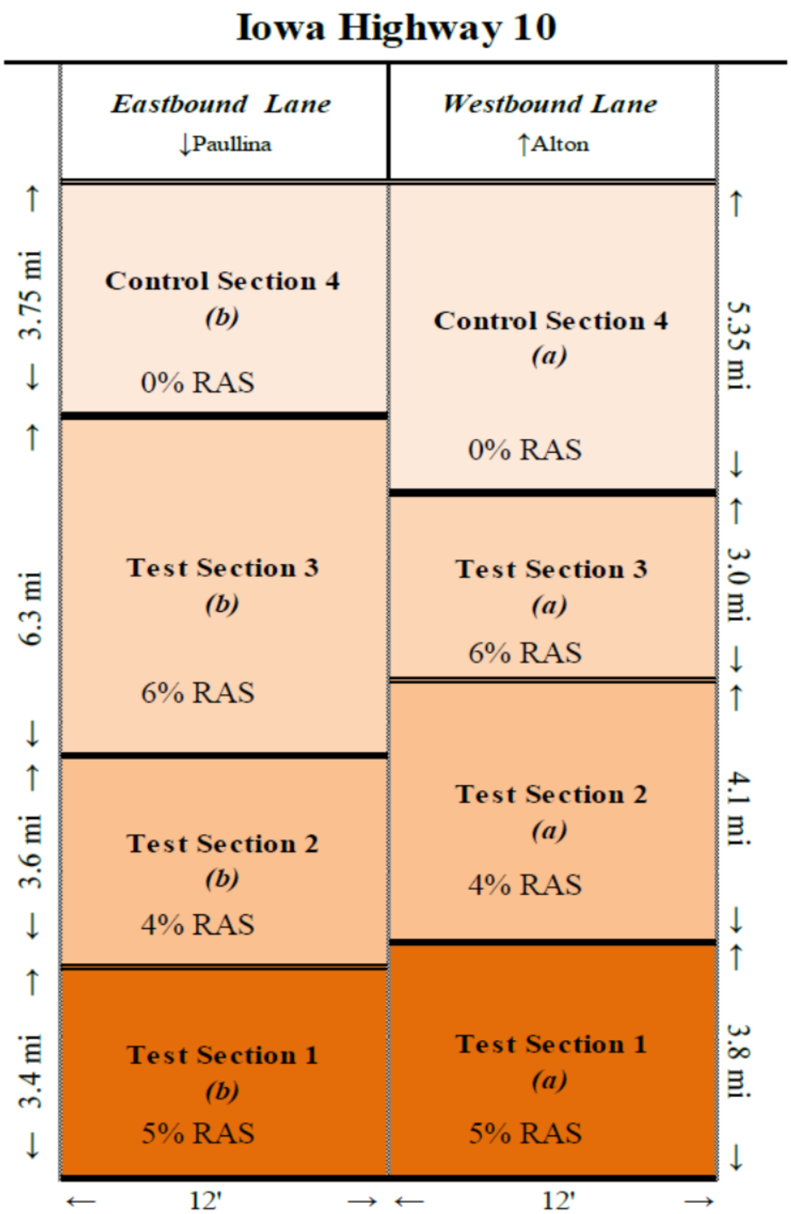


Figure 6. Plan View of Iowa Demonstration Project Test Sections (*20*).

Table 2. Mix Design Information of Test Sections on Highway 10, Iowa (*21*).

Mix properties	Section 1	Section 2	Section 3	Section 4
%RAS	5	4	6	0
%RAP	0	0	0	0
%Total asphalt content from QC results	5.5	5.4	5.5	5.4
%Binder replacement	17.5	15.1	19.8	0
RAS source	Tear-offs			
RAS grind size	<12.5			
N_{design}	76			
NMAS (mm)	12.5			
Virgin PG	PG64-22			

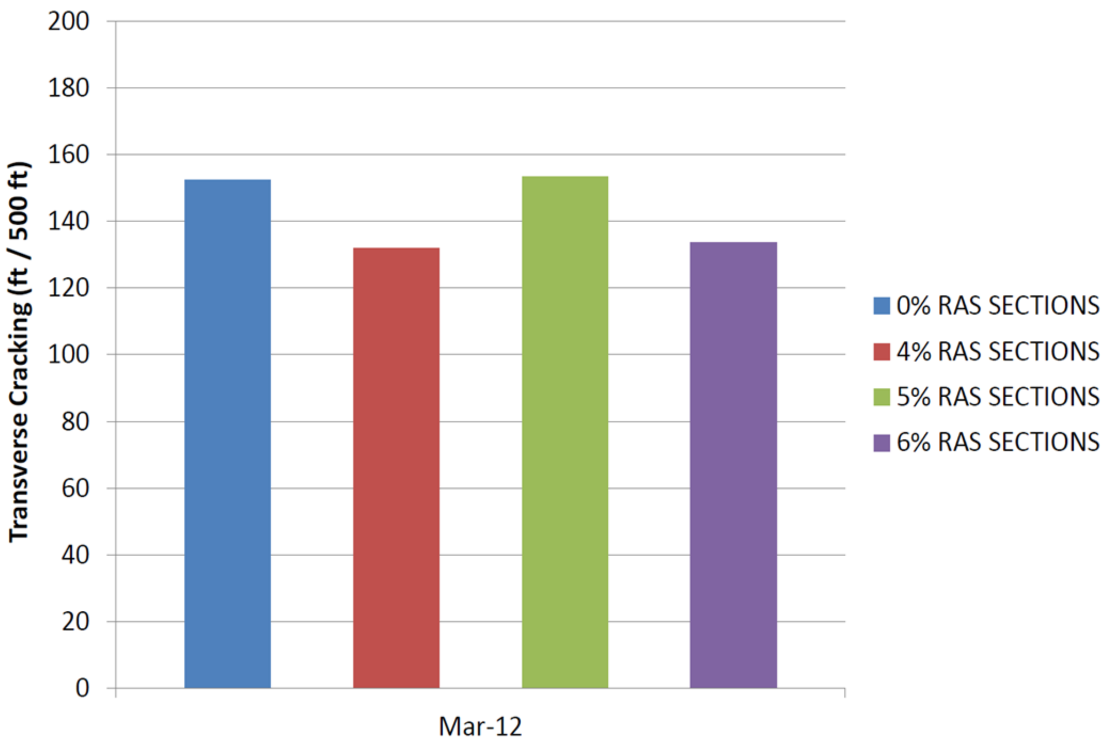


Figure 7. Observed Transverse Cracking on Field Test Sections in March 2012, Iowa (*21*).

Missouri DOT Demonstration Project

The Missouri DOT constructed the demonstration project in May and June 2010. The 8.8-mile project is located on US Route 65 south of Springfield, Missouri. The total project is 17.6 lane miles with a 3.75-in. surface layer under laid by a concrete pavement. The Missouri DOT developed this demonstration project to study the influences of RAS grind size on pavement performance and the economic feasibility of incorporating ground tire rubber (GTR) and asphalt mixes containing RAS and RAP. Figure 8 shows three paved test sections. A PG64-22 asphalt was selected as the virgin binder. The virgin binder was modified with GTR and a vestenamer polymer to achieve a 70-22 performance grade. The control section contains 15 percent RAP and 0 percent RAS. Section 2 contains 5 percent fine ground RAS in which 100 percent of the RAS particles pass the ¾-in. sieve and 95 percent of the particles pass the #4 sieve. Section 3 contains 5 percent coarse ground RAS in which 100 percent of the RAS particles pass the 1/2-in. sieve. Both Sections 2 and 3 contain 10 percent RAP so that all mixes have 15 percent recycled materials. The same aggregate gradations were designed for the three test sections. The design asphalt content was 5.3 percent. Test sections containing 5 percent RAS used 3.7 virgin binder content to achieve the design binder content. Table 3 shows more information about these three mixes. Figure 9 shows the observed transverse cracking development of each test sections. Clearly, the control section with 15 percent RAP has the least transverse cracking.

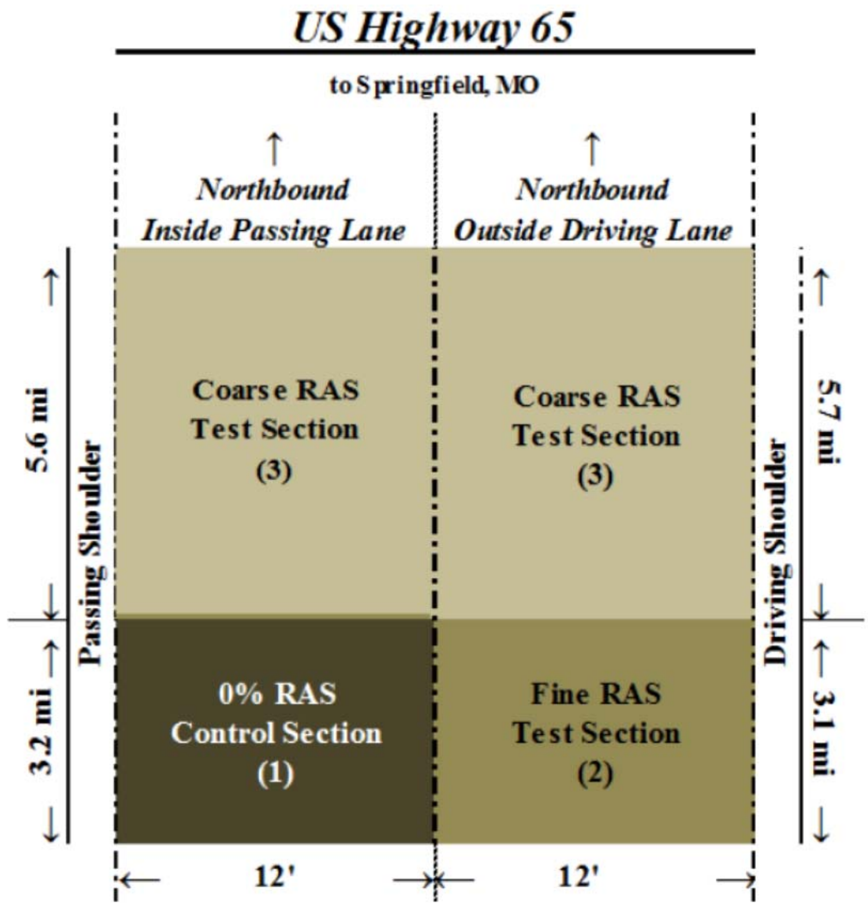


Figure 8. Plan View of Missouri Demonstration Project Test Sections (*20*).

Table 3. Mix Design Information of Test Sections on Highway 65, Missouri (*21*).

Mix properties	Section 1	Section 2	Section 3
%RAS	0	5	5
%RAP	15	10	10
%Total asphalt content from QC results	4.7	5.3	5.3
%Binder replacement	19.1	30.2	30.2
RAS source	N/A	Tear-offs	Tear-offs
RAS grind size	N/A	<9.5	<12.5
N_{design}	80	80	80
NMAS (mm)	12.5	12.5	12.5
Virgin PG	PG64-22	PG64-22	PG64-22
%GTR by wt. of asphalt content	10	10	10

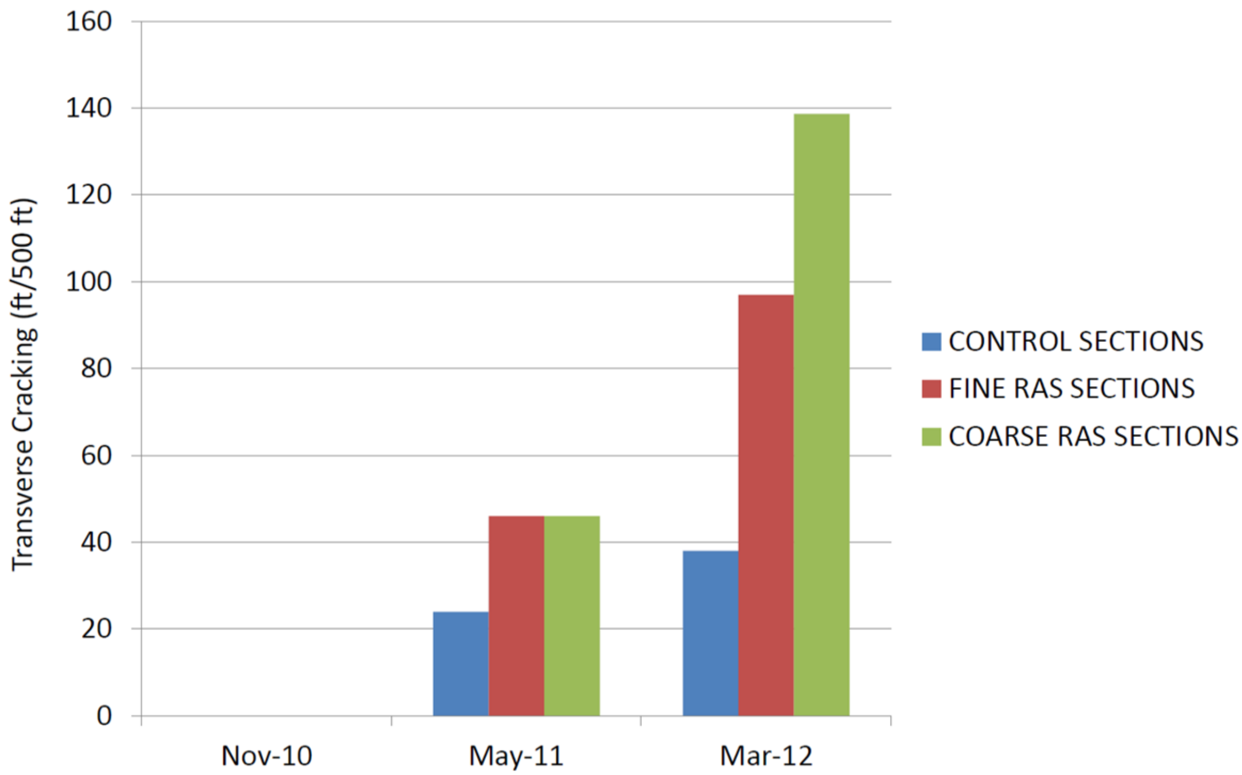


Figure 9. Observed Transverse Cracking on Highway 65, Missouri (*21*).

Indiana DOT Demonstration Project

The Indiana DOT demonstration project was completed in July 2009. The project is located on US Route 6 east of Nappanee, Indiana. The overall construction is 13.6 lane miles. A 1.5-in. surface layer was placed on top of a previously existing asphalt surface with an underlying concrete pavement. The Indiana DOT developed the demonstration project to evaluate the performance of incorporation of RAS and WMA in asphalt concrete (AC) pavements. They constructed three test sections (Figure 10). The control section used an HMA containing 15 percent fractionated RAP. Test section 2 used the same HMA with 3 percent RAS. A foaming method was applied to produce WMA that is laid down in test section 3. Test section 3 also contains 3 percent RAS. A PG70-22 asphalt was selected as the virgin binder. The design binder content was 6.2 percent. Test sections containing 3 percent RAS used 5.4 percent virgin binder content to achieve the design total binder content. Table 4 provides more information about these three mixes. Figure 11 shows the observed transverse cracking development of each test section. Clearly, the foaming WMA technology did not help improve performance of the RAS mix. The 15 percent RAP mix with 0.5 percent less asphalt binder performed similar to the two RAS mixes with 6.2 percent total asphalt content.

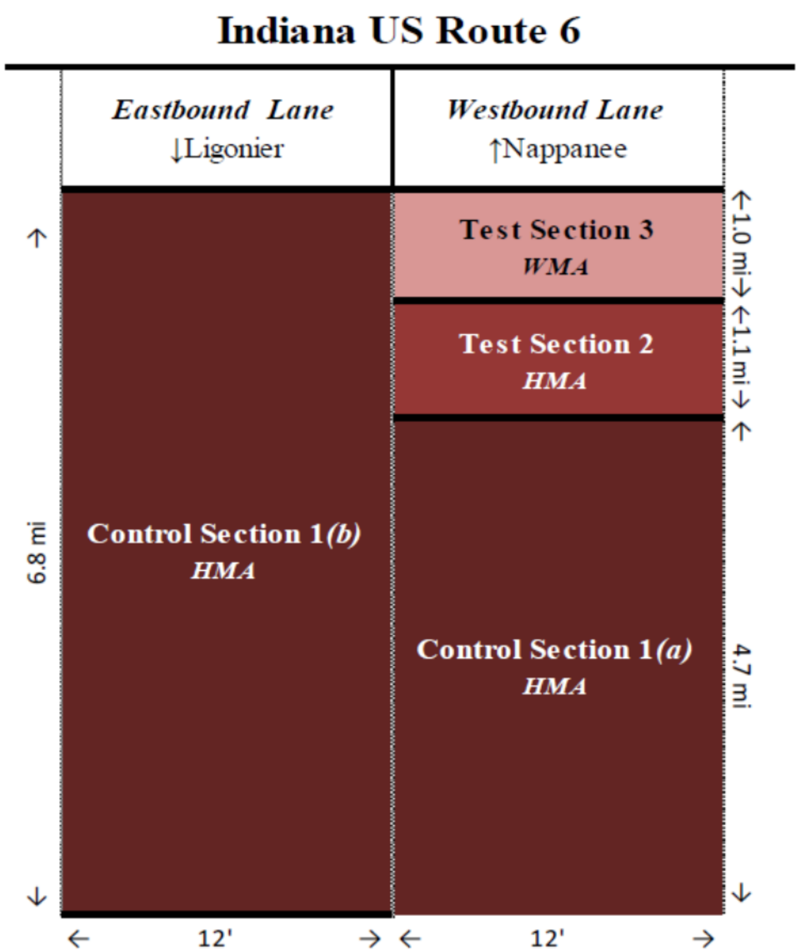


Figure 10. Plan View of Indiana Demonstration Project Test Sections (*20*).

Table 4. Mix Design Information of Test Sections on US Route 6, Indiana (*21*).

Mix properties	**Section 1**	**Section 2**	**Section 3**
%RAS	0	3	3
%RAP	15	0	0
%Total asphalt content from QC results	5.7	6.2	6.2
%Binder replacement	18.0	12.6	12.6
RAS source	N/A	Tear-offs	Tear-offs
RAS grind size	N/A	<12.5	<12.5
N_{design}	100	100	100
NMAS (mm)	12.5	12.5	12.5
Virgin PG	PG70-22	PG70-22	PG70-22
Foaming WMA	No	No	Yes

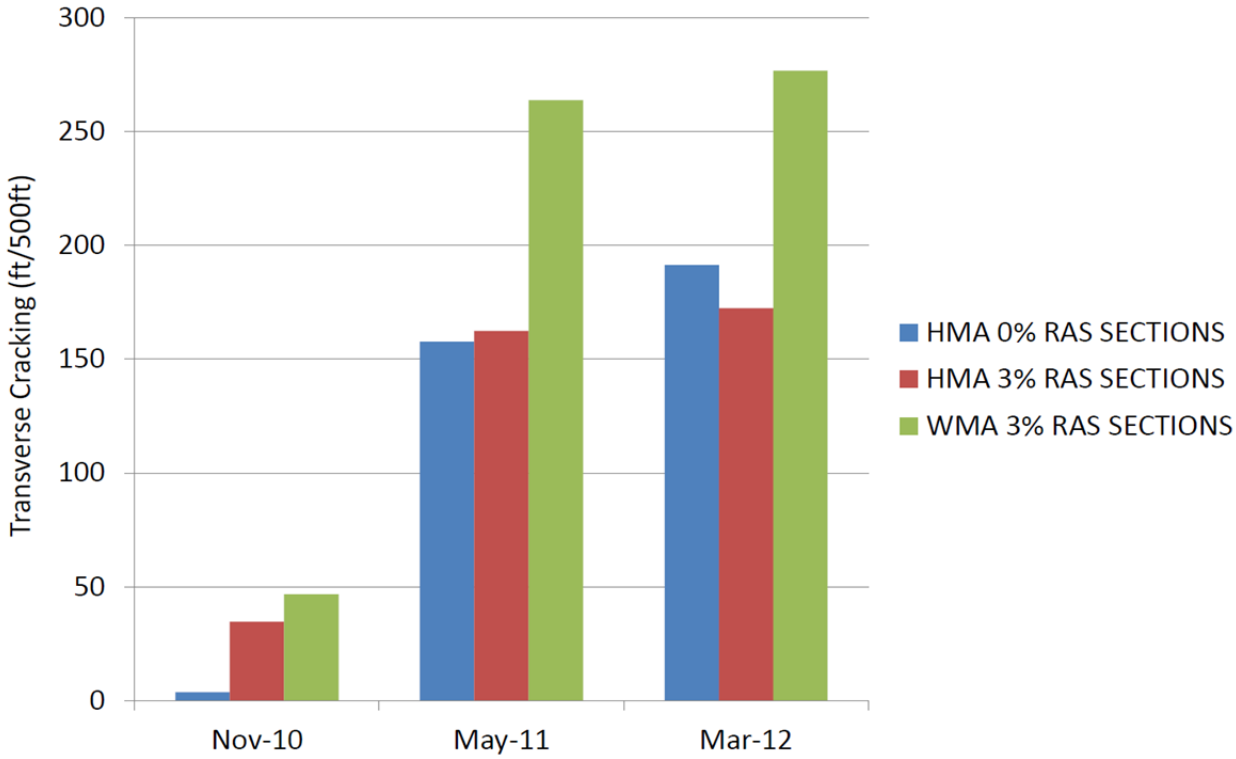


Figure 11. Observed Transverse Cracking on US Route 6, Indiana (*21*).

Other Performance Data of RAP Mixes in the Literature

RAP/RAS mixes are generally stiffer than virgin mixes. So, RAP/RAS mixes are more rutting resistant, but they will be prone to cracking, which is consistent with the findings in Texas and North America.

Recently, West et al. (*22*) compared the performance of RAP mixes with virgin mixes. They reviewed asphalt overlay sections of specific pavement studies experiment 5 (SPS5) built in a total of 18 states and provinces in North America between 1989 and 1998. Seven distress parameters from these test pavements were analyzed, including international roughness index (IRI), rutting, fatigue cracking, longitudinal cracking, transverse cracking, block cracking, and raveling. West et al. found that:

1. Overlays with mixes that contained 30 percent RAP performed as well as overlays with virgin mixes in terms of IRI, rutting, block cracking, and raveling.
2. In terms of fatigue cracking and transverse (reflective) cracking, virgin mixes edged the 30 percent RAP mixes.
3. Thicker overlays improved pavement performance, except for rutting. Milling before rehabilitation decreased IRI, fatigue cracking, and transverse cracking but increased rutting.

Hong et al. (*8*) specifically reviewed the SPS5 asphalt overlay sections on US175 near Dallas. They observed similar findings:

1. With everything else the same, an asphalt overlay with 35 percent RAP mix has half of the life of an overlay with virgin mix in terms of transverse (reflective) cracking.
2. In terms of rutting, 35 percent RAP mix is more rut resistant, and its rut depth is 70 percent that of the virgin mix.
3. If well designed (i.e., using 3 percent latex on US175), 35 percent RAP mixes can perform similar to the virgin mixes.

APPROACHES TO IMPROVING DURABILITY OF RAP/RAS MIXES IN TERMS OF MIX DESIGN

The use of RAP/RAS in asphalt mixes has generally improved rutting resistance of the mixes. Meanwhile, it results in negative effects on cracking resistance of the mixes and, consequently, on the durability of asphalt mixes. At least five approaches have been tried to improve cracking resistance of RAP/RAS mixes, as noted below:

- Reducing RAP/RAS usage (or binder replacement amount).
- Increasing design density (lowering design air voids) or reducing N_{design}.
- Using soft virgin binders especially on the low-temperature grade (i.e., PGXX-28, PGXX-34).
- Rejuvenating RAP/RAS binder.
- Combining RAP/RAS with WMA technologies.

More detailed information on each approach is described in the following text.

Reducing RAP/RAS Usage

Naturally, the first choice is to reduce the maximum amount of RAP/RAS allowed in asphalt mixes. The laboratory test results from Project 0-6092 clearly indicated that reducing RAP amount can improve cracking resistance (*23*). When RAP content is below 15 percent, the impact of RAP on cracking resistance of mixes is negligible. It is useful to improve cracking resistance of mixes containing RAP through reducing RAP usage. However, the finding from Project 0-6614 is that reducing RAS usage from 5 percent to 3 percent did not have significant improvement on cracking resistance (*7*). Further reducing the RAS amount to below 3 percent may be helpful to improve cracking resistance of mixes containing RAS, but it does not make much sense in terms of recycling itself. Reducing RAP/RAS usage can generally improve cracking resistance of RAP/RAS mixes. Actually, TxDOT already implemented this approach in the new specification. Under TxDOT's new specification, the maximum amount of recycled binder replacement allowed has been reduced to 30 percent from the previous 35 percent for surface mixes.

Increasing Design Density (or Reducing N_{design})

Another simple way to improve cracking resistance of RAP/RAS mixes is to add more virgin binder into the mixes through increasing design density (or lowering the design air voids) when selecting optimum asphalt content (OAC). Both laboratory and field test sections indicated that this is an effective method. Again, TxDOT already has adopted this approach in the specification. For example, the new specification increases the design density for RAP/RAS mix to 97 percent from 96 percent for dense-grade mixes. Since RAS binder is far stiffer than RAP binder, the RAS mixes can be designed at an even higher density, such as 97.5 percent.

One potential problem with increasing design density is field quality control and a compaction penalty or bonus. Currently, quality control and compaction penalty or bonus are established based on a design density of 96 percent. If the design density is extended too much, the whole quality control and compaction penalty or bonus system has to be re-established. The design density cannot be increased too far away from 97.5 percent.

Using Soft Virgin Binders

Under Projects 0-6092 and 0-6614, researchers investigated the benefit of using soft binders to improve cracking resistance of RAP/RAS mixes. Detailed information is provided as follows.

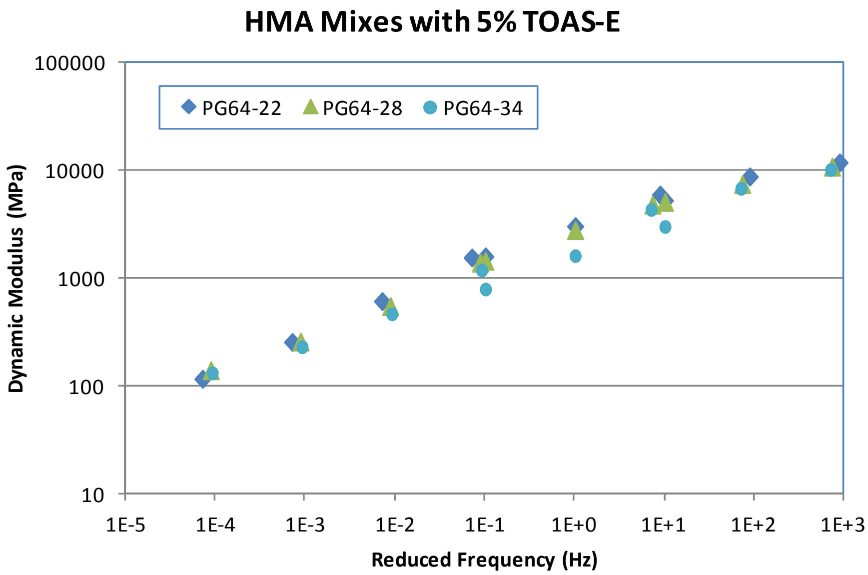
Impact of Soft Binder on RAP Mixes

A dense-graded Type C mix with PG64-22 binder and 5 percent RAS was used to evaluate the impact of soft binder on RAS mix properties. This Type C mix is a real mix placed on Section 4 of field test sections on FM973, and its design asphalt content is 5.2 percent. In addition to the virgin binder PG64-22, two more soft binders: PG64-28 and PG64-34 are evaluated here. Furthermore, two types of RAS, TOAS-E and MWAS-C, are included. A total of six mixes (two RAS and three virgin binders) listed in Table 5 were evaluated under a dynamic modulus test (American Association of State Highway and Transportation Officials [AASHTO] TP79), the Hamburg wheel tracking test (HWTT) (Tex-242-F), and Overlay Test (OT) (Tex-248-F). Note that the same 5.2 percent OAC was used for all six mixes, since the purpose is to investigate the influence of soft binders. Figure 12, Figure 13, and Figure 14 show the test results.

Table 5. RAS Mixes with Soft Virgin Binders.

RAS	5%RAS/PG64-22	5%RAS/PG64-28	5%RAS/PG64-34
TOAS-E	X	X	X
MWAS-C	X	X	X

Figure 12 shows that RAS mixes with softer binders have slightly lower moduli, but the difference among these six mixes is very small in terms of dynamic modulus. Meanwhile, compared with the 5 percent RAS/PG64-22 mix, the use of softer binders improved rutting/moisture damage, as indicated in Figure 13. The reason for the improvement is that both PG64-28 and PG64-34 are polymer-modified binders. As expected, the mixes with the MWAS-C have deeper rut depth than those with TOAS-E. Figure 14 clearly indicated that it is effective to improve cracking resistance of RAS mixes using soft virgin binders. For the cases presented here, one grade (−6°C) lower can triple the OT cycles of RAS mixes. Additionally, the mixes with the MWAS-C always have better cracking life than those with the TOAS-E. In summary, the use of soft binders has not much impact on dynamic moduli of RAS mixes, but it can improve both rutting and cracking resistance of RAS mixes, especially on cracking resistance.



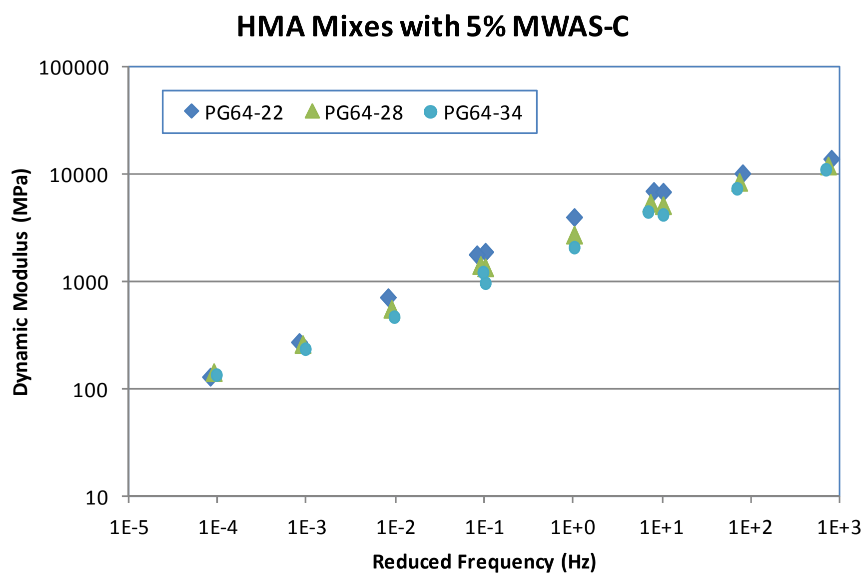


Figure 12. Impact of Soft Binders on Dynamic Modulus of 5 Percent RAS Mixes.

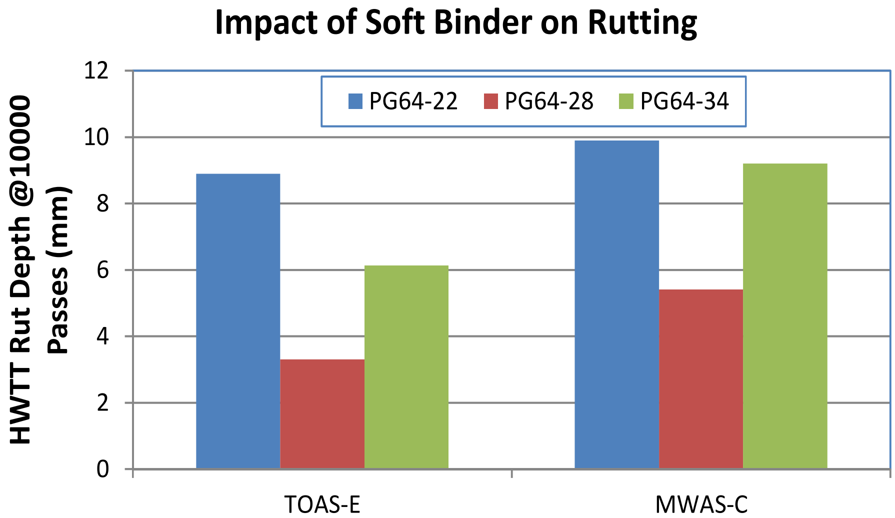


Figure 13. Impact of Soft Binders on Rutting/Moisture Damage of 5 Percent RAS Mixes.

