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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 our 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 will focus on the durability of RAP/RAS mixes. This report presents a review of using RAP/RAS in asphalt mixes, the identified research focus, and the revised field experimental test plan. Specifically, this report discusses the field performance of RAP/RAS mixes in Texas and other states, and the observed field performance data strongly support the necessity of establishing a RAP/RAS mix design system for project-specific service conditions. The best practices for using RAP/RAS in hot-mix asphalt (HMA) and warm mix asphalt (WMA) mixtures, including RAP/RAS processing, mix design, production, and field construction, are also documented. Additionally, the new specification for asphalt mixes in Texas is reviewed and then a revised field experimental test plan for validating the new specification is recommended.					
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LITERATURE REVIEW: PERFORMANCE OF RAP/RAS MIXES AND NEW DIRECTION

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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.

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CHAPTER 1

INTRODUCTION

The asphalt paving industry has always advocated recycling, including reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), tires, etc. 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, recycled asphalt shingles 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%. 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). Also, significant work has been done to address the premature cracking of RAP/RAS mixes. This report reviews and discusses all these research results and other studies at the national and international levels.

This report presents a review of using RAP/RAS in asphalt mixes, the identified research focus, and the revised field experimental test plan. Also, [Chapter 2](#) discusses 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 the best practices for using RAP/RAS in HMA/WMA mixes, including RAP/RAS processing, mix design, production, and field construction. [Chapter 4](#) documents the specification comparison among different states. A revised field experimental test plan for validating TxDOT's new specification also is discussed in [Chapter 4](#). Finally, [Chapter 5](#) presents a summary and conclusions from year one of this project.

CHAPTER 2 LITERATURE REVIEW ON RAP/RAS MIX DESIGN AND PERFORMANCE

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 our 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., 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 us define future directions.

- Field performance of RAP/RAS mixes in Texas and nationwide.
- Balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions.
- Approaches to improving durability of RAP/RAS mixes in terms of mix design.
- RAP/RAS mixes produced with WMA technologies.
- Characterization of RAP/RAS properties and binder blending.

Finally, the summary and conclusions are provided at the end of this chapter.

FIELD PERFORMANCE OF RAP/RAS/WMA MIXES IN TEXAS AND NATIONWIDE

Field performance is what pavement engineers and users really care about, regardless of the use of RAP/RAS/WMA or not. Therefore, 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 RAP/RAS Test Sections under Projects 0-6092 and 0-6614

A series of field test sections with RAP/RAS have been constructed around Texas under Projects 0-6092 and 0-6614, as shown in [Figure 1](#). [Table 1](#) lists detailed information of the field test sections ([16](#), [20](#)). These field test sections cover different applications of RAP/RAS mixes, including: (1) asphalt overlays vs. new construction, (2) cold weather vs. hot weather, (3) heavy traffic vs. low traffic, (4) thicker vs. thin asphalt layer(s), and (5) virgin mix vs. RAP only (or RAP/RAS).

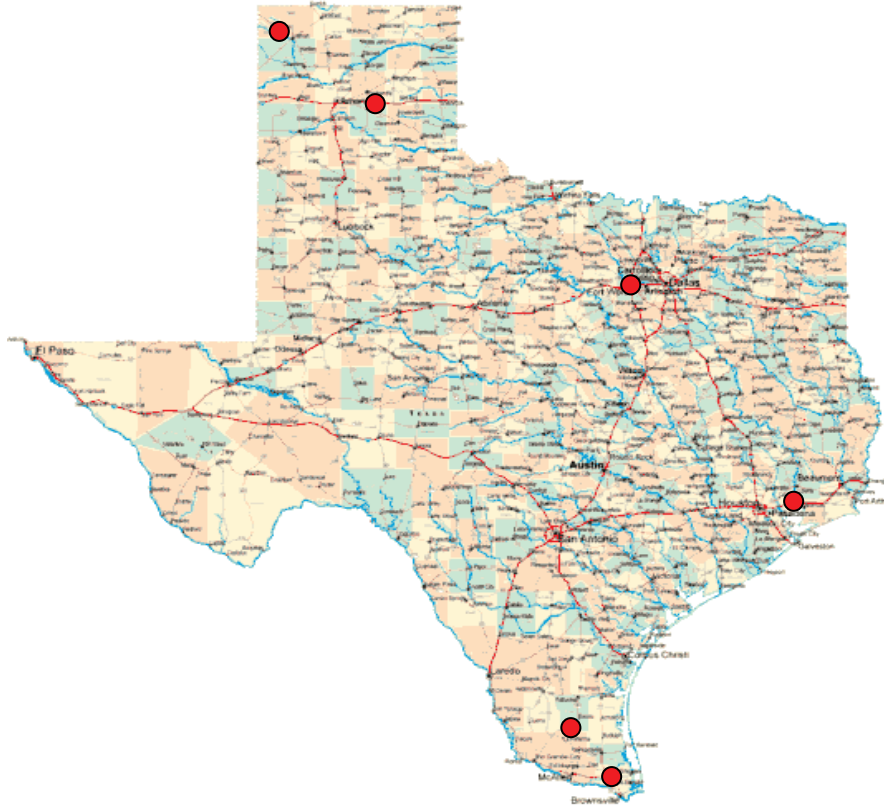


Figure 1. RAP/RAS Field Test Sections.

Performance of these field test sections is also described in [Table 1](#). When comparing the observed performance data of all the field test sections ([Table 1](#)), it may seem very confusing. RAP/RAS mixes with low Overlay test (OT) cycles performed well on SH359, SH146, and FM1017. However, those RAP mixes on IH40 and US87 performed very poorly, although these mixes had higher OT cycles. It seems that these observed performance data do not make any sense. After carefully considering all the information (traffic, climate, existing pavement conditions) presented in [Table 1](#), 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 balanced mix design procedure (discussed later).
- Cracking performance of asphalt mixes, different from rutting, is strongly connected with pavement structure. It is extremely difficult to propose a single cracking requirement for all applications.
- Cracking performance is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness.
- There is a terrible need to develop a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions, including traffic, climate, existing pavement conditions, etc.

Table 1. 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	PG 64-28	HMA	Hot summer, cold winter	30	4 inch overlay	Severe transverse cracking	10	100% reflect. cracking after 3 years
	0%RAP	PG 64-28						90	
	20%RAP	PG 64-28						103	
	35%RAP	PG 58-28						200	57% reflect. cracking after 3 years
FM1017	0%RAP	PG 76-22	HMA	Very hot summer, mild winter	0.8	New construction, 1.5 inch surface layer	N/A	28	Limited, fine cracking after 2.5 years
	20%RAP	PG 70-22						6	
	35%RAP	PG 70-22						7	
SH359	20%RAP	PG 70-22	HMA	Hot summer, mild winter	1.0	3 inch overlay	Severe transverse cracking	3	No cracking after 2.5 years
SH146	15%RAP/5% TOAS	PG 64-22	HMA	Hot summer, mild winter	1.5	New construction, 2 inch surface layer	N/A	3	No cracking after 2 years
US87	5% TOAS	PG 64-28	HMA	Hot summer, very cold winter	3.5	3 inch overlay	Severe transverse cracking	48	50% reflective cracking after 2.5 years
		PG 64-28 with 0.4% more virgin binder						96	20% reflective cracking after 2.5 years
Loop820	15%RAP/5%MWAS	PG 64-22	WMA	Hot summer, mild winter	15	2 inch overlay	Fine transverse cracks in existing CRCP	8	Perfect condition after 1 year
		PG 64-22	WMA(aditive pre-blending with RAS)					12	
		PG 64-28	WMA					22	
		PG 64-22 (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 national center for asphalt technology (NCAT) 2006. Seven RAP sections were built in 2006, as reported by Kvasnak at the RAP expert task group (ETG) meeting in October 2008 (21). The mixes used on the NCAT sections were: 1) virgin control mix with PG 67-22, 2) 20 percent RAP with PG 67-22 virgin binder, 3) 20 percent RAP with PG 76-22 virgin binder, 4) 45 percent RAP with PG 52-28 virgin binder, 5) 45 percent RAP with PG 67-22 virgin binder, 6) 45 percent RAP with PG 76-22 virgin binder, and 7) 45 percent RAP with PG 76-22 virgin binder + Sasobit. After 2 years, 10 million ESALs of traffic, only the section with 45 percent RAP mix with PG 76-22 + 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 more than 15 inch (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.

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 DOT Demonstration Project (22)

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 I94 mainline. A plan view of test cells is shown in Figure 2. 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 feet long including a 50 foot transition area. All cells are 3 inches 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 inch) NMAS (nominal maximum aggregate size) 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 PG 58-28 virgin binder was used for all 34 test sections. Table 2 shows more mix design information.

Field performance of these RAP/RAS mixes on MnRoad is shown in Figure 3. 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 JPCP has the longest transverse cracking.

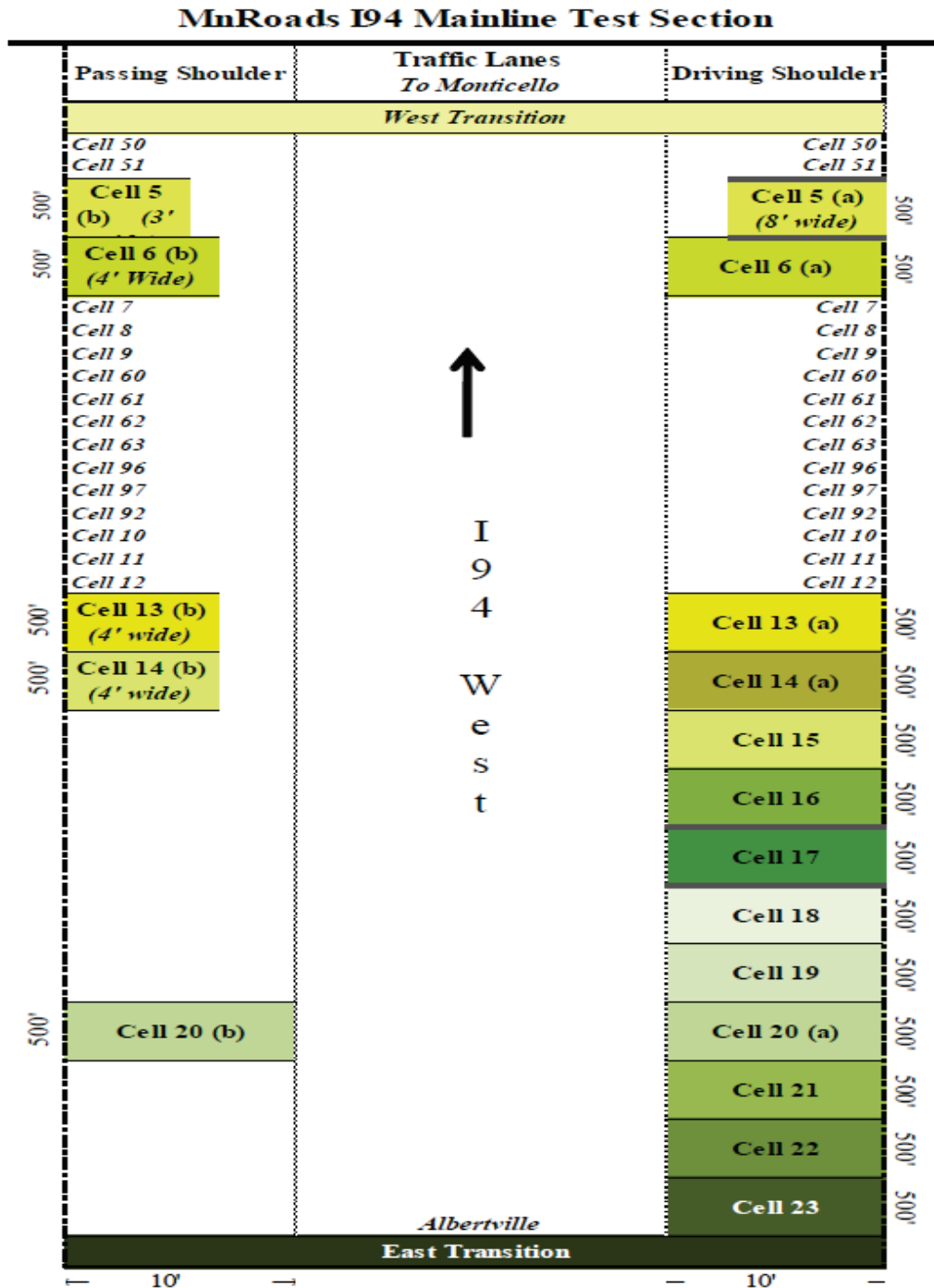


Figure 2. Plan View of MnRoad Test Cells (22).

Table 2. Mix Design Information on MnRoad RAP/RAS Mixes (23).

