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16. Abstract

In the last several years, recycled asphalt shingles (RAS), in addition to reclaimed asphalt pavement (RAP), have been widely used in Texas. The use of RAS can significantly reduce the cost of asphalt mixtures, conserve energy, and protect the environment. However, one of the major concerns is poor cracking resistance of RAS mixes due to super stiff asphalt binder in the RAS. This research focused on field performance of RAS test sections and the benefit of using rejuvenators in improving cracking resistance of RAS(/RAP) mixes. In addition, a simple cost analysis was performed to investigate the cost-benefits of using rejuvenators. It was found that both increasing design density (leading to higher virgin binder content) and using soft virgin binders (e.g. PGXX-28) can improve cracking resistance. With respect to improving cracking resistance of RAS mixes, the three rejuvenators evaluated in this research are all effective. Furthermore, the incorporation of rejuvenators also improved the moisture susceptibility and rutting resistance of the mixtures containing recycled materials. Apparently, additional tests and analyses are necessary. Specifically, field test sections with different types of rejuvenators should be constructed for further evaluation.

Additionally, the observed field performance indicated that cracking performance is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. It is extremely difficult to propose a single cracking requirement for all applications. There is a need to develop a RAP/RAS mix design and performance evaluation system for project-specific service conditions, including traffic, climate, existing pavement conditions, etc.

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FIELD PERFORMANCE OF RAS TEST SECTIONS AND LABORATORY INVESTIGATION OF IMPACT OF REJUVENATORS ON ENGINEERING PROPERTIES OF RAP/RAS MIXES

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CHAPTER 1
INTRODUCTION

In the last several years, recycled asphalt shingles (RAS), in addition to reclaimed asphalt pavement (RAP), have been widely used in asphalt mixtures. The use of RAS can significantly reduce the cost of asphalt mixtures, conserve energy, and protect the environment. There are two types of RAS in the market: manufacture waste and tear-off, although most of them are from tear-off roof shingles. It is well known that the tear-off roof shingles vary a lot in quality, and some of them may sit on a roof only a few years while others may stay there for more than 30 years. Additionally, the asphalt binders in the RAS, compared with regular asphalt paving binders, are much stiffer. The mixes containing RAS are prone to cracking. Therefore, when dealing with the use of RAS in asphalt mixes, there are often two major concerns. One concern is variability of processed RAS and the other one is durability (or premature cracking) of asphalt mixes containing RAS. These two major concerns must be addressed to best use RAS in asphalt mixes.

The overall objectives of this research project were to address these two concerns. The first concern was addressed through developing best practices for RAS processing, stockpile management, and characterizing RAS. All the best practices developed were documented in Year 1 Report 0-6614-1 entitled "Best Practice for Using RAS in HMA." Year 2 report entitled "Characterization and Best Use of Recycled Asphalt Shingles in Hot-Mix Asphalt" discussed the approaches for improving durability of RAS mixes and the construction of field test sections to validate laboratory test results. In the last year of this project, the research team focused on monitoring the field performance of test sections and exploring a new approach for improving cracking resistance of RAS mixes. This report contains the results from the last year of this project.

This report is composed of four chapters. Following this introduction (Chapter 1), Chapter 2 presents the field performance of the test sections constructed under this project. The laboratory investigation of impact of rejuvenators on engineering properties of RAS mixes is documented in Chapter 3. Finally, Chapter 4 provides a summary of findings and conclusions of this project.

Additionally, several other documents listed below are presented in the Appendices.

- Appendix A: RAS Characterization and Binder Blending Characteristics.
- Appendix B: Balanced Mix Design Method for Dense-Graded and SMA Mixes containing RAS/RAP.
- Appendix C: Guidelines and Approaches for Improving Cracking Resistance of RAS Mixes.
- Appendix D: Environmental Benefits and Cost Impacts of RAS on Asphalt Mixtures.