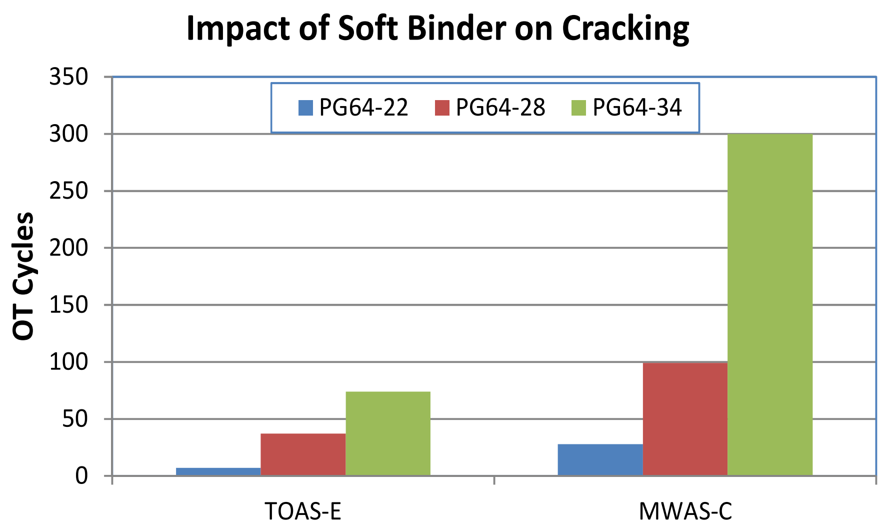
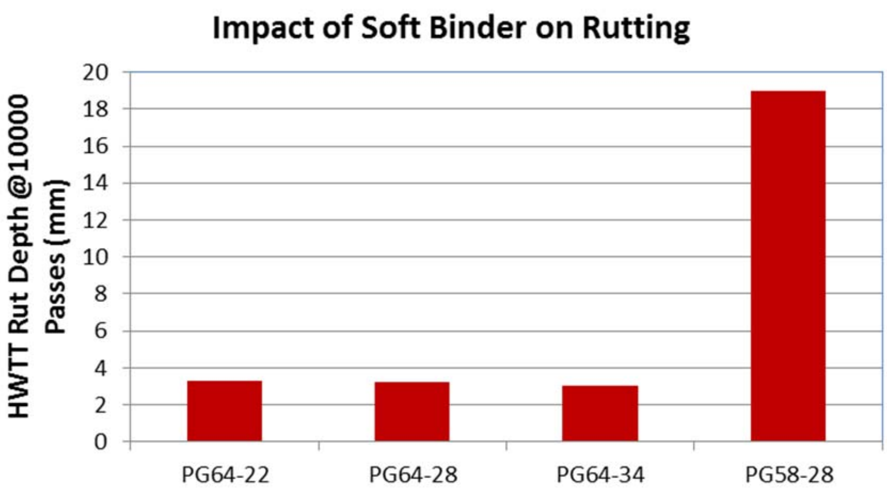


Figure 14. Impact of Soft Binder on Cracking Resistance of 5 Percent RAS Mixes.

Impact of Soft Binders on RAP Mix Properties

A dense-graded Type D mix with 15 percent RAP from the Paris District was used here for evaluating the impact of soft binders on RAP mix properties. The research team selected four virgin binders for this study: PG64-22, PG58-28, PG64-28, and PG64-34. The same aggregates, gradation and OAC, were used for all four mixes, and the only variable was type of virgin binder. Only the HWTT (Tex-242-F) and OT (Tex-248-F) tests were performed, since the dynamic modulus test did not show much difference among different RAS mixes. Figure 15 shows the HWTT and OT test results.

Similar to previous results shown in Figure 13 and Figure 14, the RAP mixes with modified soft binders have significantly better cracking resistance than the mix with PG64-22 virgin binder (Figure 15). Meanwhile, the mix with regular PG58-28 binder without any modification has a little bit better cracking resistance, but its HWTT result is too poor. The research team highly recommends using soft but highly modified binder rather than straight run soft binder (i.e., PG58-28) for improving cracking resistance of RAP mixes.



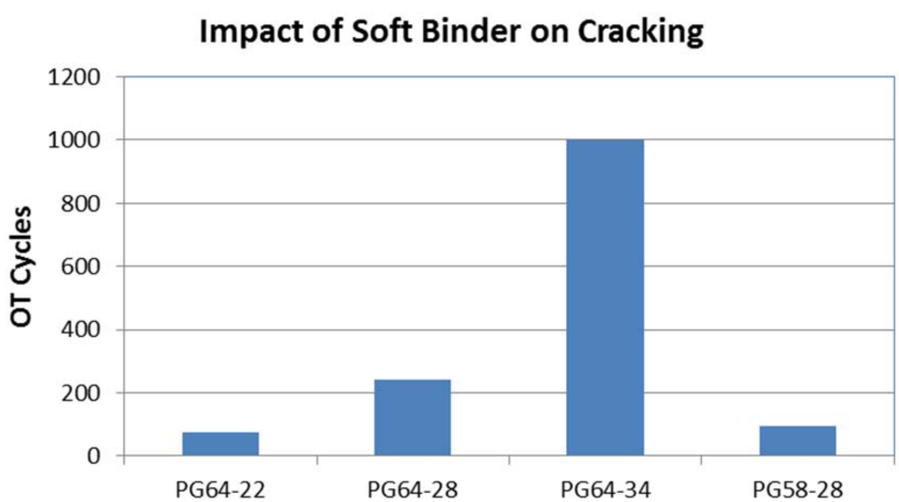


Figure 15. Impact of Soft Binders on Rutting/Moisture Damage and Cracking Resistance of RAP Mixes.

Summary

The test results discussed above clearly indicated that the use of soft and modified asphalt binder (i.e., PGXX-28, PGXX-34) can effectively improve cracking resistance of RAP/RAS mixes without sacrificing much rutting/moisture damage resistance. Dynamic modulus is not a good indicator for cracking resistance of RAP/RAS mixes.

Use of Rejuvenators and Softening Agents for RAP/RAS

Another choice is to rejuvenate RAP/RAS binder using rejuvenating agents. Recycled asphalt binder from RAP/RAS can be very stiff. Some people even argued that the RAP/RAS cannot be treated as asphalt binder due to severe aging, and its chemical composition is different from regular asphalt binder. In order to activate the aged RAP/RAS binder, it is necessary to reconstitute the chemical composition of RAP/RAS binder. Two methods have been used to soften the stiff RAP/RAS binders in the past: softening agents and rejuvenators. Softening agents are used to lower the viscosity of aged bitumen. Examples of softening agents include asphalt flux oil, lube stock, and slurry oil. Rejuvenating agents, on the other hand, have the purpose of reconstituting the binder's chemical composition (*24*) and consist of lubricating and extender oils containing a high proportion of maltene constituents. The most important goal of rejuvenator products is to restore the asphaltenes/maltenes ratio. In general, rejuvenating agents should have a high proportion of aromatics that are necessary to keep the asphaltenes dispersed, but they should contain a low content of saturates that are highly incompatible with the asphaltenes. They should be composed in such a way that they increase the peptizing power of the maltene phase (*25*).

The use of rejuvenators sounds like a good idea and potentially improves cracking resistance of RAP/RAS mixes, but there are lots of practical and technical issues when applied to normal asphalt plant operations. Furthermore, the effectiveness of a rejuvenator depends on the uniform dispersion of the rejuvenator within the recycled mixture and the diffusion of the rejuvenator into the aged binder coating outside of the aggregate. While the diffusion of the rejuvenator into the recycled binder would be better if the rejuvenator was mixed with RAP and/or RAS before the RAP/RAS materials were added in the plant, this process would be difficult to implement in the field. Some contractors already had concerns about the potential hazards (safety and other issues) when using rejuvenators in the plant. There are also other production factors to consider. For example, where, when, and how should RAP/RAS stockpiles be pre-treated? Researchers should not only evaluate the effectiveness of rejuvenators or softening agents in the laboratory, but the feasibility of using rejuvenators in the plant and what modifications are also required in this study.

Most recently, Tran et al. evaluated one rejuvenator, Cyclogen® L, that does not contain asphalt binder (*26*). Instead of treating RAP/RAS with Cyclogen® L, Tran et al. blended the Cyclogen® L with virgin binder, and then mixed them with virgin aggregates, RAP, and RAS to make specimens for laboratory testing. The findings from Tran et al. are described as follows:

- The desired amount of rejuvenator can be determined based on a linear relationship between the rejuvenator content and critical low temperature of the blend of recycled binder and rejuvenator. In this study, researchers selected a rejuvenator content of 12 percent by the total weight of recycled binders to restore the performance properties of the recycled binders to meet the requirements for a PG67-22, which is the performance grade of the virgin binder.
- Dynamic modulus test data indicated that the use of rejuvenator at the determined content in the recycled mixtures softened the stiffness of these mixtures; however, these mixtures were still stiffer than the virgin mix in both long- and short-term aged conditions.

- The resistance of the five mixtures to low-temperature cracking was evaluated using the indirect tension test (IDT) procedure. The control mixture exhibits the lowest critical failure temperature (−27.7°C), followed by the 50 percent RAP mixture with rejuvenator, then the 20 percent RAP plus 5 percent RAS mix with rejuvenator, and the 20 percent RAP plus 5 percent RAS mix (without rejuvenator). A mix with a lower critical failure temperature would have better resistance to low-temperature cracking.
- OT results showed that the virgin mix has the highest average number of cycles to failure that is statistically different from those of the recycled mixes. Among the recycled mixtures, the 20 percent RAP plus 5 percent RAS mix with rejuvenator has the highest average number of cycles to failure, followed by 50 percent RAP mix with rejuvenator, 20 percent RAP plus 5 percent RAS mix, and 50 percent RAP mix. Note that only three OT specimens were used and the maximum opening displacement was 0.013 in.
- The rutting resistance of the five mixtures was evaluated using the asphalt pavement analyzer (APA). All the mixtures exhibited APA manual rut depths less than 5.5 mm, which was determined based on the past research at the National Center for Asphalt Technology (NCAT) Pavement Test Track; none of the five mixtures were suspected to fail in terms of rutting

Finally, Tran et al. concluded that the use of rejuvenator in the recycled mixtures improved the cracking resistance of these mixtures without adversely affecting their resistance to moisture damage and permanent deformation. They also recommended that the rejuvenator, which is pre-blended with the virgin binder, be used to improve the cracking resistance of asphalt mixtures with high RAP and RAS contents. However, since the virgin binder pre-blended with the rejuvenator may be much softer than the normal grade of asphalt being used, good mixing of the binder pre-blended with the rejuvenator, aggregate, and recycled material is important to produce a good asphalt mixture that can avoid premature rutting failures. Apparently, further research in this area should be conducted to evaluate other rejuvenators and the use of rejuvenator in asphalt mixtures with higher recycled contents and with tear-off RAS.

Combining RAP/RAS with WMA Technologies

Currently, the use of recycled materials (RAP/RAS) is also allowed with asphalt mixes produced with WMA technologies. WMA produced with RAP and RAS can significantly reduce the cost of asphalt mixtures, conserve energy, and protect the environment. Additionally, the use of WMA technologies will help reduce virgin binder aging during the production, which may be beneficial to cracking resistance of RAP/RAS mixes. However, this is a very complicated issue. Up to now, there is no solid laboratory and field test data to support it.

CHAPTER 3
LABORATORY EVALUATION ON DURABILITY PROBLEMS OF RAP/RAS BINDERS AND MIXES

Both RAP and RAS have been widely used in asphalt mixes and the trend seems to use more and more. Although the use of RAP/RAS improves the rutting resistance of asphalt mixes, the durability (or cracking) is the main concern of the field performance of RAP/RAS mixes. There is a need to improve the durability of RAP/RAS mixes. To achieve this object, a series of laboratory tests were conducted to investigate the impact RAP/RAS blended binders and RAP/RAS asphalt mixes on performance properties. This chapter describes laboratory tests conducted for this study and test results.

IMPACTS OF RECYCLED BINDER ON BLENDED BINDER PROPERTIES

Binders in RAP and RAS are much stiffer and harder than virgin asphalt binders. Adding RAP/RAS into the asphalt mixes can improve their rutting resistance, but in most cases cause concerns on potential premature cracking. To address the cracking concerns of mixes containing RAP/RAS, different approaches have been used, such as soft virgin binders or higher asphalt content. Most recently, rejuvenators are introduced to further soften and rejuvenate the aged RAP/RAS binders. It is critical to investigate the interaction among virgin binder, RAP/RAS binders, and rejuvenators. Although it is difficult to quantify how much actual blending occurs during mix design, plant production, and later in the service, it is important to study the effect of recycled binders or rejuvenators on the total blended binder in terms of binder blending and the rheology of the total combined binder. There are three ways to perform the investigation:

- Backcalculation of binder blending information from mixture test (such as dynamic modulus test).
- Backcalculation of binder blending information from mortar test.
- Characterization of properties of binder blend with extracted RAP/RAS binders.

Researchers found that the first and second approaches are not good methods because of uncertainties, whereas the third approach would be a good way to study the effect of recycled binders on the total blended binder. The main idea of the third approach is to extract the binders from the RAP or RAS and then blend the extracted binders with virgin binder and rejuvenators. The following sections discuss the blending characteristics among virgin binder, RAP binder, RAS binder, and rejuvenators based on the third approach.

Blending between Virgin Binder and RAS Binder

Many efforts have been made to evaluate the blending between virgin binders and RAP binders, and all results indicated that the RAP binders linearly blend with virgin binders. Compared to virgin/RAP binder blending, there was very little work done on virgin/RAS binders blending in the literature, although AASHTO PP53, *Standard Practice for Design Consideration when Using Reclaimed Asphalt Shingle (RAS) in New Hot-Mix Asphalt (HMA)*, recommends that the linear blending used for virgin/RAP binders blending also be used with virgin/RAS binders. One reason may be the difficulty in grading RAS binder using regular DSR and BBR. This study investigated the full blending charts for three virgin binders and four RAS binders extracted/recovered from both TOAS and MWAS. Detailed information is presented below.

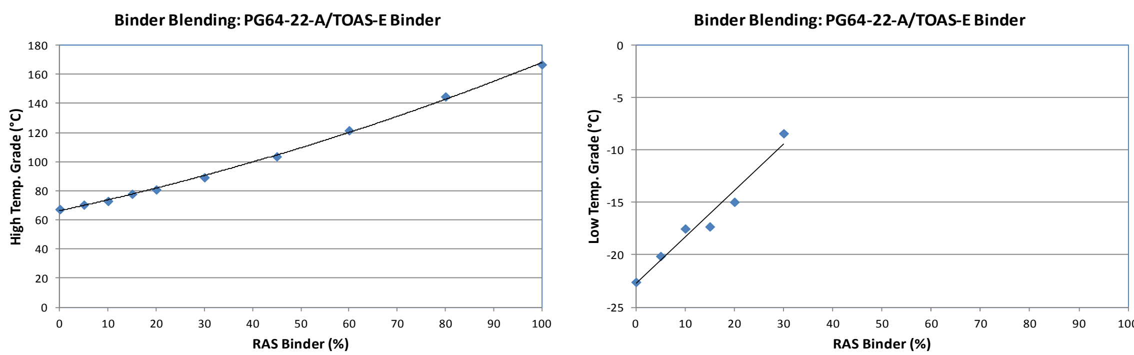
Virgin and RAS Binders

Three virgin binders selected for blending are PG64-22-A, PG64-22-B, and PG64-28, and the four RAS binders are TOAS-A, TOAS-E, MWAS-A, and MWAS-C. With these selected binders, a total of four combinations of virgin/RAS binders, as listed below, were evaluated under this study. Note that these four combinations have been used in the field test sections:

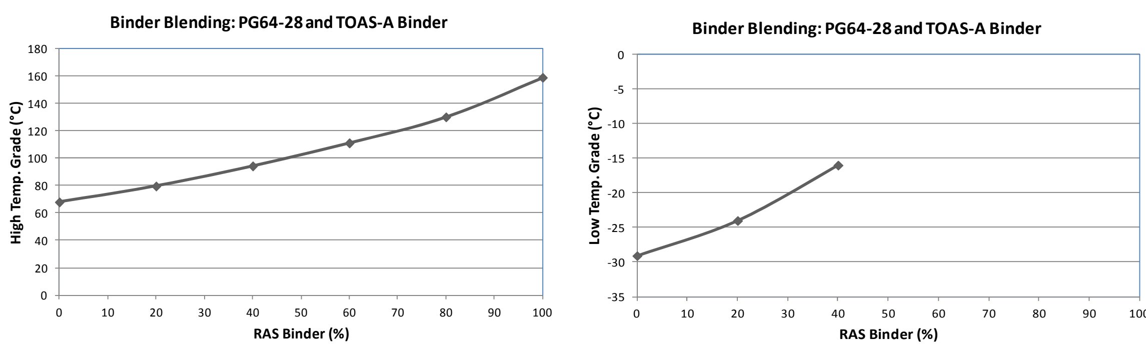
- Virgin Binder: PG64-22-A and RAS Binder: TOAS-E.
- Virgin Binder: PG64-28 and RAS Binder: TOAS-A.
- Virgin Binder: PG64-22-B and RAS Binder: MWAS-A.
- Virgin Binder: PG64-22-B and RAS Binder: MWAS-C.

Laboratory Testing, Results, and Analysis

For each combination, different percentages of virgin and RAS binders were blended and then evaluated through DSR and BBR testing in terms of the high and low PG temperatures. The test results for these four combinations are presented in Figure 16 and Figure 17, respectively.

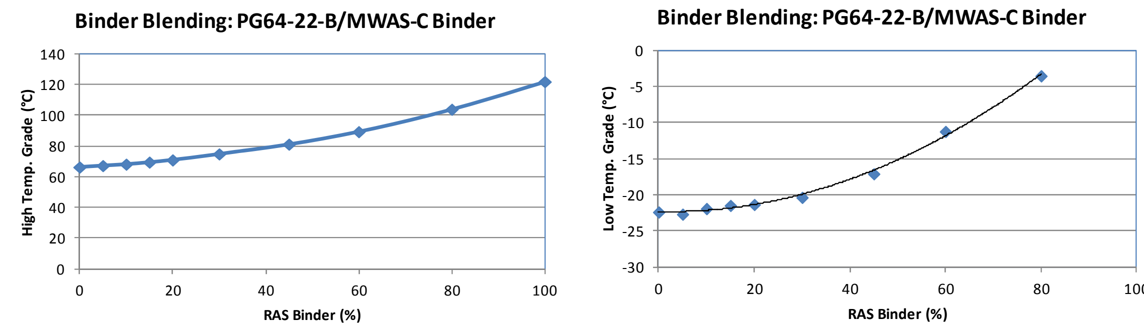


(a) Binder Blending between PG64-22-A and TOAS-E Binder.

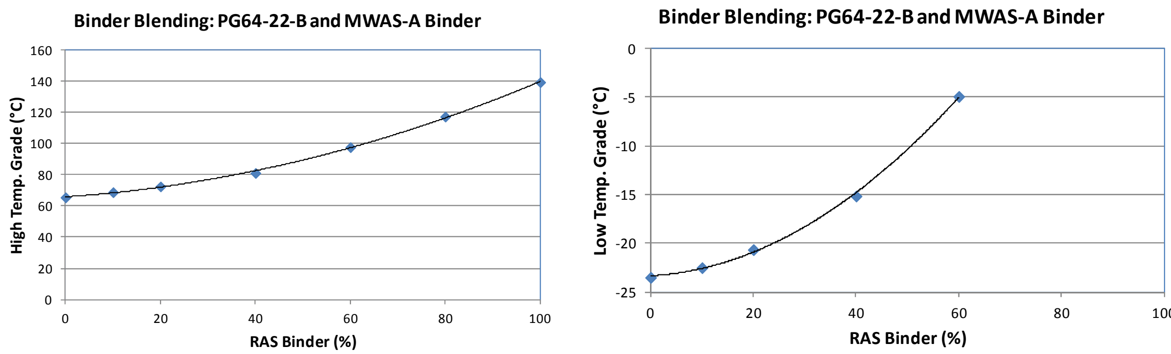


(b) Binder Blending between PG64-28 and TOAS-A Binder

Figure 16. Binder Blending: Virgin Binders/TOAS Binders.



(a) Binder Blending between PG64-22-B and MWAS-C Binder



(b) Binder Blending between PG64-22-B and MWAS-A Binder

Figure 17. Binder Blending: Virgin Binders/MWAS Binders.

The following observations are made from Figure 16 and Figure 17:

- Generally the virgin and RAS binders blending is non-linear.
- For practical application, the linear blending chart can still be used if the RAS binder percentage is less than 30 percent, which is consistent with the finding from a previous study conducted by Bonaquist (*27*). Within 30 percent RAS binder, not only is the linear blending chart applicable, but the regular DSR and BBR can also be used to evaluate the high and low PG temperatures of the blended binders.
- Increasing the RAS binder amount will make the blended binder stiffer and accordingly, better rutting resistance but poorer cracking resistance. Adding 20 percent RAS binder can make a PGXX-22 virgin binder become a PGXX-16 (or even a PGXX-10 shown in Figure 16a) blended binder. Additionally, the necessity of using the PGXX-28 virgin binder is clear if one targets to get a PGXX-22 blended binder when the 20 percent RAS binder is added (Figure 16b). Note that the 20 percent RAS binder is corresponding to 5 percent RAS in weight of the total mix when assumed that the OAC of a RAS mix is 5 percent and the RAS contains 20 percent asphalt binder in it.
- Impact of MWAS binders on the high and low PG temperatures of virgin binders is different from that of TOAS binders. Compared to the TOAS binders (Figure 17), the MWAS binders (Figure 17) have less impact on PG temperatures of virgin binders, which makes sense since TOAS binders are much stiffer than those MWAS binders. It is

necessary to consider differentiating the MWAS from the TOAS when designing HMA containing RAS.

Evaluation of Blending among Virgin/RAP/RAS Binders

The use of both RAP and RAS in HMA has become a regular practice in asphalt industry, so this study also briefly explored the blending among virgin/RAP/RAS binders. The same two virgin binders (PG64-22-A and PG64-22-B), two RAS binders (MWAS-A and TOAS-E), and two RAP binders (RAP-A and RAP-B) were selected. Again, four combinations listed below were evaluated with different percentages of binder contents through DSR and BBR testing:

- TOAS-E RAS Binder (=20 percent of the total binder), varying PG64-22-A and RAP-A.
- RAP-A Binder (=20 percent of the total binder), varying PG64-22-A and TOAS-E.
- MWAS-A Binder (=5 percent of the total binder), varying PG64-22-B and RAP-B.
- RAP-B Binder (=10 percent of the total binder), varying PG64-22-B and MWAS-A.

The DSR and BBR test results of these four combinations are shown in Figure 18, Figure 19, Figure 20, and Figure 21, respectively. From these figures the following observations are made:

- As long as RAS binder content is fixed in the blending process, the virgin/RAP binders follows linear blending line, as seen in Figure 18 and Figure 20. Both high and low temperatures of PG of the combined binder increases linearly with adding RAP binder. When RAP binder content is fixed, the virgin/RAS binders blending, again, is non-linear (see Figure 19 and Figure 21).
- When RAS binder is already blended with virgin binder, adding more RAP binder makes the blended binder even stiffer. For example, as shown in Figure 18, 20 percent RAS binder itself already modified the PG64-22-A binder to a PG81-15 binder. Adding any RAP binder (even 5 percent RAP binder) will worsen the cracking resistance of the combined binder. The similar finding for fixing RAP binder but adding more RAS binder to the virgin binder can be observed in Figure 19, Figure 20, and Figure 21.

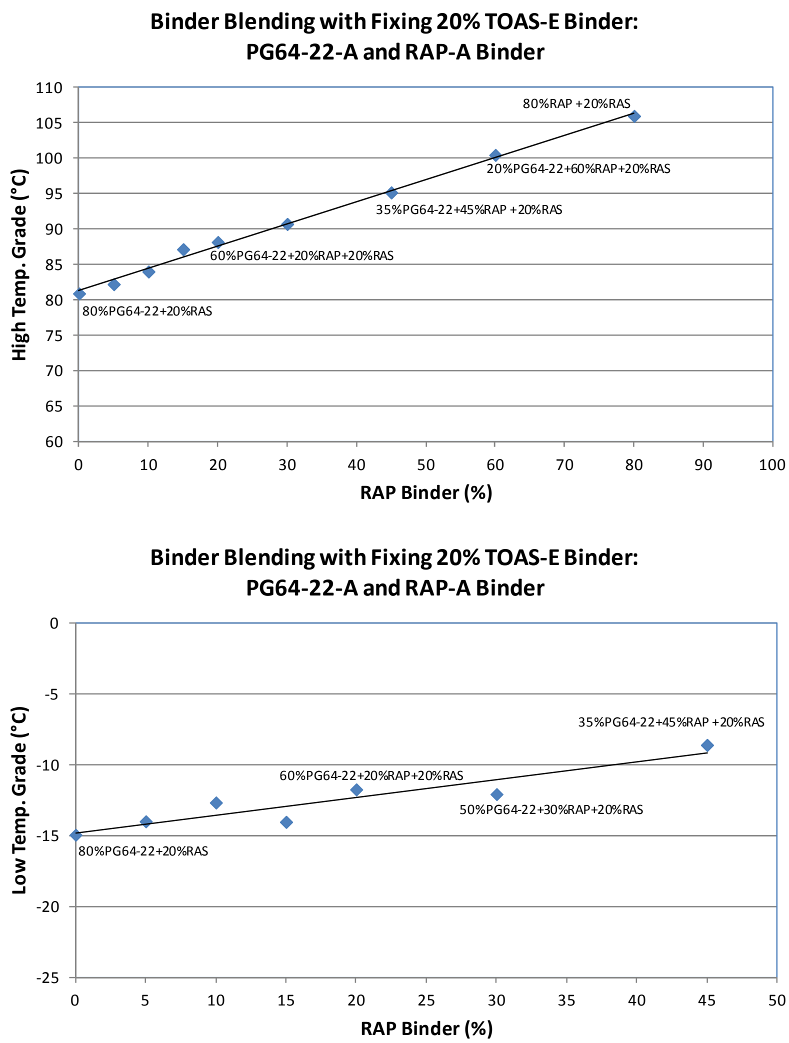


Figure 18. Binder Blending with Fixing 20 Percent TOAS-E Binder and Varying PG64-22-A and RAP-A Binder.

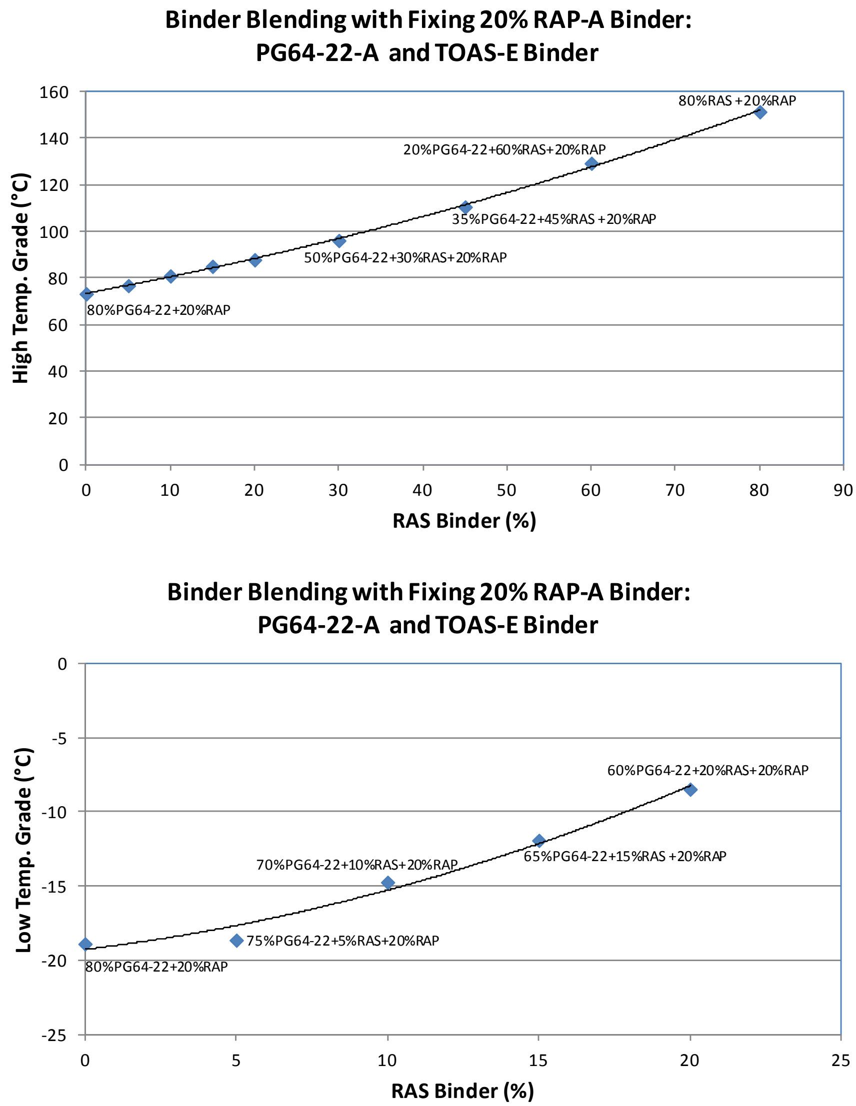
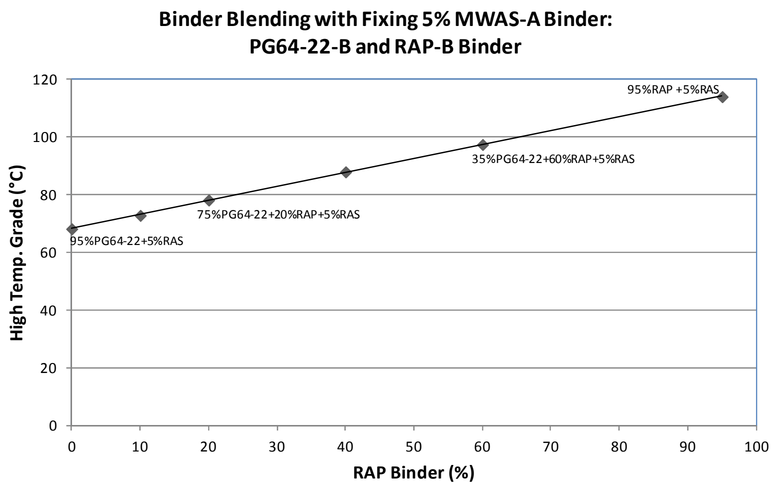


Figure 19. Binder Blending with Fixing 20 Percent RAP-A Binder and Varying PG64-22-A and TOAS-E Binder.



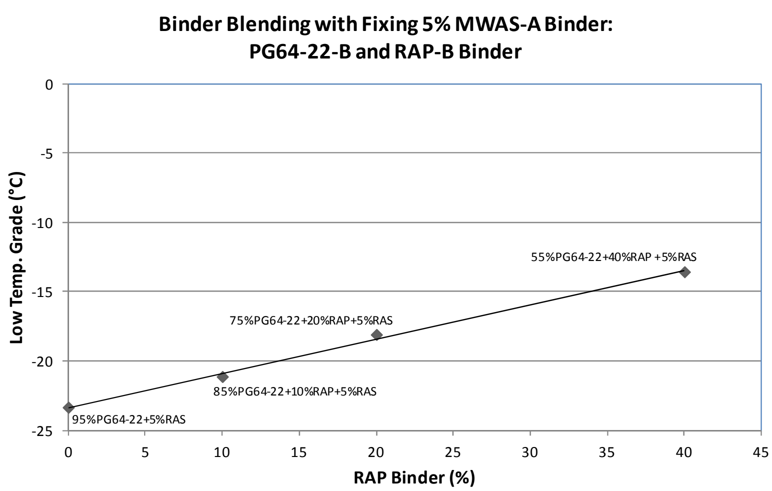
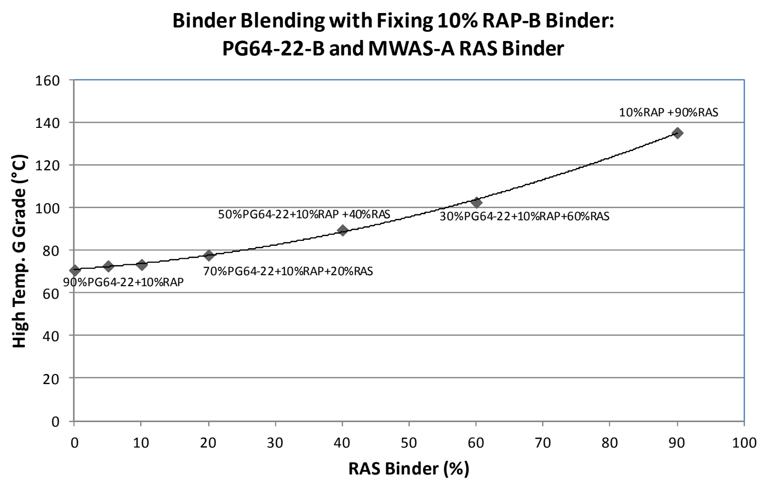


Figure 20. Binder Blending with Fixing 5 Percent MWAS-A Binder and Varying PG64-22-B and RAP-B Binder.