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	PG 58-28	PG 58-28	PG 58-28

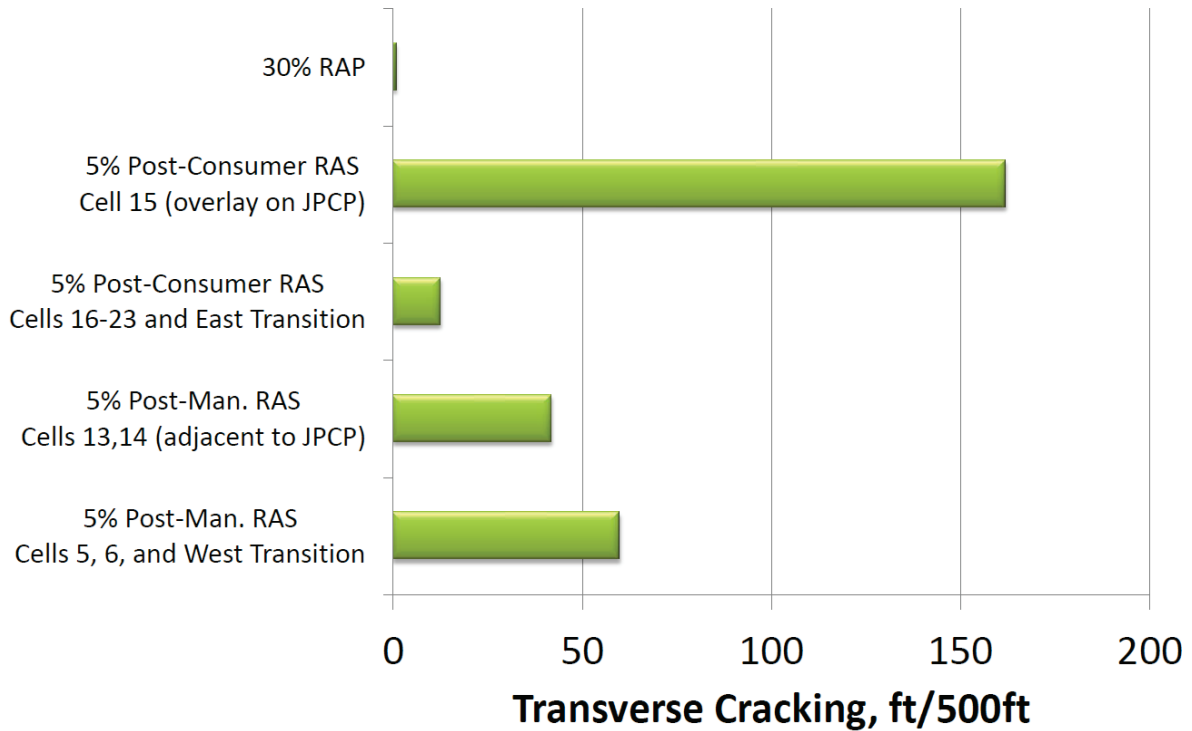


Figure 3. Cracking Performance of RAP/RAS Mixes on MnRoad (23).

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 inch thick surface course with an underlying granular base. Figure 4 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. Detailed mix design information is listed in Table 3. The observed transverse cracking data are shown in Figure 5. It seems that there is no difference among these four test sections in terms of transverse cracking.

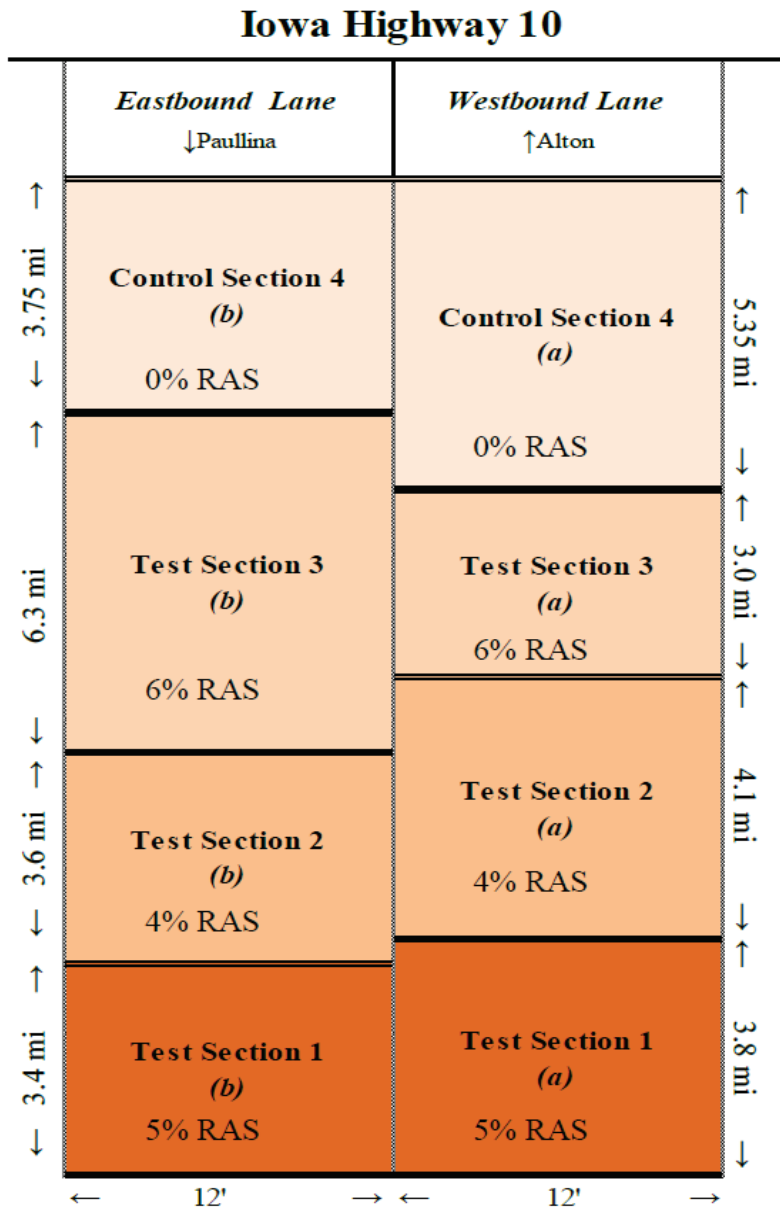


Figure 4. Plan View of Iowa Demonstration Project Test Sections (22).

Table 3. Mix Design Information of Test Sections on Highway 10, Iowa (23).

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	PG 64-22			

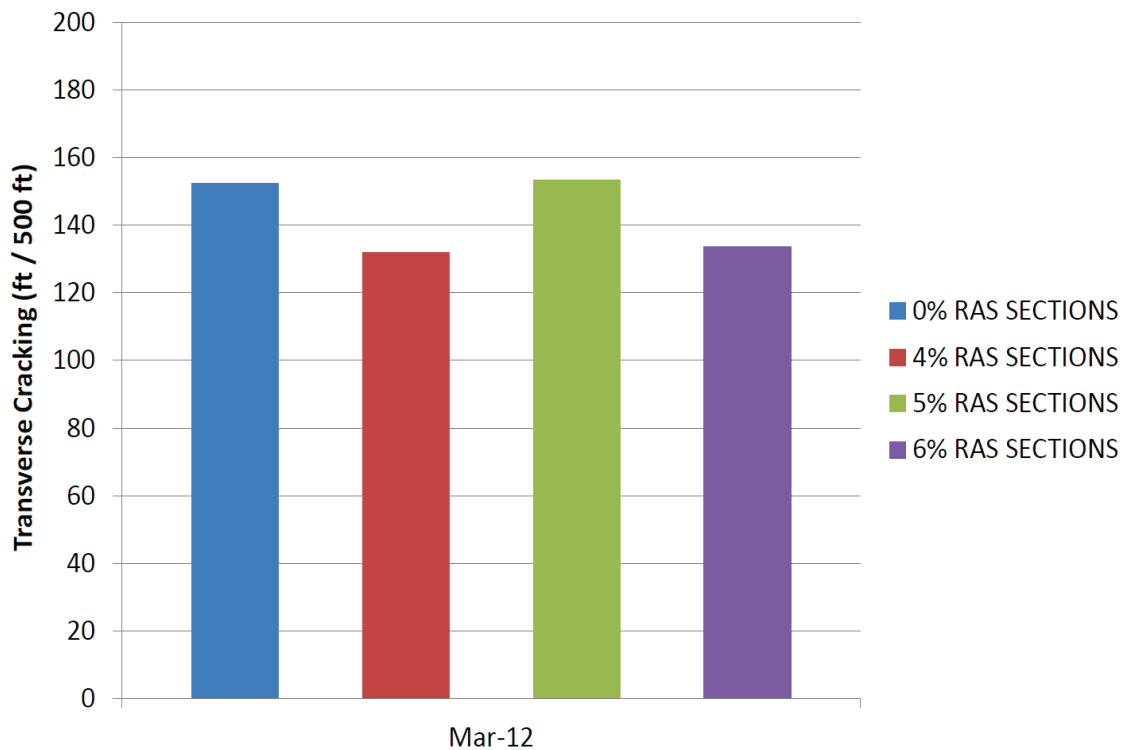


Figure 5. Observed Transverse Cracking on Field Test Sections in March 2012, Iowa (23).

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 inch 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. Three test sections were paved as shown in Figure 6. A PG 64-22 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 3/4 inch 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 inch 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. More information about these three mixes is provided in Table 4. Figure 7 shows the observed transverse cracking development of each test sections. Clearly, the control section with 15 percent RAP has the least transverse cracking.

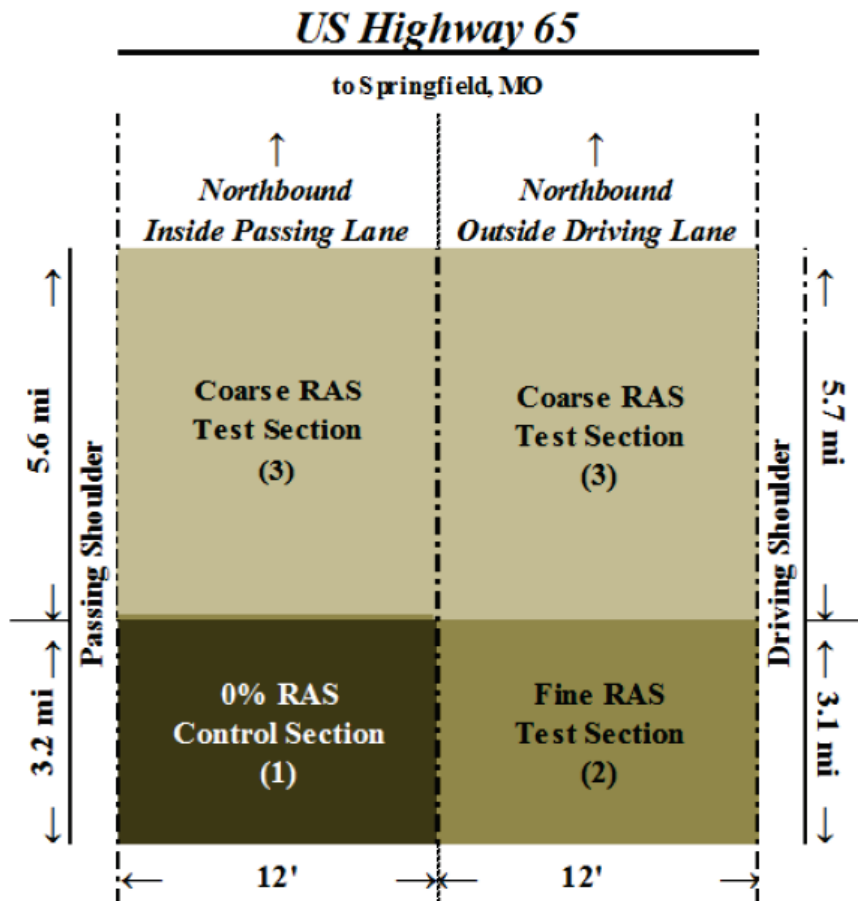


Figure 6. Plan View of Missouri Demonstration Project Test Sections (22).

Table 4. Mix Design Information of Test Sections on Highway 65, Missouri (23).

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	PG 64-22	PG 64-22	PG 64-22
%GTR by wt. of asphalt content	10	10	10

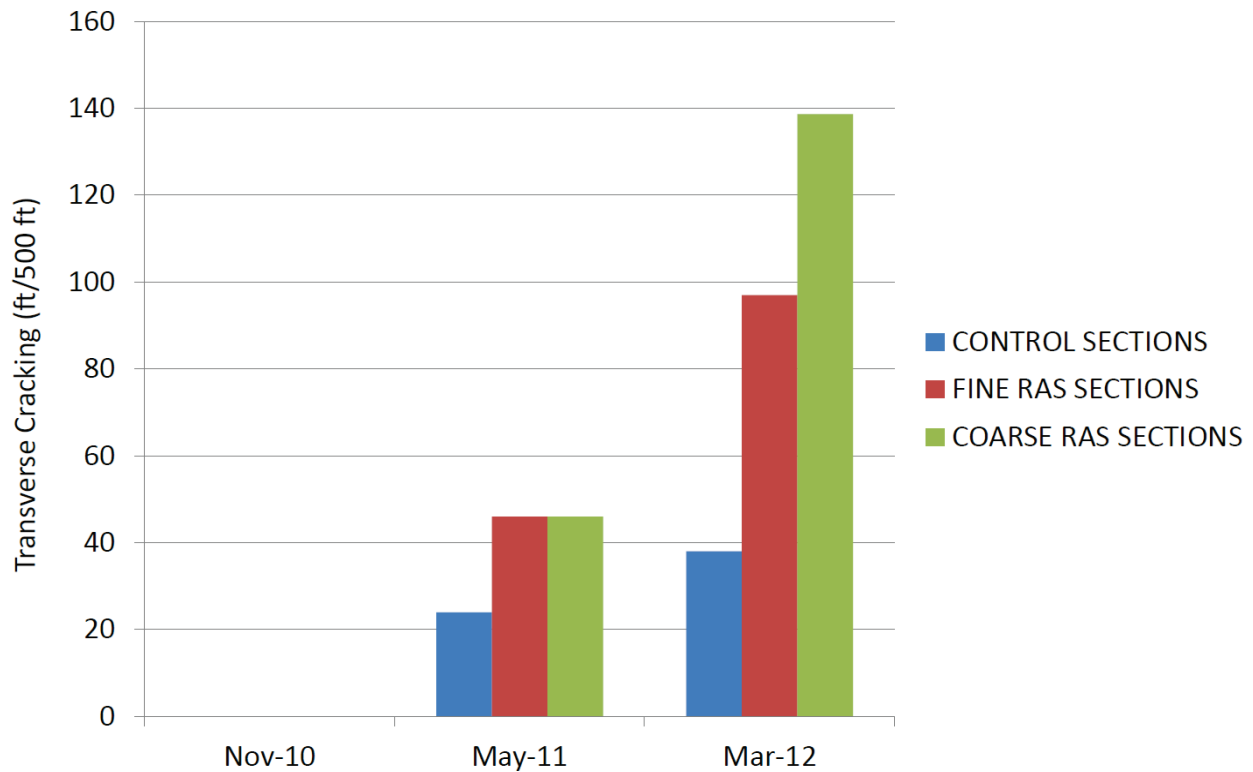


Figure 7. Observed Transverse Cracking on Highway 65, Missouri (23).