CHAPTER 2
FIELD PERFORMANCE OF RAS TEST SECTIONS INCLUDING FM 973

INTRODUCTION

A series of field test sections with RAS have been constructed around Texas in the last 3 years, as listed in Table 1. When selecting the test sections, the research team paid specific attention to service conditions of each RAS mix, which include pavement structure, traffic, climate, existing pavement conditions for asphalt overlays, and mix engineering properties. It is obvious that the same mix could perform completely differently when placed under two different service conditions: cold and heavy traffic loading vs. warm and light traffic loading. Specifically, this study addresses the following factors which significantly influence performance of RAS mixes:

- Asphalt overlays vs. new construction pavements.
- Cold weather vs. hot weather.
- Heavy traffic vs. low traffic.
- Thicker vs. thin asphalt layer(s).
- Virgin mix vs. RAS only or RAP/RAS.

This chapter documents each of these field RAP/RAS test sections and associated field performance in different climatic zones.

Table 1. Field RAP/RAS Test Sections.

Test Section				District	Traffic (mESAL/ 20 Years)	Overlay/new construction	Existing condition if overlay
Highway	**RAP/RAS**	**Virgin binder**	**HMA/ WMA**				
SH146	15%RAP/ 5%RAS	PG64-22	HMA	Houston	1.5	New construction, 2-inch surface layer	N/A
Loop820	15%RAP/5%RAS (manufacture waste shingles)	PG64-22	WMA	Fort Worth	15	2-inch overlay	Existing continuously reinforced concrete pavement has some fine transverse cracks.
		PG64-22	WMA (additive pre-blending with RAS)				
		PG64-28	WMA				
		PG64-22 (with 0.4% more virgin binder)	WMA				
FM973	0%RAP	PG70-22	HMA	Austin	3.0	2-inch overlay	A variety of cracking (longitudinal, transverse, fatigue cracking)
	30%RAP	PG64-22					
	15%RAP/ 3%RAS						
	5%RAS						
	30%RAP	PG58-28					
	15%RAP/ 3%RAS						
	0%RAP	PG70-22	WMA Foaming				
	0%RAP	PG70-22	WMA Evotherm				
	15%RAP/ 3%RAS	PG64-22					

RAP/RAS TEST SECTION ON SH 146 AND OBSERVED FIELD PERFORMANCE

A field test section was constructed on SH 146 in Houston area where the winter weather is mild. Again, the test section on SH 146 was a new construction pavement with a total asphalt layer of 5 inches. A dense-graded Type C mix with 15 percent RAP/5 percent RAS was used in the top 2 -inch (50 mm) surface layer. The mix designed by the contractor had excellent rutting/moisture damage resistance with a Hamburg rut depth of 2.1 mm after 20,000 passes. Meanwhile, its cracking resistance was very poor with Overlay Test (OT) cycles of 3. The main features of this section were 1) new construction pavement, 2) both RAP and RAS in the mix, 3) excellent rutting/moisture damage resistance but poor cracking resistance of the RAP/RAS mix, 4) surface layer sitting on a good foundation, and 5) hot summer and mild winter conditions.

Since the completion of construction on Oct. 8, 2010, this test section has been monitored five times on April 8, 2011; December 16, 2011; May 18, 2012; December 14, 2012; and May 10, 2013. The test section was in perfect condition: no rutting and cracking, as shown in Figure 1.

Figure 1. Good Condition of the RAP/RAS Test Section on SH 146, Houston.