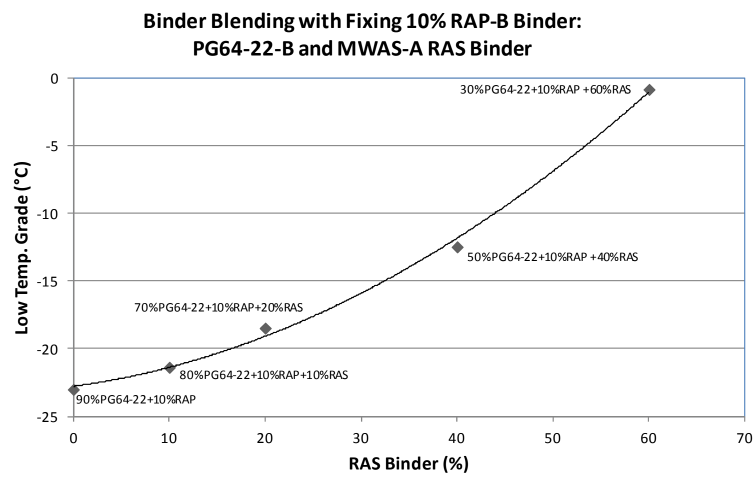


Figure 21. Binder Blending with Fixing 10 Percent RAP-B Binder and Varying PG64-22-B and MWAS-A Binder.

Evaluation of Blending among Virgin/RAP/RAS Binders and RAP/RAS Rejuvenators

Materials from the field demonstration project on SH31 were used here. The mix design called 10 percent RAP and 5 percent MWAS and a Lion PG64-22 virgin binder. Three rejuvenators: Evoflex, Hydrogreen, and ERA were blended with RAP/MWAS/PG64-22 binders. For each blend, 10.8 percent RAP binder and 18.4 percent MWAS binder were fixed but varying amount of PG64-22 and each rejuvenator. Four blending ratios of each rejuvenator to the total binder (by weight) used in this study were 0, 2, 5, and 10 percent. A total of 10 blends (Table 6) were graded through the Superpave PG system. Figure 22 shows PG high and low grades for each blend. The linear blending concept is valid for all 10 blends. Meanwhile, 10 percent rejuvenator is high enough to make the final blend meet the specification requirements for both high and low PG grades (say PG70-22) for Texas conditions on SH31.

Table 6. Multiple Blends for RAP/RAS/PG64-22/Rejuvenators.

RAP binder/RAS binder/virgin binder	Hydrogreen	Evoflex	ERA
10.8%/18.4%/70.8%	0%	0%	0%
10.8%/18.4%/68.8%	2%	2%	2%
10.8%/18.4%/65.8%	5%	5%	5%
10.8%/18.4%/60.8%	10%	10%	10%

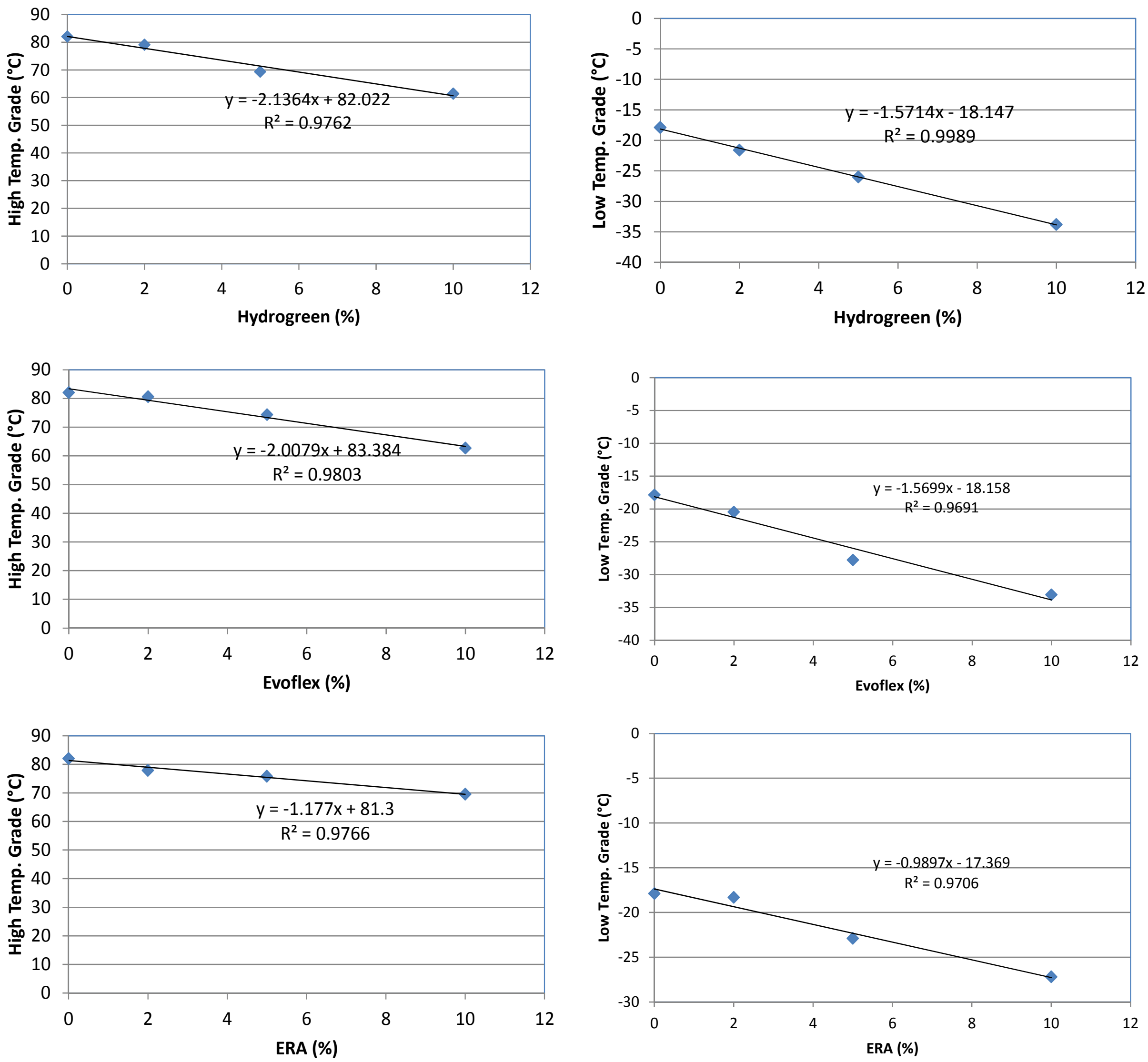


Figure 22. Validation of Regional Linear-Blending Concept for Multiple Blends.

Summary

Based on the results presented above, if rejuvenators are allowed in the asphalt mixes, more RAP/RAS can be used in the asphalt mixes. Ten percent rejuvenator is more than enough to make the final blend meet the specification requirements for both high and low PG grades (say

PG70-22) for Texas conditions on SH31. Adding rejuvenators into the asphalt mixes can potentially improve asphalt mix cracking resistance and make a better recycled asphalt mix. However, some concerns have been raised on the long-term performance of rejuvenators, which should be carefully studied.

IMPACTS OF CHANGES IN MIX DESIGN ON THE DURABILITY OF RAP/RAS MIXES

TxDOT proposed specification allows fractionated RAP and RAS to be used in WMA mixes, SMA mixes, and Superpave mixes. For SMA mixes, a maximum of 15 percent recycled asphalt binder is allowed for surface mixes, and a maximum of 20 percent and 30 percent recycled asphalt binder can be used in Superpave and WMA mixes for surface layer, respectively. In order to ensure the quality of those mixes (WMA, SMA, and Superpave mixes), researchers evaluated the impact of RAP/RAS on the performance and engineering properties of WMA, SMA, and Superpave mixes.

Materials and Mixes

Table 7 shows basic information on two different WMA mixes and their control (HMA) mixes. As shown in the table, those mixes were produced with a PG64-22 asphalt binder at a total content of 5.2 percent, virgin aggregates, and RAP and/or RAS. RAS contents of 2.5 percent and 4.2 percent in the table are in percent of aggregate, and they are 3 percent and 5 percent in percent of total mix, respectively. In addition, an Evotherm and/or a rejuvenating agent (PC-1862) were used to produce WMA mixes.

Similarly, Table 8 summarizes basic information on four different SMA mixes tested. As shown in the table, the control SMA mix was produced with virgin aggregates and a PG70-22 asphalt binder at a total content of 6.0 percent. Counterparts were produced by replacing the percent of aggregates with RAP or RAS. Also, the control and the 20 percent RAP mixes were laboratory-mixed and laboratory-compacted, while both the 5 percent manufacturer RAS and the 5 percent tear-off RAS mixes were plant-mixed and laboratory-compacted. As mentioned earlier similarly, a RAS content of 4.4 percent in the table is in percent of aggregate, and it is 5 percent in total mix.

Table 9 illustrates gradation of the aggregates and asphalt content used in the Superpave mix design. As shown in the table, the Superpave mix contained 24.7 percent RAP (24.6 percent in total mix) and 1.6 percent RAS (2 percent in total mix), respectively. In order to compare to the control Superpave mix, three different counterparts were produced using a PG58-34 asphalt binder and adding different dosages (i.e., 0.6 percent on total binder and 0.75 percent on total weight of RAP/RAS) of another rejuvenating agent (Hydrogreen) to the control Superpave mix. This study used the dosage recommended by each manufacturer.

Table 7. Design Gradation and Asphalt Content of WMA Mixes.

WMA Mixes	% Aggregates							Recycled to Total Binder (%)	AC (%)/PG Grade
	Type-C	Type-D	Type-F	Manufactured Sand	Field Sand	RAP (%)	RAS (%)		
Control-1 (HMA)	26	19	21	22	7.8	-	4.2	19.2	5.2 / 64-22
Control-1-PC1862 (HMA)	26	19	21	22	7.8	-	4.2		
WMA-1-PC1862	26	19	21	22	7.8	-	4.2		
Control-2 (HMA)	24	17	18	17	6.5	15	2.5	26.0	
WMA-2	24	17	18	17	6.5	15	2.5		

Table 8. Design Gradation and Asphalt Content of SMA Mixes.

SMA Mixes	% Aggregates							Recycled to Total Binder (%)	AC (%)/PG Grade
	Type-C	3/8" Bin	Type-D SAC A	Fly Ash	Field Sand	RAP (%)	RAS (%)		
Control	31	26	29	7.0	7.0	-	-	0.0	6.0 / 70-22
20% RAP	31	25	18	6	-	20	-	16.7	
5% Manf. RAS	27	32	28	8.6	-	-	4.4	15.0	
5% Tear-off RAS	27	32	28	8.6	-	-	4.4	15.0	

0.2% fiber added to each mix

Table 9. Design Gradation and Asphalt Content of Control Superpave Mix.

Combination of Materials		Sieve Analysis								
Aggregate Sources	%	1"	¾"	½"	#4	#8	#16	#30	#50	#200
B Rock	15.0	100	81.3	4.8	1.4	1.2	1.0	1.0	1.0	1.0
Gra_4	8.0	100	100	97.8	2.8	1.2	1.0	0.9	0.9	0.4
D/F Blend	6.0	100	100	100	29.3	4.6	1.3	0.4	0.2	0.1
Screenings	31.8	100	100	100	96.5	56.6	27.0	12.0	3.1	1.0
Washed Sand	11.9	100	100	100	100	85.6	72.4	51.9	12.4	1.0
Hydrate	1.0	100	100	100	100	100	100	100	100	100
RAP	24.7	100	100	100	41.6	28.3	20.9	16.3	11.3	3.4
RAS	1.6	100	100	100	100	99.4	75.0	64.9	58.2	26.3
Combined Gradation	100	100	97.2	85.5	57.7	38.3	24.9	16.3	7.4	2.9
AC (%) and PG Grade		4.7 / PG58-28								
Recycled to Total Binder (%)		31.9								

Laboratory Tests, Results, and Discussion

Researchers performed several laboratory tests in this study. Table 10 shows the laboratory test matrix for the laboratory testing plan, which includes a total of 115 specimens (43 WMA, 36 SMA, and 36 Superpave specimens). Following TxDOT's specification, for SMA mixes the control mix and 20 percent RAP mix were mixed at 300°F and compacted at 275°F after 2 hours oven curing process. Plant mixes, 5 percent manufacturer RAS and 5 percent tear-off RAS mixes, were compacted at 275°F after 2 hours oven curing process. For Superpave mixes, the control mix and both rejuvenated mixes were mixed at 275°F, cured for 2 hours at 250°F before compacting OT specimens, and cured for 4 hours at 250°F prior to compacting Hamburg specimens and dynamic modulus specimens, respectively. For the PG58-34 mix, the mixing temperature was 290°F and then the remaining conditions were the same with the control mix. For WMA mixes, they were mixed and cured at 275°F for 2 hours before compaction, while their control (HMA) mixes were mixed at 290°F and cured at 275°F for 2 hours.

Table 10. Testing Matrix for Each Mix.

Mix Type		Hamburg	Overlay	Dynamic Modulus
WMA	Control-1 (HMA)	2	3	2
	Control-1-PC1862 (HMA)	2	5	2
	WMA-1-PC1862	2	5	2
	Control-2 (HMA)	2	5	2
	WMA-2	2	5	2
SMA	Control Mix	2	5	2
	20% RAP	2	5	2
	5% Manufacturer RAS	2	5	2
	5% Tear-off RAS	2	5	2
Superpave	Control Mix: PG58-28	2	5	2
	PG58-34	2	5	2
	PG58-28 w/ 0.6% Hydrogreen	2	5	2
	PG58-28 w/ 0.75% Hydrogreen	2	5	2

Hamburg Wheel Tracking Test and Associated Results

Hamburg testing was conducted at a temperature of 122°F (50°C) in accordance with TEX-242F, *Test Procedure for Hamburg Wheel-Tracking Test (HWTT).* A Superpave gyratory compactor was used to produce cylindrical specimens with a diameter of 6 in. (150 mm) and a height of 2.4 in. (62 mm). A masonry saw was used to cut along the edge of the cylindrical specimens. The target air void of specimens was 7 percent ± 1 percent. To evaluate the rutting susceptibility and moisture resistance, researchers submerged the specimens under water at a temperature of 122°F (50°C) during the test, and a linear variable differential transducer (LVDT) device measured deformations. The stop criterion was rut depth of 0.5 in. (12.5 mm) or 20,000 passes.

Table 11 summarizes the rut depth of each test, and Figure 23 shows typical images of specimens after testing. WMA-1-PC1862 and Control-1- PC1862 mixes showed a good HWTT result compared to the control-1 mix. This implies that the rejuvenating agent, PC1862, improved the rutting and moisture resistance of HMA mix and also worked well with the WMA technology. For SMA mixes, the control mix failed at 15,500 passes, while counterparts passed. The 5 percent tear-off RAS mix exhibited the best performance, followed by the 20 percent RAP mix, the 5 percent manufacturer RAS mix, and the control mix. For Superpave mixes, the HWTT result of the PG58-34 mix dramatically improved HWTT results compared to the control mix. The incorporation of 0.6 percent Hydrogreen to the mix reduced the rutting and moisture resistance compared to the control mix. On the other hand, the incorporation of 0.75 percent Hydrogreen to the mix significantly improved HWTT results compared to the control mix and 0.6 percent Hydrogreen mix. One possible reason for this result would be much less amount of virgin binder used since the same amount of virgin binder was backed out as Hydrogreen was added. The amount of virgin binder subtracted from 0.75 percent rejuvenated mix was approximately 6.6 percent of the total virgin binder needed, while the amount of virgin binder subtracted from 0.6 percent rejuvenated mix was approximately 0.9 percent of the total virgin binder needed. The use of less virgin binder may increase the rutting performance of the 0.75 percent rejuvenated mix. The impact of rejuvenating agents on mix performance should be investigated further in the future.

Table 11. Summary of Hamburg Test Results.

Mix Type		5,000	10,000	15,000	20,000	Failure
WMA	Control-1 (HMA)	3.40	6.23	12.33	-	15,000
	Control-1- PC1862 (HMA)	2.59	3.14	3.56	4.02	20,000
	WMA-1-PC1862	2.85	3.55	4.34	5.40	20,000
	Control-2 (HMA)	n/a	8.57	n/a	n/a	n/a
	WMA-2	n/a	7.78	n/a	n/a	n/a
SMA	Control Mix	5.98	7.96	12.09	-	15,500
	20% RAP	4.01	5.25	6.41	7.41	20,000
	5% Manufacturer RAS	5.71	7.09	8.24	9.38	20,000
	5% Tear-off RAS	3.88	4.73	5.28	5.65	20,000
Superpave	Control Mix: PG58-28	3.29	4.44	6.01	8.88	20,000
	PG58-34	2.49	2.98	3.40	3.74	20,000
	PG58-28 w/ 0.6% Hydrogreen on total binder	3.37	5.00	9.38	12.78	17,500
	PG58-28 w/ 0.75% Hydrogreen on total RAP/RAS	3.01	3.63	4.01	4.32	20,000

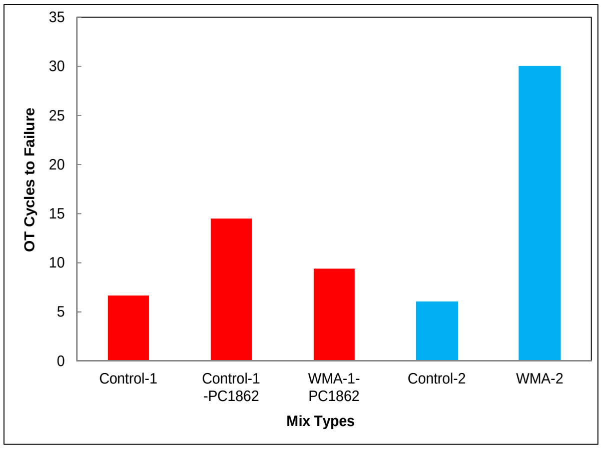
(a) Control Mix: PG58-28 | (b) PG58-34 | (c) PG58-28 w/ 0.6% Hydrogreen on total binder | (d) PG58-28 w/ 0.75% Hydrogreen on total RAP/RAS

Figure 23. Pictures of Each Superpave Mix after HWTT.

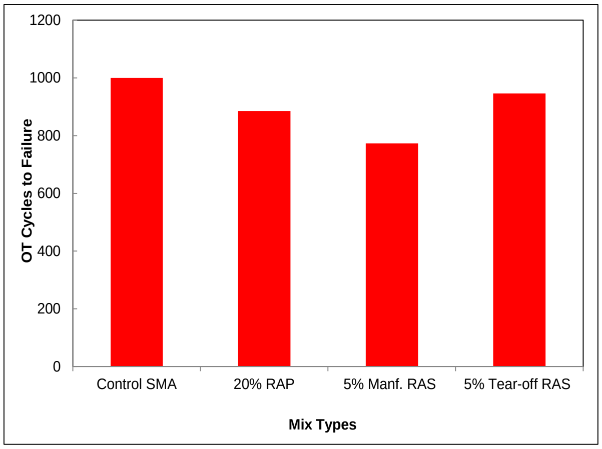
Overlay Test and Associated Results

OT was used to represent the reflective cracking potential of the asphalt mixtures. This test procedure is described in TEX-248-F, *Test Procedure for Overlay Test (OT).* Five trimmed specimens from each mixture targeting air void of 7 percent ± 1 percent were prepared according to the standard. Before testing, individual OT specimens were placed inside the environmental chamber for temperature equilibrium, targeting the testing temperature of 77°F (25°C). The sliding block applied tension in a cyclic triangular waveform to a constant maximum displacement of 0.025 in. (0.06 cm). The sliding block reached the maximum displacement and then returned to its initial position in 10 seconds. The time, displacement, and load corresponding to a certain number of loading cycles were recorded during the test.

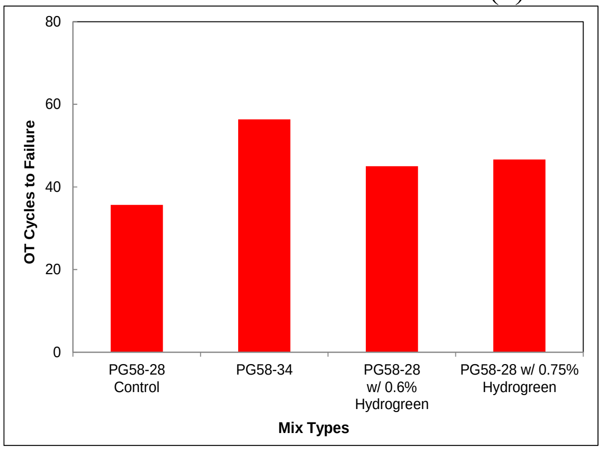
Figure 24 shows the reflective cracking life from each mix tested (average loading cycles of the five specimens). The control-1-PC1862 mix exhibited longer cracking life than that of the control mix. PC1862 improved the cracking resistance of HMA mix but it did not show such improvement for the WMA-1-PC1862 mix. On the other hand, the WMA-2 mix showed significant improved cracking resistance compared to the control-2 mix. For SMA mixes, the control mix exhibited the highest cracking life, followed by the 5 percent tear-off RAS mix, the 20 percent RAP mix, and the 5 percent manufacturer RAS mix. Although the reflective cracking life of counterparts was lower than that of the control mix, they showed good cracking resistance. For Superpave mixes, the PG58-34 mix exhibited the best performance, followed by the 0.75 percent Hydrogreen mix and the 0.6 percent Hydrogreen mix, respectively. The control mix showed the lowest value of cracking life. Based on the limited test results, asphalt mixes containing RAP/RAS showed similar or better cracking resistance compared to their control mixes except the SMA mixes when rejuvenator agents or a lower PG binder was used together. When rejuvenator agents are considered, special care will be needed in terms of the dosage since the rejuvenator percentage significantly affects the properties of asphalt mixes (*28*).



(a) WMA Mixes



(b) SMA Mixes



(c) Superpave Mixes

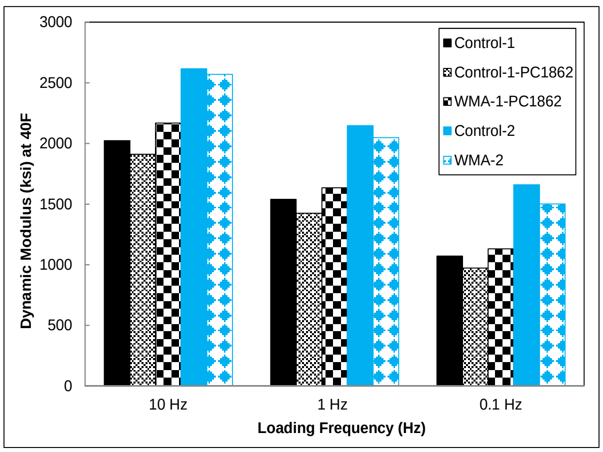
Figure 24. OT Results.

Dynamic Modulus Test and Associated Results

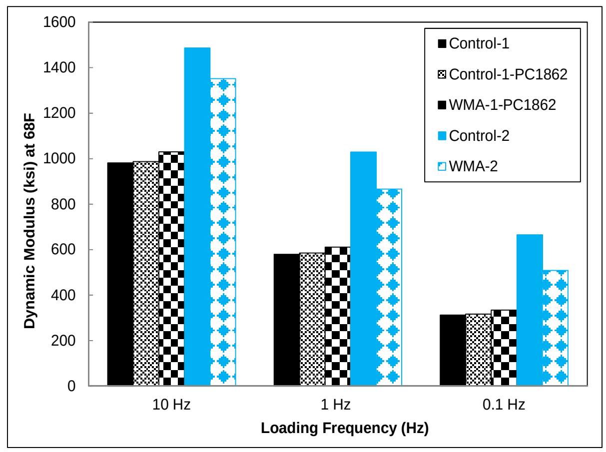
The dynamic modulus test measured changes in the viscoelastic stiffness of the asphalt mixtures. The test was conducted following the standard, AASHTO TP79-11, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The Superpave gyratory compactor was used to produce cylindrical samples with a diameter of 6 in. (150 mm) and a height of 6.7 in. (170 mm). The samples were then cored and cut to produce cylindrical specimens with a diameter of 4 in. (100 mm) and a height of 6 in. (150 mm). The target air void of the cored and cut specimens was 7 percent ± 1 percent. To measure the axial displacement of the testing specimens, researchers glued mounting studs to the surface of the specimens so that three LVDTs could be installed on the surface of the specimens through the studs at 120° radial intervals with a 2.8 in. (70 mm) gauge length. Three temperatures of 40, 68, and 104°F (4, 20, and 40°C, respectively) and either six and or seven loading frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz, and 0.01 Hz (104°F only) were used. Two replicates were tested, and average values of dynamic modulus at each different testing temperature over the range of loading frequencies were obtained.

Figure 25, Figure 26, and Figure 27 present the dynamic modulus values obtained from different loading frequencies (10, 1, 0.1 Hz and 0.01 Hz for 104°F only) at the testing temperatures. The

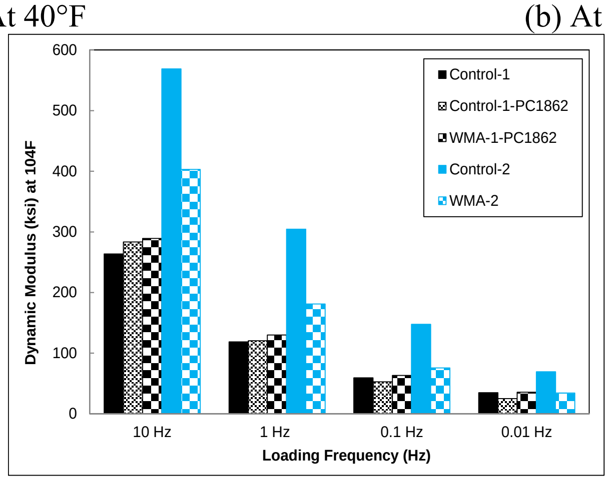
WMA-1-PC1862 mix showed higher dynamic modulus compared to counterparts at all loading frequencies and testing temperatures. Also, the WMA-2 mix showed similar dynamic modulus compared to the control-2 at testing temperatures of 40°F and 68°F but the stiffness difference between the control-2 mix and the WMA-2 mix was significantly increased at high temperature (104°F). Similar behavior was observed from SMA mixes. On the other hand, there was no significant difference found among Superpave mixes at all the testing temperatures. Overall, SMA mixes containing RAP/RAS showed higher stiffness characteristic than the control mix, while Superpave mixes containing RAP/RAS exhibited similar characteristics to the control mix. This finding indicates that RAP/RAS and the rejuvenator affected the stiffness characteristics of WMA, SMA, and Superpave mixes. In the future, the impact of rejuvenators on performance and engineering properties of asphalt mixes containing RAP/RAS should be investigated for further evaluation.



(a) At 40°F

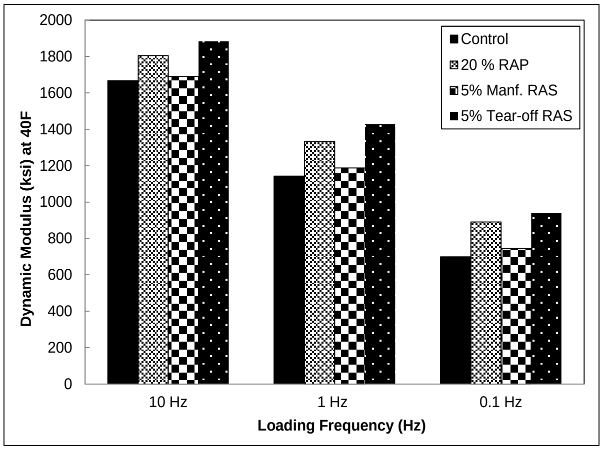


(b) At 68°F

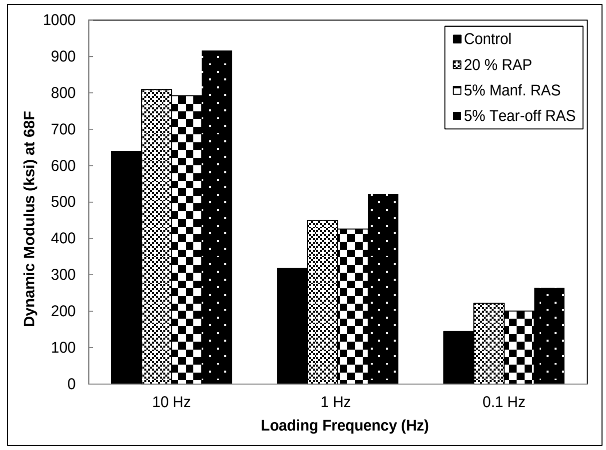


(c) At 104°F

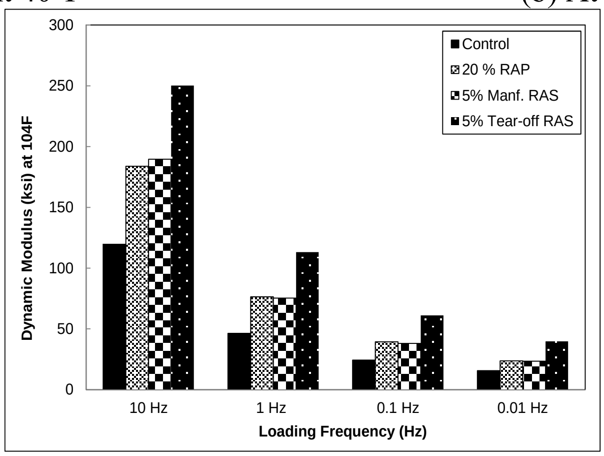
Figure 25. Dynamic Modulus Test Results of WMA Mixes.



(a) At 40°F

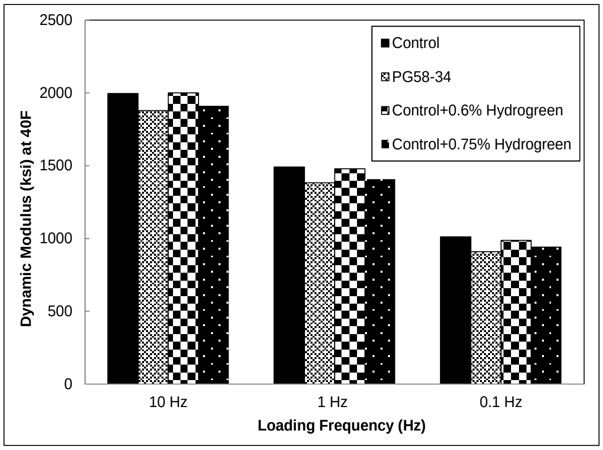


(b) At 68°F

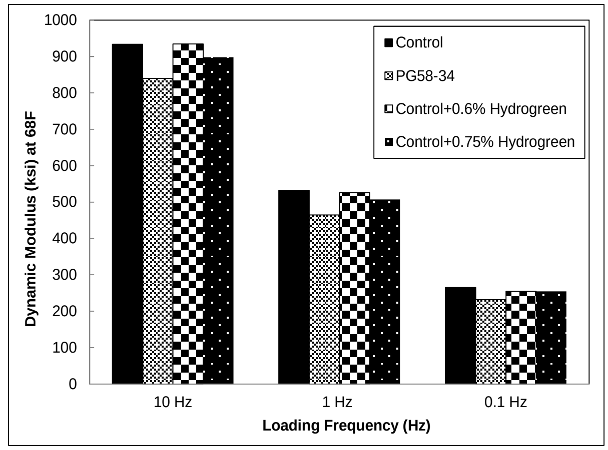


(c) At 104°F

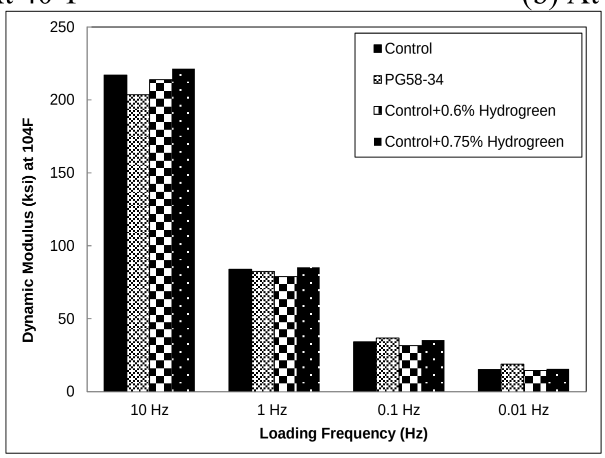
Figure 26. Dynamic Modulus Test Results of SMA Mixes.



(a) At 40°F



(b) At 68°F



(c) At 104 °F

Figure 27. Dynamic Modulus Test Results of Superpave Mixes.

SUMMARY

This chapter investigated the impacts of RAP/RAS on the performance and engineering properties of WMA, SMA, and Superpave mixes. Several laboratory tests were employed to compare the performance and engineering properties of the control mixes with those of counterparts. Based on the test results, the following conclusions can be made:

- With respect to rutting resistance, overall, asphalt mixes containing RAP/RAS exhibited better rut resistance than their control mixes.
- WMA mixes showed similar or better cracking resistance than their control (HMA) mixes, while SMA mixes containing RAP/RAS showed lower reflective cracking life than that of the control mix. Although their reflective cracking life was lower than that of the control mix, they showed a good cracking resistance. Also, all counterparts over the control Superpave mix exhibited improved cracking resistance when a rejuvenator agent or a lower PG binder was used.
- SMA mixes containing RAP/RAS showed higher stiffness characteristic than the control mix, while WMA and Superpave mixes showed similar stiffness characteristics compared to their control mixes.