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 inch 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 warm mix asphalt in asphalt concrete pavements. They constructed three test sections as shown in Figure 8. The control section used a hot mix asphalt containing 15 percent fractionated recycled asphalt pavement (FRAP). Test section 2 used the same hot mix asphalt with 3 percent RAS. A foaming method was applied to produce warm mix asphalt that is laid down in test section 3. Test section 3 also contains 3 percent RAS. A PG 70-22 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 5 provides more information about these three mixes. Figure 9 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.

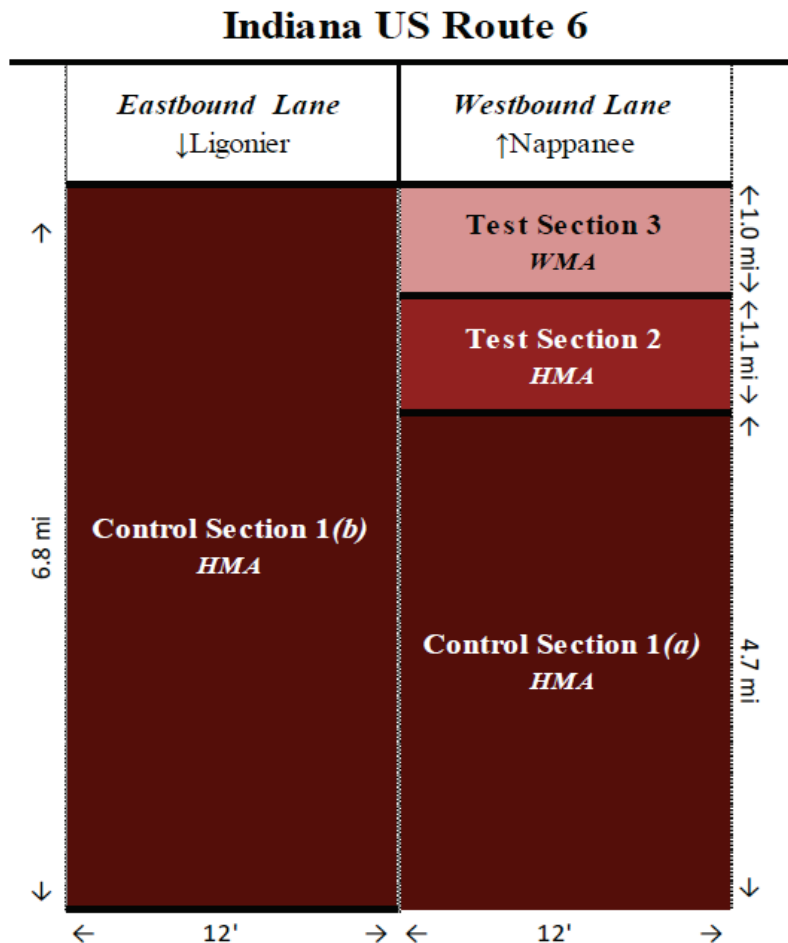


Figure 8. Plan View of Indiana Demonstration Project Test Sections (22).

Table 5. Mix Design Information of Test Sections on US Route 6, Indiana (23).

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	PG 70-22	PG 70-22	PG 70-22
Foaming WMA	No	No	Yes

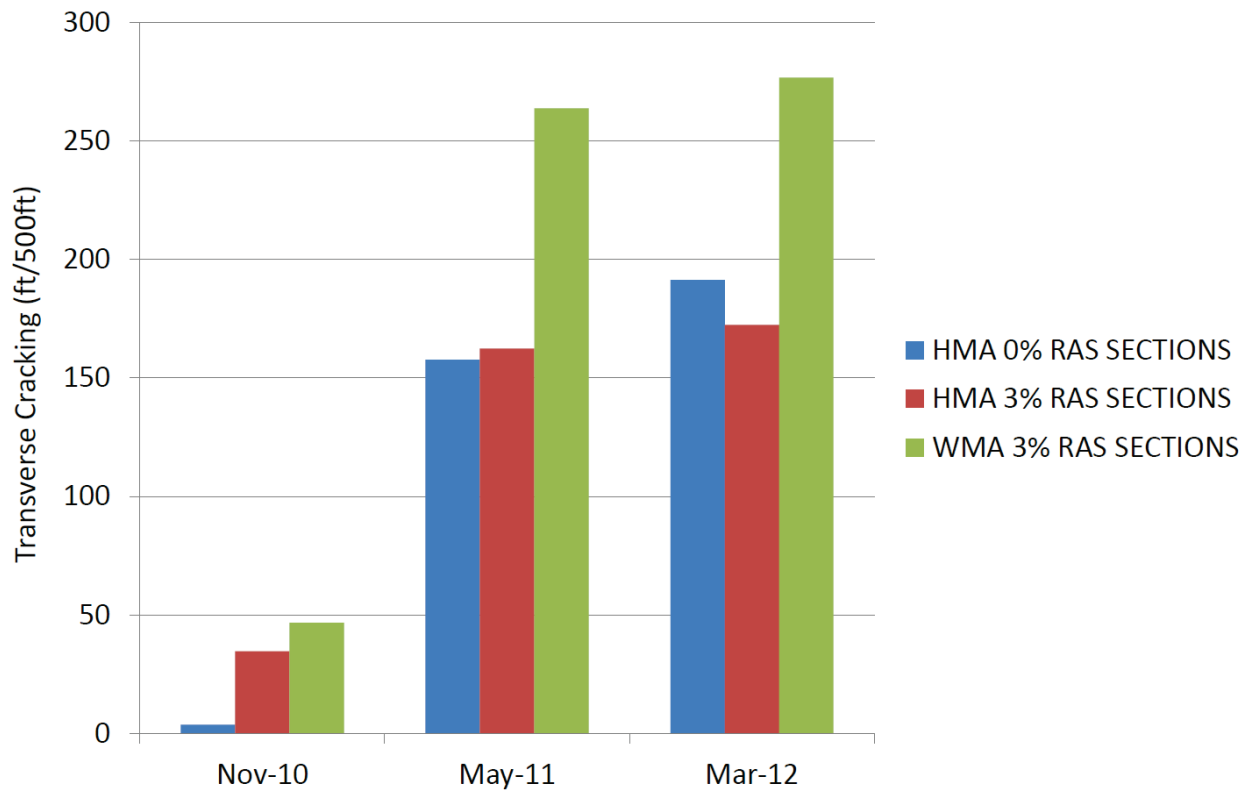


Figure 9. Observed Transverse Cracking on US Route 6, Indiana (23).

Other Performance Data of RAP Mixes in the Literature

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

Recently, Randy West et al. (24) 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. Randy 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.

Feng Hong, Dar-Hao Chen, and Magdy Mikhail (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.

Summary

Based on the field performance data the following findings and conclusions are offered:

- RAP/RAS mixes normally have better rutting resistance, but poor cracking resistance.
- Under the national pooled fund study TPF-5(213), RAP mixes generally performed better than RAS mixes.
- RAP/RAS mixes can have similar or better performance than virgin mixes provided that they are designed following the balanced mix design procedure (discussed in next section).
- Cracking performance is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. Therefore, it is extremely difficult to propose a single cracking requirement for all applications. In order to design a mix with acceptable cracking performance, regardless of having RAP/RAS, we must integrate mix design with pavement performance evaluation for project-specific service conditions.

- There is a terrible need to develop a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions, including traffic, climate, existing pavement conditions, and etc.
- So far no data are available for performance of SMA, PFC, and Superpave mixes with RAP/RAS in Texas. Furthermore, the impact of WMA technologies on performance of RAP/RAS mixes should be investigated as well.

BALANCED RAP/RAS MIX DESIGN AND PERFORMANCE EVALUATION SYSTEM FOR PROJECT-SPECIFIC SERVICE CONDITIONS

Since rutting is not a problem for RAP/RAS mixes, and it is well controlled through the Hamburg wheel tracking test, the cracking issue primarily observed in the field should be the main focus when designing mixes containing RAP/RAS. Therefore, the philosophy of developing mix design and a performance evaluation procedure is to meet volumetric cracking requirements first, while ensuring acceptable rutting and moisture damage resistance. Table 6 lists potential cracking distresses when mixtures containing RAP/RAS are used under different applications.

Table 6. Potential Major Cracking Distresses for Different Applications.

Applications		Main concerns
Asphalt overlay	AC/existing AC/granular base	Reflective cracking, fatigue cracking, or thermal cracking
	AC/existing AC/cement stabilized base	Reflective cracking, thermal cracking
	AC/jointed PCC	Reflective cracking, thermal cracking
	AC/CRCP	Thermal cracking, reflective cracking
New pavement	Surface layer	Thermal cracking, fatigue cracking (top-down)
	Intermediate layer(s)	
	Bottom layer	Fatigue cracking

Currently, asphalt mix design in Texas is based on volumetric properties of asphalt mixtures plus checking potential rutting and moisture damage. TxDOT already established the rutting/moisture damage requirements for mixes with different binders in the asphalt mix specification. For example, rut depth of a mix with PG 76-22 binder should be less than 0.5 inch (12.5 mm) after 20,000 passes. However, there is no cracking requirement on dense-graded, Superpave, and SMA mixes in the specification. As clearly observed in the field and discussed previously, it may be difficult to establish a single cracking requirement, because cracking performance of asphalt mixes depends on traffic, climate, pavement structure, and existing pavement conditions for asphalt overlays. Therefore, a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions, rather than a single cracking requirement, should be developed, and then implemented to ensure the mixes are designed with acceptable field performance.

In the last several years, the researchers at TTI have made significant progress toward the goal of a balanced RAP/RAS mix design and performance evaluation system, as noted below:

- Balanced mix design for overlay mixes developed under Project 0-5123 and documented in Report FHWA/TX-06/0-5123-1 (25).
- Mechanistic-empirical asphalt overlay thickness design and analysis system developed under Project 0-5123 and documented in Report FHWA/TX-09/0-5123-3 (26).
- High RAP mix design methodology with balanced performance developed under Project 0-6092 and documented in Report FHWA/TX-11/0-6092-2 (27).
- Balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions developed under Project 0-6092 and documented in Report FHWA/TX-13/0-6092-3 (20).

Figure 10 shows the balanced RAP/RAS overlay mix design and performance evaluation system for project-specific conditions proposed under Project 0-6092. Basically, 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, with OT cycles as an input, as shown in Figure 11. If the predicted performance meets the requirements, then the mix design process is done; otherwise one needs change virgin binder, RAP/RAS, or aggregates and repeat the mix design process.

Compared with TxDOT's current mix design procedure, the balanced RAP/RAS overlay mix design and performance evaluation system proposed under Project 0-6092 is a step forward and has four advantages:

1. Evaluates cracking resistance directly rather than indirectly through VMA.
2. Balances both rutting/moisture damage and cracking requirements.
3. Connects cracking requirement with project-specific service conditions.
4. Integrates mix design with pavement structure design.

Meanwhile, there are several things listed below that need further development.

- Conditioning temperature and time for RAP/RAS/WMA.
The conditioning temperature and time have significant impact on design asphalt content, rutting (or permanent deformation) resistance, moisture damage, cracking resistance, dynamic modulus. This issue must be investigated in order to establish a useful mix design system.
- Compactability (or workability) of RAP/RAS/WMA.
There are some concerns regarding the field compaction issue of RAP/RAS mixes. It is necessary to evaluate this issue during the mix design process.
- Fatigue and thermal cracking prediction.
The balanced mix design system shown in Figure 10 is mainly for asphalt overlays. The new pavement construction will be different from asphalt overlays. As noted in Table 6, fatigue cracking rather than reflective cracking needs to be addressed. Additionally, thermal cracking, regardless of overlays or new construction, is another major distress in Texas cold areas (i.e., Panhandle area). Thus, these two types of cracking should be considered as well.

- Rutting prediction.