RAS TEST SECTION ON U S87 AND OBSERVED FIELD PERFORMANCE

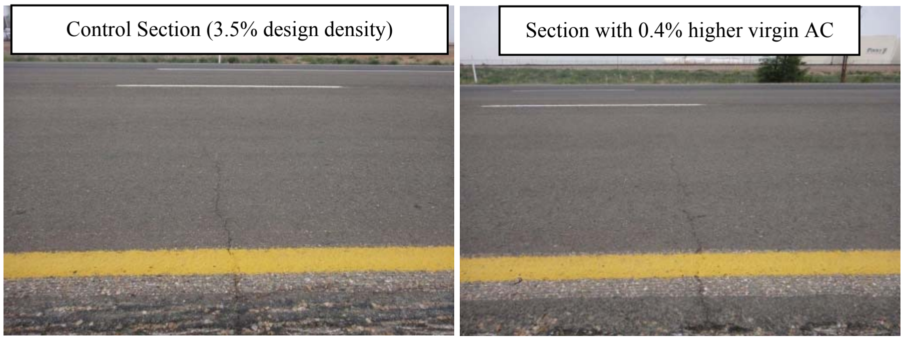
Two 3-inch thick asphalt overlay test pavements were constructed end to end in the same lane and travelling direction on US 87 in Dalhart (Amarillo District) of Texas in late October 2010. The original objective of these two test pavements was to validate the effectiveness of decreasing the lab design air voids (effectively increasing asphalt content) on improving cracking resistance of RAS mixes. The RAS mixes used on the two test pavements are exactly the same (aggregates, gradation, virgin binder, and RAS) except for the optimum asphalt content (OAC); OAC for the control section was 4.6 percent while the other was 5.0 percent. Table 2 shows the mix design information. Dalhart has even colder winters than Amarillo. US 87 in Dalhart has medium traffic with around 5 million Equivalent Single Axle Load (ESAL) in 20 years. The existing asphalt pavement exhibited severe transverse cracking. Cold weather and severe existing pavement cracking plus high traffic make these two pavements a good case study to rapidly validate the effectiveness of decreasing design air voids on improving cracking resistance of RAS mixes.

After completion of construction of these two RAS test pavements, five field surveys were conducted on April 5, 2011; December 15, 2011; May 30, 2012; December 19, 2012; and May 14, 2013. So far, no rutting has been observed, but reflective cracking occurred in both test sections. Figure 2 shows the observed reflective cracking and its development history. Again, prior to placing the overlay, the researchers documented and mapped the number of pre-existing cracks in each pavement. The reflective cracking rate is therefore defined as the ratio of the number of observed reflective cracks to the original number of cracks before the 3-inch overlay.

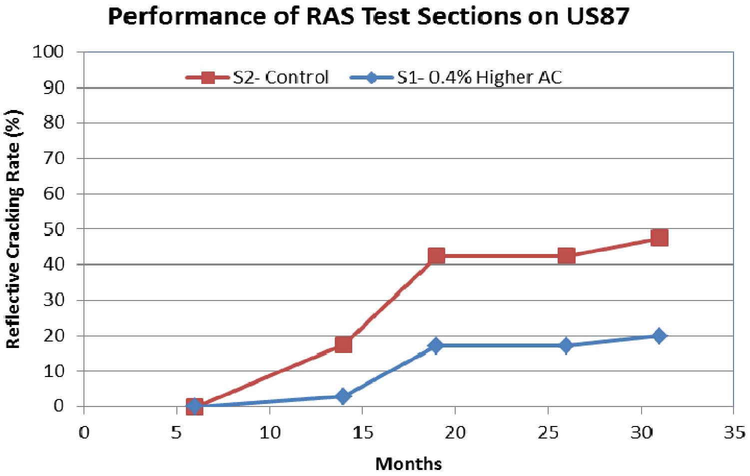
Compared to the RAP/RAS mixes paved on SH 146, the mixes on US 87 had much better cracking resistance. However, due to cold weather in Dalhart, US 87 performed worse than SH146 in terms of cracking performance.

Table 2. Mix Design Information of the Two RAS Test Sections on US 87.

Section	RAS (%)	Virgin binder	Designer	OAC (%)	HWTT rut depth@ 15,000 passes	OT cycles of plant mixes
1	5	PG64-28	Contractor	5.0 corresponding to 2.7% design air void	12.0 mm	96
2	5	PG64-28	Contractor	4.6 corresponding to 3.5% design air void	8.7 mm	48



(a) Observed Reflective Cracking



(b) Reflective Cracking Development

Figure 2 Observed Reflective Cracking and Its Development History of the RAS Test Sections on US 87.