CHAPTER 4
INVESTIGATION OF OVEN CURING CONDITIONS FOR RAP/RAS/WMA

The environmental factors such as temperature and moisture over time have a significant impact on asphalt mix properties and field performance. Asphalt mixes experience aging through oxidation under various environmental conditions during their in-place service lives. Aging of the original asphalt binder due to oxidation is extremely complicated phenomena because of the various environmental factors involved. This issue is more complicated when RAP and/or RAS are used in asphalt mixes. Current laboratory short-term aging procedures (such as AASHTO R 30) simply keep mixes at an elevated temperature for a period of time (typically 2 or 4 hours) before compacting them to a known density, regardless of WMA mixes or mixes containing RAP/RAS. Additionally, many studies have used the plant-mixed and laboratory-compacted (PMLC) samples for calibrating and validating performance models (such as fatigue cracking model, rutting model, etc.). In order to have confidence in the results obtained from these tests, establish a proper method of aging samples particularly for those obtained for the trial batch or those pulled from behind the paver. Large differences in test results can potentially occur, depending on the size of sampling container, aging, and sample age at the time of testing. It is also critical for DOTs to have defensible aging protocols as the performance tests may be used in remove and replace decisions.

It is important establish proper laboratory aging protocols, since the oven aging temperature and time are critical to asphalt mix design, quality control, and engineering properties used for pavement design and performance prediction. This chapter evaluated the relationship of the engineering properties of PMLC samples at different laboratory aging conditions, and then compared with the actual field cores (plant-mixed and field-compacted [PMFC]) taken soon after placement and different service ages. Additionally, this study investigated the effect of sampling container size on engineering properties of asphalt mixes. Finally, practical laboratory short-term aging time for each mix type was recommended.

RESEARCH METHODOLOGY

Figure 28 describes the research methodology employed in this study. Three dense-graded asphalt mixes were selected in this study: a virgin Type-D mix produced at hot-mix temperature, a Type-D mix with RAP and RAS produced at warm-mix temperature, and a Type-D mix with RAP and RAS designed using the balanced mix design (BMD) method and produced at hot-mix temperature. All plant mixes were sampled at the construction site during the construction time in February 2013. Plant mixes were brought back to the TTI McNew lab and reheated to fabricate specimens at the field compaction temperatures. To investigate the effect of sampling container size on engineering properties of asphalt mixes, the three plant mixes were collected into three different containers such as 5-gallon bucket, 4-in. deep pan, and 2-in. deep pan.

Field cores were taken at different ages of the pavement: 0-month (just after construction, February 2013), 6-month (August 2013), and 14-month (April 2014), and brought back to TTI for laboratory testing which includes HWTT, OT, IDT, resilient modulus (Mr) test, and dynamic modulus test.

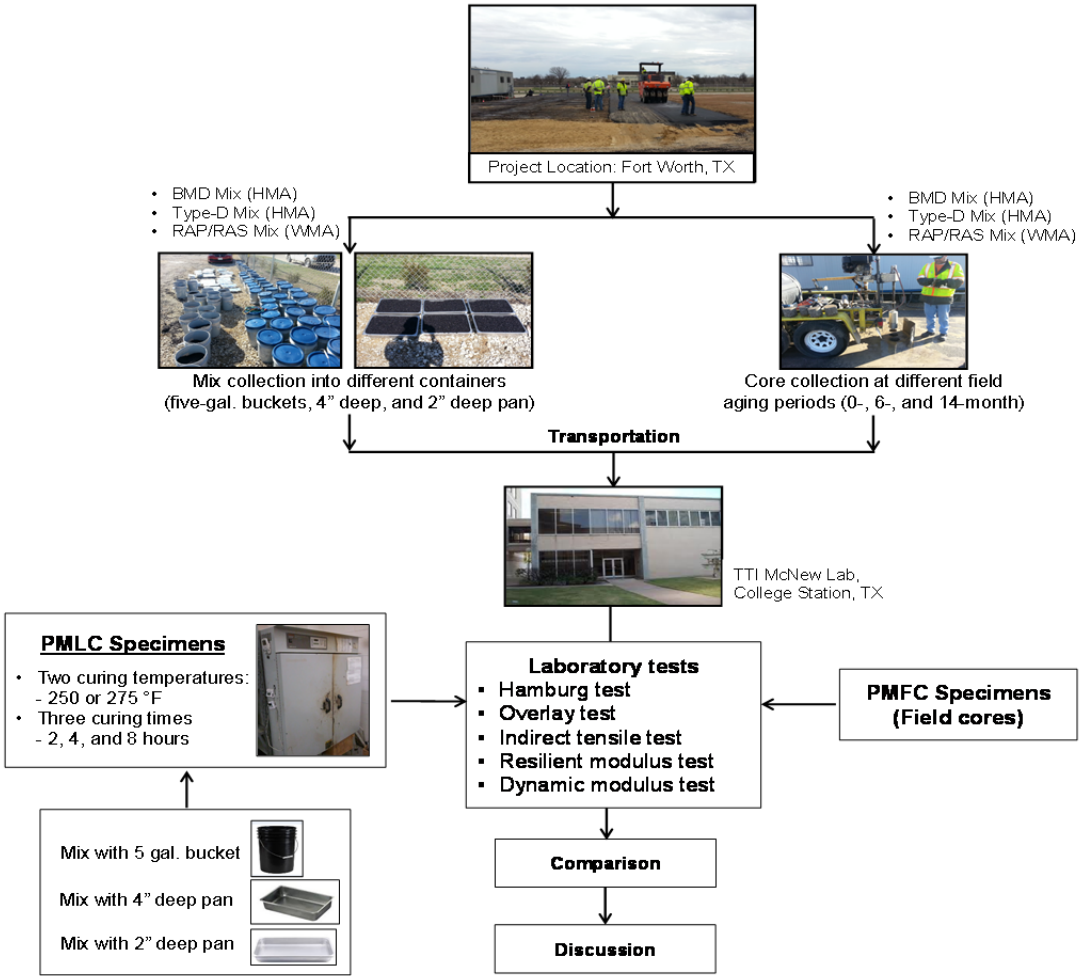


Figure 28. Research Methodology.

WEATHER CONDITION OF PROJECT LOCATION

The weather condition of the project location because the environmental conditions affect asphalt mix properties and field performance. Temperature would be the most important factor in terms of aging and significantly affect pavement performance, so the temperature history of the project location was obtained. Figure 29 shows the average monthly high and low temperature since construction. As shown in the figure, after construction the air temperature increased up to 98°F in August 2013 and decreased nearly to 32°F in January 2014. This weather condition will be discussed later.

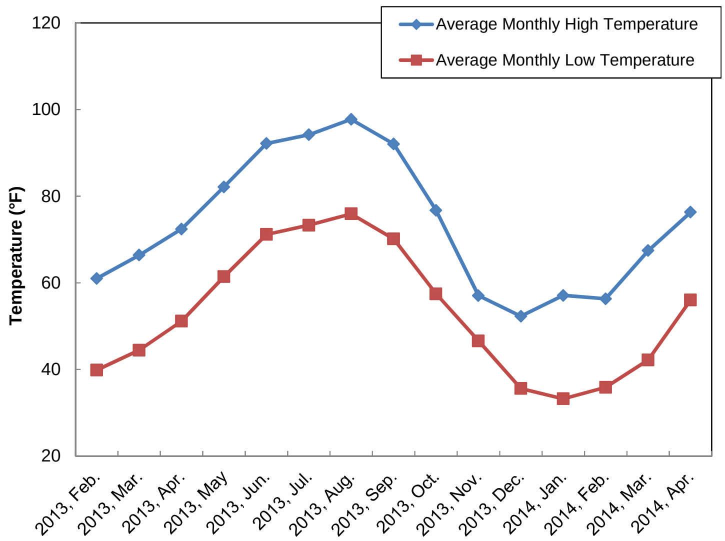


Figure 29. Weather Condition of the Project Location during Service Period (*29*).

MATERIALS

Table 12 summarizes basic information on the three asphalt mixes, such as source of aggregates, percent of aggregates, asphalt binder content, binder grade, RAP, and RAS. As presented in the table, the virgin Type-D mix produced as HMA is the control mix. On the other hand, both the BMD mix (HMA) and the RAP/RAS mix include a RAP content of 15 percent and a RAS content of 3 percent. The RAP/RAS mix is WMA mix that could be compared to the BMD and the Type-D mixes. The recommended compaction temperature for these mixes is 250 or 275°F, respectively, according to TEX-206-F, *"Compacting Specimens Using the Texas Gyratory Compactor (TGC)."* The thickness of each mix in the field was 2 in.

Table 12. Summary of Information on Each Mix.

Mix	% Rock				RAP (%)	RAS (%)	OAC (%)	PG	LAS (%)
	BPD	BPMS	MCMS	FS					
Type-D	61	-	30	9.0	-	-	4.8	64-22	1
BMD	48	29	-	5.6	15	3	5.5	64-28	1
RAP/RAS	48	29	-	5.6	15	3	5.0	64-22	1

BPD: Bridgeport D rock
FS: Field sand
BPMS: Bridgeport manufactured sand
OAC: Optimum asphalt content
MCMS: Mill Creek manufactured sand
LAS: Liquid anti-strip
Compaction temperature: 250°F for RAP/RAS mix and 275°F for Type-D and BMD mixes

LABORATORY TESTS, RESULTS, AND DISCUSSION

As mentioned earlier, PMLC specimens (and PMFC cores) were tested for investigating the impact of laboratory aging conditions, container size, field aging period, and recycled materials on the performance and engineering properties of asphalt mixes. Three different aging times (2, 4, and 8 hours), three different containers (i.e., 5-gallon bucket, 4-in. deep pan, and 2-in. deep pan), and two aging temperature conditions (250 or 275°F) were considered in this study. Table 13 shows the laboratory test matrix for the whole study, which includes a total of 297 PMLC specimens and a total of 111 PMFC specimens.

Table 13. Laboratory Test Matrix.

PMLC Specimens					
Container Size	Aging Time (hour)	HWTT	OT	IDT	Dynamic Modulus
5-gal. bucket	2	2	5	2	2
	4	2	5	2	2
	8	2	5	2	2
4" deep pan	2	2	5	2	2
	4	2	5	2	2
	8	2	5	2	2
2" deep pan	2	2	5	2	2
	4	2	5	2	2
	8	2	5	2	2
Number of specimens tested **(99/mix)**		18	45	18	18
Total number of specimens		• 135°C aging condition: = 99 × 2 (mixes) = 198 specimens • 120°C aging condition: = 99× 1 (mix) = 99 specimens • Total = 198 + 99 = **297 specimens tested**			

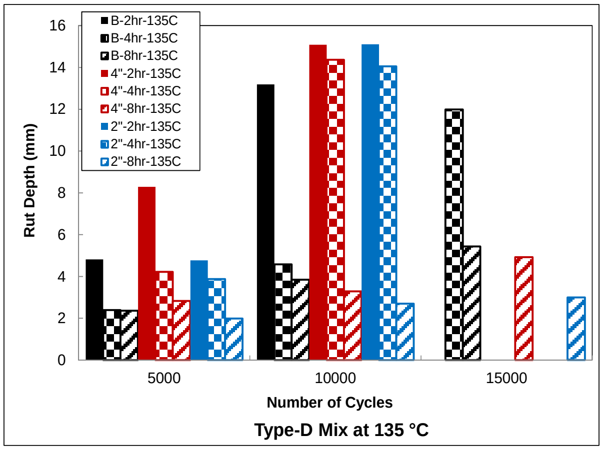
PMFC Specimens					
Mix	HWTT	OT	IDT	Mr	Dynamic Modulus
Type-D	2	5	2	2	2
BMD	2	5	2	2	2
RAP/RAS	2	5	2	2	2
Number of specimens tested **(39/month)**	6	15	6	6	6
Total number of specimens	• 0-month aging condition = 39 specimens • 6-month aging condition = 39 specimens • 14-month aging condition = 33 specimens (No IDT) • Total = 39 + 39 + 33 = **111 specimens tested**				

Hamburg Wheel Tracking Test and Associated Results

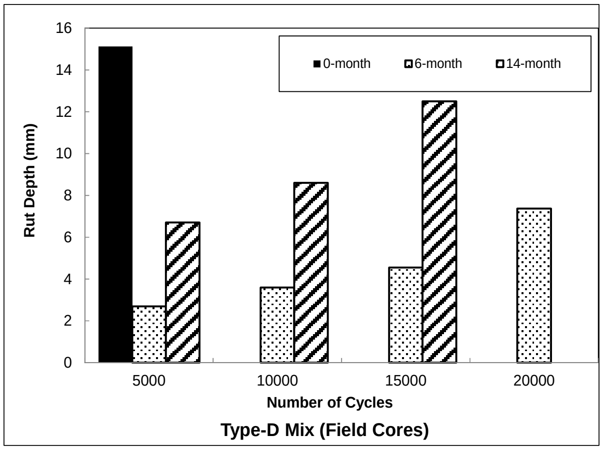
Figure 30 shows the rut depth of each mix for each test case. In addition, the rut depths of the PMFC specimens at different field aging periods (i.e., 0-, 6-, and 14-month period) were plotted together with horizontal solid or dashed lines in the figures. The following observations are made from figures:

- **Impact of container size:** It is difficult to find a clear trend because several test cases of Type-D and RAP/RAS mixes failed at earlier passes. However, the BMD mix showed a very clear trend. For the same aging time, the impact of container size on the rutting resistance was not significant until 10,000 passes but smaller container size (i.e., 2 in. deep pan) showed much lower rut depth than those of bigger container sizes at 15,000 and 20,000 passes. This implies that it is crucial to use right size of container to simulate aging effects.

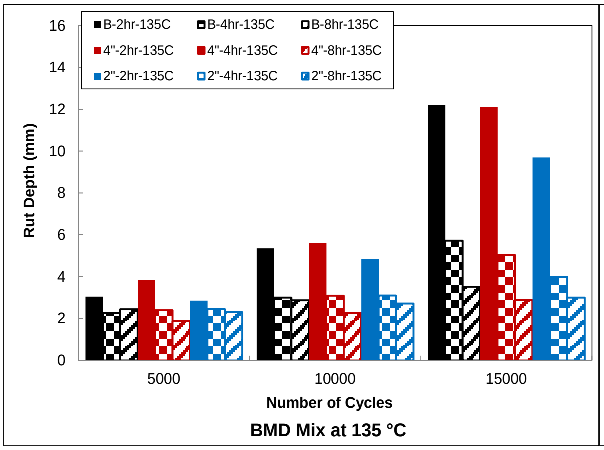
- **Impact of aging time:** For the same container size, the rut depth was generally lowered as the aging time increased from 2 hours to 8 hours.
- **Impact of field aging period:** For all three mixes, the rut resistance of PMFC specimens just after construction (0-month) was very poor. After six months, all mixes showed very good rut resistance compared to 0-month case. This is because the weather condition during the initial 6-month period (summer season) significantly affected the HWTT results. Contrary to expectation, all mixes after 14-month aging period resisted slightly less than the ones with 6-month aging period. It is difficult to find any possible reasons for this result at this moment but researchers plan to keep monitoring the performance of these field mixes in near future. Additional tests will be performed and finding relevant to this result will be presented.
- **Comparisons among mix types:** For both PMLC and PMFC specimens, the performance of the BMD (HMA) mix showed better rut resistance than those of the Type-D and the RAP/RAS (WMA) mixes. Recycled materials (RAP and RAS) in the BMD mix made the mix stiff so that it showed better rut resistance than that of the Type-D.



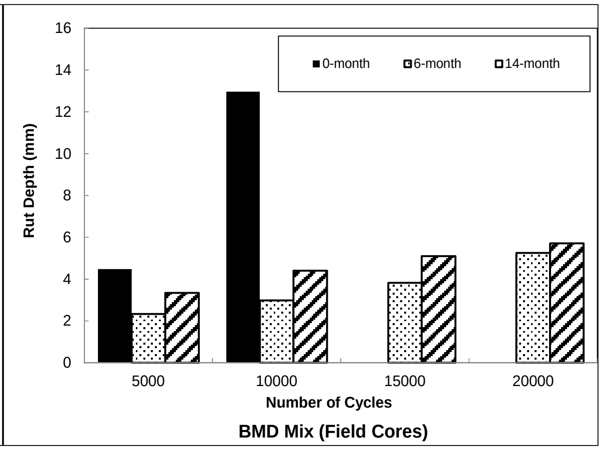
(a) Type-D PMLC specimens



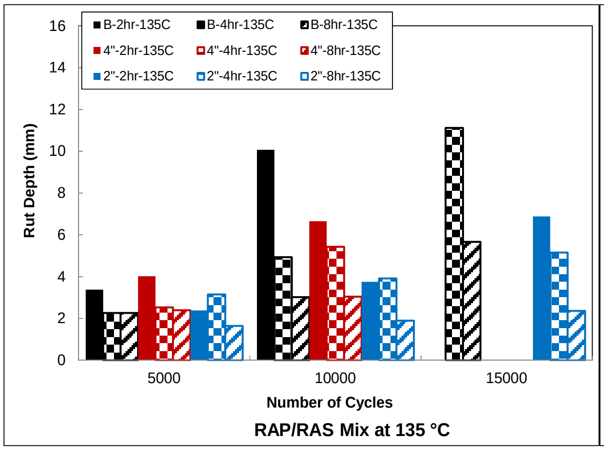
(b) Type-D PMFC specimens



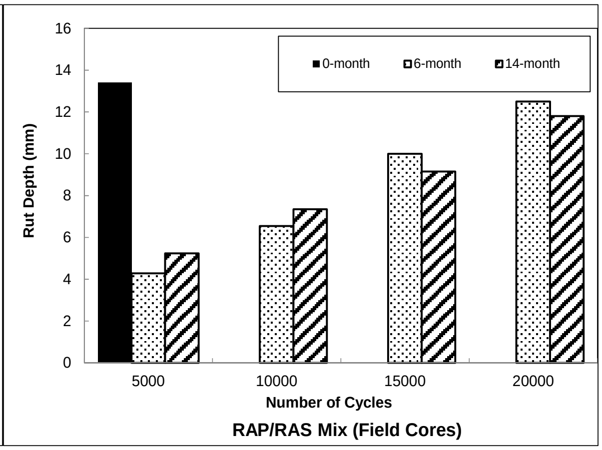
(c) BMD PMLC specimens



(d) BMD PMFC specimens



(e) RAP/RAS PMLC specimens



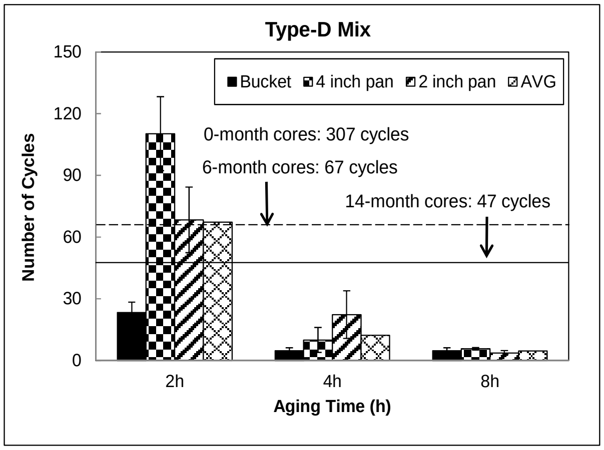
(f) RAP/RAS PMFC specimens

Figure 30. Hamburg Test Results from Different Containers and Aging Conditions.

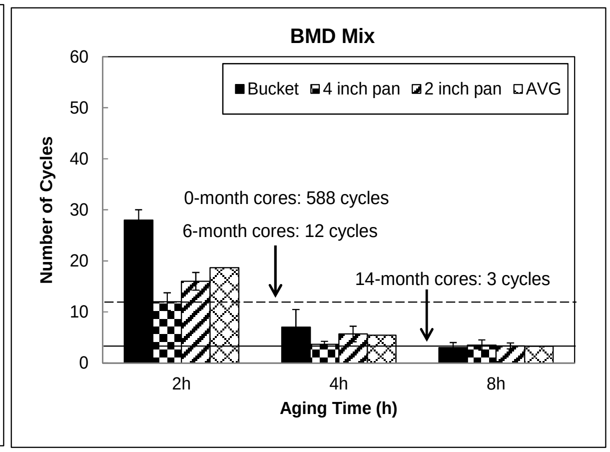
OT and Associated Results

Figure 31 presents the reflective cracking life (average loading cycles of the five specimens) from each test case. In addition, those of PMFC specimens at different field aging periods (i.e., 0-, 6-, and 14-month period) were plotted together with horizontal solid or dashed lines in the figures. The following observations are made from figures:

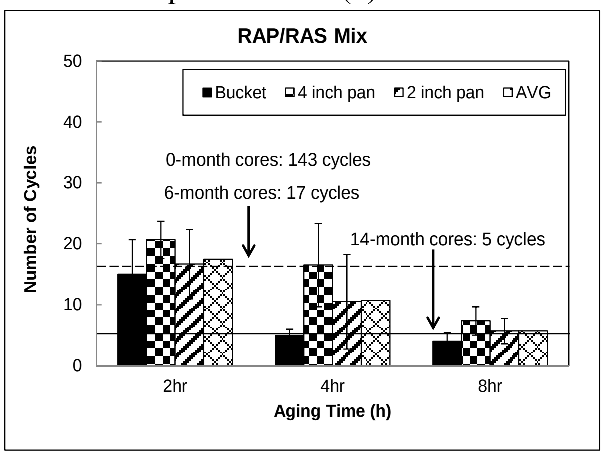
- **Impact of container size:** A clear trend from all test cases was not observed for the same aging time. Sometimes bucket mixes showed higher cracking resistance than those of 2 or 4 in. pans or vice versa; other times they exhibited similar cracking resistance.
- **Impact of aging time:** Generally, the cracking resistance was lowered as the aging time increased from 2 hours to 8 hours.
- **Impact of field aging period:** The cracking resistance of PMFC specimens of all three mixes was dramatically decreased as the field aging period increased. The influence of the initial aging period (6-month period) on the cracking resistance of PMFC specimens was very significant because the mixes experienced the first summer during the initial aging period.
- **Comparisons among mix types:** PMLC specimens of the Type-D (HMA) mix exhibited the best performance, followed by the BMD (HMA) and RAP/RAS (WMA) mix. This is because the Type-D mix is softer than others, which included recycled materials in the mixes. For PMFC specimens at 0-month, the BMD mix exhibited the best performance, followed by the Type-D and RAP/RAS mix. However, the Type-D mix showed the highest value of cracking life after 6- and 14-month field aging period.



(a) Type-D PMLC and PMFC Specimens



(b) BMD PMLC and PMFC Specimens



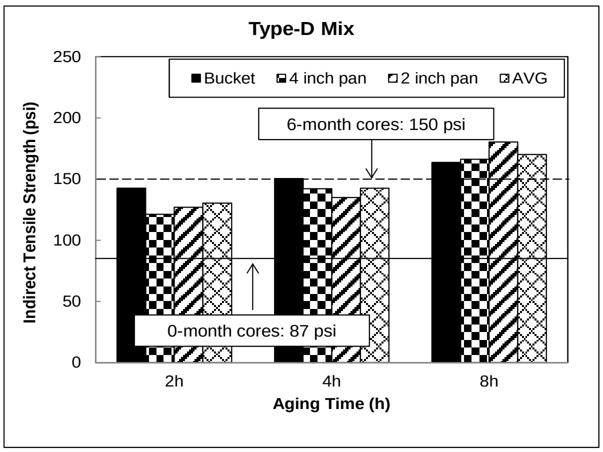
(c) RAP/RAS PMLC and PMFC Specimens

Figure 31. OT Test Results from Different Containers and Aging Conditions.

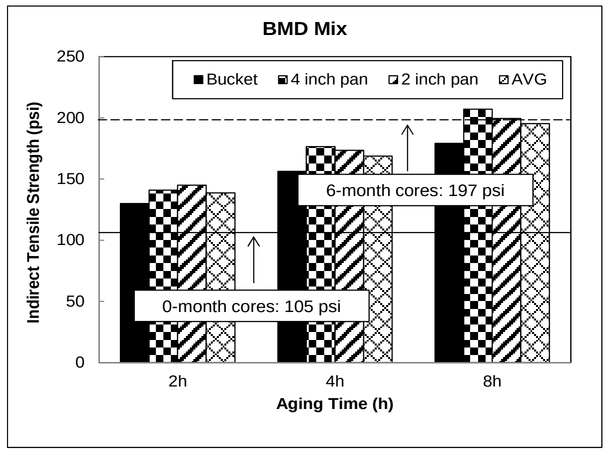
IDT and Associated Results

IDT was used to determine the tensile strength of compacted asphalt mixes. The test was conducted following the standard, TEX-226-F, *Indirect Tensile Strength Test*. PMLC and PMFC specimens were prepared in accordance with the test procedure, and for PMLC specimens the target air void was 7 percent ± 1 percent. The test specimens were placed long enough in the constant temperature apparatus to ensure a consistent temperature of 77°F (25°C) before testing. A controlled deformation rate of 2 in. (51 mm) per minute was applied to the test specimen, and the applied vertical load at failure of the specimen was recorded to calculate the tensile strength of mixes. Average tensile strength values from two replicates for each mix were obtained. PMFC specimens taken from two different aging periods (0- and 6-month) were only used to compare to PMLC specimens due to material limitations. Figure 32 presents the indirect tensile strength from each test case is presented in. Those of PMFC specimens at different field aging periods (i.e., 0- and 6-month period) were also plotted together with horizontal solid or dashed lines in the figures. The following observations are made from figures:

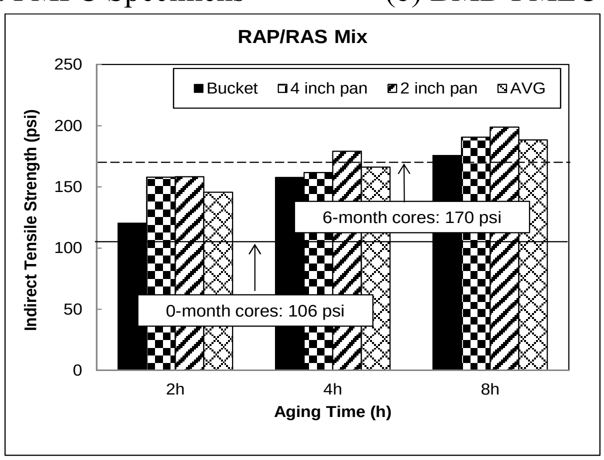
- **Impact of container size:** As presented in OT results, a clear trend from all test cases was not observed for the same aging time. Overall, they exhibited similar indirect tensile strengths.
- **Impact of aging time:** As expected, the indirect tensile strength of all three mixes increased as the aging time increased but not significantly.
- **Impact of field aging:** As expected, the indirect tensile strength increased as the length of field aging period increased (from 0-month to 6-month) approximately from 60 percent to 87 percent.
- **Comparisons among mix types:** PMLC specimens of the RAP/RAS mix exhibited the best performance, followed by the BMD and the Type-D mix for the same aging time. Similar test results from PMFC specimens were shown but PMFC specimens of the BMD mix exhibited a bit higher indirect tensile strengths that those of the RAP/RAS mix at 6-month aging period.



(a) Type-D PMLC and PMFC Specimens



(b) BMD PMLC and PMFC Specimens



(c) RAP/RAS PMLC and PMFC Specimens

Figure 32. IDT Test Results from Different Containers and Aging Conditions.

Resilient Modulus Test and Associated Results

The Mr test was used to determine the elastic modulus of PMFC specimens only due to the limited time and efforts. The Mr values were calculated based on AASHTO TP31-96, (*Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension*). The test PMFC specimens were placed long enough in the constant temperature apparatus to ensure a consistent temperature of 77°F (25°C) before testing. The repeated load in the indirect tension mode was applied in the form of a haversine curve with a loading time of 0.1 second and a rest period of 0.9 second in one cycle, up to 106 cycles. The horizontal recoverable deformations were measured and average Mr values from two replicates were obtained. Figure 33 shows the Mr of PMFC specimens at different field aging periods (0-, 6-, and 14-month). As clearly seen in the figure, the Mr of all mixes increased as the length of field aging period increased (from 0-month to 6-month) approximately from 42 percent to 132 percent. However, the Mr of all mixes after 14-month aging period was similar to those of 6-month aging period cases. This indicates that the weather condition during the initial 6-month period affected gaining of the resilient modulus, while the influence of the weather condition from 7-month to 14-month period was not significant.

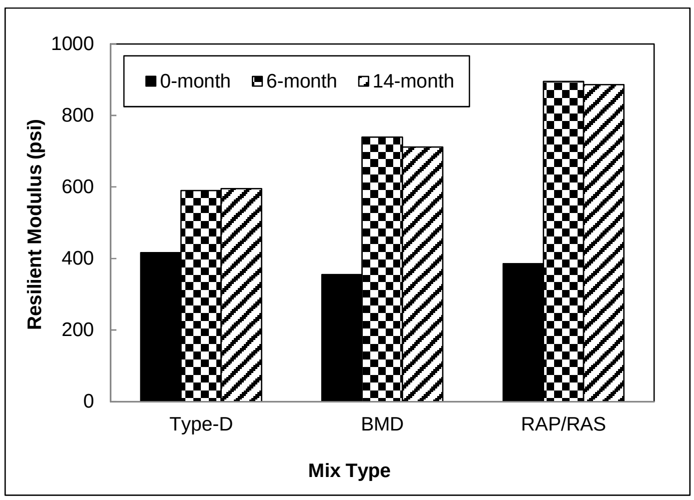


Figure 33. Mr Test Results of PMFC Specimens at Different Field Ages.

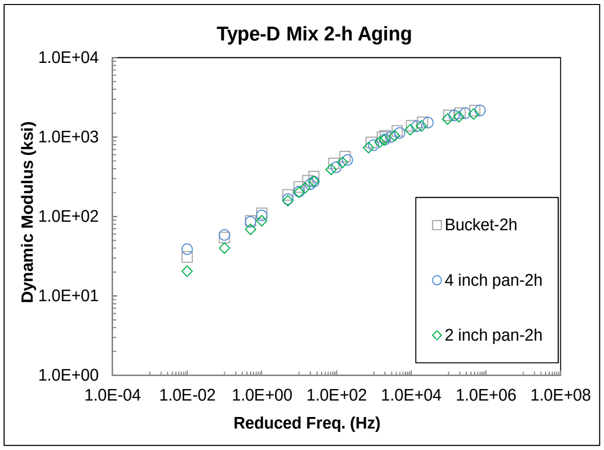
Dynamic Modulus Test and Associated Results

Two replicates were tested and average values of dynamic modulus at each different testing temperature over the range of loading frequencies were obtained. In order to measure the dynamic modulus of PMFC specimens (Figure 34), small scale cylindrical specimens with a diameter of 1.5 in. (38 mm) and a height of 4.3 in. (110 mm) were prepared based on the study conducted by Li and Gibson (*30*). Then, the same testing procedure was followed for testing. The details on the feasibility to perform dynamic modulus tests using small scale specimens are well described in the study mentioned above. The following observations are made from figures:

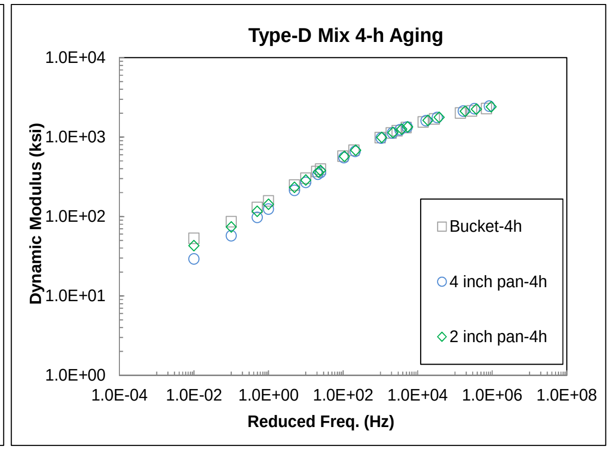
- **Impact of container size:** To investigate the impact of container size on the dynamic modulus of mixes for the same aging time, the master curves at the reference temperature of 104°F are plotted in Figure 35. Although a clear trend was not observed from the Type-D mix, the smaller container size of the BMD and RAP/RAS mixes clearly exhibited higher stiffness characteristics than those of bigger container sizes. This characteristic was especially clear at the low frequency loading levels.

- **Impact of aging time:** Figure 36 investigates the effect of aging time on the dynamic modulus of mixes using the same data set used in Figure 35. Those of PMFC specimens at different field aging periods (i.e., 0-, 6-, and 14-month period) are also plotted together in the figures for further discussion. For the same container size, the stiffness of all mixes generally increased with aging time.
- **Impact of field aging:** Figure 36 presents the dynamic modulus values of PMFC specimens at different field aging periods. The stiffness of mixes increased as the length of field aging periods increased from 0-month to 6-month. However, the dynamic modulus values of PMFC specimens at 14-month aging period were similar to those of 6-month aging period or a bit lower.
- **Comparisons among mix types:** With respect to stiffness characteristic comparisons for mixes, the BMD and RAP/RAS mixes showed slightly higher stiffness than those of Type-D mix over aging period. A figure for this comparison result is not presented in this paper due to space limitations.