The research team assumes that the rutting issue is addressed through the Hamburg wheel tracking test and associated specification requirements. There is no rutting prediction involved in the balanced mix design system shown in Figure 10. However, it is necessary to expand it to include rutting prediction through establishing the relationship between the Hamburg wheel tracking test and the repeated load test.

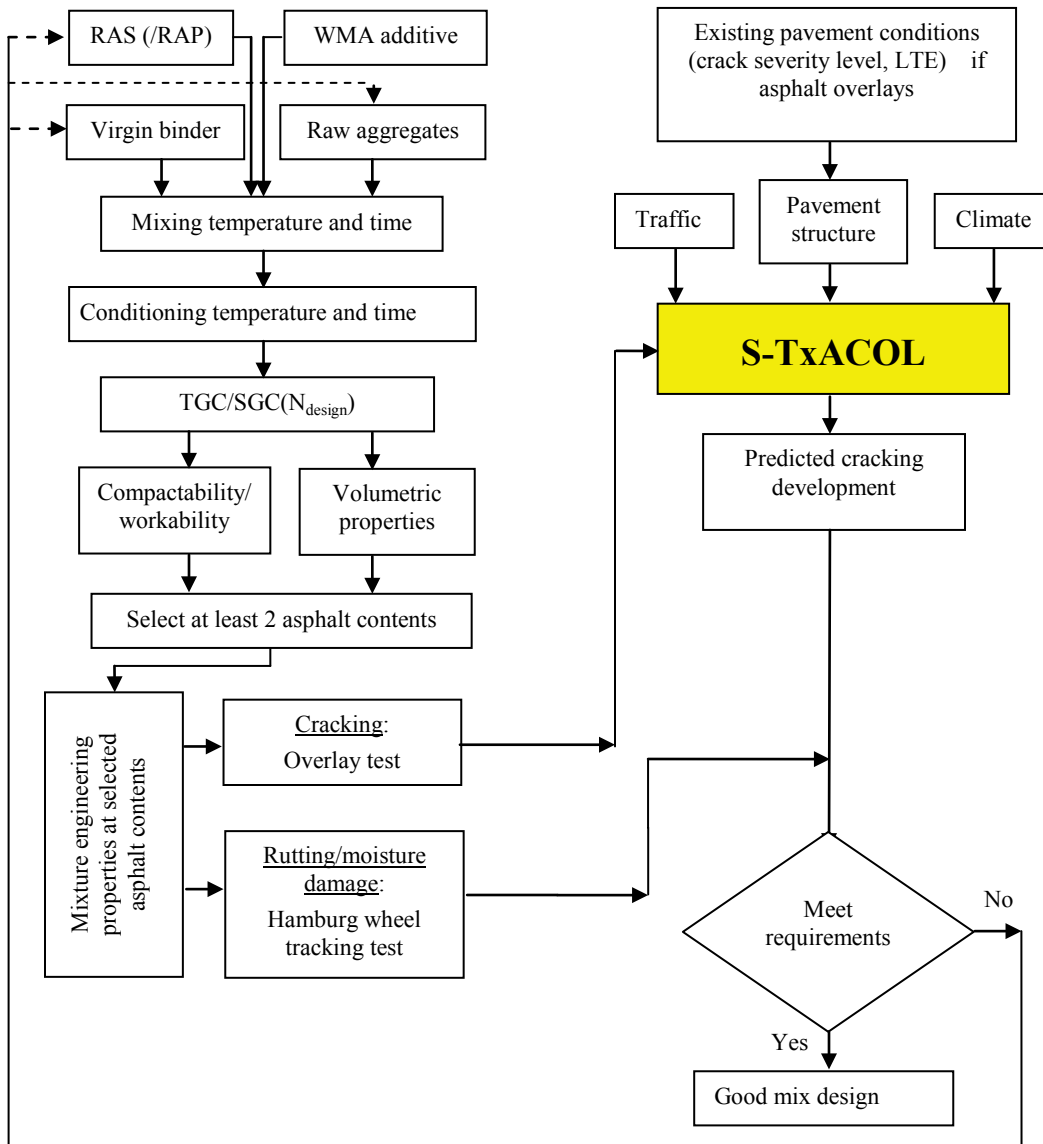


Figure 10. Balanced RAP/RAS Overlay Mix Design for Project-Specific Service Conditions (20).

AC Overlay1

Material Type: Thickness(inch):

Thermal Coefficient of Expansion (1e-6 in/in/F): Poisson Ratio:

Superpave PG Binder Grading

High Temp (C)	Low Temp (C)	
	-22	-28
64		
70		
76		

Modulus Input

Level 3 (Default Value) Level 2 (Witzcak Model) Level 1 (Test Data)

Default Value |

No Input Needed.

OT Cycles (Temp.=25C , OD=0.025")

OK Cancel

Figure 11. OT Cycles Input Interface for S-T_xACOL.

Summary

TTI researchers have proposed a balanced RAP/RAS overlay mix design and performance evaluation system. The proposed mix design and performance evaluation system integrated mix design with pavement structure design for project-specific service conditions. Meanwhile, the new system needs further development in four areas: 1) conditioning temperature and time for RAP/RAS/WMA, 2) compactability (or workability) of RAP/RAS/WMA mixes, 3) fatigue and thermal cracking prediction, and 4) rutting prediction.

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 effect 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., PG XX-28, PG XX-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 (27). When RAP content is below 15 percent, the impact of RAP on cracking resistance of mixes is negligible. Therefore, it is very 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 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. Therefore, 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. 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 compaction penalty and bonus. Currently, quality control and compaction penalty and 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 and bonus system has to be re-established. Therefore, 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 PG 64-22 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 PG 64-22, two more soft binders: PG 64-28 and PG 64-34 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 7 were evaluated under a dynamic modulus test (AASHTO TP79), the Hamburg wheel tracking test (HWTT) (Tex-242-F), and OT (Tex-248-F).

Note that the same 5.2 percent optimum asphalt content (OAC) was used for all six mixes, since the purpose is to investigate the influence of soft binders. Figures 12, 13, and 14 show the test results.

Table 7. RAS Mixes with Soft Virgin Binders.

RAS	5%RAS/PG 64-22	5%RAS/PG 64-28	5%RAS/PG 64-34
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/PG 64-22 mix, the use of softer binders improved rutting/moisture damage, as indicated in Figure 13. The reason for the improvement is that both PG 64-28 and PG 64-34 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 very 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; whereas, it can improve both rutting and cracking resistance of RAS mixes, especially on cracking resistance.

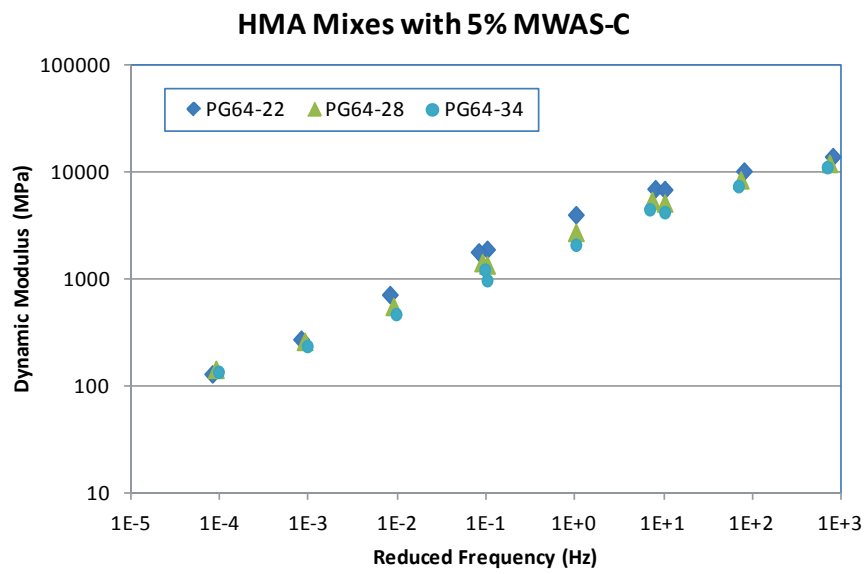
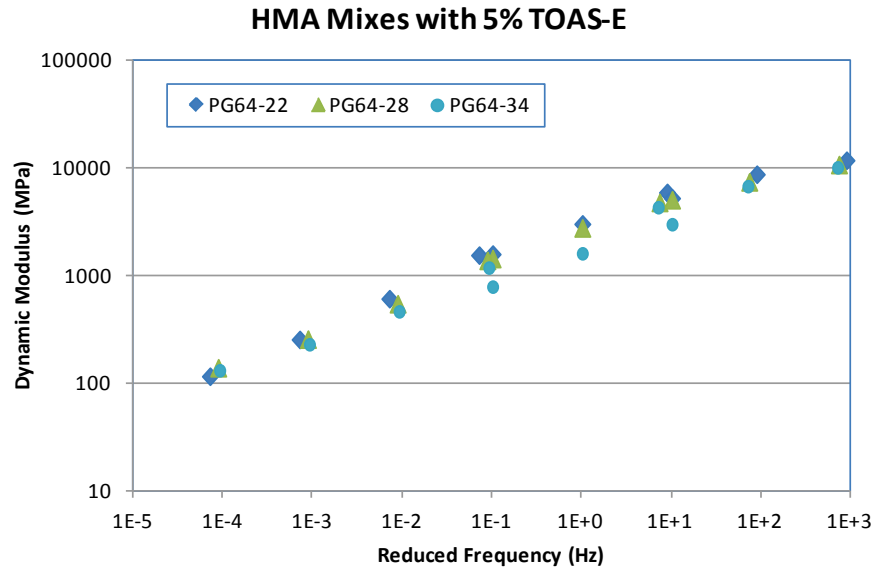


Figure 12. Impact of Soft Binders on Dynamic Modulus of 5 Percent RAS Mixes.

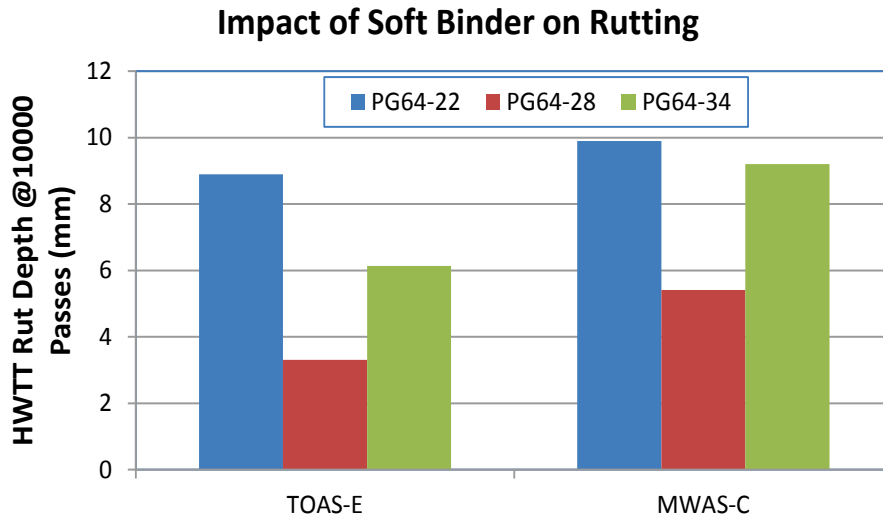


Figure 13. Impact of Soft Binders on Rutting/Moisture Damage of 5 Percent RAS Mixes.

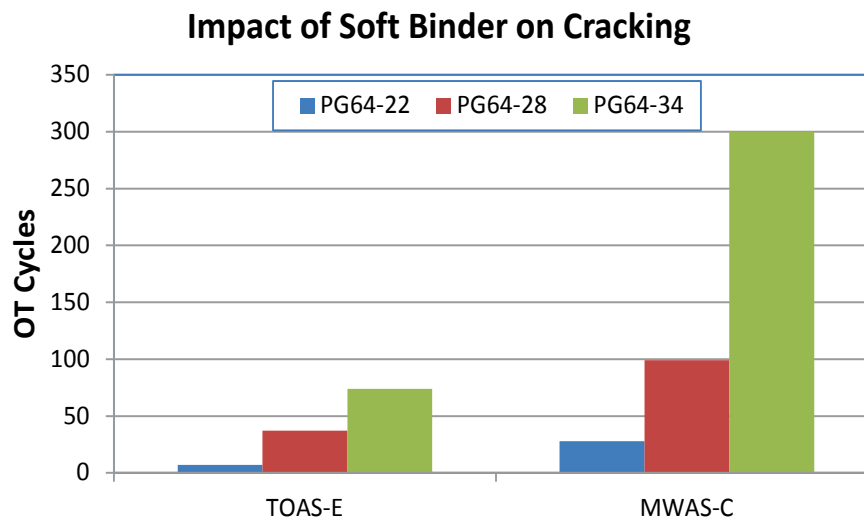


Figure 14. Impact of Soft Binder on Cracking Resistance of 5 Percent RAS Mixes.

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: PG 64-22, PG 58-28, PG 64-28, and PG 64-34. The same aggregates, gradation and OAC, were utilized 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 Figures 13 and 14, the RAP mixes with modified soft binders have significantly better cracking resistance than the mix with PG 64-22 virgin binder, as seen in Figure 15. Meanwhile, the mix with regular PG 58-28 binder without any modification has a little bit better cracking resistance, but its HWTT result is too poor. Therefore, the research team highly recommends using soft but highly modified binder rather than straight run soft binder (i.e., PG 58-28) for improving cracking resistance of RAP mixes.