FIELD TEST SECTIONS ON FM973 AND OBSERVED PERFORMANCE

A comprehensive series of experimental asphalt overlay test sections were constructed on FM973 near the Austin Bergstrom International Airport. Compared to the cold weather in

Amarillo, the weather in the Austin area is warm. Different from US 87, this roadway experiences very heavy truck traffic as it carries traffic from several aggregate quarries and concrete batch plants. A total of nine test sections were built between December 2011 and January 2012. One of the objectives of the test sections on FM 973 was to evaluate the effectiveness of using soft binder on improving cracking resistance of RAP/RAS mixes. Table 3 lists all the mixes used in field test sections and associated laboratory test results. The main features of these nine sections are:

- HMA vs. RAP/RAS mixes.
- HMA vs. WMA.
- WMA: Foaming vs. Evotherm additive.
- PG 64-22 vs. PG 58-28.

These test sections provided an opportunity for comparing performance of HMA mixes with WMA mixes side by side. Prior to the 2-inch (50 mm) asphalt overlay, the overall pavement condition was not bad, but some areas had severe longitudinal cracking and fatigue cracking along the wheel passes. The overall deflection measured using falling weight deflectometer was around 11 mils (0.28 mm).

Since the completion of construction, these nine test sections have been trafficked for 18 months. Three surveys were performed in March 2012, July 2012, and April 2013. None of the distress was observed in the first two surveys. However, lots of cracks were observed in April 2013, as shown in Figure 3. Table 3 lists the calculated reflective cracking rate for each test section. Note that prior to placing the overlay, the number of pre-existing cracks in each section was documented and mapped. The reflective cracking rate is therefore defined as the ratio of the number of reflective cracks to the original number of cracks before the 2-inch (100 mm) overlay. Figure 4 shows the relationship between OT cycles and reflective cracking rate. It can be seen that a threshold of OT cycles may exist for FM 973. Below it, reflective cracking may occur quickly. Certainly the OT threshold value varies with weather, traffic, pavement structure, material properties, and other factors.

Table 3. Nine Test Sections on FM 973, Austin.

Section No.	Type	Virgin Binder	RAP	RAS	Hamburg Rut Depth@10,000 passes (mm)	OT Cycles	Reflective Cracking Rate (%)
1	HMA	70-22	0	0	5.81	41	0
2	HMA	64-22	30	0	7.11	7	8
3	HMA	64-22	15	3	8.57	6	75
4	HMA	64-22	0	5	4.22	7	100
5	HMA	58-28	30	0	13.09	38	6
6	HMA	58-28	15	3	5.20	20	1
7	WMA	70-22	0	0	12.38	46	25
8	WMA	70-22	0	0	9.02	68	8
9	WMA	64-22	15	3	7.78	30	3

Figure 3. Observed Cracks on Sections 5 and 6.