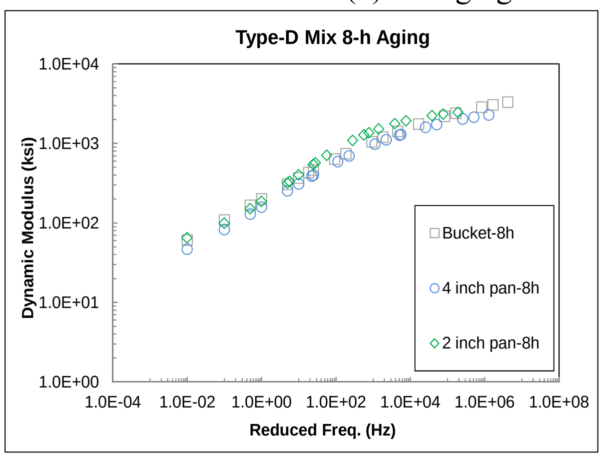
Figure 34. Small Scale PMFC Specimens for Dynamic Modulus Test.



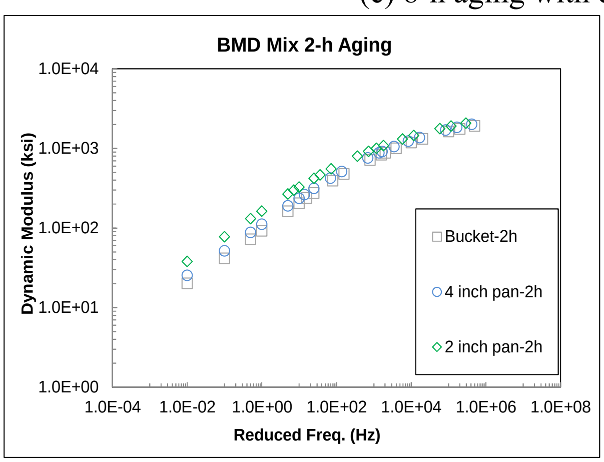
(a) 2-h aging with different containers



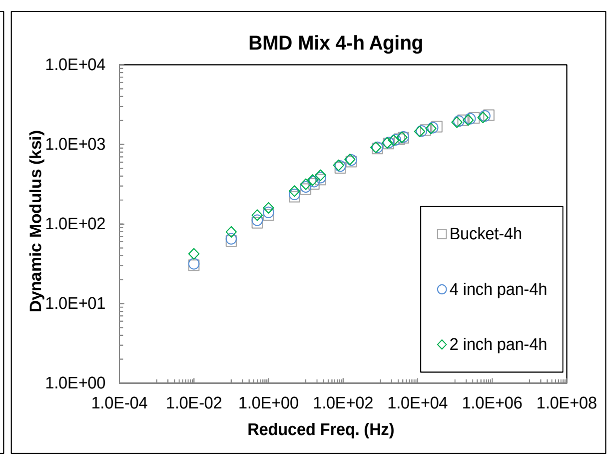
(b) 4-h aging with different containers



(c) 8-h aging with different containers

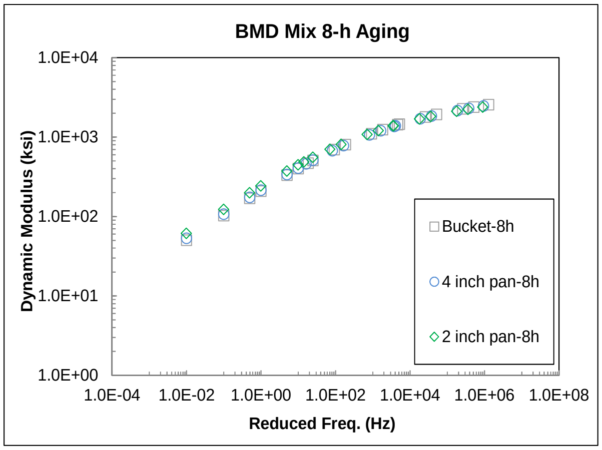


(d) 2-h aging with different containers

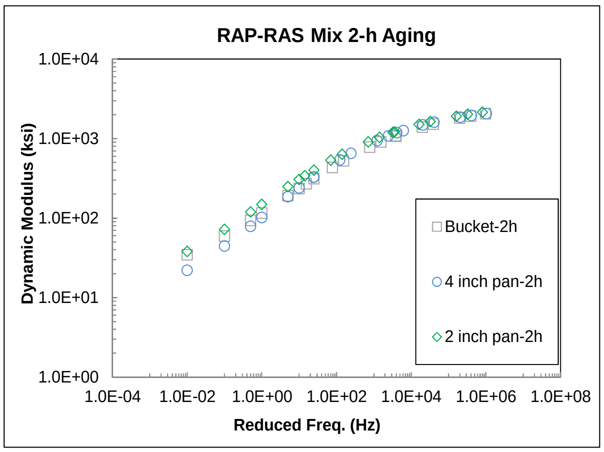


(e) 4-h aging with different containers

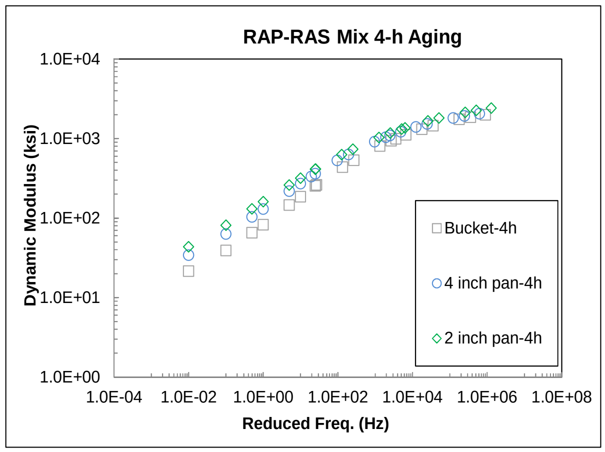
Figure 35. Master Curves of PMLC Specimens from Different Containers and Aging Conditions.



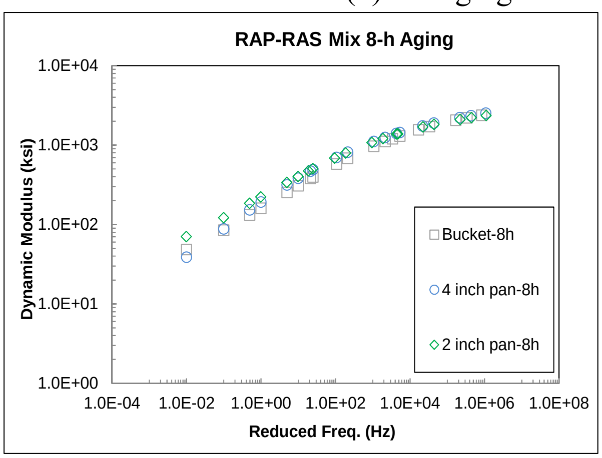
(f) 8-h aging with different containers



(g) 2-h aging with different containers

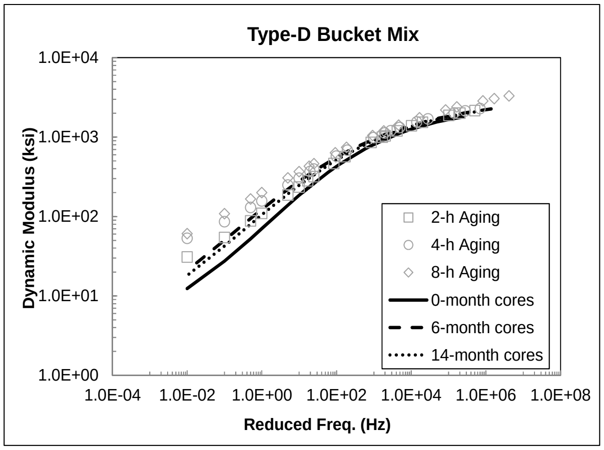


(h) 4-h aging with different containers

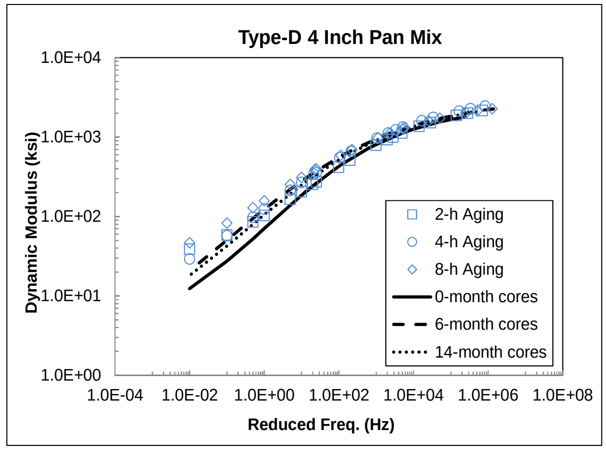


(i) 8-h aging with different containers

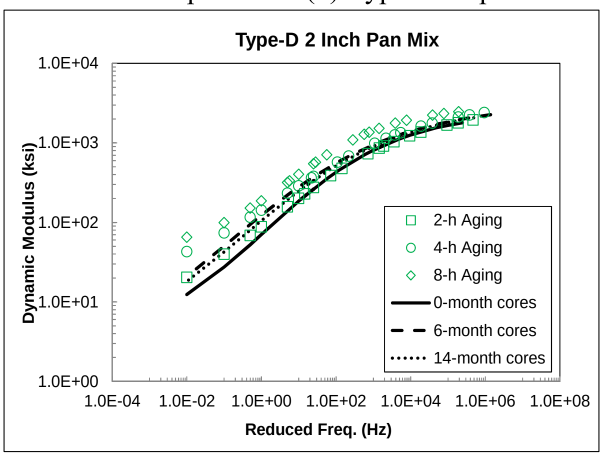
Figure 35. Master Curves of PMLC Specimens from Different Containers and Aging Conditions (Continued).



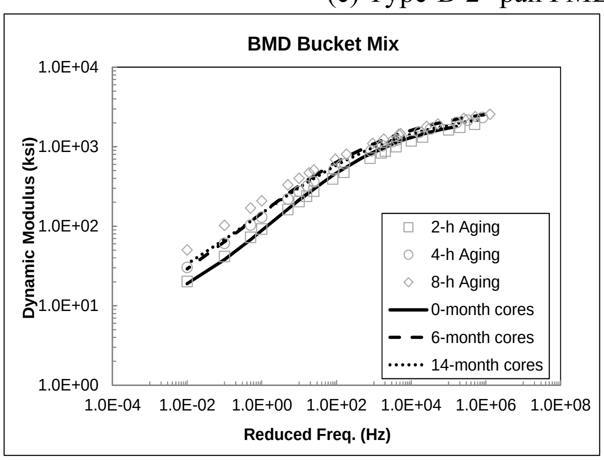
(a) Type-D bucket PMLC and PMFC specimens



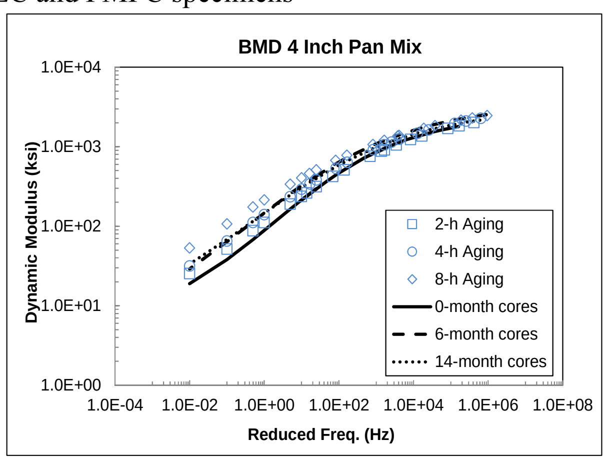
(b) Type-D 4" pan PMLC and PMFC specimens



(c) Type-D 2" pan PMLC and PMFC specimens

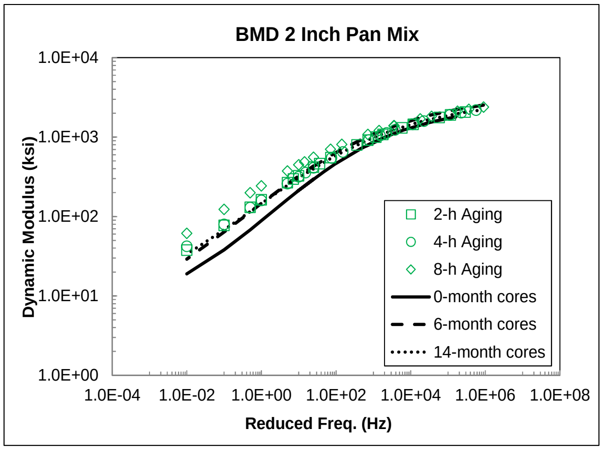


(d) BMD bucket PMLC and PMFC specimens

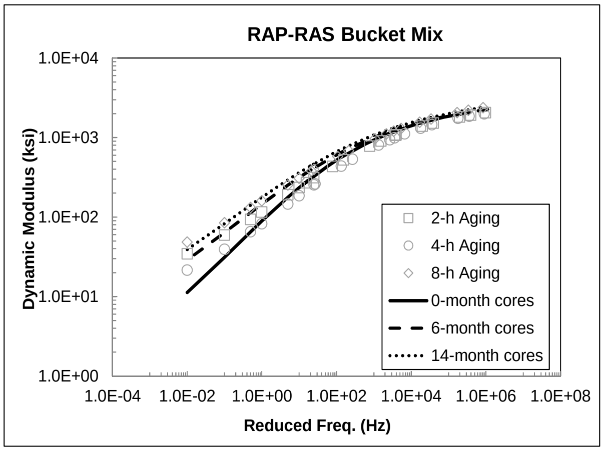


(e) BMD 4" pan PMLC and PMFC specimens

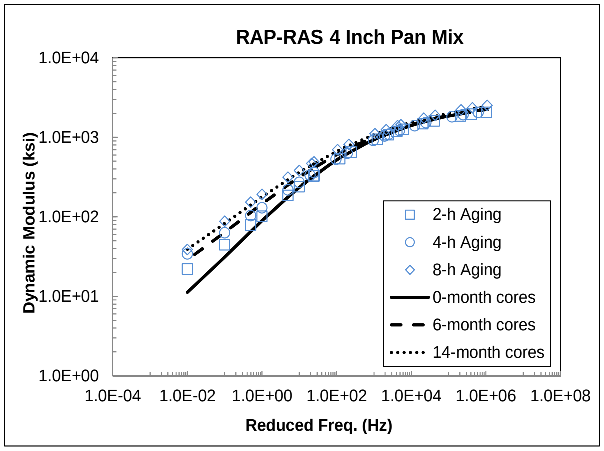
Figure 36. Comparisons of Master Curves between PMLC and PMFC Specimens.



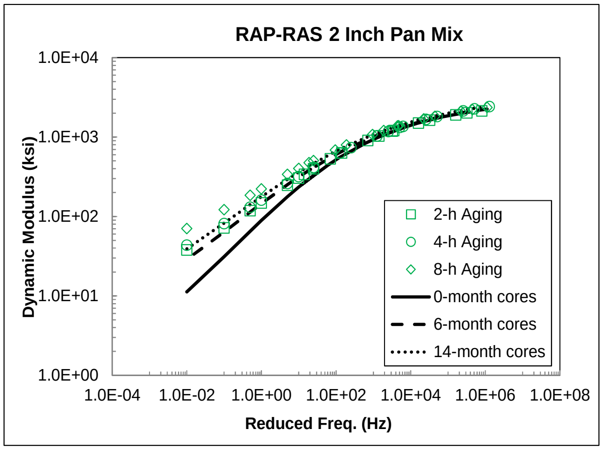
(f) BMD 2" pan PMLC and PMFC specimens



(g) R/R bucket PMLC and PMFC specimens



(h) R/R 4" pan PMLC and PMFC specimens



(i) R/R 2" pan PMLC and PMFC specimens

Figure 36. Comparisons of Master Curves between PMLC and PMFC Specimens (Continued).

RECOMMENDED LABORATORY AGING TIME

As mentioned earlier, the primary objective of this research was to establish a laboratory aging protocol for PMLC samples. Table 14 recommends laboratory short-term aging time at the compaction temperatures for each mix type based on the initial field performance (i.e., six months after construction). As shown in the table, a different aging time for individual test of each mix is recommended based on test results. Aging time for HWTT of RAP/RAS mix was not recommended because test results were not reliable to recommend. Also, researchers recommend using a right sampling container size for plant mixes that are aged in 2- or 4-in. deep pans in the oven. If buckets are used for sampling plant mixes, researchers recommend that mixes be spread evenly out into a 2- or 4-in. deep pan during the aging process in the oven.

Table 14. Recommended Laboratory Oven Aging Time (Hour).

Mix	Hamburg	Overlay	IDT	Dynamic Modulus
Type-D (HMA)	4	2	4	4
BMD (HMA)	4	2	4	4
RAP/RAS (WMA)	n/a	2	2	4

SUMMARY

This chapter investigated the impacts of laboratory oven aging conditions, including aging time, container size, field aging period, and mix types, on a variety of engineering properties of asphalt mixes. Various laboratory tests were employed to compare changes of the engineering properties of field cores at different field aging period. Based on the laboratory test results, researchers recommend practical laboratory aging time for molding PMLC samples and the size of container for sampling plant mixes. The following provides a summary and conclusions of this study:

- Based on the test results, container size may affect the performance and engineering properties of asphalt mixes depending on testing temperature. For Hamburg test results, there was no container size effect observed up to 10,000 passes; however, 2-in. pan mixes showed lower rut depth than 4-in. mixes and bucket mixes after 10,000 passes. Similarly, dynamic modulus of 2-in. pan mixes had higher stiffness characteristics than those of 4-in. mixes and bucket mixes at the reference temperature of 104°F. On the other hand, the impact of container size on the OT and the IDT test results was not significant at the testing temperature of 77°F. Careful selection of container size must be considered in asphalt mix design and quality control.
- The aging time clearly affected the performance and engineering properties of asphalt mixes. As expected, longer oven aging time showed less Hamburg rut depth, lower overlay cycle, higher IDT, and higher stiffness characteristics.

- Recycled materials (RAP/RAS) also affected the performance and engineering properties of asphalt mixes. The BMD mix had lower Hamburg rut depth, lower overlay cycle, higher IDT, resilient modulus, and dynamic modulus characteristics than those of the Type-D (control mix). Although the RAP/RAS (WMA) mix showed bad rut resistance compared to the BMD (HMA) mix, it showed better cracking resistance, higher indirect tensile strength and resilient modulus, and similar stiffness characteristics.
- Researchers made recommendations on laboratory oven aging time based on laboratory test results of plant-mixed and laboratory compacted samples by comparing with the initial field performance of asphalt mixes. However, only one weather condition and short-term aging time were considered in this study. Additional tests are necessary for a strong conclusion.

CHAPTER 5
FIELD PERFORMANCE OF RAP/RAS TEST SECTIONS AND FORENSIC STUDY

It is critical to evaluate the impact of RAP/RAS used in HMA and WMA on the field performance problems of the asphalt mixes. In order to identify how significant they are and which approach to improve the durability problems of mixes, various field test sections were constructed and their field performances were evaluated through field survey. Researchers have collected and assembled all essential information on the field test sections before and after construction, including materials collection such as plant mixes and field cores for the laboratory tests. In addition to field survey, a forensic study was conducted to find out the reasons for good and poor performance of RAP/RAS mixes. Detailed information is described in remaining sections of this chapter.

FIELD TEST SECTIONS AND PERFORMANCE

Field performance survey on a variety of virgin mixes and RAP/RAS used in HMA and WMA mixes were conducted. Researchers have monitored test sections constructed under existing TxDOT's research projects. Detailed information on each test section is provided below.

Amarillo IH40

The four RAP test sections shown in Figure 37 were constructed on IH40 near Amarillo, Texas, on Aug. 11, 2009. The existing pavement has a total of 8 in. of existing HMA with severe thermal related transverse cracking, which extends the full depth of the HMA (Figure 38). 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 make this a good case study to rapidly evaluate the impact of different RAP layers on pavement performance.

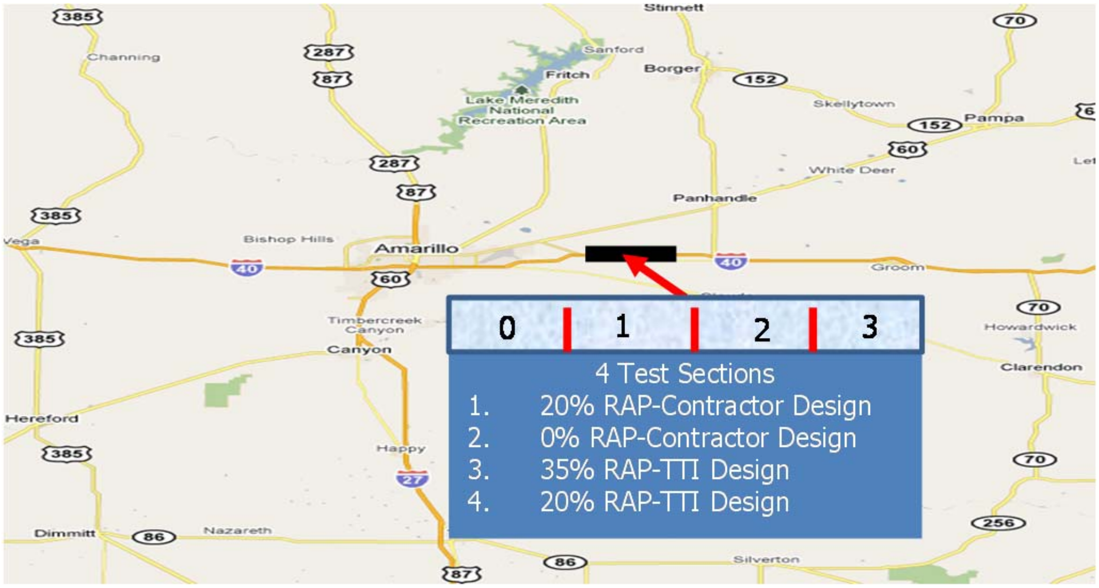


Figure 37. Four RAP Test Sections on IH40 near Amarillo, Texas.

Figure 38. 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 37, 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.

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. 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 39 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 PG64-22 virgin binder yielded very poor OT results). Figure 39 shows 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.

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. 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 in terms of rutting, 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. Table 15 details the 20 percent RAP mix design information.

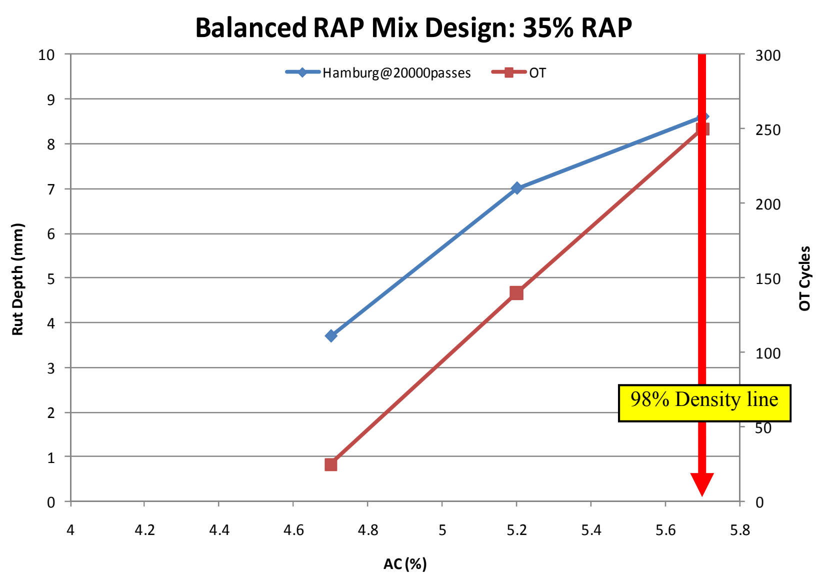


Figure 39. Balanced RAP Design for 20 Percent RAP Mix of Section #2.

Similarly, the 20 percent RAP mix used in Section #3 was designed with different aggregate gradation from the one in Section #0, as illustrated in Figure 40. 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 15 details the 20 percent RAP mix design information.

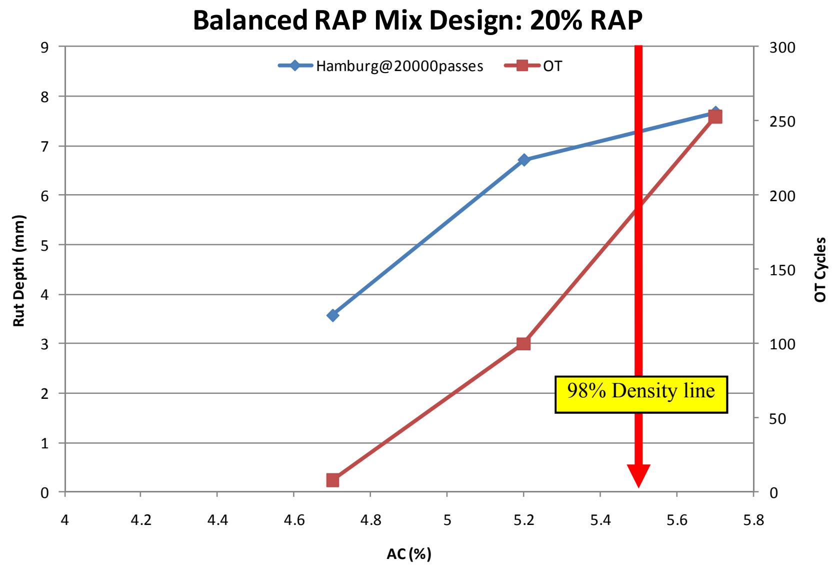


Figure 40. Balanced RAP Design for 20 Percent RAP Mix of Section #3.

Table 15. 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 mm	10
1	0	PG64-28	Contractor	TxDOT's Tex-204-F	4.8	4.38 mm	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 Aug. 11, 2009. Since then eight field surveys have been conducted on Apr. 22, 2010; Sept. 8, 2010; Apr. 5, 2011; Dec. 15, 2011; May 30, 2012; Dec. 19, 2012; May 16, 2013; and June 8, 2014, respectively. So far no rutting has been observed, but reflective cracking was observed on all four test sections on the third survey. Table 16 lists detailed reflective cracking observations for each section. Figure 41 shows the development of reflective cracking. Prior to placing the overlay, the number of pre-existing cracks in each section was documented and mapped. The reflective cracking rate is 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 16. 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. 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.

Table 16. Field Performance Survey: Reflective Cracking Rate (%).

Survey Time	Months since Construction	Section 0 (20% RAP - Contractor)	Section 1 (0% RAP - Contractor)	Section 2 (35% RAP -TTI)	Section 3 (20% RAP -TTI)
8/11/2009	0	0	0	0	0
4/22/2010	8	0.0	0.0	0.0	0.0
9/8/2010	13	36.1	20.0	0.0	4.2
4/5/2011	20	83.3	52.5	28.6	50.0
12/15/2011	28	97.2	65.0	38.1	83.3
5/30/2012	33	100.0	80.0	57.1	95.8
12/19/2012	40	100	90	81.0	100
5/16/2013	45	100	95	83.3	100
6/8/2014	58	100	100	85.7	100
OT cycles		10	50	200	125

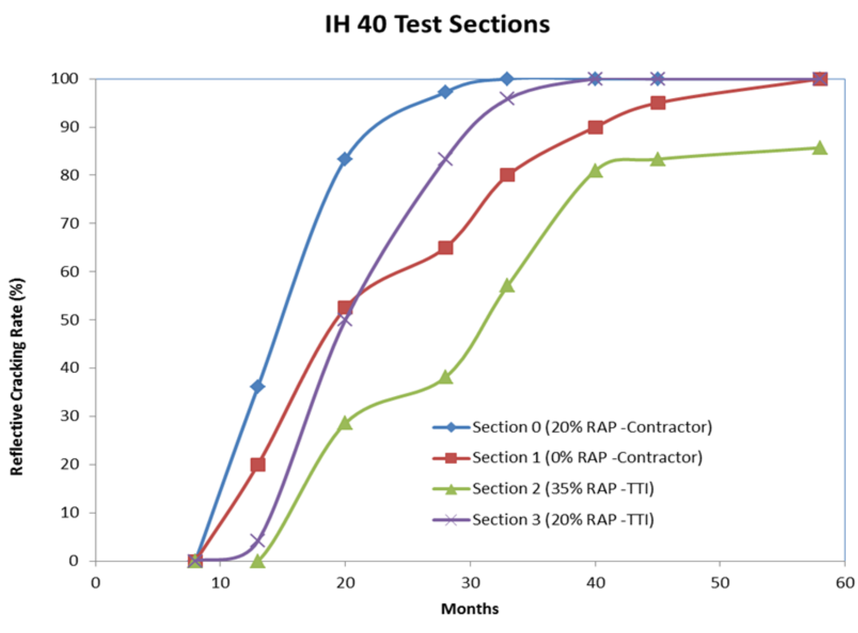


Figure 41. Relationship between OT Cycles and Observed Reflective Cracking Rate.

Pharr 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 BMD method. Table 17 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 42 shows the pavement conditions of the three RAP sections surveyed on April 12, 2011. So far rutting and cracking has not occurred. After reviewing the low OT cycles of these two 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 18. Recall that 1) FM1017 is new construction with a stiff base, 2) there are no pre-existing cracks to initiate reflection cracks, 3) the traffic is very light on this highway, 4) the climate is very mild with no cold weather, and 5) 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 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 17. 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 42. RAP Test Sections on FM1017: No Rutting and Cracking on April 12, 2011.

Table 18. RAP Sections on FM1017 vs. IH40.

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

Amarillo US87

Two 3-in. thick asphalt OT pavements were constructed end to end in the same lane and traveling direction on US87, Amarillo, Texas, in late October 2010. The main objective of these two test pavements was to validate the effectiveness of decreasing design air voids on improving cracking resistance of RAS mixes. The RAS mixes used on the two test pavements are exactly the same (aggregates, gradation, virgin binder, and RAS) except for the OAC; OAC for the control section was 4.6 percent while the other is 5.2 percent. 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 for Amarillo range from 48°F (9°C) in January to 92°F (33°C) in July. US87 in Amarillo has medium traffic with around 5 million ESALs in 20 years. The existing asphalt pavement exhibited severe transverse cracking. Cold weather and severe existing pavement cracking plus high traffic make these two pavements a good case study to rapidly validate the effectiveness of decreasing design air voids on improving cracking resistance of RAS mixes.

After completion of construction of these two RAS test pavements, seven field surveys were conducted on Apr. 5, 2011; Dec. 15, 2011; May 30, 2012; Dec. 19, 2012; May 14, 2013; June 7, 2014; and March 7, 2015. So far, no rutting has been observed, but reflective cracking occurred in both test pavements (Figure 43). Figure 44 shows the development history of the observed reflective cracking. Prior to placing the overlay, the number of pre-existing cracks in each pavement was documented and mapped. The reflective cracking rate is defined as the ratio of the number of observed reflective cracks to the original number of cracks before the 3-in. overlay. Apparently, decreasing design air voids significantly improved reflective cracking performance of the RAS mix on US87, which is clearly shown in Figure 44.

Figure 43. Observed Reflective Cracking of RAS Test Pavements on US87, Amarillo.

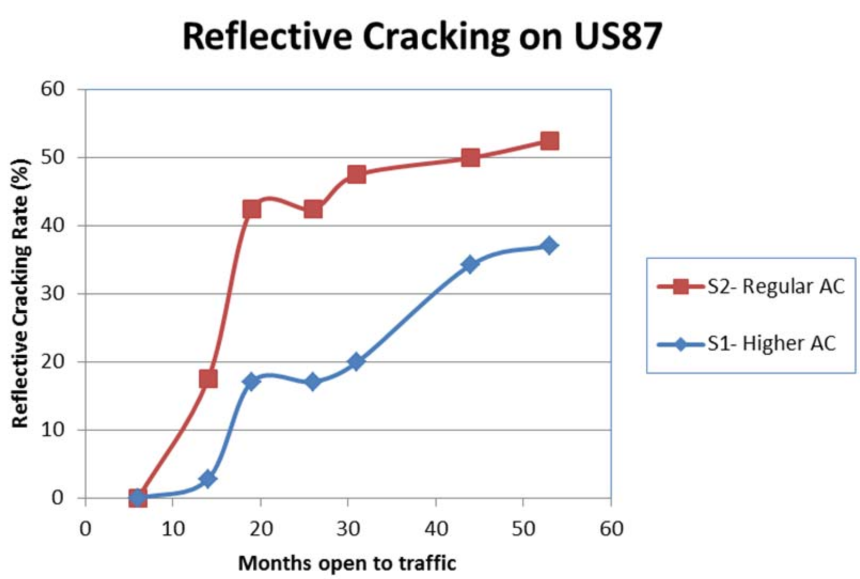


Figure 44. Reflective Cracking Development of RAS Test Pavements on US87, Amarillo.