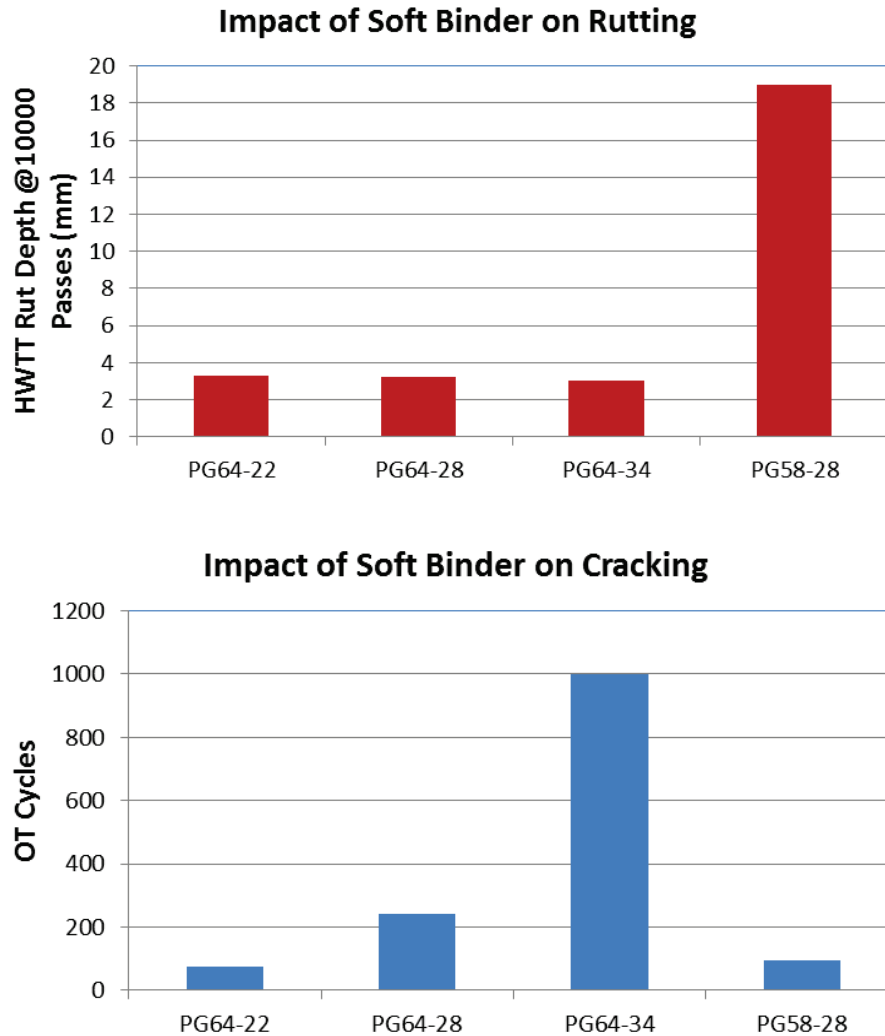


Figure 15. Impact of Soft Binders on Rutting/Moisture Damage and Cracking Resistance of RAP Mixes.

Summary

The test results discussed above clearly indicated that the use of soft and modified asphalt binder (i.e., PG XX-28, PG XX-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. It is a well-known fact that 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. Thus, 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 (28) 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 (29).

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? Therefore, the 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 (30). 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, the 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 PG 67-22, 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.
- Overlay test 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 inch.
- The rutting resistance of the five mixtures was evaluated using the APA. All the mixtures exhibited APA manual rut depths less than 5.5 mm, which was determined based on the past research at the NCAT Pavement Test Track; thus, 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 our 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. More discussion on RAP/RAS/WMA is provided in the next section.

Summary

All these five approaches can improve cracking resistance of RAP/RAS mixes to some extent and each approach has its pros and cons. It is difficult to recommend a certain approach for all potential applications without conducting a cost-benefit for each approach in terms of field performance. Therefore, it is highly recommended that the cost-benefit analysis be performed under this study for each approach discussed previously.

RAP/RAS MIXES PRODUCED WITH WMA TECHNOLOGIES

In the last six years, WMA technologies have been widely used in both Texas and nationwide. Most recently, they have been combined with RAP/RAS to produce RAP/RAS/WMA mixes. The following subsections discuss different aspects of RAP/RAS/WMA mixes.

WMA Technologies

In Texas, WMA is defined as HMA that is produced within a target temperature discharge range of 215°F and 275°F using TxDOT-approved WMA additives or processes. WMA is allowed for use on all projects and is required when shown on plans. The maximum placement or target discharge temperature for WMA may be set at a value less than 275°F when shown on the plans. Also, TxDOT-approved WMA additives or processes may be used to facilitate mixing and compaction of HMA produced at target discharge temperatures greater than 275°F; however, such mixtures will not be defined as WMA.

When WMA technologies were introduced to the U.S. in 2004, only a few WMA additives or processes were available. There are now (August 2013) over 30 WMA technologies available in the U.S. In Texas a total of 13 WMA technologies (see [Table 8](#)) are approved by TxDOT, and they can be further classified into three major categories: 1) organic additives (e.g., Sasobit), 2) chemical additives (e.g., Evotherm, Cecabase RT) with typical dosage rate of 0.2 to 0.5 percent of the binder, 3) foaming with additives (e.g., Advera) with typical dosage rate of 0.25 to 0.30 percent by weight of mix, and foaming with water injection systems (e.g., double barrel green, Terex) typically adding 1 to 2 percent water by weight of binder. The three most common WMA technologies used are: 1) foaming with water injection system, 2) Evotherm, and 3) Sasobit.

Table 8. TxDOT-Approved WMA Products and Technologies (3/22/2013).

Process Type	WMA Technology	WMA Supplier
Chemical Additive	Advera (Synthetic Zeolite)	PQ Corporation
	Aspha-Min (Synthetic Zeolite)	Aspha-Min
	Astech PER (Hydrogreen)	Meridian Technologies
	Cecabase RT	Arkema Inc.
	Evotherm	MeadWestvaco Asphalt Innovations
	QPR QualiTherm	QPR Quality Pavement Repair
	Rediset WMX	AkzoNobel Surface Chemistry
	Rediset LQ 1106	AkzoNobel Surface Chemistry
	ZycoTherm	Zydex Industries
Organic Additive	Sasobit	Sasol Wax Americas, Inc.
Foaming Process	ALmix WarmWare	ALmix
	Double Barrel Green	Astec Industries, Inc.
	HydroFoam IEQ	East Texas Asphalt Co., Ltd.
	Terex	Terex Roadbuilding
	Maxam	Maxam Equipment
	Ultrafoam GX	Gencor Industries

Benefits of RAP/RAS Mixes Produced with WMA Technologies

The original purpose of using WMA was to reduce emissions, especially in non-attainment areas. Additionally, the use of WMA can have the following benefits:

- Reduce fuel sue.
- Reduce binder oxidation during production.
- Improve field compaction especially for late season paving.
- Avoid the bump when overlaying pavements with joint/crack sealants.
- Allow long haul distance.

When combining with RAP/RAS, the WMA technologies can improve the ability to properly coat aggregates and RAP/RAS during production. Again, the lower production temperatures will reduce plant aging of binders, which may allow for increased use of RAP/RAS without grade bumping.

Issues and Concerns for Research on RAP/RAS Mixes Produced with WMA Technologies

The use of WMA has significant benefits in different areas, as discussed previously. However, several issues still need to be addressed.

Virgin/RAP/RAS Binder Blending at Lower Production Temperature

There is concern about the blending among virgin binder, RAP, and RAS when RAP/RAS mixes are produced at HMA temperatures. This concern becomes even greater when RAP/RAS mixes are combined with different WMA technologies and are produced at temperatures 30–50°F lower than those of HMA. There is even some concern regarding the melting of the tear-off shingles at WMA temperature. Consequently, this has an impact on the active binder from RAP/RAS, the blending, the true, total asphalt binder content, and even the VMA calculation. This issue must be addressed.

Laboratory Mixing Temperature and Time

For virgin mixes, TxDOT has established clear guidelines for laboratory mixing temperature and time that depend on virgin binder PG grade. However, there is not much information available on the subject for RAP/RAS/WMA mixes. Note that we should differentiate the true WMA production from the compaction aid using WMA technologies. A survey should be conducted in Texas to identify the plant production temperatures most often used for RAP/RAS/WMA. Also, researchers should make a comparison of laboratory produced mixes with plant produced mixes in terms of Rice specific gravity and other volumetric properties.

Aging Development of Plant-Mixed, Field-Compacted Cores with Time

It is well known that aging has an effect on asphalt mix properties including Rice specific gravity, air voids, VMA, modulus, rutting resistance, and cracking resistance. In order to correctly characterize and model asphalt mix properties, it is very important to define the aging development of asphalt mixes with time in the field. Also, the aging development for different mixes, virgin mixes with and without WMA and RAP/RAS mixes with and without WMA, may be different. However, there are still lots of unknown factors in this area, especially for RAP/RAS/WMA mixes. Therefore, researchers should make significant efforts to define the aging development of RAP/RAS/WMA mixes in the field.

Laboratory Compaction Temperature and Time

As noted above, laboratory compaction temperature and time have extensive influence on asphalt mix properties because they directly connect with asphalt binder aging and absorption. In order to define the laboratory-compaction temperature and time, we need to know field-aging development of asphalt mixes with time. With the known field-aging development, we can select the compaction temperature and time under which the laboratory-mixed and compacted mixes have similar engineering properties to those plant-produced and field-compacted mixes. The laboratory compaction temperature and time have impact not only on mix design but also on mix engineering properties and consequently on field performance prediction. Therefore, this issue must be investigated.

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 PG of RAP binders ranges from 82 to 115°C. The biggest concern is the RAS binder, as shown in Figure 16. 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.

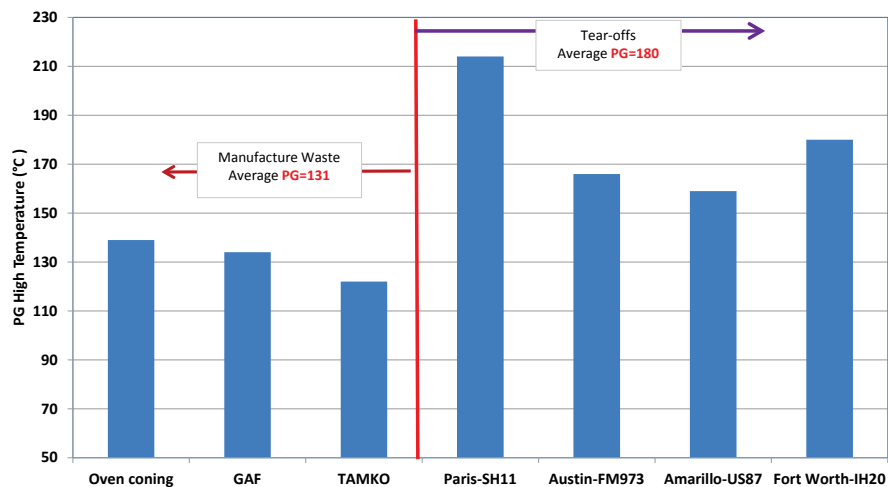


Figure 16. DSR Test Results of RAS Binders.

RAP/RAS and Virgin Binder Blending

One of the concerns with using RAP/RAS mixes is the effect of the recycled RAP/RAS binder on the performance grade 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 (NCHRP) 9-12. Recently, Fujie Zhou et al. under Project 0-6092 verified the linear blending chart using Texas RAP and virgin binders. Figure 17 shows an example of blending between a RAP binder (PG 115-3) and a virgin PG 64-22 binder. In this case, the lower PG end will not meet PG XX-22 requirement if 20 percent recycled RAP binder is blended with a PG 64-22 binder. To keep -22°C as the lower end, there are at least three options: 1) use less recycled RAP binder (say 15 percent), 2) select softer virgin binder (say PG XX-28), and 3) increase design density and indirectly increase the virgin binder content/reduce recycled RAP

binder. Note that the case shown in Figure 17 will be the worst scenario because normally the RAP binder is much softer than this RAP binder: PG 115-3.

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 research 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 (ABCD). So far the results clearly indicated that the blending between RAS binder and virgin binder is not linear blending, as shown in Figure 18. Again, 20 percent RAS binder will disqualify the combined binder from meeting the PG XX-22.

Current study on binder blending under Projects 0-6092 and 0-6614 needs to expand 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.

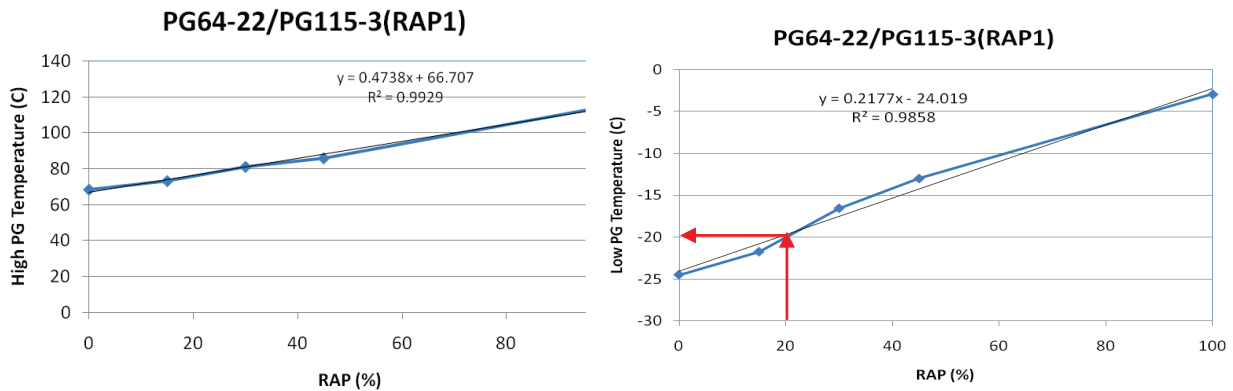


Figure 17. Linear Blending Chart between RAP Binder and Virgin Binder.