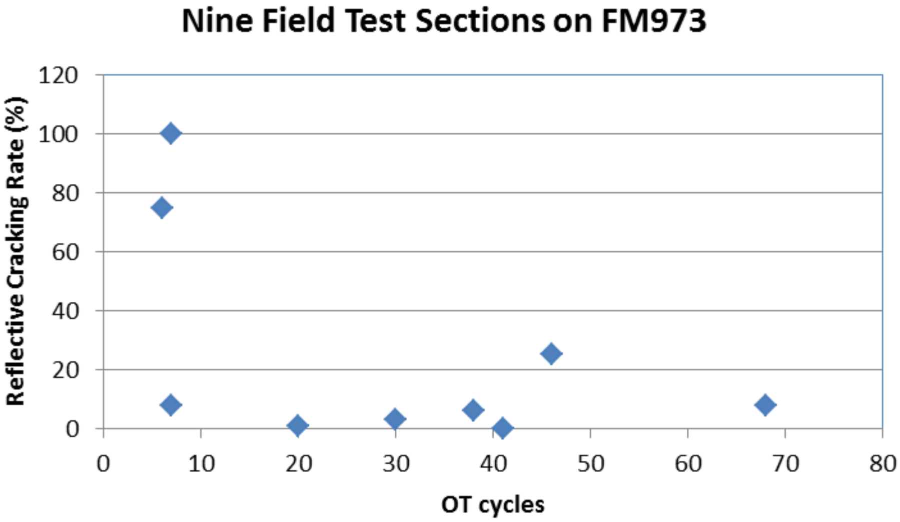


Figure 4. OT Cycles vs. Reflective Cracking Rate.

RAP/RAS FIELD TEST SECTIONS ON LOOP 820, FORT WORTH

Most recently, four field test sections were constructed on Loop 820 in Fort Worth side by side. Table 4 presents detailed information on these four test sections. The main features of these four test sections are: 1) RAP/RAS/WMA with Advera additive, 2) soft virgin binder without changing the OAC, 3) extra virgin binder without changing virgin binder grade, and 4) pre-blending WMA additive with processed RAS. Additionally, these four test sections have a 2-inch asphalt overlay over cracked continuously reinforced concrete pavement (CRCP), as shown in Figure 5. These test sections provided opportunity to check the impact of soft binder and extra virgin binder on rutting and cracking performance of RAP/RAS mixes.

The test sections were built on July 19, 2012. These four test sections are in good conditions and no distress has been observed yet. These sections need to be continuously monitored.

Table 4. Four Field Test Section on Loop 820.

Test section	Virgin binder	OAC (%)	WMA additive: Advera	HWTT rut depth@ 10,000 passes	OT cycles of plant mixes
Section 0	PG 64-22	5.1	Advera as external additive	7.2mm	8
Section 1	PG 64-22	5.1	Advera pre-blended with processed RAS	10.6mm	12
Section 2	PG 64-28	5.1	Advera as external additive	8.2mm	22
Section 3	PG 64-22	5.5	Advera as external additive	16.5mm	24

(a) Fine Cracks on CRCP (b) Good Condition after 1 Year Service

Figure 5. RAP/RAS Test Sections on Loop 820, Fort Worth.

SUMMARY AND DISCUSSION

Table 5 summarizes the field test sections and the observed performance. Reviewing the data in Table 5, one may wonder: Does OT have any relationship with field performance? RAP/RAS mixes with low OT cycles performed well on SH 146. However, those RAS mixes on US 87 showed reflective cracking very early, 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 presented in Table 5, several important observations can be made:

- Increasing design density (leading to higher virgin binder content) can improve cracking resistance.
- 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 need to develop a RAP/RAS mix design and performance evaluation system for project-specific service conditions, including traffic, climate, existing pavement conditions, etc.

Performance data of high RAP test sections on the NCAT 2006 further supported the observations. Seven RAP sections were built in 2006, as reported by Kvasnak at the RAP ETG meeting in October 2008 (*Kvasnak, 2008*). 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.
7) 45 percent RAP with PG 76-22 virgin binder + Sasobit.

After two years and 10 million ESALs of traffic, only the section with 45 percent RAP mix with PG 76-22 + Sasobit had cracks, and all other six sections had 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 layers. The RAS test sections under this study and those at NCAT 2006 test track clearly indicate the importance of developing RAP/RAS mix design and performance evaluation system for project-specific service conditions.