Fort Worth Loop820

Four field test sections were constructed on Loop820 in Fort Worth side by side. Table 19 presents detailed information on these four test sections. The main features of these four test sections are: 1) RAP/RAS/WMA with Advera additive, 2) soft virgin binder without changing the OAC, 3) extra virgin binder without changing virgin binder grade, and 4) pre-blending WMA additive with processed RAS. Additionally, these four test sections have a 2-in. asphalt overlay over cracked continuously reinforced concrete pavement (CRCP), as shown in Figure 45. These test sections provided opportunity to check the impact of soft binder and extra virgin binder on rutting and cracking performance of RAP/RAS mixes.

The test sections were built on July 19, 2012. These four test sections are in good conditions and only a few construction joints needed some sealing work. These sections need to be continuously monitored.

Table 19. Four Field Test Section on Loop820.

Test section	Virgin binder	OAC (%)	WMA additive: Advera	HWTT rut depth@ 10,000 passes	OT cycles of plant mixes
Section 0	PG64-22	5.1	Advera as external additive	7.2mm	8
Section 1	PG64-22	5.1	Advera pre-blended with processed RAS	10.6mm	12
Section 2	PG64-28	5.1	Advera as external additive	8.2mm	22
Section 3	PG64-22	5.5	Advera as external additive	16.5mm	24

Figure 45. RAP/RAS Test Sections on Loop 820, Fort Worth on June 12, 2014.

Houston SH146

A field test section was constructed on SH146 in Houston area where the winter weather is mild. Again, the test section on SH146 was a new construction pavement with a total asphalt layer of 5 in. A dense-graded Type C mix with 15 percent RAP/5 percent RAS was used in the top 2-in. (50 mm) surface layer. The mix designed by the contractor had excellent rutting/moisture damage resistance with a Hamburg rut depth of 2.1 mm after 20,000 passes. Meanwhile, its cracking resistance was very poor with OT cycles of 3. The main features of this section were 1) new construction pavement, 2) both RAP and RAS in the mix, 3) excellent rutting/moisture damage resistance but poor cracking resistance of the RAP/RAS mix, 4) surface layer sitting on a good foundation, and 5) hot summer and mild winter conditions.

Since the completion of construction on Oct. 8, 2010, this test section has been monitored six times on April 8, 2011; December 16, 2011; May 18, 2012; December 14, 2012; May 10, 2013, and Dec. 18, 2014. After four years' service, the test section showed some longitudinal and transverse cracking, as illustrated in Figure 46. Some sealing work is needed.

Figure 46. Pavement Condition of the RAP/RAS Test Section on SH146, Houston on December 18, 2014.

Survey Results of SH359

An asphalt OT section with 20 percent RAP was constructed on SH359 eastbound in March 2009. The overlay thickness was 3 in. (Figure 47), and Figure 48 shows the overview of the SH359 test section.

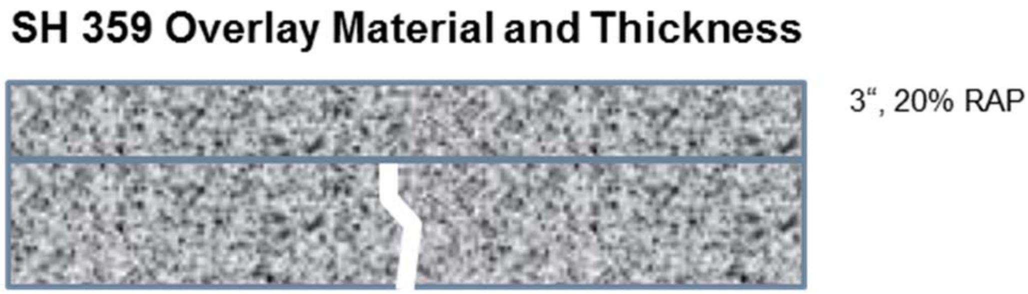


Figure 47. Schematic Diagram of the SH359 Pavement Structure.

Figure 48. Overview of the SH359 Test Section.

The surveys were conducted on Dec. 20, 2010; April 11, 2011; Dec. 19, 2011; and May 24, 2012; Dec. 20, 2012; and May 15, 2013. No cracking or rutting was found during these surveys (Figure 49). On May 15, 2013, researchers tried to perform survey and found that the test section was covered by a seal coat, so the survey on the test section was stopped.

Figure 49. No Crack, No Rutting in the SH359 Test Section, as of 12/20/2012.

Austin FM973

TxDOT setup an experimental overlay on FM973 in Travis County under Austin District in order to conduct testing and long-term performance monitoring for several research projects. This experimental construction project (STP 1102 (371)) was planned to study the different aspects of WMA, and the effect of RAP and RAS on the performance of HMA and WMA mixes.

The project site is located on FM973 just north of the Austin Bergstrom International Airport (Figure 50). The length of the project is approximately 2.91 miles starting near the intersection with FM969 (north end). The south end is approximately 1900 ft south of Green Grover road. At this location, FM973 is a two-lane two-way highway with significant percentage of truck traffic. Within the project limit, there is an aggregate quarry and concrete plant that generates very high volume truck traffic. Nine test sections were laid out using nine different mixtures. Figure 50 and Figure 51 show the sections layout.

Figure 50. Project Limit with Satellite View.

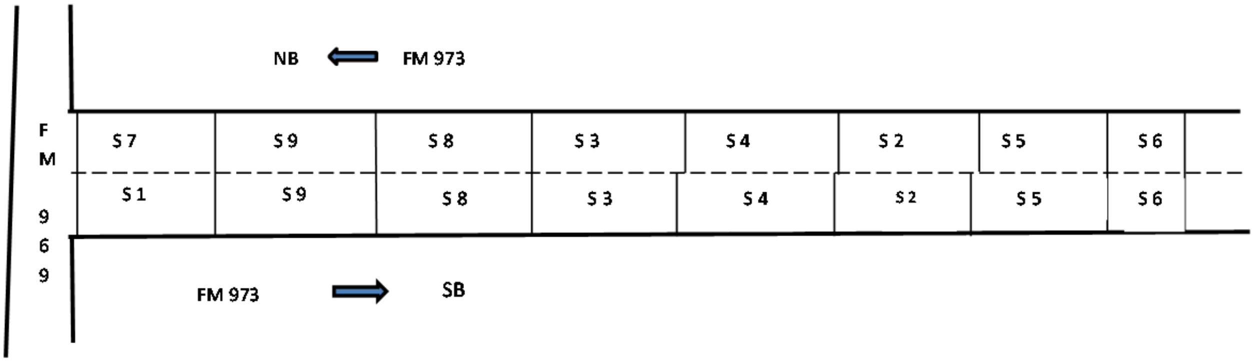


Figure 51. Schematic Diagram of Test Sections Layout (Not to Scale).

Traffic Data

FM973 near the test section experience moderate to high volume traffic. Current (2011) traffic data were reported as 11,000 and 11,300 annual average daily traffic (AADT) for the north and south end, respectively. Percent truck traffic was reported from 4.2 to 4.3 percent. Due to the presence of an aggregate quarry and concrete mix plant, approximately at the middle of the project side, this road occasionally gets heavy truck traffic.

Mixture and Materials

Nine different mixtures were designed and paved on nine test sections on this 2.9-mile overlay project. Table 20 and Figure 51 show the description of the mixtures and schematic plan of the test sections, respectively. All nine mixtures basically used same aggregate structure. It was TxDOT Type C (12.5 mm NMAS) surface mix. This project used three different grades of binder. PG70-22 (SBS modified binder) and PG58-28 binder were supplied by Valero Asphalt Company from their Corpus Christi, Texas, refinery. Pelican Refining Company supplied necessary PG64-22 (unmodified) binder from their Channelview, Texas, facility. These mixtures used virgin limestone from Cemex Aggregate located just across the asphalt mix plant. RAP and RAS came from various sources.

Table 20. List of Test Sections with Their Construction Date.

Section No.	Lot No.	Mixture Description				Date of Paving	Comment
		Type	Binder	RAP %	RAS %		
1	1	HMA	PG70-22	0	0	12/01/11	Control Mix
7	2	WMA (Foaming)	PG70-22	0	0	12/01/11	
9	3	WMA (Evotherm)	PG64-22	15	3	12/13/11	
8	4	WMA (Evotherm)	PG70-22	0	0	01/04/12	
3	5	HMA	PG64-22	15	3	01/05/12	
4	6	HMA	PG64-22	0	5	01/06/12	
2	7	HMA	PG64-22	30	0	01/16/12	
5	8	HMA	PG58-28	30	0	01/17/12	
6	9	HMA	PG58-28	15	3	01/18/12	

Preconstruction Survey

TTI researchers conducted a preconstruction visual survey for the entire project length to record the cracking and other distresses. The survey was performed at the last week of November 2011, days before the starting of overlay placement based on theStrategic Highway Research Program Distress Manual whichcan be found at http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/reports/03031/.

Figure 52 shows pavement conditions before the asphalt overlay. Some patching work was done in the north end of FM973, as shown in Figure 53.

Figure 52. Typical Distresses prior to Paving at Test Section.

Figure 53. Patching Area prior to Paving at the North End of the Test Section.

Post Construction Survey

The same researcher conducted a visual survey of test sections in March 2012, July, 2012, April 2013, and June 2014. Both transverse and longitudinal cracks were observed on FM973(Figure 54). Figure 55 shows the total cracking development history. The mixes with 5 percent RAS had the highest crack length. Such combination should be avoided in the future mixes. Additionally, the use of soft virgin binder (PG58-28) improved cracking resistance of asphalt mixes.

Figure 54. Cracking Observed on FM973.

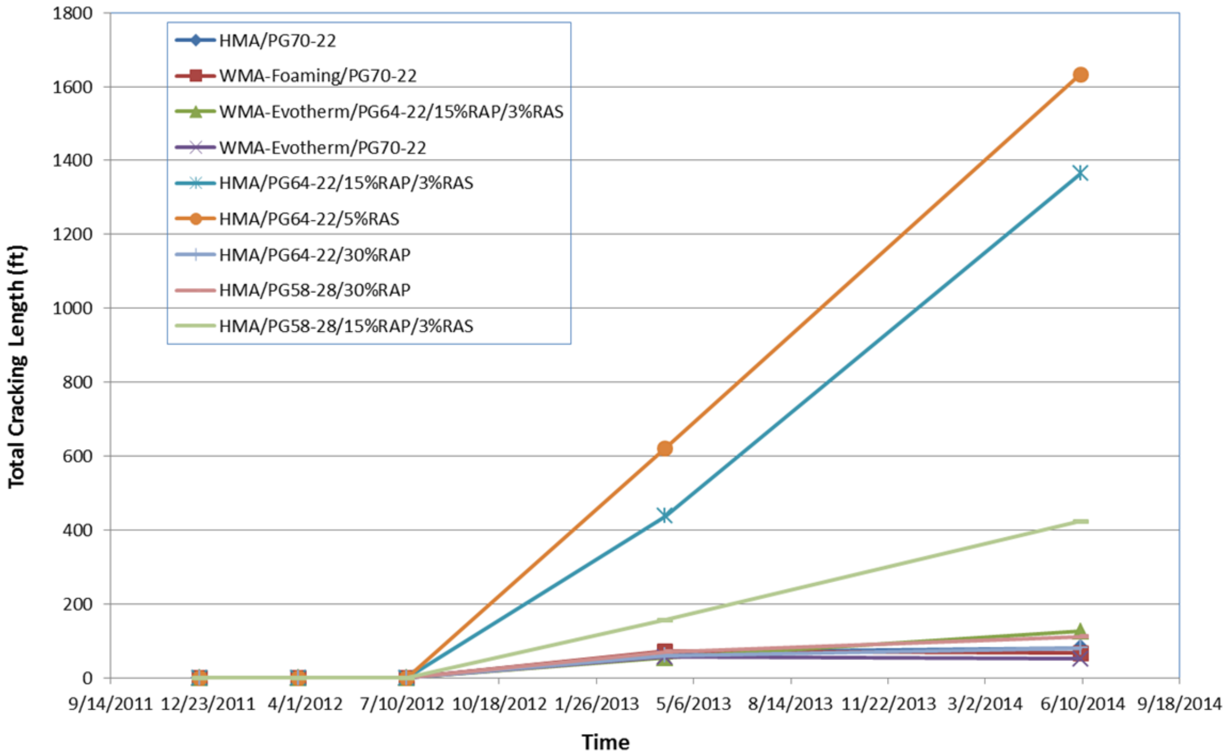


Figure 55. Cracking Development on FM973.

Amarillo SH15

The four SH15 test sections are parts of an overlay project constructed on October 7, 2013. The overlay is composed of 1.5 in. of Type D mix and 1 in. of Type F mix. The differences among the four test sections involve different binder types and/or binder content used in the Type D mix. The four test sections are located end to end on the eastbound side of SH15, at the north end of Perryton in Amarillo. Figure 56 shows the start point of Section 1 (Point A) and the end point of Section 4 (Point B). The start point of Section 1 (Point A) is about 4.3 miles away from the US83–SH15 intersection. Each test section is about 1000 ft.

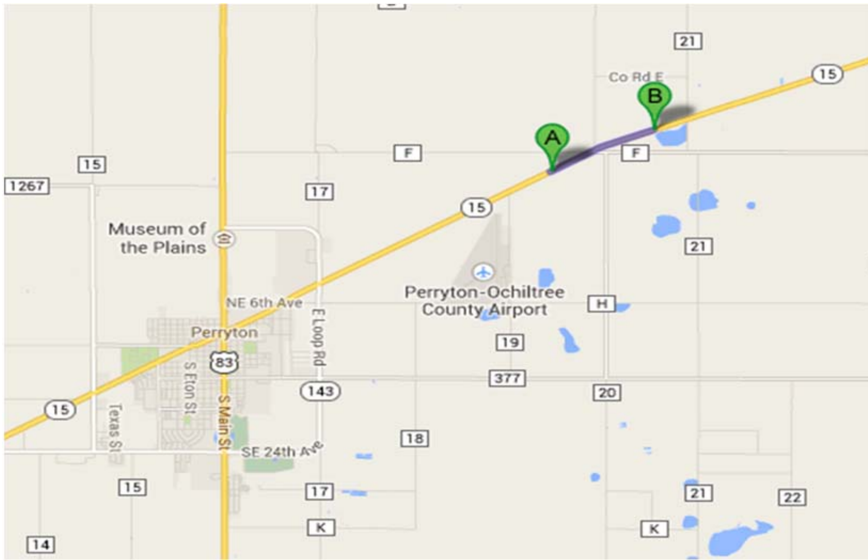


Figure 56. Location of SH15 Test Sections.

Asphalt Mix Types of SH15 Test Sections

The Type D mixes of the four test sections are all warm mixes. The binder types and asphalt contents of the SH15 test sections are:

- Section 1: PG58-28, 5.5 percent.
- Section 2: PG58-28, 5.8 percent.
- Section 3: PG64-34, 5.8 percent.
- Section 4: PG64-34, 5.5 percent.

Section 1 uses the control mix, Section 2 uses the mix with the same binder but a higher asphalt content, and Section 3 and Section 4 use the softer but highly modified binder PG64-34 with different asphalt contents. The mix designs follow TxDOT specification.

SH15 Existing Pavement Conditions

The existing pavement was AC pavement with some transverse and longitudinal cracking (Figure 57). Ground Penetrating radar data were collected before the milling work and showed that the existing AC pavement thickness was about 2.5 in. After that, researchers milled about 1 in. of the existing pavement and replaced it with 1 in. of Type F mix. No obvious transverse cracks were observed in the shoulder or the milled surface during construction.

Figure 57. Existing Pavement Condition of SH15 Test Sections.

Field Test Section Survey

Since the completion of test section construction, the four test sections on SH15 performed well. Neither rutting nor cracking was observed yet. On Section 4, there was some segregation, as shown in Figure 58 (the pavement condition after a heavy rain on June 7, 2014). The research team recommends that these four sections be monitored at least three more years.

Figure 58. Field Survey of SH 15 Test Sections.

Summary

When comparing the observed performance data of all the field test sections (Table 21), one may get very confused. RAP/RAS mixes with low OT cycles performed well on SH359, SH146, and FM1017. However, those RAP/RAS mixes on IH40 and US87 performed poorly, although these mixes had higher OT cycles. It seems that these observed performance data do not make sense. After carefully considering all the information presented in Table 21, several important observations can be made:

- RAP (or RAS) mixes can have similar or better performance than virgin mixes provided that they are designed following the BMD procedure.
- Cracking performance of asphalt mixes, in contrast to rutting performance, is strongly related to the existing pavement structure. It is extremely difficult to propose a single cracking requirement for all projects.
- Cracking performance is also influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness.
- There is an urgent need to develop a RAP/RAS mix design system for project-specific conditions, including traffic, climate, existing pavement conditions, etc.

Table 21. Field RAP/RAS Test Sections and Observed Performance.

Test Section				Weather	Traffic (mESAL /20 Years)	Overlay/new construction	Existing condition if overlay	OT cycles	Performance
Highway	RAP/RAS	Virgin binder	HMA/ WMA						
IH40	20%RAP	PG64-28	HMA	Hot summer, cold winter	30	4" overlay	Severe transverse cracking	10	100% reflect. cracking after 3 years
	0%RAP	PG64-28						90	
	20%RAP	PG64-28						103	
	35%RAP	PG58-28						200	57% reflect. cracking after 3 years
FM1017	0%RAP	PG76-22	HMA	Very hot summer, mild winter	0.8	New construction, 1.5" surface layer	N/A	28	Limited, fine cracking after 2.5 years
	20%RAP	PG70-22						6	
	35%RAP	PG70-22						7	
SH359	20%RAP	PG70-22	HMA	Hot summer, mild winter	1.0	3" overlay	Severe transverse cracking	3	No cracking after 2.5 years
SH146	15%RAP/ 5% TOAS	PG64-22	HMA	Hot summer, mild winter	1.5	New construction, 2" surface layer	N/A	3	No cracking after 2 years
US87	5% TOAS	PG64-28	HMA	Hot summer, very cold winter	3.5	3" overlay	Severe transverse cracking	48	50% reflective cracking after 2.5 years
		PG64-28 with 0.4% more virgin binder						96	20% reflective cracking after 2.5 years
Loop820	15%RAP/ 5%MWAS	PG64-22	WMA	Hot summer, mild winter	15	2" overlay	Fine transverse cracks in existing CRCP	8	Perfect condition after 1 year
		PG64-22	WMA(additive pre-blending with RAS)					12	
		PG64-28	WMA					22	
		PG64-22 (with 0.4% more virgin binder)	WMA					24	

Note: ESAL-Equivalent single axle load

The observations are further supported by performance data of high RAP test sections on the NCAT 2006. Seven RAP sections were built in 2006, as reported by Kvasnak at the RAP expert task group (ETG) meeting in October 2008 (*31*). The mixes used on the NCAT sections were: 1) virgin control mix with PG67-22, 2) 20 percent RAP with PG67-22 virgin binder, 3) 20 percent RAP with PG76-22 virgin binder, 4) 45 percent RAP with PG52-28 virgin binder, 5) 45 percent RAP with PG67-22 virgin binder, 6) 45 percent RAP with PG76-22 virgin binder, and 7) 45 percent RAP with PG76-22 virgin binder + Sasobit. After 2 years, 10 million ESALs of traffic, only the section with 45 percent RAP mix with PG76-22 + Sasobit had cracks and the other six sections have almost no cracks at all. Further investigation found that the cracks observed were reflective cracking. The seven RAP test sections on NCAT test sections were milling and inlays that were sitting on a more than 15-in. (375 mm) thick existing asphalt layer. The RAP test sections under this study and those at the NCAT 2006 test track clearly indicate the importance of developing a RAP/RAS mix design and performance evaluation system for project-specific service conditions.

FORENSIC INVESTIGATIONS ON FIELD TEST SECTIONS

The purpose of this task is to conduct forensic investigation on limited RAP/RAS sections with poor or good performance. This section documents the forensic investigation on three sections on US62, Childress District. Detailed information is presented in the remaining sections of this section.

Childress District US62/70

Three field test sections were constructed on eastbound direction of US62/70 in the Childress District on October 3, 2013. The purpose of these three test sections was to verify the excellent laboratory cracking resistance of mixes with softer binder PG64-34. Figure 59 shows the locations of three test sections, and each section is around 1,500 ft long.

It was a milling and inlay job. There were lots of existing transverse cracks before the milling (Figure 60). A total of 8-in. existing asphalt layers were milled first, and then a 2-in. Type D and 3 in. Type B were inlaid. The same Type B was used for all three field test sections, but the top surface Type D mixes varied:

- Section 1: RAP/RAS mix with PG64-34.
- Section 2: Virgin mix with PG70-28.
- Section 3 (control section): RAP/RAS mix with PG70-28.

All three test sections have the same total asphalt content: 5.5 percent. The only difference between Sections 1 and 3 is the virgin binder type: PG64-34 versus PG70-28. Figure 61 shows OT results of plant mixes sampled during the construction. Note that both Sections 1 and 2 mixes did not fail at 1,000 cycles, although the OT was stopped. Generally, it was assumed that mixes with 1,000 cycles had a good cracking resistance for warm climates.

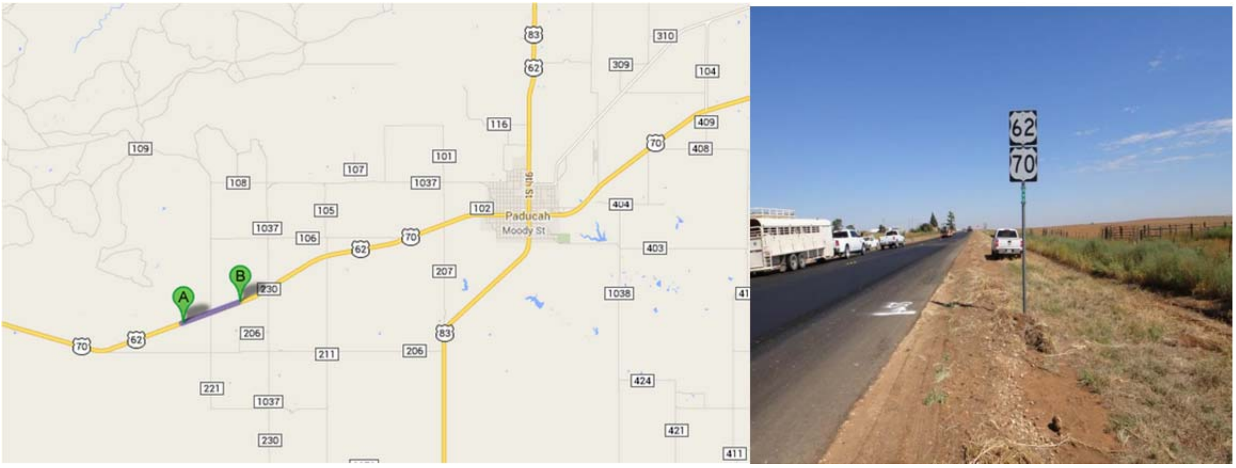


Figure 59. Location of Test Sections on US62/70.

Figure 60. Existing Pavement Conditions of US62 Test Sections.

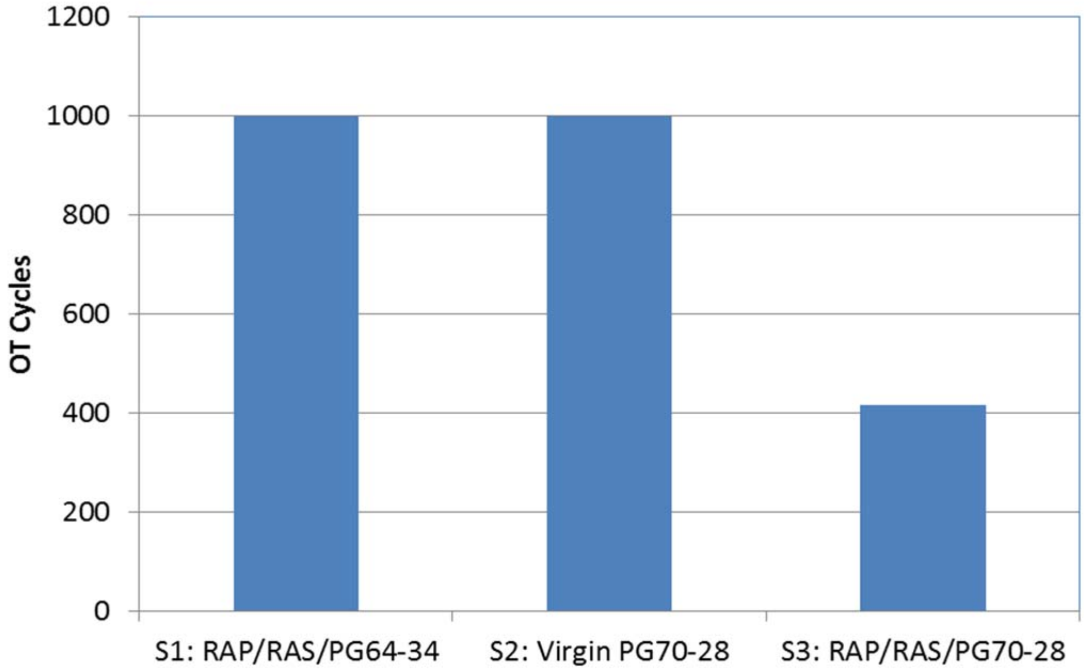


Figure 61. OT Results of Mixes Used in Test Sections.

Review of Pavement Design Information

Figure 62 shows the US62 pavement design. Figure 62 reveals two important points that could be used for determining the uniformity of the existing pavement structure in the whole project:

- The whole existing pavement structure was very uniform from the beginning to the end of this project; it was composed of 8-in. existing asphalt layer, 11-in. granular base, followed by 6-in. concrete slab and subgrade. The existing 8-in. asphalt layer was supposed to be milled off, and then the 3-in. Type B mix and 2-in. Superpave C mix should be sitting on the 11-in. granular base. If this is true, then reflective cracking should not be an issue. If the existing asphalt layer was thicker than 8 in., then reflective cracking still potentially is an issue.
- The old 6-in. concrete slab was not in the center of the pavement. Instead, the old slab was leaned more towards eastbound from the center of the pavement as shown in Figure 62. However, part of the old slab was also on westbound. If the same mix was used in both eastbound and westbound, reflective cracking should be observed in both directions. For this study, Sections 1 and 2 on eastbound used better mixes and all the mix used on westbound was the same control mix as Section 3. The cracking condition of westbound of US62 can provide key information regarding the uniformity of the existing pavement structure.

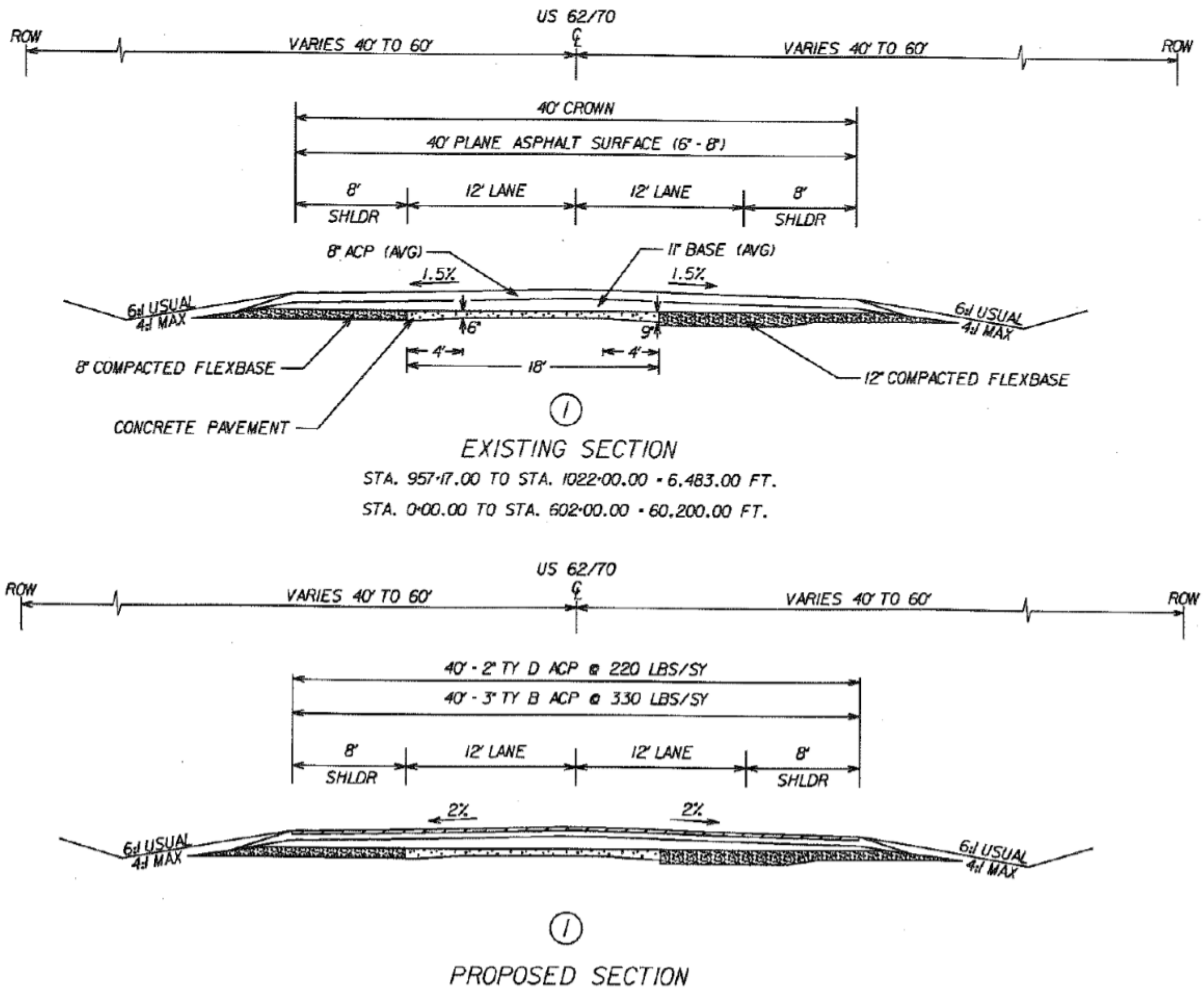


Figure 62. US62 Existing Pavement Cross Section and Proposed Section.

Field Cracking Survey

Figure 63**Error! Reference source not found.** shows the photos of three test sections on US62. Reviewing these photos, there was no cracking on the westbound side of Section 1, but the westbound sides of Sections 2 and 3 cracked. Considering the pavement cross sections shown in Figure 62, it is a reasonable assessment that Section 1 had different pavement structure from Sections 2 and 3. Additionally, Section 1 is on the top of a hill (**Error! Reference source not found.**a). That probably is the main reason for no cracking observed on Section 1.

(a) Section 1: RAP/RAS Mix with PG64-34 - No Transverse Cracking.

(b) Section 2: Virgin Mix with PG70-28 - Transverse Cracking.

Figure 63. Cracking Conditions on Sections 1, 2, and 3 on US62.

(3) Section 3: RAP/RAS Mix with PG70-28-Transverse Cracking.

Figure 63. Cracking Conditions on Sections 1, 2, and 3 on US62 (Continued).

Field Cores from the Three Sections

Thirteen cores were taken from each test section. The purposes of taking the cores are three folds: 1) verification of the pavement structure (including existing pavement), 2) identification of origination of the cracking, and 3) laboratory testing. Figure 64 shows the cores taken from three sections on US62. In contrary to the pavement design (Figure 63**Error! Reference source not found.**), there was around 4 in. old asphalt layer left over. Additionally the existing 4-in. asphalt layer cracked very badly. This very severe cracking of the existing asphalt layer led to early reflective cracking. Figure 65 clearly shows the reflective cracking on US62.

The cores taken were further evaluated in the laboratory in terms of cracking resistance, as discussed in the next section.

Figure 64. Cores Taken from Three Test Sections on US62.

Figure 65. A Typical Core Indicating Reflective Cracking on US62.

Laboratory Cracking Tests

The four cracking tests were used in this study to evaluate cracking resistance of the cores from US62.

Texas OT

OT is a TxDOT standard test method to determine the susceptibility of asphalt mixtures to fatigue and reflection cracking. The test procedure is described in in Tex-248-F: Overlay Test. The key parts of the OT consist of two steel plates underlying an asphalt mix sample; one plate is fixed and the other is movable horizontally to simulate the opening and closing of joints or cracks in the existing pavements beneath an overlay. Figure 66 shows the OT tester and a typical test result.