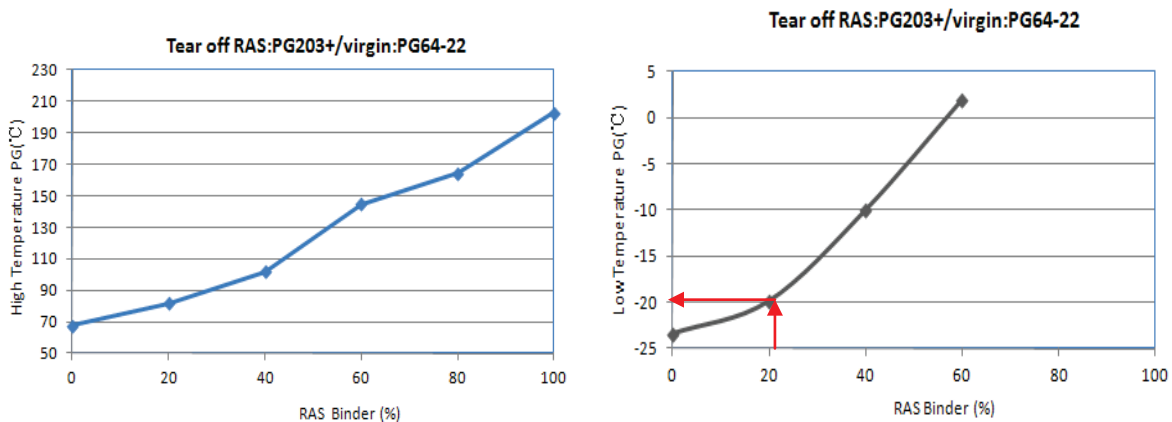


Figure 18. Blending Chart between a Tear-off RAS Binder and a PG 64-22 Virgin Binder.

SUMMARY AND CONCLUSIONS

Based on the information assembled and presented above, the following summary and conclusions are offered:

- Field performance of RAP/RAS mixes.
 - RAP/RAS mixes normally have better rutting resistance, but poor cracking resistance.
 - Under the national pooled fund study TPF-5(213), RAP mixes generally performed better than RAS mixes.
 - RAP/RAS mixes can have similar or better performance than virgin mixes provided that they are designed following the balanced mix design procedure.
 - Cracking performance is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. Therefore, it is extremely difficult to propose a single cracking requirement for all applications. In order to design a mix with acceptable cracking performance, regardless of having RAP/RAS, we must integrate mix design with pavement performance evaluation for project-specific service conditions.
 - There is a terrible need to develop a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions, including traffic, climate, existing pavement conditions, etc.
 - So far no data are available for performance of SMA, PFC, and Superpave mixes with RAP/RAS in Texas.

- RAP/RAS mix design.

A balanced RAP/RAS overlay mix design and performance evaluation system has been proposed. The proposed mix design and performance evaluation system integrated mix design with pavement structure design for project-specific service conditions.

Meanwhile, the new system needs further development in four areas:

- Conditioning temperature and time for RAP/RAS/WMA.
 - Compactability (or workability) of RAP/RAS/WMA mixes.
 - Fatigue and thermal cracking prediction.
 - Rutting prediction.
- Approaches for improving cracking resistance of RAP/RAS mixes.
 - At least five approaches listed below have been tried to improve cracking resistance of RAP/RAS mixes. TxDOT has implemented the first four approaches in the new specification. Rejuvenating RAP/RAS binders is under investigation under Project 0-6614. As noted previously, the big concern is the long-term benefit of using WMA technologies to improve cracking resistance of RAP/RAS mixes, which should be investigated in detail.
 - Reducing RAP/RAS usage (or binder replacement amount).
 - Using soft virgin binders especially on the low temperature grade (i.e., PG XX-28, PG XX-34).
 - Increasing design density (lowering design air voids) or reducing N_{design} .
 - Combining RAP/RAS with WMA technologies.

- Rejuvenating RAP/RAS binder.
 - These five approaches can improve cracking resistance of RAP/RAS mixes to some extent, and each approach has its pros and cons. It is difficult to recommend a certain approach for all potential applications without conducting a cost-benefit for each approach in terms of field performance. Therefore, it is highly recommended that the cost-benefit analysis be performed under this study for each approach discussed previously.
- RAP/RAS/WMA mixes.

Not much research has been performed in this area, especially the long-term performance of RAP/RAS/WMA mixes in the field. Specifically, there are four issues for further investigation:

- Virgin/RAP/RAS binder blending at lower production temperature.

There has been concern about the blending among virgin binder, RAP, and RAS when RAP/RAS mixes are produced at HMA temperatures. This concern becomes even greater when RAP/RAS mixes are combined with different WMA technologies and are produced at the temperatures of 30–50°F lower than those of HMA. Some people even doubt the melting of the tear-off shingles at WMA temperature. Consequently, this has impact on the active binder from RAP/RAS, the blending, the true, total asphalt binder content, and even the VMA calculation. This issue must be addressed.
- Laboratory mixing temperature and time.

For virgin mixes, TxDOT has established clear guidelines for laboratory mixing temperature and time that depend on virgin binder PG grade. However, there is not much information available on the subject for RAP/RAS/WMA mixes. Note that we should differentiate the true WMA production from the compaction aid using WMA technologies. A survey should be conducted in Texas to identify the plant production temperatures most often used for RAP/RAS/WMA. Also, compare laboratory-produced mixes with plant-produced mixes in terms of Rice specific gravity and other volumetric properties.
- Aging development of plant-mixed, field-compacted cores with time.

It is well known that aging has an effect on asphalt mix properties including Rice specific gravity, air voids, VMA, modulus, rutting resistance, and cracking resistance. In order to correctly characterize and model asphalt mix properties, it is very important to define the aging development of asphalt mixes with time in the field. Also the aging development for different mixes: virgin mixes with and without WMA, RAP/RAS mixes with and without WMA, may be different. However, there are still lots of unknown factors in this area, especially for RAP/RAS/WMA mixes. Therefore, significant efforts should be made to define the aging development of RAP/RAS/WMA mixes in the field.

- Laboratory compaction temperature and time.

As noted above, laboratory compaction temperature and time have extensive influence on asphalt mix properties because they directly connect with asphalt binder aging and absorption. In order to define the laboratory compaction temperature and time, we need to know field-aging development of asphalt mixes with time. With the known field-aging development, we can select the compaction temperature and time under which the laboratory-mixed and compacted mixes have similar engineering properties to those plant-produced and field-compacted mixes. The laboratory compaction temperature and time have impact not only on mix design but also on mix engineering properties and, consequently, on field performance prediction. Therefore, this issue must be investigated.

CHAPTER 3

BEST PRACTICES FOR USING RAP/RAS IN HMA/WMA MIXES

Field performance of asphalt mixes containing RAP/RAS is influenced by many factors, including RAP/RAS processing, mix design, plant production, and field construction. TTI researchers, collaborating with TxDOT and the Texas Asphalt Pavement Association (TxAPA), has developed and taught several best practice workshops for using RAP/RAS in asphalt mixes. [Chapter 3](#) documents all the best practices for using RAP/RAS in HMA/WMA mixes.

RAP PROCESSING AND STOCKPILE MANAGEMENT

RAP processing and stockpile management are key to having high-quality RAP and consistent RAP mixes. The researchers developed best practices for RAP processing and stockpile management based on field observation and the interactions with TxDOT's personnel and contractors. A six-step RAP processing and stockpile management guideline is presented below.

1. Eliminate Contamination

The first step to control the quality of RAP materials is to eliminate contamination. It is acknowledged that RAP processing/fractionating is a critical step in reducing the RAP variability. RAP fractionation in itself will help. However, it will not solve all the RAP variability and other problems. For example, if you fractionate one contaminated pile of RAP, you will get two contaminated piles of RAP. Both TxDOT and contractors will benefit from keeping deleterious materials out of any RAP stockpile from the beginning.

Contamination may occur from milled-up paving geosynthetics (fabrics, grid), reflective lane markers (yellow or white), and dumping general road debris with dirt and vegetation on the pile. In some cases, the multiple-source RAP stockpiles were believed to contain construction trash. [Figure 19](#) shows an extreme example in which concrete trash and reinforced steels were mixed with RAP stockpile. Another type of contamination may be due to unstable, unconditioned, sunken earth surface. Any potential contamination to RAP stockpiles should be avoided in order to improve the RAP quality and, accordingly, pavement performance.



Figure 19. Contaminated RAP Stockpile.

2. Separate RAP Stockpiles from Different Sources

It is always important to separate RAP stockpiles obtained from different sources. In most cases, it is unnecessary to crush or fractionate a single source RAP stockpile with a known source. As shown previously, the separated, unfractionated RAP materials that TxDOT owned have a similar quality to that of crushed RAP. Well-separated stockpiles can save lots of time and cost for crushing or fractionating RAP. In particular, when a large quantity of millings occurs from a single project, it is always worthwhile to keep the milled RAP separate from other RAP stockpiles.

3. Blend or Mix before Processing RAP Stockpiles

The whole purpose of processing a multiple-source RAP stockpile is to obtain a uniform RAP. One of the observations during the field visits is that the mixing process is rarely carried out before RAP crushing or fractionation. Current practice for processing multiple-source RAP stockpiles is to use a front-end loader or other machines to sequentially dig into the stockpiles to feed into a RAP crushing or fractionating machine. Such operating sequence often makes it difficult to truly meet the purpose of processing the multiple-source RAP stockpiles. Therefore, when the RAP materials are excavated, it is essential to randomly dig into the RAP pile from different angles so that the RAP material feeding into the crusher or fractionating machine at any time gets mixed up.

4. Process (Crush or Fractionate) RAP Stockpiles

4.1 Crush or Fractionate RAP

There has been a lot of discussion about fractionating RAP, but the current practice for RAP processing is to crush all RAP materials to a single maximum size, in most cases, either 1/2 inch or 3/8 inch. Unlike crushing, fractionating the RAP involves simply screening RAP materials into two or more sizes. The fractionated RAP is often split into coarse and fine fractions. The

coarse RAP stockpile will contain only the RAP material retained over a 3/8 in. screen or 1/2 in. screen; the fine RAP stockpile will contain only the RAP material passing the 3/8 in. screen or 1/2 in. screen. In comparing RAP fractionation with simply crushing RAP, there are benefits and some additional costs for fractionation. For example, RAP fractionation can provide designers more flexibility to choose different percentages of the coarse and fine RAP with virgin aggregates to meet both gradation and volumetric requirements. Generally speaking, it is easier to use more total fractionated RAP than crushed RAP.

4.2 Avoid Over-Crushing

Most contractors crush all RAP materials to a single maximum size, such as 1/2 in. or 3/8 in., so that the crushed RAP can be used in, for most cases, asphalt overlay mixes (dense-graded Type C or D). When crushing large aggregate particles in the RAP, it may generate too much fines (or dust passing #200 sieve size). Note that the excess dust often controls the percentage of RAP being used in a new mix during RAP mix design process. Another scenario is to further crush the RAP materials to 1/4 in. size. Theoretically, it is always better to crush RAP materials into finer size so that it is possible to better control the gradation and use more fine RAP with high asphalt binder content. However, crushing RAP to a smaller size often generates more dust that limits the percentage of smaller RAP used in the new mix. The authors of this report have experienced such a scenario when designing RAP mixes for field experimental test sections. Therefore, it is important to avoid excessive crushing of RAP materials.

5. Store the Processed RAP Using a Paved, Sloped Surface

Another aspect of managing RAP stockpiles is to store the RAP processed using a crusher or fractionation machine. It is a well-known fact that RAP has a tendency to hold water; in many instances, the RAP moisture content limited the percentage of RAP used, reduced the overall production rates, and raised the drying and heating cost for superheating the virgin aggregates. Therefore, it is beneficial and critical to minimize the RAP moisture content. Several measures are proposed to reduce RAP moisture content during stockpiling the processed RAP, and they are discussed below:

5.1 Conical vs. Horizontal Stockpiles

As documented in “Recycling Hot-Mix Asphalt Pavements” (12), the RAP in the early days were piled in low, horizontal piles for fear that high, conical stockpiles would cause RAP to pack together with the weight of the pile. However, past experience indicated that this is not the case. Additionally, RAP has a tendency to hold water and the low, horizontal stockpiles often retain higher moisture accumulation than the tall, conical stockpiles. In general, tall, conical stockpiles are preferred.

5.2 Use a Paved, Sloped Surface Area

While waiting for the contractors, the authors observed that at least one contractor already started using the paved, sloped surface to stockpile RAP materials. Using the paved surface under stockpiles not only can contribute to drainage from RAP stockpiles, but it also provides an even hard-surfaced area to minimize material loss and contamination of underlying materials. Meanwhile, providing a slope to the paved surface under the stockpile away from the side where

the front-end loader moves RAP materials to cold feed bin, as [Figure 20](#) shows, will allow rainwater to drain away, allowing drier RAP materials to go into the plant.