Different from the other three cracking tests, the OT is a cyclic displacement-controlled test with a triangle loading wave form of 10 seconds per cycle. Basically, a typical OT specimen is 6-in. long by 3-in. wide and 1.5-in. high that can be easily prepared with a laboratory compactor or field cores. It is often run at room temperature (77°F) with a maximum opening displacement of 0.025 in., although both test temperature and opening displacement can vary. The test failure is defined as 93 percent load reduction from the maximum load measured at the first cycle. At the end of the test, the number of load cycles to failure is reported. Additionally, fracture properties (*A* and *n*) can be deduced from the measured load versus displacement curve if needed (*32*).

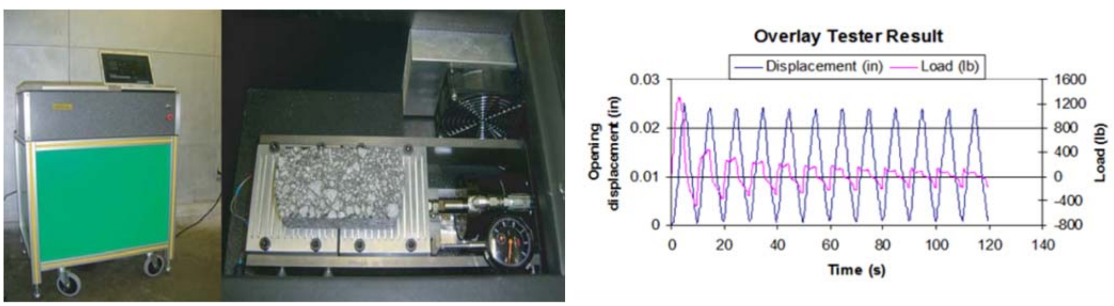


Figure 66. OT Used for This Study and a Typical Result.

Disk-Shaped Compact Tension (DCT)

DCT is an ASTM standard test method to evaluate low temperature cracking resistance of asphalt mixtures, and the detailed test procedure is described in ASTM D7313-13: Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry. DCT is a monotonic test with a 2-in. (50 mm) thick disk-shape specimen with two 1-in. holes, and a 2.46-in. notch (Figure 67) is pulled apart until the post peak level has reduced to 0.1 kN. DCT is often conducted at 10°C warmer than the PG low temperature grade in a crack-mouth opening displacement (CMOD) controlled mode with an opening rate of 1 mm/min. Figure 67 shows DCT test setup used in this study and a typical test curve. The fracture energy (G_f) is calculated by determining the area under the Load-CMOD curve normalized by the initial ligament length and thickness. The larger the G_f, the better the cracking resistance of asphalt mixtures.

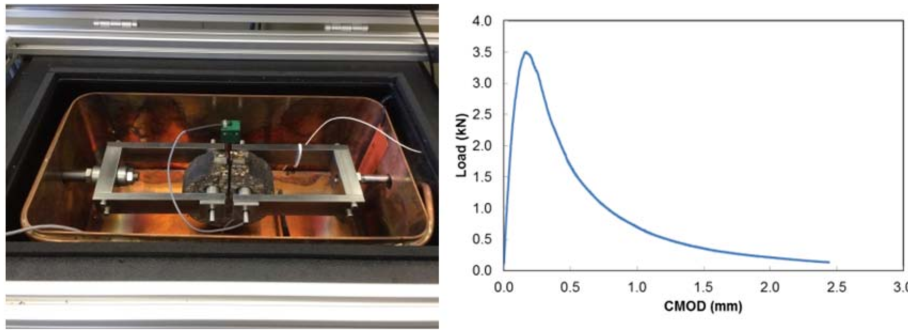


Figure 67. DCT Test Setup Used for This Study and a Typical Result.

Semicircular Bend Geometry –Louisiana Transportation Research Center

The Semicircular Bend Geometry (SCB)- Louisiana Transportation Research Center (LTRC) measures asphalt mixture crack propagation of a SCB specimen at intermediate temperature. A draft test procedure was recently proposed by Mohammad and co-workers at LTRC (*33-36*), and the test procedure is under evaluation by an ASTM working group. The SCB-LTRC test is a monotonic test and often run at room temperature (77°F) with a loading rate of 0.5 mm/min in a cross-head controlled mode.

SCB specimens are cut from a laboratory molded specimen with a thickness of 2.25 in. or a field core. The SCB specimens are notched at three depths: 1.0, 1.25, and 1.5 in., and two or three replicates for each notch depth are needed for SCB testing. The SCB-LTRC test was conducted using the AMPT with a SCB fixture (Figure 68) in this study. The critical strain energy release rate (*Jc*) is the absolute value of the ratio of the slope of the fracture energies versus the notch depths to specimen thickness (Figure 68). Higher *Jc* values are desirable for better fracture-resistant mixtures. A threshold of a minimum *Jc* of 0.40 kJ/m^2 has been recently suggested as a failure criterion (*36*).

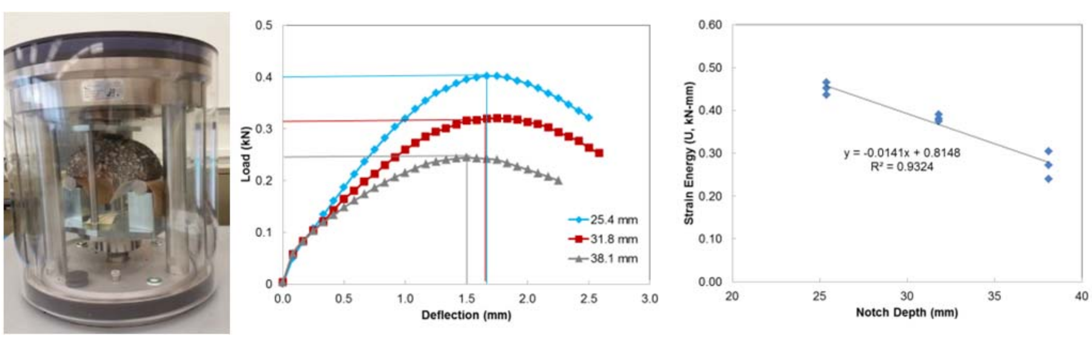


Figure 68. SCB-LTRC Test Setup Used for This Study and a Typical Result.

SCB-Illinois

SCB-Illinois (IL) is a new cracking test to evaluate cracking resistance of asphalt mixtures at low temperatures. A draft test procedure was recently proposed by Al-Qadi and his coworkers at the University of Illinois (*37*). Basically, it is a modified version of AASHTO TP105: Standard Method of Test for Determining the Fracture Energy of Asphalt Mixture Using the Semicircular Bend Geometry (SCB). Although both the SCB-IL and AASHTO TP105 evaluate low temperature cracking resistance of asphalt mixes using a SCB specimen with the same notch depth of 15 mm, SCB-IL is significantly different from AASHTO TP105 in the following ways:

- Test temperature: 25°C (or 77°F).
- Specimen thickness: 50 mm.
- Loading rate: 50 mm/min.
- Cracking indicator: flexibility index (FI).
- Loading head: swiveling loading head (see Figure 69).

Figure 69 shows the SCB-IL test setup used for this study and a typical test result. Note that FI is the ratio of the fracture energy to the absolute value of slope of the load-displacement curve at the inflection point after the post-peak representing average crack growth rate. FI provides a means to identify brittle mixes that are prone to premature cracking. The larger the FI, the better low temperature cracking resistance the mix is.

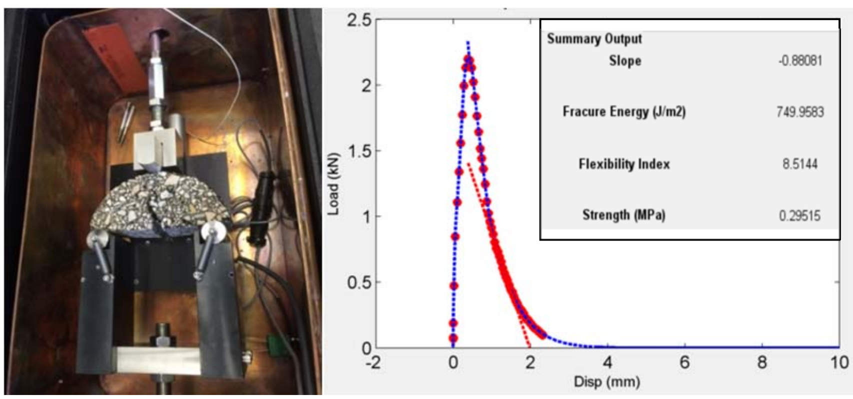


Figure 69. SCB-IL Test Setup Used for This Study and a Typical Result.

Test Results and Analysis

Figure 70 shows the test results. OT, DCT, and SCB-IL results match the field observation (Figure 71): the virgin mix is better than the RAP/RAS mix. Also, these three cracking tests showed that the virgin mix had the best cracking resistance followed by the RAP/RAS mix with PG64-34 binder. The RAP/RAS mix with PG70-28 had the worst cracking resistance. However, the SCB-LTRC showed differently and needs more field validation.

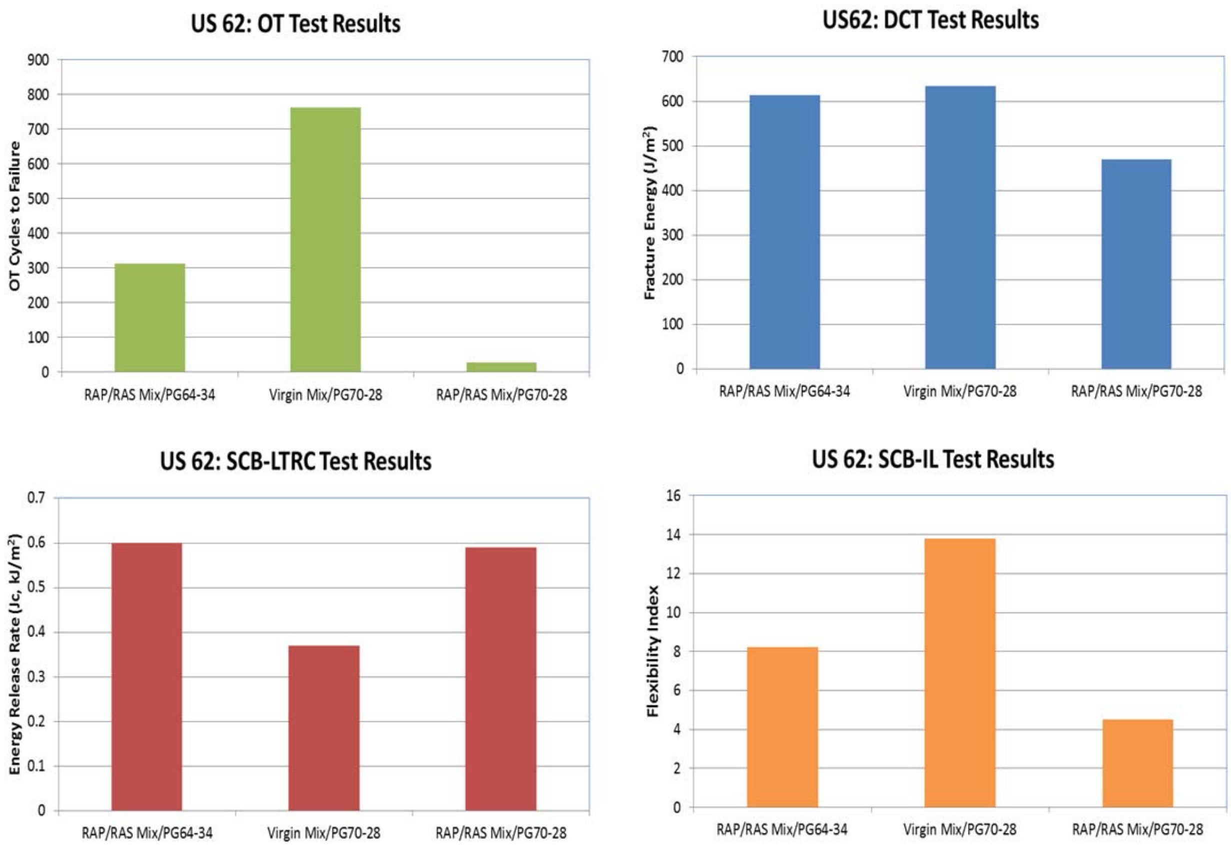


Figure 70. Laboratory Cracking Test Results.

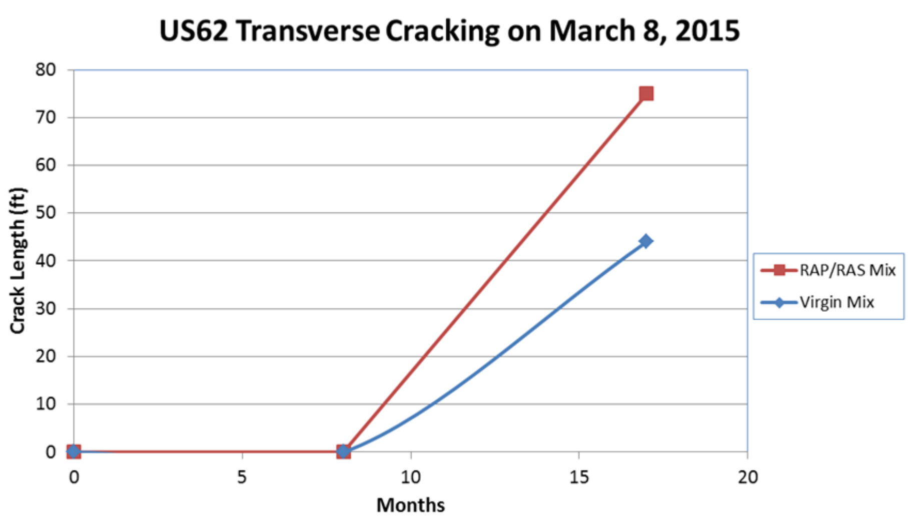


Figure 71. Cracking Development on US62 Test Sections.

Summary

Two of the three test sections on US62 showed early cracking. A forensic study was performed on these sections. Based on the work performed, the following conclusions were made:

- There was around 4-in. cracked asphalt layer of existing pavement left before placing the new 5-in. asphalt layer. These badly cracked asphalt layers led to early reflective cracking.
- Three cracking tests: OT, DCT, and SCB-IL clearly differentiate cracking resistance of asphalt mixes. The SCB-LTRC did not do well on US62 sections.

CHAPTER 6
LIFE CYCLE COST ANALYSIS ON RAP/RAS MIXES

Researchers conducted a pavement LCCA of each approach improving durability of RAS/RAP mixes based on laboratory test results. Researchers chose the Amarillo, Austin, and Pharr Districts, which represent cold, moderate, and hot areas, respectively, to demonstrate the analysis processes. Running an LCCA can be done in several ways, but the most widely accepted method is using software. The Federal Highway Administration's (FHWA's) RealCost software is the most versatile package, compared to other existing LCCA packages (*38*). RealCost was developed based on a Microsoft Excel macro and has both spreadsheet and screen input interfaces. In this project, researchers used RealCost as a tool to compare the total user and agency costs of project implementation alternatives. RealCost is appropriate to be applied in comparing project implementation alternatives that will yield the same level of service and benefits to the project user at any specific volume of traffic. This session first provides an overview of FHWA RealCost and then describes the input information of the alternatives for each district: Amarillo, Austin, and Pharr. Finally, the session presents the analysis results.

OVERVIEW OF FHWA REALCOST

An FHWA interim technical bulletin (*39*) provides technical guidance and recommendations on good practices in conducting an LCCA in pavement design. It also incorporates risk analysis, a probabilistic approach to describe and account for the uncertainties inherent in the decision process. It deals specifically with the technical aspects of long-term economic efficiency implications of alternative pavement designs. The bulletin is intended for state highway agency personnel responsible for conducting and/or reviewing pavement design LCCAs. The LCCA process steps are:

- Establish design alternatives.
- Determine activity timing.
- Estimate costs (agency and user).
- Compute life-cycle costs.
- Analyze the results.

RealCost incorporates initial and discounted future agency, user, and other relevant costs over the life of alternative investments. It attempts to identify the best value (the lowest long-term cost that satisfies the performance objective being sought) for investment expenditures.

The RealCost interface requires the user to enter inputs in various screens (Figure 72), and it then applies a series of algorithms to determine which of the given alternatives is the superior choice based on the inputs. To be most accurate, an LCCA requires precise information pertaining to the specific job being assessed. However, for the purposes of this research, some scenarios had to be hypothesized.

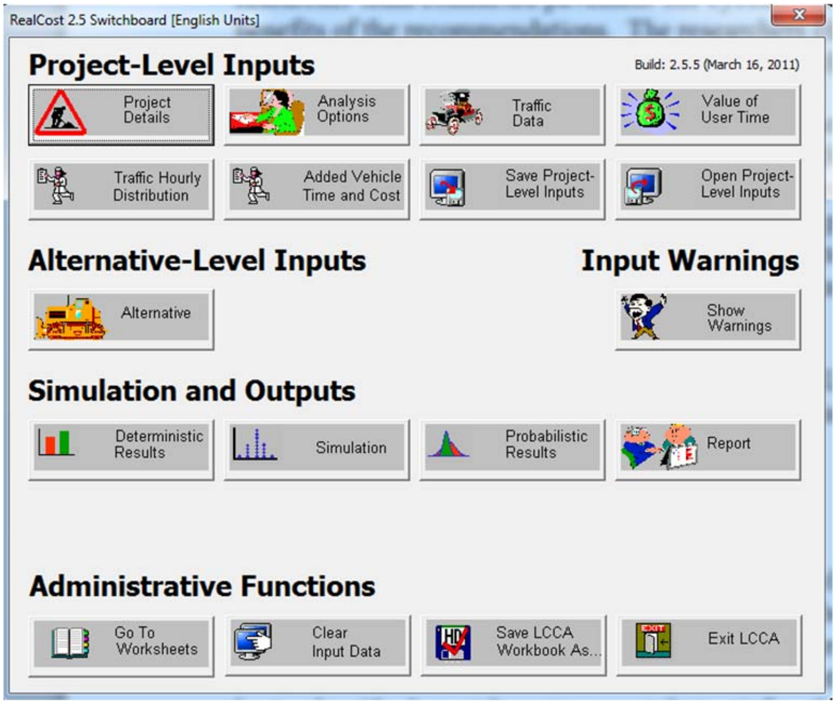


Figure 72. Interface of FHWA RealCost Software.

INPUTS OF FHWA REALCOST

Due to the complex nature of the inputs required, and in order to obtain the best representative numbers, researchers gathered inputs from several sources to perform LCCAs for the case studies contained below. The inputs are discussed in the order in which they appear in the RealCost program. After the general discussion of inputs that apply to all cases, the specific inputs are discussed for different districts.

For this project, researchers hypothesized a 2-in. overlay 2 mi long for all analyses; the traffic was assumed to be 3 million ESALs. For simplicity, a typical pavement structure was considered in this study, including an existing AC (8-in. thick), granular base (8-in. thick), and subgrade.

PROJECT DETAIL INPUTS

The project details consist of the general information of a project being analyzed. Figure 73 shows an example of the project details screen.

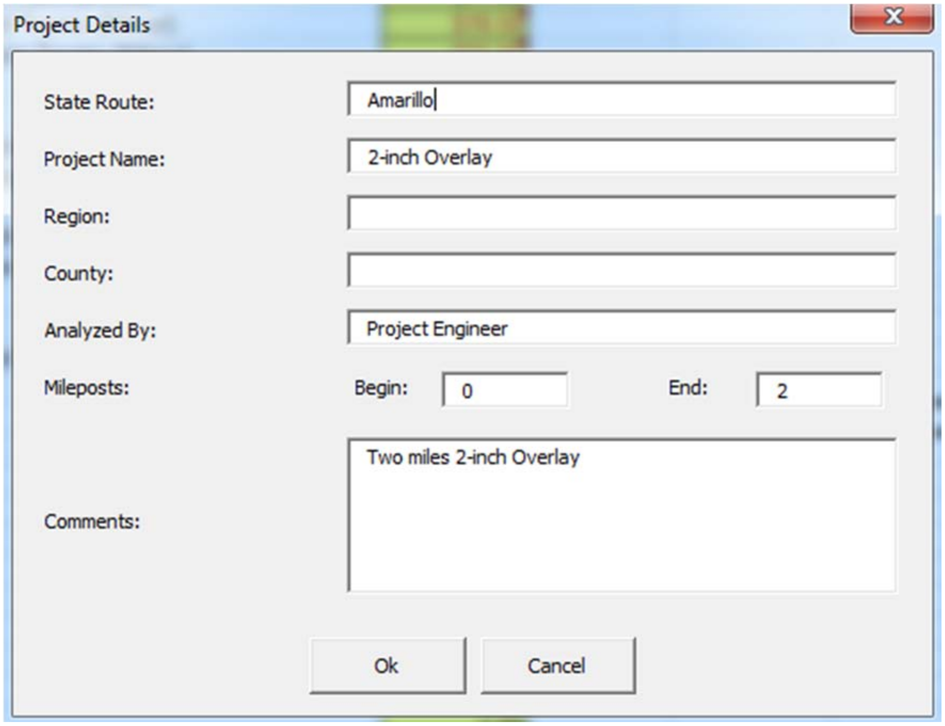


Figure 73. Example of Project Details Screen.

ANALYSIS OPTION INPUTS

The analysis option inputs include:

- Analysis Units—English or metric. All LCCAs in this project used English.
- Analysis period (years)—The number of years for which the program would run the analysis.
- Discount Rate (percent)—The discount rate the program would apply to the costs for the analysis period. This number is generally between 2–4 percent nationally. A discount rate of 4 percent was used on all LCCAs in this project.
- Beginning of Analysis Period—The year the user wants the analysis to begin. All LCCAs in this project were run beginning in 2014.
- Include Agency Cost Remaining Service Life Value (check box)—This box was left checked in all LCCAs run.
- Include User Costs in Analysis (check box)—This box was left checked in all LCCAs run.
- User Cost Computation Method—Users choose “calculated” or “specified.” Calculated was selected for all LCCAs run.
- Traffic Direction—Users select “one-way” or “both.” Both was specified for all LCCAs in this project.

- Include User Cost Remaining Value (check box)—This box was left checked for all LCCAs run in this project.
- Number of Alternatives—Researchers selected two mix types in this analysis. They are the SMA mix and the Superpave mix. Two mixes from each mix type were chose to compare each other (i.e., SMA control mix (virgin aggregates) vs. 5 percent Manufacturer RAS mix and Superpave control mix (PG58-22) vs. PG58-34 mix). Therefore, a total of four alternatives were made in this analysis.

Figure 74 shows an example of the analysis options screen.

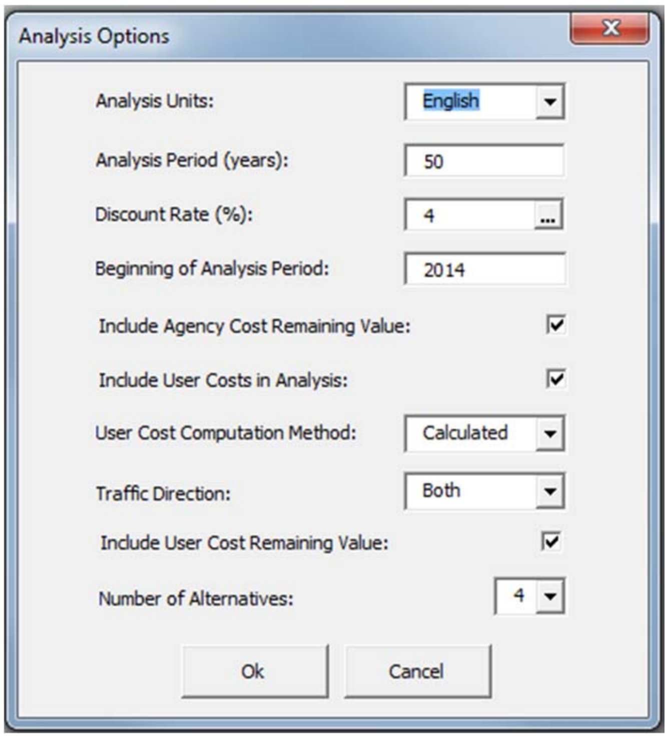


Figure 74. Example of Analysis Options Screen.

TRAFFIC DATA INPUTS

To calculate user costs, the program uses work zone traffic data. The inputs include:

- AADT at Beginning of Analysis Period (total both directions)—the AADT level for the year in which the analysis period is set to begin. An AADT of 20,000 was used for this study since this traffic level is similar to 3 million ESALs (20 years) based on past research experiences (*40*).
- Single Unit Trucks as Percentage of AADT—Based on both national and local information (*41*), the single unit truck percentage was set at 7 percent.
- Combination Trucks as Percentage of AADT—Based on both national and local information, the combination unit truck percentage was set at 8 percent.
- Annual Growth Rate of Traffic—An average annual growth rate of 2.5 percent was assumed for this analysis.

- Speed Limit under Normal Operating Conditions—This input was defined as 65, as that is a common speed limit in Texas on two-lane state highways.
- Lanes Open in Each Direction under Normal Conditions—As the example was set as a two-lane condition, the input here was defined as 1.
- Free Flow Capacity (vphpl)—RealCost has a built-in free flow capacity calculator, which was used to calculate the free flow capacity.
- Queue Dissipation Capacity (QC)—An 1800 passenger cars per hour per lane (pcphpl) value was used, which represented a good physical feature of the road.
- Maximum AADT (both directions)—The default value 100,000 was used for this project.
- Maximum Queue Length—Research suggests that 7 miles is the maximum acceptable queue length (*41*), so that number was used in this project.
- Rural or Urban Hourly Traffic Distribution—Urban was assumed for this project.

Figure 75 shows an example of the traffic data screen. Note that traffic data have no impact on the agency cost, so this input was not considered a key focus.

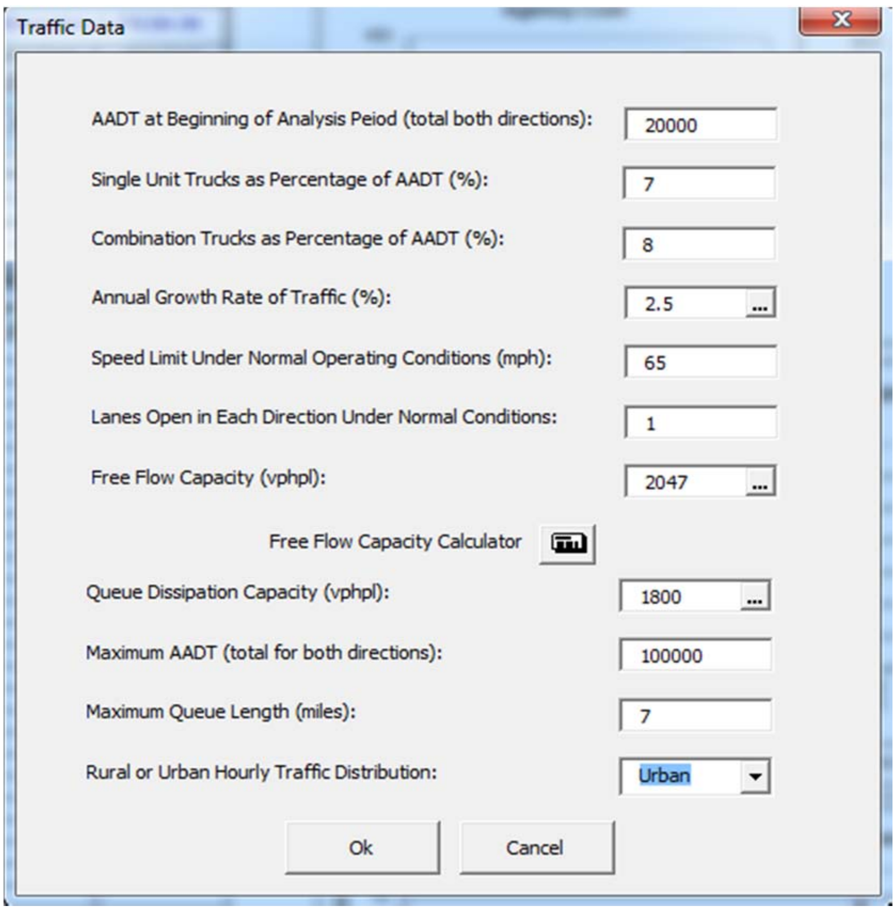


Figure 75. Example of Traffic Data Screen.

VALUE OF USER TIME INPUTS

The value of user time is used to calculate user costs. There are many factors to consider when calculating user cost, and the process can be very complicated. For this project, researchers based calculations on predetermined average highway user cost, and the default values in the software were accepted:

- Value of Time for Passenger Cars ($/hour)—$11.50.
- Value of Time for Single Unit Trucks ($/hour)—$18.50.
- Value of Time for Combination Trucks ($/hour)—$21.50.

Figure 76 shows an example of the value of user time screen.

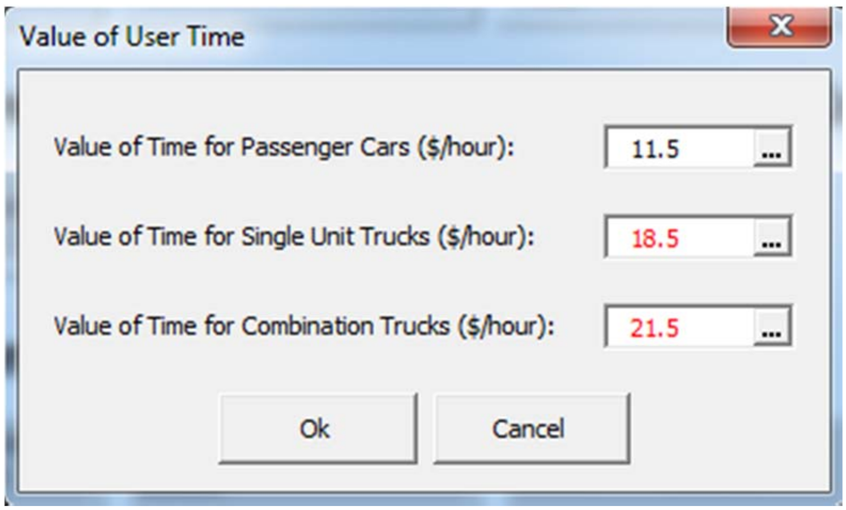


Figure 76. Example of Value of User Time Screen.

ALTERNATIVE-LEVEL INPUTS

As mentioned above, during this research, the alternatives included four mixes. For each alternative, the initial agency construction cost is calculated below.

According to Copeland (*42*), there are four cost categories for asphalt production: material, plant production, trucking, and lay down. Among them, the most expensive production cost category is materials, comprising 70 percent of the cost to produce HMA. Table 22 shows the construction cost for each alternative. The cost of each material was simply assumed to calculate the cost of each mix in $/ton based on the literature. The calculation was performed based on the following assumptions:

- AC overlay thickness: 2 in.
- Asphalt content: 6 percent for SMA mixes and 4.7 percent for Superpave mixes.
- Asphalt binder cost: $620/ton for PG58-28 and PG70-22, and $685/ton for PG58-34.
- Virgin aggregates: $13.5/ton.
- RAP/RAS for Superpave mix: $4.5/ton
- Manufacturer RAS for SMA mix: $6.5/ton
- Asphalt mixture density after compaction: 145 lb per cubic ft (SF).

Table 22. Initial Construction Agency Cost Calculation.

Mix Type	Asphalt Mixture Cost ($/ton)	Material and Construction Cost ($/ton)	Material and Construction Cost ($/CF)	Agency Construction Cost ($)
Formula	A	B=A/0.7	C=B*145/2000	D=C*2*5280*24*2/12
Superpave control mix	31.9	45.6	3.30	139,558
Superpave PG58-34	34.1	48.7	3.53	149,183
SMA Control mix	50.1	71.6	5.19	219,180
SMA 5% Manufacturer RAS	43.5	62.1	4.51	190,306

For each alternative input, rehabilitation activity data need to be provided. To determine the activity timing, the asphalt overlay cracking life should be predicted. Texas Asphalt Concrete Overlay Design and Analysis System (TxACOL) was used to predict the asphalt overlay cracking life. Table 23 lists the performance predictions from the TxACOL program, which were then used to determine the activity timing in RealCost.

Table 23. Predicted Cracking Life for Different Alternatives.

District	Mix Type	Cracking Life (Months/Years)
Amarillo	Superpave control mix	21 / 1.8
	Superpave PG58-34	27 / 2.3
	SMA Control mix	119 / 9.9
	SMA 5% Manufacturer RAS	99 / 8.3
Austin	Superpave control mix	29 / 2.4
	Superpave PG58-34	36 / 3.0
	SMA Control mix	170 / 14.2
	SMA 5% Manufacturer RAS	135 / 11.3
Pharr	Superpave control mix	35 / 2.9
	Superpave PG58-34	49 / 4.1
	SMA Control mix	239 / 19.9
	SMA 5% Manufacturer RAS	174 / 14.5

Since the cracking life is defined as the month number needed for the reflective cracking rate to reach 50 percent, the rehabilitation activity hypothesized that at the end of the cracking life, half of the cracked area (25 percent of the whole pavement area) needed to be replaced. Both the activity timing and cost could be estimated.