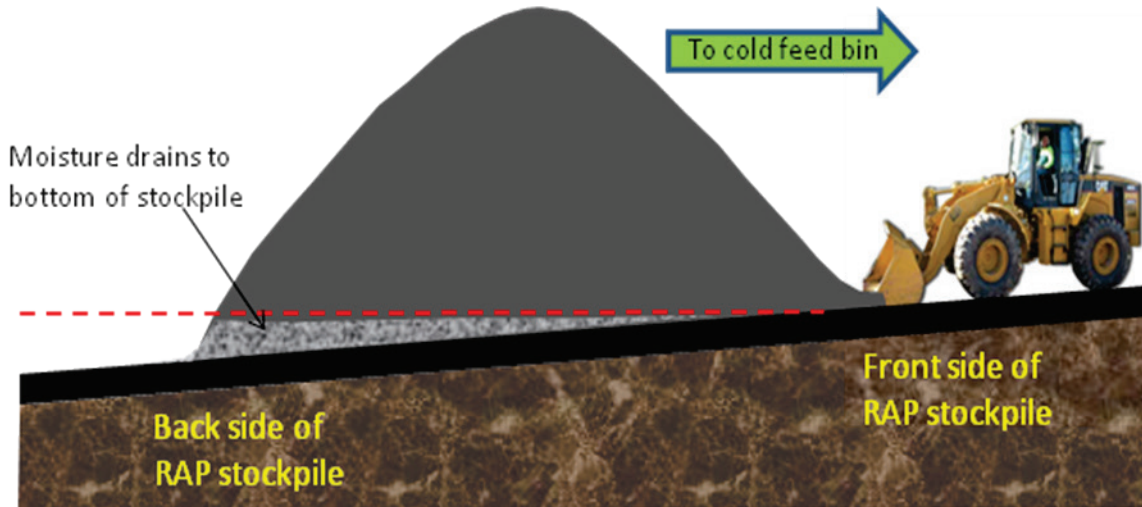


Figure 20. Illustration of Paved, Sloped Surface under RAP Stockpiles.

5.3. Cover RAP Stockpiles if Necessary

Currently, relatively few contractors cover any of their RAP stockpiles, but covering RAP stockpiles to minimize RAP moisture content is even more economical than covering virgin aggregate stockpiles. RAP should never be covered with a tarp or plastic, however. It is best to store RAP materials under the roof of an open-sided building (see [Figure 21](#)). Free air can pass over the RAP, but the RAP is protected from precipitation.

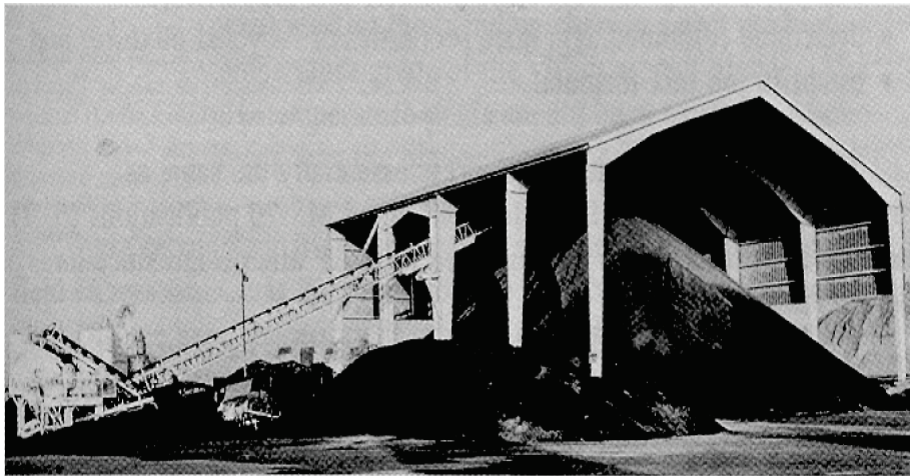


Figure 21. Storing RAP under a Covered Roof (5).

6. Characterize the Processed RAP and Mark Stockpiles

A good practice some contractors have been adopting is to characterize the processed RAP right after the stockpile has been built at its final location, then marking or numbering the stockpile. A minimum of five RAP samples collected from each RAP stockpile should be obtained and tested before making a mix design. Both average values and associated standard deviations of RAP asphalt content and aggregate gradation should be recorded. To produce a consistent RAP mix the associated standard deviations of the RAP asphalt content and aggregate gradation should be carefully observed. With these measured data including both average values and associated standard deviations of RAP asphalt content and aggregate gradation, contractors can evaluate their RAP processing operations, and consider improving them.

RAS PROCESSING AND STOCKPILE MANAGEMENT

RAS processing is one of the critical steps for using the RAS in asphalt mixes and producing high quality RAS mixes. There are two types of RAS: (MWAS) and (TOAS). For use in HMA, MWAS has traditionally been preferred over TOAS, primarily because MWAS contains fewer contaminants (14, 15), plus the asphalt in MWAS is less oxidized (9). MWAS only requires grinding with little or no sorting, inspection, testing, or separation of undesirable materials. Specifically, there is no need for asbestos testing for MWAS. However, MWAS is geographically significantly more restricted than TOAS, as shingle manufacturing facilities are typically located only in densely populated areas. In contrast, TOAS is more readily available to contractors and recyclers. The main concerns with TOAS are potential asbestos, deleterious materials (including metal, wood, plastic, paper, etc.), and very hard, highly oxidized asphalt. Consequently, it becomes more difficult to process the TOAS, and asbestos testing is required in Texas.

Processing RAS basically includes five steps: collecting, sorting, grinding, screening, and storing the processed RAS, plus asbestos testing for the TOAS. The research team visited different recyclers and contractors in Texas and reviewed published literature to identify the best practices for each of these steps. Figure 22 shows the best practices identified; detailed explanations and associated guidelines follow.

Step 1: Collecting



Step 2: Asbestos testing for TOAS



Step 3: Sorting



Step 4: Grinding



Step 5: Screening



Step 6: Storing



Figure 22. Proposed RAS Processing Steps.

1. Collecting

Quality (cleanness) of RAS and a sustainable supply are two major issues related to collecting RAS. MWAS is relatively clean, but its supply is limited. In contrast, TOAS has relatively more supplies, but its cleanness (or contamination) is a bigger problem. According to Krivit (13), the two basic types of strategies to develop a clean, secure supply are:

- *Source Separated*—Attracting high quality, separated loads of clean TOAS. The roofing contractor or hauler must first separate the non-shingle debris (e.g., plastic, metal, wood) before tipping at the shingle recycling plant. Source-separated TOAS should be kept separate from other roofing debris at the demolition site before loading and then be loaded separately onto haul units.
- *Mixed Roofing Material*—Attracting mixed loads of TOAS without requiring source separation, such that the shingle recycler conducts most, if not all, of the materials separation. Non-shingle debris is sorted from the tear-off shingles at a recycling facility. TOAS recyclers might instruct their suppliers to load the shingles first, at the bottom of the haul unit. Then, the non-shingle debris, which they place on top of the shingles layer, can be easily separated when the load is tipped at the recycling plant.

Under either strategy, Krivit (13) continues, TOAS recyclers must work proactively with suppliers to ensure that no asbestos containing material (ACM) is delivered to the recycling plant. After the TOAS is tipped at the recycling plant, a second stage of quality inspection and sorting occurs. Most facilities use both manual separation (e.g., ‘dump and pick’, sorting conveyors) and mechanical equipment (e.g., screens, air classifiers). Shingle recyclers have demonstrated a wide variety of techniques to cost-effectively meet and exceed the minimum waste sampling and asbestos testing requirements. They have recently developed innovations, such as establishing in-house laboratories that use standard detection methods and certified personnel. Such internal laboratories minimize the turnaround time for test results. Together with other in-house personnel training and supplier technical assistance, TOAS recyclers are proactively managing their supplies through upstream quality control and quality assurance.

Hansen (15) points out that as part of the quality control and acceptance program, shingle recycling operations need an inspection and testing plan for waste shingles delivered to the site, which should include:

- Type and quality of material that is acceptable.
- Criteria for rejecting loads.
- An asbestos management plan.

A list of prohibited materials for TOAS recyclers should include (13):

- Cementitious shingles, shake shingles, and transite siding that may contain ACM.
- Any type of hazardous waste (e.g., mercury-containing devices such as thermostats, paint, solvents, or other volatile liquids).
- Significant amounts of other debris that are not asphalt shingles (e.g., plastic, paper, glass, or metal).
- Significant amounts of trash.

2. Asbestos Testing for TOAS

According to Hansen (15), the main issue that impedes recycling of TOAS is concern over potential asbestos content. In the past, asbestos was sometimes used in manufacturing asphalt shingles and other shingle installation materials. Asphalt shingle manufacturers generally acknowledged that, between 1963 and the mid-1970s, some manufacturers did use asbestos in the fiber mat in some of their shingle products, but the total asbestos content of those shingles was always less than 1 percent. Other materials used in shingles, such as some tarpapers and some types of asphalt cement, also reportedly contained asbestos. In reality, while asbestos was heretofore used in some asphalt roofing materials, asbestos was rarely used in the shingles themselves.

Since TOAS may contain asbestos, the Texas Department of State Health Service (TDSHS) regulations of asbestos-containing materials include TOAS. More detailed information on the asbestos program can be found at TDSHS' website: <http://www.dshs.state.tx.us/asbestos/pubs.shtm>. Generally, asbestos testing (Figure 23) involves sampling each layer of roofing material. Representative samples must be properly selected, labeled, recorded in a sample log book, and then sent to an accredited asbestos testing laboratory for assay of asbestos content. TOAS recyclers should contact the appropriate state environmental and/or health agency to determine specific requirements for sample collection, analytical procedures, data reporting, and records preservation.



Figure 23. Setup for Asbestos Testing (13).

Krivit (13) advised that shingle recycling operators should attend state-sponsored training courses to become licensed asbestos inspectors. Trained personnel should inspect each load to visually detect possible ACM. This will help increase the awareness of potential asbestos containing materials and allow company personnel to help provide accurate, timely, and state-approved information and related technical assistance to material suppliers and other customers. Shingle recycling operators should contact their state representative for the National Emission Standards for Hazardous Air Pollutants (NESHAP) to explore technical assistance resources, including a listing of organizations providing asbestos inspector training. The website www.shinglerecycling.org is an excellent source of EPA and other regulatory information regarding asbestos, management, and recommended best practices. Specifically, in Texas TCEQ

has several regulations that may impact asphalt shingle processors, which can be found using the following links:

- Recycling:
http://www.tceq.state.tx.us/permitting/waste_permits/msw_permits/MSW_amIregulatedr/ecycling.html
- Industrial Storm Water:
http://www.tceq.texas.gov/permitting/stormwater/TXR05_AIR.html
- Storm Water from Construction Activities:
http://www.tceq.texas.gov/permitting/stormwater/TXR15_AIR.html

3. Sorting

Generally, little sorting work is needed for MWAS. However, substantial sorting work is required for TOAS because various debris (e.g., nails, wood, and insulation) contaminate this type of shingle. Any debris must be removed to prevent equipment damage during size reduction and produce high-quality processed RAS. There is no standard processing equipment to accomplish this task; in most cases, the debris has to be sorted out manually (see Figure 24).



Figure 24. Sorting RAS Manually.

Note that most facilities will recover metal and cardboard (perhaps in baled form) as secondary recyclable products. Trash from such sorting consists of plastic, non-recyclable metal, and paper. Recovery rates of TOAS from mixed waste sorting systems range from 15 to over 90 percent, depending on the feedstock and the efficiency of the separation (13).

4. Grinding

The vast majority of RAS used in asphalt paving mixes is ground into pieces smaller than ½ inch (13 mm) in size using a shingle grinding or shredding machine consisting of a rotary shredder and/or a high-speed hammer mill. It seems logical that, as shingles are ground finer, more RAS asphalt can be mobilized into the paving mixture.

According to Krivit (13), each grinder manufacturer uses a unique combination of material handling and size reduction designs. RAS sizing is a key specification and will determine the product's suitability for various applications. For example, the larger particle size (+ ¾ in.) may be more suitable for aggregate supplement. In general, the grinder will include a loading hopper; a grinding chamber that includes cutting teeth, sizing screens, and exit conveyor; and a feeding drum to present the shingles into the grinding chamber. A pulley head magnet at the end of the exit conveyor is standard equipment for removing nails and other ferrous metal. The final RAS product is stacked using a stacking conveyor and/or front-end loader. During visits to recyclers and contractors, the research team noted that it is important and necessary to pick up some debris left in the sorted, clean pile before feeding to the grinder (see Figure 25).



Figure 25. Preparation for Grinding.

To prevent agglomerating during grinding, the material may be passed through the grinding equipment only once to reduce heating, or it is kept cool with water spray at the hammer mill. However, the application of water is not very desirable, since the processed material becomes quite wet and must be dried (thus incurring additional fuel cost) prior to introduction into the HMA (10).

5. Screening

Ground shingles may contain oversize pieces that do not meet the specification requirement. To remove the oversize pieces, the operators ideally should screen the processed RAS using a trommel screener (Figure 26). This equipment can help customize the size of processed RAS, thus guaranteeing that the specifications are met. Furthermore, the oversize pieces can be reground to the ideal size. Chesner et al. (10) contends that scrap shingle greater than ½ inch may not readily disperse in HMA and may function much like aggregate particles; too small particles can release short fibers, which act as a filler substitute. Hansen (15) adds that several HMA producers have found that grinding to less than ¾ inch improves blending. TxDOT specifies 100 percent passing the ½-inch sieve with 95 percent passing the ¾-inch sieve.



Figure 26. Screening RAS Using Trommel Screen Machine.

6. Storing

Storing the processed RAS is typically conducted similar to that of aggregate or RAP. Because the average gradation of RAS is very small, a stockpile can absorb a large amount of water, which can cause problems during HMA mixing (inadequate coating), compaction (mat tenderness), and performance (higher stripping potential) as well as require more fuel for drying. Ideally, a RAS stockpile should be covered (Figure 27). Additionally, it is important to keep loaders off RAS stockpiles and separate high AC RAS (tear-offs) from low AC RAS (manufacture waste).

Button et al. (9) deduced that, during static storage in a stockpile, shredded roofing shingle material can agglomerate. High temperatures and the stickier manufacturing waste shingles can magnify this issue. Significant agglomeration or consolidation of processed roofing material necessitates reprocessing and rescreening prior to introduction into the hot mix plant. To mitigate this problem, processed roofing shingle scrap may be blended with a small amount of less sticky carrier material, such as sand or RAP, to prevent the RAS particles from clumping together.



Figure 27. Covered RAS Storing Facility.

RAP/RAS MIX PRODUCTION

Producing RAP/RAS mixes is similar to virgin mixes. Normally RAP/RAS is treated like virgin aggregates with a cold bin and is fed into the plant. However, there are some specific issues that are worth watching when producing RAP/RAS mixes:

- Keep RAP and RAS bins separate.
- Keep the RAP/RAS bin empty when not in use.
- Use a vibratory scalping screen to help break down or remove clumps that may be in the RAS material before entering the drum ([Figure 28](#)).
- Do not superheat the mix; it makes the RAS mix stiffer and more difficult to work with in the field.
- Avoid holding RAS mix in silo overnight.
- Consider the following things when using WMA additives:
 - Plant introduction issues.
 - Anti-strip replacement.
 - Required dosage.
 - Cost.



Figure 28. Vibratory Scalping Screen (19).

RAP/RAS MIX CONSTRUCTION

No special techniques or equipment are required for placing and then compacting RAP/RAS mixes. Therefore, the existing construction specification (Item 341) for regular HMA/WMA is applicable to RAP/RAS mixes. However, failure to properly address RAP/RAS processing as well as inadequate QC of RAP/RAS will significantly increase the likelihood of problems in placement and compaction of RAP/RAS mixes in the field. Again, there are several specific issues to consider during RAP/RAS mix construction:

- Weather conditions.
- Haul distance.
- The trucks that haul the mix.
- Time the mix sets in trucks (do not allow to set too long on job site).
- RAP/RAS mix temperature (check when unloading trucks).
- Time to stiffen (mix tends to stiffen quicker in trucks than standard hot mix).
- Difficulty to hand work (more difficult).
- Mat sensitivity to temperature segregation (can be more sensitive).
- Use of WMA as a compaction aid (consider using when needed).

SUMMARY

This chapter presents the best practices for using RAP/RAS in asphalt mixes (including both HMA and WMA) in terms of processing RAP/RAS, RAP/RAS mix production in the plant, and RAP/RAS mix construction in the field.

CHAPTER 4 REVIEW OF NEW SPECIFICATION, DISTRICT PRACTICES, AND PROPOSED VALIDATION PLAN

TxDOT’s new specification for asphalt mixes became effective in March 2013. This chapter discusses the new specification and compares it with other states’ specification. Also, the research team develops a field experimental test plan to validate the new specification.

TXDOT AND OTHER STATES’ SPECIFICATIONS

Currently most states allow use of RAP in HMA, but not all states allow using RAS. Texas is one of the states allowing both RAP and RAS including tear-offs. It is useful to compare Texas’ specification with other states. For simplicity, only the states allowing both RAP and RAS including tear-offs are listed in [Tables 9–14](#).

Table 9. Texas Specification.

PG Binder Originally Specified ¹	Allowable Substitute PG Binder		Maximum Ratio of Recycled Binder to Total Binder ² (%)		
	HMA	WMA ³	Surface	Intermediate	Base
76-22	70-22 or 64-22	70-22 or 64-22	20.0	20.0	20.0
	70-28 or 64-28	70-22 or 64-22	30.0	35.0	40.0
70-22	64-22	64-22 or 58-28	20.0	20.0	20.0
	64-28 or 58-28	64-22 or 58-28	30.0	35.0	40.0
64-22	58-28	64-22 ⁴ or 58-28	20.0	20.0	20.0
	58-28	64-22 ⁴ or 58-28	30.0	35.0	40.0
76-28	70-28 or 64-28	70-28 or 64-28	20.0	20.0	20.0
	64-34	70-28 or 64-28	30.0	35.0	40.0
70-28	64-28 or 58-28	64-28 or 58-28	20.0	20.0	20.0
	64-34 or 58-34	64-28 or 58-28	30.0	35.0	40.0
64-28	58-28	64-28 ⁴ or 58-28	20.0	20.0	20.0
	58-34	64-28 ⁴ or 58-28	30.0	35.0	40.0

1. Use no more than 20.0% recycled binder when using the PG binder originally specified.
2. Combined recycled binder from RAP and RAS.
3. WMA as defined in Section 3XXX.2.F.2, “Warm Mix Asphalt (WMA)”
4. This originally specified binder is allowed when used in combination with WMA.

Table 10. Alabama Specification (31).

Mix	Maximum Allowable % (Percentage by Weight of Total Aggregates)			
	Combined RAP and RAS	RAP	Tear-off RAS	Manufacture waste RAS
Surface	15	20	3	5
Intermediate	20	25	3	5
Bituminous base	20	25	3	5

Table 11. Georgia Specification (31).

Plant	Maximum Allowable % (Percentage by Weight of Total Mixture)			
	Combined RAP and RAS	RAP	Tear-off RAS	Manufacture waste RAS
Drum plant	0	40	5	5
Batch plant	0	25	5	5

Note: Georgia requires that the combined virgin and recycled binder after RTFO conditioning has an absolute viscosity at 60°C between 600 and 1600 Pa·s.

Table 12. Minnesota Specification (31).

Traffic Level (MESAL)	Maximum Allowable % (Percentage by Weight of Total Mixture)					
	RAP		Tear-off RAS		Manufacture waste RAS	
	Surface	Lower	Surface	Lower	Surface	Lower
<1	30	40	5	5	5	5
1 to <3	30	30	5	5	5	5
3 to <10	30	30	0	5	5	5
10 to <30	30	30	0	0	5	5

Table 13. Missouri Specification (31).

Maximum Allowable % (Percentage by Weight of Total Mixture)	
RAP	RAS
Up to 20% RAP of the mixture without changing the grade of virgin binder	7% RAS in mixtures without changing the grade of the binder provided the binder replacement is less than 30%.
Greater than 20% RAP is permitted provided a blending chart analysis shows the blended binder meets the specified performance grade	

Note: Missouri specification does not address combining RAP and RAS in the same mixture.

Table 14. Virginia Specification (31).

Mix	Max. Allowable Binder Replacement for Mixtures with Both RAP and RAS	Maximum Allowable % (Percentage by Weight of Total Mixture)	
		RAP	RAS
Surface	25	30	5
Intermediate	25	30	5
Bituminous base	25	35	5

Reviewing these specifications, several observations are offered:

- TxDOT’s specification falls within the range of the maximum allowable RAP/RAS usage of other states.
- Specifically, there are two big concerns regarding the new specification, as described below:
 - Although both the use of WMA technology and the softer asphalt binders (XX-28 or XX-34) are listed equally in the specification, do these two approaches have the same effect on improving cracking resistance of RAP/RAS mixes?
 - High recycled asphalt binder content is allowed when using WMA technologies. As noted previously, 13 WMA technologies are available in TxDOT’s approval list. Do all these WMA technologies have the same effect on improving cracking resistance of RAP/RAS mixes?
- Additionally, the new specification does not address the use of rejuvenators for improving cracking resistance. As discussed in [Chapter 2](#), the use of rejuvenators is one of the ways to improve cracking resistance of asphalt mixes containing RAP/RAS.

Therefore, both laboratory tests and field experimental test sections should be conducted to further validate the new specification and address these concerns. Since it is difficult, if not impossible, to duplicate the WMA mix production process in the laboratory, the recommended testing plan will focus on field experimental test sections as discussed in the next section.

RECOMMENDED FIELD EXPERIMENTAL TEST SECTIONS

As discussed in [Chapter 2](#), field performance of RAP/RAS mixes is influenced by many factors including traffic, climate, existing pavement conditions, and asphalt mix properties. When designing the test sections, these critical factors should be considered. After discussion with the project monitoring committee, the research team recommends the following experimental test plan as listed in [Table 15](#) to address the three major concerns on the new specification: WMA technologies, softer binder, and rejuvenators. Note that the climatic factor is considered through building test sections at different environmental zones; the traffic and existing pavement condition factors are addressed through building the sections on different highways.

Table 15. Recommended Field Experimental Test Sections.

District	Purpose	Test Section	
Wichita Falls	Impact of softer binder and Man. Waste vs. Tear-offs.	0	Control as it is (HMA/PG 64-22/20%Recycle binder) Section 1 or 3 will become Section 0
		1	HMA/PG 64-22/20%Recycle binder (Manufacture waste)
		2	HMA/PG 64-28/20%Recycle binder (Manufacture waste)
		3	HMA/PG 64-22/20%Recycle binder (Tear-offs)
		4	HMA/PG 64-28/20%Recycle binder (Tear-offs)
Bryan	Validate the new spec. (WMA vs. softer binder)	0	Control as it is (HMA/PG 64-22/20%Recycle binder)
		1	WMA-Foaming/PG 64-22/>20%Recycled binder
		2	WMA-Chemical/PG 64-22/>20% Recycled binder
		3	HMA/PG 64-28/>20% Recycled binder
Tyler (APAC)	Impact of rejuvenators	0	Control as it is (HMA/PG 64-22/5% Manuf. RAS)
		1	HMA/PG 64-22/5% Manuf. RAS/Rejuv 1
		2	HMA/PG 64-22/5% Manuf. RAS/Rejuv 2
		3	HMA/PG 64-22/5% Manuf. RAS/Rejuv 3
Amarillo	Softer binder at cold weather	0	Control as it is (HMA/PG 64-28/20%Recycled binder)
		1	HMA/PG 64-34/20%Recycled binder
		2	HMA/PG 64-34/30%Recycled binder
		3	WMA-Chemical/PG 64-28/30%Recycled binder
Lufkin (East Texas Asphalt)	Design methods: Dense-grade, Superpave, balanced mix design	0	Control as it is (HMA/PG 64-22/20%Recycled binder-Dense-graded-TGC)
		1	HMA/PG 64-22/20%Recycled binder-Dense-graded-SGC
		2	HMA/PG 64-22/20%Recycled binder-Superpave-SGC
		3	HMA/PG 64-XX/20%Recycled binder-Balanced approach

SUMMARY

This chapter compared TxDOT’s new specification with other states’ specifications. It was found that TxDOT’s specification falls within the range of the maximum allowable RAP/RAS

usage of other states. Three major concerns on the new specification were discussed and a field experimental test plan was developed to validate the new specification and address these concerns.

CHAPTER 5 SUMMARY AND CONCLUSIONS

This report presents a review of using RAP/RAS in asphalt mixes, and it documents the best practices for using RAP/RAS in HMA/WMA mixes, including RAP/RAS processing, mix design, production, and field construction. The new specification for asphalt mixes is reviewed and some concerns on the new specification are discussed, and a series of field experimental test sections are recommended to address these concerns. Based on the data and information assembled and presented in this report, the following conclusions and recommendations are offered:

- Dense-graded RAP/RAS mixes can have similar or better performance than virgin mixes provided that they are properly designed. RAP/RAS mixes often have better rutting resistance, but poor cracking resistance. Under the national pooled fund study TPF-5(213), RAP mixes generally performed better than RAS mixes. So far no data are available for performance of SMA, PFC, and Superpave mixes with RAP/RAS in Texas.
- Cracking performance is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. Therefore, it is extremely difficult, if not impossible, to propose a single cracking requirement for all applications. There is a terrible need to develop a balanced RAP/RAS mix design for project-specific service conditions.
- A balanced RAP/RAS overlay mix design for project-specific service conditions has been developed under previous research projects. This includes a performance evaluation system in which the Hamburg wheel tracking test and associated criteria are used to control rutting/moisture damage and the OT test is used to control reflection cracking. This balanced mix design system should be used for designing the RAP/RAS mixes.
- At least five approaches have been tried to improve cracking resistance of RAP/RAS mixes. TxDOT has implemented the first four approaches in the new specification. However, the true effect of each approach, including the rejuvenators, needs to be further investigated through field experimental test sections.
- Reviewing TxDOT's new specification and other states' specifications, it was found that TxDOT's specification falls within the range of the maximum allowable RAP/RAS usage of other states. However, three concerns with the new specification were identified: WMA technologies, softer asphalt binders, and rejuvenators. A total of 21 field experimental test sections are recommended to address these concerns.

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