Researchers determined the other activity inputs based on various factors, as discussed below:

- User Work Zone Costs—This was left as Calculated on the analysis options screen, so the user was not able to enter any input in this box.
- Work Zone Duration—This was the number of days lanes would be closed; it was assigned a value of 0 for initial construction and then 5 days for the other maintenance activities.
- Number of Lanes Open in Each Direction During Work Zone—As this was a two-lane highway, traffic had to be able to move even when there was work going on, so one lane was assumed to be open in each direction, whether by diversion to a frontage road or other means.
- Activity Service Life—This was the amount of time the activity was intended to survive with minimal maintenance until another activity was needed. The predicted cracking life for each alternative was provided here. For example, 1.8 was the input for the case of alternative Superpave Control PG58-28 in the Amarillo District.
- Activity Structural Life—The activity service life of the first activity was the anticipated service life of the pavement. For concrete roads, this was assumed to be 50 years.
- Maintenance Frequency—The number of years maintenance was to be performed. It was assumed the cracks needed to be sealed every 5 years. The crack number was assumed to be 704 cracks for 2 miles (15-ft long between two cracks), which is 16,896 ft (24-ft long for each crack); at $2/ft crack sealing cost, that is $33,792 every 5 years. Spread out annually, that cost is $6758.40 per year.
- Work Zone Length (mile)—The work zone length is the length of the lane closure. This was assumed as 1 mile.
- Work Zone Speed Limit (mph)—Typically 5–10 miles less than the posted speed limit. Researchers used 65 as the input here, 5 mph less than the normal posted speed of 70 on most state highways.
- Work Zone Capacity (WC)—20 percent of maximum pcphpl, which is 360, was assumed.
- Traffic Hourly Distribution—“Weekday 1” was chosen for all LCCAs run for this project.

Figure 77 shows an example of activity input under Alternative 1 (Superpave Control PG58-28) in the Pharr District case. In this case, 18 activities were assigned to cover the analysis period of 50 years. In this input screen, the agency cost of Activity 1 was the initial construction cost, $139,558. The agency cost of other activities was the rehabilitation cost, assumed to be 25 percent of the initial construction cost. The milling cost was assumed to be included in this rehabilitation cost. The agency cost of each activity (starting from Activity 2) for the alternatives Superpave control, Superpave PG58-34, SMA control, and SMA 5 percent Manufacturer RAS were $34,889, $37,296, $54,795, and $47,577, respectively.

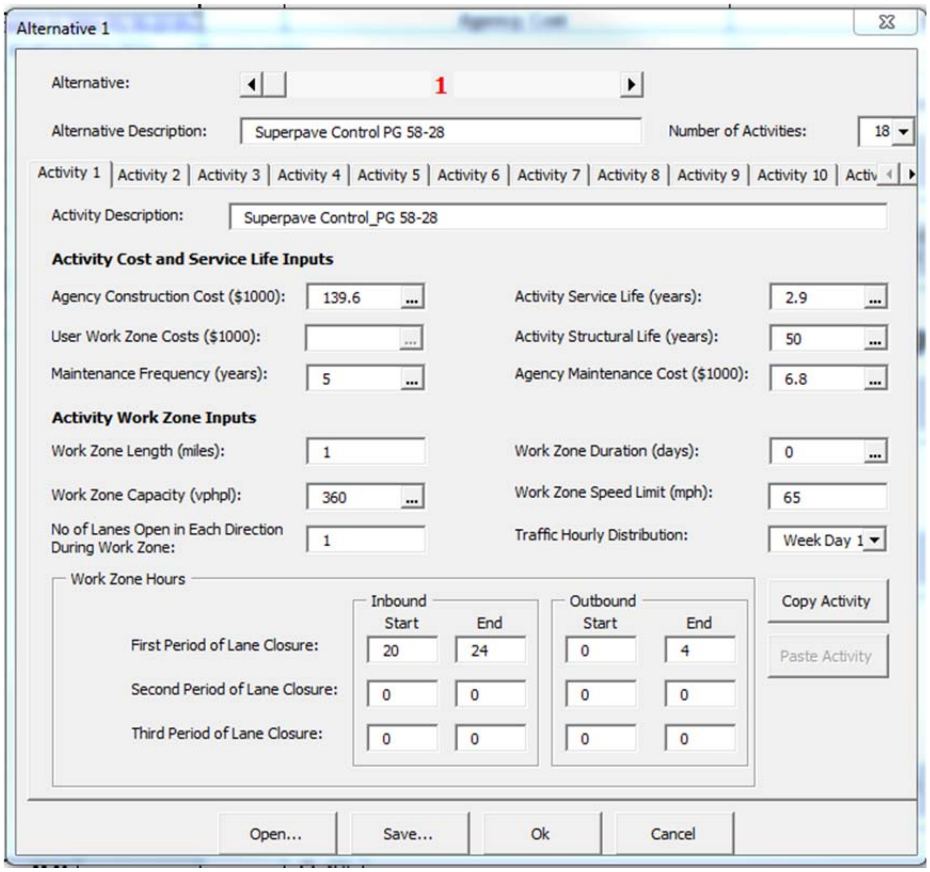


Figure 77. Example of Alternative and Activity Input Screen.

LCCA RESULTS

Below are the alternative comparison results for each district. LCCA is a concept of the time value of money. A given amount of money received one day has a higher value than the same amount received at a later date. One way to understand this concept is to think about how funds received today may be invested and immediately begin to earn interest. A number of techniques based on the concept of discounting are available (*43*). In FHWA RealCost, costs occasioned at different times are converted to the present value approach (also known as present worth), but the equivalent uniform annual cost (EUAC) is also provided.

Amarillo District

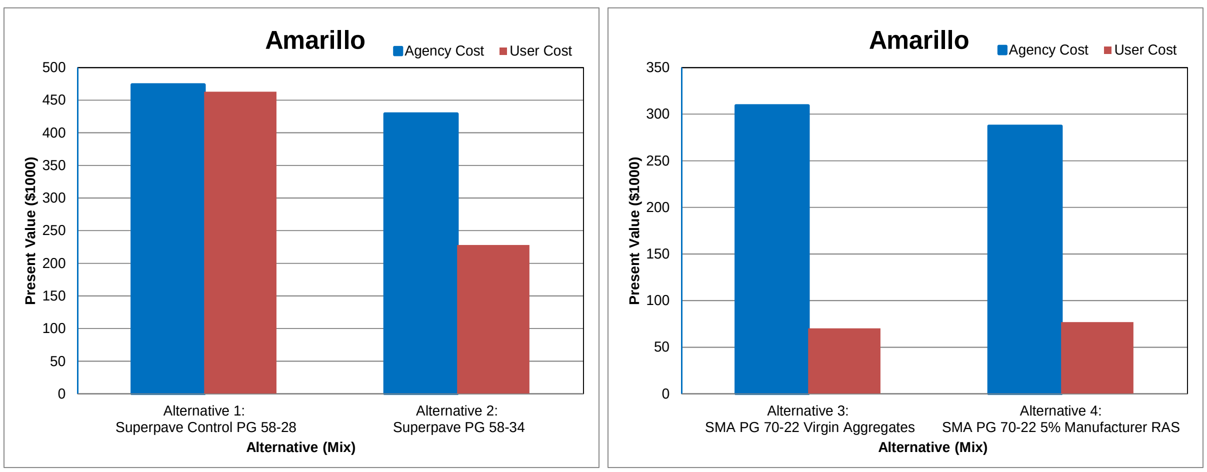
Table 24, Table 25, and Figure 78 show the LCCA results for the Amarillo District. According to the results and based on the lowest agency cost, the better options are Superpave PG58-34 between Alternative 1 and Alternative 2, and SMA PG70-22 5 percent manufacturer RAS between Alternative 3 and Alternative 4. A user cost comparison was not the focus of this research since the inputs of traffic were assumed to be identical for each scenario. Traffic inputs are typically difficult to quantify, and the values associated with user costs are often disputed.

Table 24. LCCA Results of Amarillo: Alternative 1 vs. Alternative 2.

Total Cost				
	Alternative 1: Superpave Control PG58-28		Alternative 2: Superpave PG58-34	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$595.53*	*$805.06*	*$536.15*	*$411.74*
Present Value	**$473.60**	**$463.05**	**$428.93**	**$228.19**
EUAC	$22.05	$21.56	$19.97	$10.62
Lowest Present Value Agency Cost		**Alternative 2: Superpave PG58-34**		
Lowest Present Value User Cost		**Alternative 2: Superpave PG58-34**		

Table 25. LCCA Results of Amarillo: Alternative 3 vs. Alternative 4.

Total Cost				
	Alternative 3: SMA PG70-22 Virgin Aggregates		Alternative 4: SMA PG70-22 5% Manufacturer RAS	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$364.44*	*$128.55*	*$346.24*	*$139.34*
Present Value	**$309.15**	**$70.22**	**$287.10**	**$76.91**
EUAC	$14.39	$3.27	$13.36	$3.58
Lowest Present Value Agency Cost		**Alternative 4: SMA PG70-22 5% Manufacturer RAS**		
Lowest Present Value User Cost		**Alternative 3: SMA PG70-22 Virgin Aggregates**		



(a) Alternative 1 vs. Alternative 2 (b) Alternative 3 vs. Alternative 4

Figure 78. LCCA Results of Amarillo: Present Value of Agency and User Cost.

Austin District

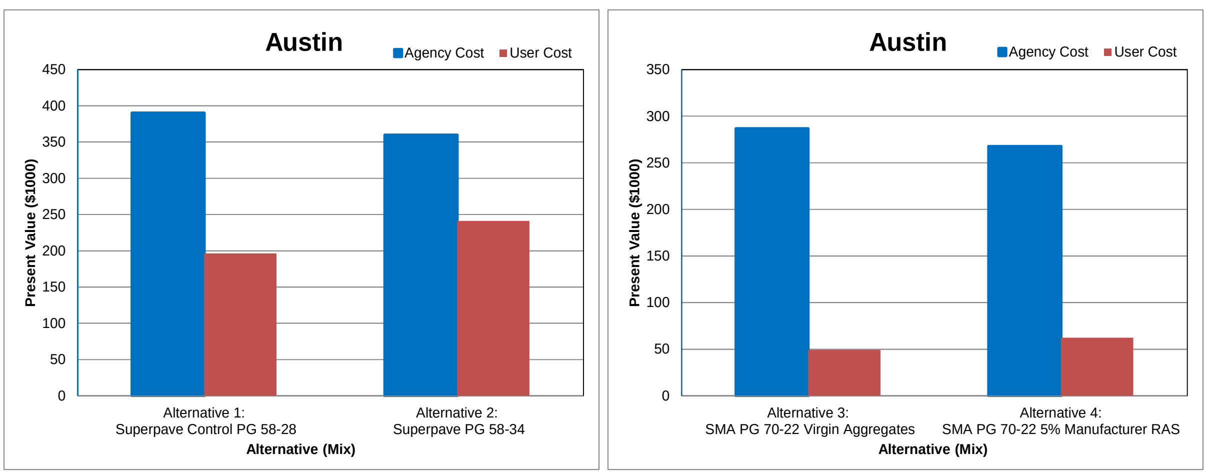
Table 26, Table 27, and Figure 79 show the LCCA results for the Austin District. According to the results and based on the lowest agency cost, the better options are Superpave PG58-34 between Alternative 1 and Alternative 2, and SMA PG70-22 5 percent manufacturer RAS between Alternative 3 and Alternative 4.

Table 26. LCCA Results of Austin: Alternative 1 vs. Alternative 2.

Total Cost	Alternative 1: Superpave Control PG58-28		Alternative 2: Superpave PG58-34	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$485.81*	*$357.50*	*$441.63*	*$433.68*
Present Value	**$390.12**	**$196.39**	**$359.63**	**$241.33**
EUAC	$18.16	$9.14	$16.74	$11.23
Lowest Present Value Agency Cost	**Alternative 2: Superpave PG58-34**			
Lowest Present Value User Cost	**Alternative 1: Superpave Control PG58-28**			

Table 27. LCCA Results of Austin: Alternative 3 vs. Alternative 4.

Total Cost	Alternative 3: SMA PG70-22 Virgin Aggregates		Alternative 4: SMA PG70-22 5% Manufacturer RAS	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$337.82*	*$89.04*	*$324.39*	*$113.36*
Present Value	**$286.62**	**$49.40**	**$267.59**	**$62.29**
EUAC	$13.34	$2.30	$12.46	$2.90
Lowest Present Value Agency Cost	**Alternative 4: SMA PG70-22 5% Manufacturer RAS**			
Lowest Present Value User Cost	**Alternative 3: SMA PG70-22 Virgin Aggregates**			



(a) Alternative 1 vs. Alternative 2 (b) Alternative 3 vs. Alternative 4

Figure 79. LCCA Results of Austin: Present Value of Agency and User Cost.

Pharr District

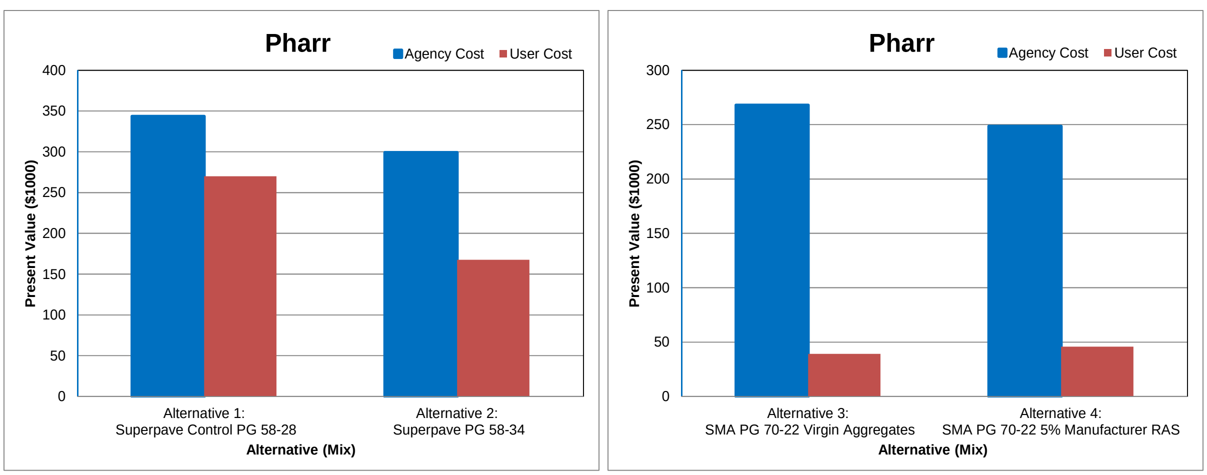
Table 28, Table 29, and Figure 80 show the LCCA results for the Pharr District. In this case, according to the results and based on the lowest agency cost, the better options are Superpave PG58-34 between Alternative 1 and Alternative 2, and SMA PG70-22 5 percent manufacturer RAS between Alternative 3 and Alternative 4.

Table 28. LCCA Results of Pharr: Alternative 1 vs. Alternative 2.

Total Cost	Alternative 1: Superpave Control PG58-28		Alternative 2: Superpave PG58-34	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$423.20*	*$484.87*	*$358.23*	*$301.49*
Present Value	**$343.60**	**$269.98**	**$299.23**	**$167.45**
EUAC	$15.99	$12.57	$13.93	$7.80
Lowest Present Value Agency Cost	**Alternative 2: Superpave PG58-34**			
Lowest Present Value User Cost	**Alternative 2: Superpave PG58-34**			

Table 29. LCCA Results of Pharr: Alternative 3 vs. Alternative 4.

Total Cost	Alternative 3: SMA PG70-22 Virgin Aggregates		Alternative 4: SMA PG70-22 5% Manufacturer RAS	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$310.97*	*$71.22*	*$295.61*	*$83.76*
Present Value	**$267.91**	**$39.16**	**$248.51**	**$45.75**
EUAC	$12.47	$1.82	$11.57	$2.13
Lowest Present Value Agency Cost	**Alternative 4: SMA PG70-22 5% Manufacturer RAS**			
Lowest Present Value User Cost	**Alternative 3: SMA PG70-22 Virgin Aggregates**			



(a) Alternative 1 vs. Alternative 2 (b) Alternative 3 vs. Alternative 4

Figure 80. LCCA Results of Pharr: Present Value of Agency and User Cost.

SUMMARY

The FHWA RealCost analysis results showed the best options (based on lowest agency costs) for each scenario, which is based on cracking life and mixture OT cycles. The analysis results clearly showed financial benefits of RAP/RAS mixes. Especially, the SMA 5 percent manufacturer RAS mix showed lower agency costs than that of the SMA control mix even though its OT cycle to failure was lower than that of the SMA control mix.

CHAPTER 7
RECOMMENDATIONS FOR RAP/RAS MIXES

The laboratory test results and field performance results from this study indicated that the cracking resistant of RAP/RAS mixes can be effectively improved. Based on the findings presented in earlier chapters, the recommendations for RAP/RAS mixes are made as follows:

- Use rejuvenators for higher recycled binder contents. Select carefully the rejuvenator dosage. The rejuvenator dosage can be determined based on the specification requirements for both high and low PG grades of blended asphalt binders (i.e., RAP/RAS/virgin binder/rejuvenator).
- Use soft virgin binders (i.e., PGXX-28 or PGXX-34) for RAP/RAS mixes.
- Increase design density of RAP/RAS mixes (add more virgin binder into RAP/RAS mixes).
- Evaluate blending among virgin, RAP and/or RAS binder by extracting the binders from recycled materials.
- Use the BMD procedure for RAP/RAS mixes. Figure 81 shows the balanced RAP/RAS overlay mix design and performance evaluation system for project-specific conditions. The proposed system is an expanded balanced overlay mix design procedure in which cracking performance is evaluated through a simplified asphalt overlay performance analysis system, S-TxACOL.

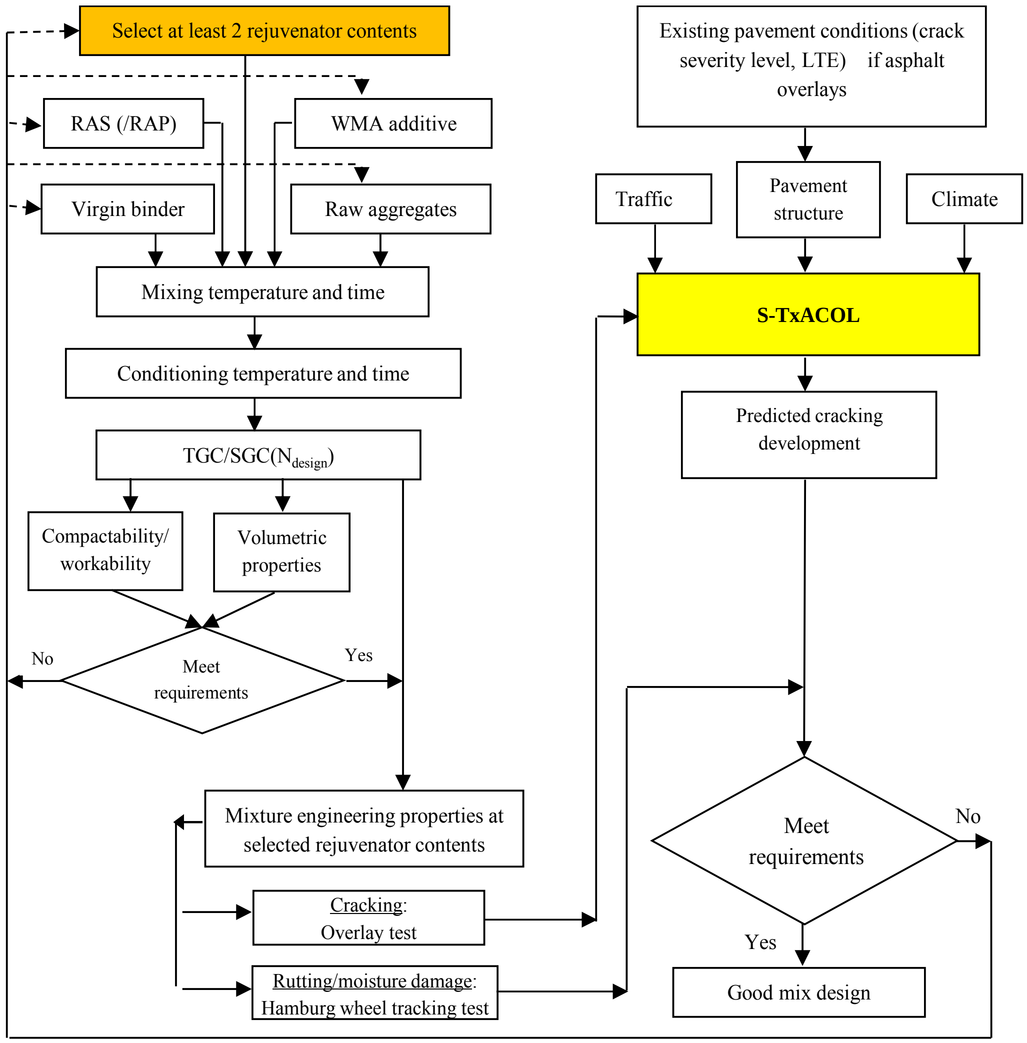


Figure 81. Balanced Rejuvenator/RAP/RAS/Virgin Binder Mix Design for Project-Specific Service Conditions.

CHAPTER 8
SUMMARY AND CONCLUSIONS

In the last several years, RAP and RAS have been widely used in asphalt mixes in Texas. The use of RAP/RAS can significantly reduce the initial cost of asphalt mixtures, conserve energy, and protect the environment. There are always two main concerns: variability of RAP/RAS and durability (or cracking) of RAP/RAS mixes. Past studies in Texas have clearly indicated that both RAP and RAS have acceptable variability following the best practices for handling RAP/RAS. This study focuses on the durability problems of RAP/RAS asphalt mixes. Based on the research presented in this report, the following conclusions are offered.

- More RAP/RAS can be used in the asphalt mixes if rejuvenators are allowed in the asphalt mixes. Ten percent rejuvenator is more than enough to make the final blend meet the specification requirements for both high and low PG grades (say PG70-22).
- So far no data have been available for performance of SMA, PFC, and Superpave mixes with RAP/RAS in Texas. Based on the laboratory evaluation, WMA, SMA, and Superpave mixes containing RAP/RAS may exhibit similar cracking resistance to their control mixes.
- TxDOT has established guidelines for laboratory curing protocols for virgin mixes, whereas those for RAP/RAS/WMA mixes are not available. This study performed an extensive laboratory tests to establish curing protocols for those mixes. Different oven curing time conditions for RAP/RAS/WMA mixes were recommended for individual mechanical testing. Also, careful selection of container size must be considered to asphalt mix design and quality control.
- Based on the field survey results, RAP/RAS mixes can have similar or better performance than virgin mixes provided that they are designed following the BMD procedure.
- Increasing virgin binder content through decreasing design air voids significantly improved reflective cracking performance of the RAS mix.
- However, cracking performance of asphalt mixes is strongly related to the existing pavement structure. Researchers recommend developing a RAP/RAS mix design system for project-specific conditions, including traffic, climate, existing pavement conditions.
- Researchers used a forensic study to investigate the reasons for bad performance of field test sections. The forensic study allows TxDOT different options to avoid problems occurring in the future.
- Continuous field monitoring of existing field test sections significantly benefits TxDOT.

REFERENCES

1. P. Kandhal and R. B. Mallick. *Pavement Recycling Guidelines for State and Local Governments—Participant's Reference Book*, Report No. FHWA-SA-98-042, Federal Highway Administration, Washington, D.C., 1997.
2. NCHRP, *Recycling Materials for Highways*, NCHRP Program Synthesis of Highway Practice No. 54, Transportation Research Board, Washington, D.C., 1978.
3. J. A. Epps, D. N. Little, R. J. Holmgreen, and R. L. Terrel. *Guidelines for Recycling Pavement Materials,* NCHRP Report No. 224, Transportation Research Board, Washington, D.C., 1980.
4. R. McDaniel, and R. M. Anderson. *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*, NCHRP Report No. 452, Transportation Research Board, Washington, D.C., 2001.
5. D. Newcomb, E. R. Brown, and J. A. Epps. *Quality Improvement Series 124: Designing HMA Mixtures with High RAP Content: A Practical Guide*, National Asphalt Pavement Association, Lanham, Maryland, 2007.
6. R. West. "Performance Studies of Asphalt Pavements with Greater than 25% RAP," presented at RAP ETG meeting, December 2009, http://www.morerap.us/files/meetings/12-09/west-performance-studies-asphalt-pavements.pdf, Accessed on July 21, 2011.
7. A. Copeland, J. D'Angelo, R. Dongre, S. Belagutti, and G. Sholar. "Field Evaluation of a High Reclaimed Asphalt Pavement/Warm Mix Asphalt Project in Florida: A Case Study," *Transportation Research Record*, No. 2179, Transportation Research Board, Washington, D.C., 2010, pp. 93–101.
8. F. Hong, D. Chen, and M. Mikhail. "Long-Term Performance Evaluation of Recycled Asphalt Pavement Results from Texas: Pavement Studies Category 5 Sections from the Long-Term Pavement Performance Program," *Transportation Research Record.* No. 2180, Transportation Research Board, Washington, D.C., 2010, pp. 58–66.
9. J. W. Button, D. Williams, and J. Scherocman. *Roofing Shingles and Toner in Asphalt Mixtures.* Research Report 1344-2F, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1996.
10. W. H. Chesner, R. J. Collins, and M. H. MacKay. *User Guidelines for Waste and By-Product Materials in Pavement Construction.* Report No. FHWA-RD-97-148, Office of Engineering Research and Development, Federal Highway Administration, McLean, Virginia, 1997.
11. NAHB (National Association of Home Builders) Research Center. *From Roofs to Roads. Recycling Asphalt Roofing Shingles into Paving Materials.* Upper Marlboro, Maryland, 1999.
12. National Asphalt Pavement Association (NAPA), "Recycling Hot-Mix Asphalt Pavements." Information Series 123, Lanham, Maryland, 2007.

13. D. Krivit. *Recycling Tear-Off Asphalt Shingles: Best Practices Guide.* The Construction Materials Recycling Association (CMRA), Eola, Illinois, 2007. (http://www.shinglerecycling.org/sites/www.shinglerecycling.org/files/shingle_PDF/ShingleRecycling-BPG-DFK-3-22-2010.pdf).

14. G. W. Maupin, Jr. *Use of Manufactured Waste Shingles in a Hot Mix Asphalt Field Project.* Report No. VTRC 08-R11, Virginia Transportation Research Council, Virginia Department of Transportation, Charlottesville, Virginia, 2008.

15. K. Hansen. *Guidelines for the Use of Reclaimed Asphalt Shingles in Asphalt Pavements.* Information Series 136, National Asphalt Pavement Association, Lanham, Maryland, 2009.

16. F. Zhou, H. Li, S. Hu, J. Button, and J. Epps, *Characterization and Best Use of Recycled Asphalt Shingles in Hot-Mix Asphalt*, Research Report FHWA/TX-13/0-6614-2, Texas Transportation Institute, College Station, Texas, October 2012.

17. R. West. *Reclaimed Asphalt Pavement Management: Best Practices.* Draft report, National Center for Asphalt Technology, Auburn, Alabama, 2010. http://www.morerap.us/files/rap-best-practices.pdf. Accessed July 6, 2011.

18. F. Zhou, G. Das, T. Scullion, and S. Hu, *RAP Stockpile Management and Processing in Texas: State of the Practice and Proposed Guidelines*, Research Report FHWA/TX-10/0-6092-1, Texas Transportation Institute, College Station, Texas, February 2010.

19. F. Zhou, J. W. Button, and J. A. Epps, *Best Practice for Using RAS in HMA*, Research Report FHWA/TX-12/0-6614-1, Texas Transportation Institute, College Station, Texas, April 2012.

20. J. Yu. *Modification of Dynamic Modulus Predictive Models for Asphalt Mixtures Containing Recycled Asphalt Shingles*, Master's Degree Thesis, Iowa State University, 2012.

21. C. Williams, *Performance of Recycled Shingles in HMA-Update on Pooled Fund Study TPS-5(213)*, Presented at RAP ETG meeting, July 2012. http://www.morerap.us/meetings/july-2012.html. Accessed on November 29, 2012.

22. R. West, J. Michael, R. Turochy, and S. Maghsoodloo. "Use of Data from Specific Pavement Studies Experiment 5 in the Long-Term Pavement Performance Program to Compare Virgin and Recycled Asphalt Pavements," In *Journal of Transportation Record*, Transportation Research Board, Washington, D.C., 2011.

23. F. Zhou, S. Hu, X. Hu, G. Das, and T. Scullion, *High RAP Mix Design Methodology with Balanced Performance*, Research Report FHWA/TX-11/0-6092-2, Texas Transportation Institute, College Station, Texas, November 2011.

24. J. Shen, S. Amirkhanian, and J. A. Miller, "Effects of rejuvenating agents on Superpave mixtures containing reclaimed asphalt pavement," *J. Mater. Civil Eng.* 19 (5) (2007) 376–384.

25. R. L. Venable, J. C. Petersen, R. E. Robertson, *Investigation of Factors Affecting Asphalt Pavement Recycling and Asphalt Compatibility*, U.S. Department of Energy, Technical Information Center, Washington, D.C., 1983.

26. N. Tran, A. Taylor, and R. Willis, *Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents*, NCAT Report 12-05, National Center for Asphalt Technology, Auburn, Alabama, 36830.

27. R. Bonaquist, *Effect of Recovered Binders from Recycled Shingles and Increased RAP Percentages on Resultant Binder PG*, SPR# 0092-10-06, Advanced Asphalt Technologies, LLC, December 2011.

28. J. Shen, S. Amirkhanian, and B. Tang, "Effects of Rejuvenator on performance-Based Properties of Rejuvenated Asphalt Binder and Mixtures," *Construction and Building Materials*, 21, pp. 958-964, 2007.

29. WFAA.com, Weather webpage. http://www.wfaa.com/weather, July 2014.

30. X. Li, and N. Gibson, "Using Small Scale Specimens for AMPT Dynamic Modulus and Fatigue Tests," *Journal of the Association of Asphalt Paving Technologists*, Vol. 82, 2013, pp. 579–615.

31. A. Kvasnak. "NCAT RAP Research," presented at RAP ETG meeting, October 2008 http://www.morerap.us/files/meetings/10-08/ncat-rap-research.pdf. Accessed on July 21, 2011.

32. F. Zhou, S. Hu, T. Scullion, "Development and Verification of the Overlay Tester Based Fatigue Cracking Prediction Approach," *Journal of the Association of Asphalt Paving Technologists*, Vol. 76, pp. 627-662, 2007.

33. Z. Wu, L. Mohammad, L. B. Wang, M. A. Mull, "Fracture Resistance Characterization of Superpave Mixtures Using the Semi-Circular Bending Test," *Journal of ASTM International*, Vol. 2, No. 3, March 2005.

34. M. Elseifi, L. Mohammad, H. Ying, and S. Cooper III, "Modeling and Evaluation of the Cracking Resistance of Asphalt Mixture Using Semi-Circular Bending Test at Intermediate Temperature," *Journal of the Association of Asphalt Paving Technologists*, Vol. 81, pp. 277–302, 2012.

35. M. Kim, L. Mohammad, and M. Elseifi, "Characterization of Fracture Properties of Asphalt Mixtures as Measured by Semicircular Bend Test and Indirect Tension Test," *Journal of Transportation Research Record*. No. 2296, pp. 115–124, 2012.

36. M. Kim, L. Mohammad, H. Challa, and M. Elseifi, "A Simplified Performance-Based Specification for Asphalt Pavements," *Journal of the Association of Asphalt Paving Technologists*, Accepted in Volume 84.

37. AASHTO, AASHTO T XX-XX, Determining the Fracture Potential of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB) at Intermediate Temperature, American Association of State and Highway Transportation Officials, Washington, D.C., Revised Draft (05-17-2015).

38. G. Lamptey, M. Ahmad, S. Labi, and K.C. Sinha, *Life Cycle Cost Analysis for INDOT Pavement Design Procedures*, Report No. FHWA/IN/JTRP-2004/28. Purdue University, 2005.

39. J. Walls, and M.R. Smith, *Life-Cycle Cost Analysis in Pavement Design- In Search of Better Investment Decisions*, Pavement Division Interim Technical Bulletin. FHWA, U.S. Department of Transportation, Washington, D.C., 1998.

40. S. Hu, F. Zhou, and T. Scullion, *Development of Texas Mechanistic-Empirical Flexible Pavement Design System (TxME),* Report No. FHWA/TX-12/0-6622-2. Texas A&M Transportation Institute, College Station, TX, 2014.

41. S. Ryu,, P. Choi, W. Zhou, S. Saraf, S. Senadheera, J. Hu, S. Siggiqui, D. Fowler, and M.C. Won, *Optimizing Concrete Pavement Type Selection Based on Aggregate Availability*, Report No. FHWA/TX-13-0-8881-1. Texas Tech University, Lubbock, TX, 2013.

42. A. Copeland, *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice,* Final Report, No. FHWA-HRT-11-021, Office of Infrastructure Research and Development Federal Highway Administration, 2011.

43. FHWA, *Life-Cycle Cost Analysis Primer*, U.S. Department of Transportation, Washington, D.C., 2002.