Table 5. Field RAP/RAS Experimental 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						
SH146	15%RAP/ 5% Tear off RAS	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% Tear-off RAS	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
FM973	0%RAP	PG 70-22	HMA	Hot summer and mild winter	3.0	2-inch overlay	A variety of cracking	41	0% reflective cracking after 18 months
	30%RAP	PG64-22						7	8% reflective cracking after 18 months
	15%RAP/ 3%RAS							6	75% reflective cracking after 18 months
	5%RAS							7	100% reflective cracking after 18 months
	30%RAP	PG 58-28						38	6% reflective cracking after 18 months
	15%RAP/ 3%RAS							20	1% reflective cracking after 18 months
	0%RAP	PG 70-22	WMA Foaming					46	25% reflective cracking after 18 months
	0%RAP	PG 70-22	WMA Evotherm					68	8% reflective cracking after 18 months
	15%RAP/ 3%RAS	PG 64-22						30	3% reflective cracking after 18 months
Loop820	15%RAP/5% RAS (manufact-ure waste shingles)	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(additive pre-blending with RAS)					12	
		PG 64-28	WMA					22	
		PG 64-22 (with 0.4% more virgin binder)	WMA					24	

CHAPTER 3
IMPACT OF REJUVENATORS ON RAP/RAS MIX PROPERTIES

Asphalt binder in RAS is extremely stiff, and asphalt mixes containing RAS often have good rutting resistance but poor cracking resistance. Some approaches need to be taken to balance the performance of RAS mixes. In general, there are at least four approaches:

- Reducing RAS usage (i.e., from 5 percent to 3 percent).
- 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}.
- Rejuvenating RAS binder in the mix design process.

The first three approaches have been discussed in the Year 2 report (Zhou et al. 2013), and their effectiveness in improving cracking performance of RAS mixes is documented in Chapter 2. This chapter presents the last approach: Rejuvenating asphalt binder in RAS.

BACKGROUND

Many recent studies on use of recycled materials in HMA can be found in the literature. Zhou et al. (2012) reported the best practices for the use of RAS in HMA in terms of RAS processing, characterizing the processed RAS, RAS mix design, production, and field construction. They found that tear-off shingles had higher binder content than manufacture waste shingles. Also, the tear-off shingles had various binder contents (23–28 percent), while that of manufacture waste shingles was a consistent 20 percent binder content. Williams et al. (2011) evaluated the engineering and performance properties of mixtures that contained various percentages of RAP and 5 percent RAS. Their test results indicated that mixtures containing 5 percent RAS and up to 35 percent RAP with the virgin PG 58-22 may exhibit sufficient crack resistance, while mixtures containing more than 40 percent total recycled materials will be more prone to cracking. A similar study conducted by Nash et al. (2011) evaluated the performance of high RAP asphalt mixtures in Florida. They found no significant difference between 0 percent and 30 percent RAP mixtures but a decreased performance trend when RAP was used more than 30 percent.

The literature shows that many researchers have made tremendous efforts to use high content recycled materials in HMA mixtures. However, one reason for state transportation agencies' reluctance to use more RAP and RAS is the concern that the resultant mixtures will be too stiff and consequently less workable and difficult to compact in the field, which may ultimately lead to premature field failure (Mogawer et al., 2012). In attempt to reduce the stiffness of RAP and/or RAS mixtures, a softer binder or rejuvenator can be used. Recently, rejuvenating agents have been receiving attention from the pavement research community because rejuvenators can improve the engineering properties of asphalt mixtures containing high content recycled materials. Generally, a rejuvenator is a kind of asphalt additive to soften the stiffness of the oxidized asphalt mixtures. Rejuvenators typically contain a high proportion of maltenes constituents that help re-balance the composition of the aged binder that lost its maltenes during construction and service (Terrel and Epps, 1989). According to Carpenter and Wolosick (1980), the working mechanism (or diffusion process) of a rejuvenator consists of the following four steps:

1. The rejuvenator forms a very low viscosity layer that surrounds the asphalt-coated aggregate which is highly aged binder layer.
2. The rejuvenator begins to penetrate into the aged binder layer, decreasing the amount of raw rejuvenator that coats the particles and softening the aged binder.
3. No raw rejuvenator remains, and the penetration continues, decreasing the viscosity of the inner layer and gradually increasing the viscosity of the outer layer.
4. After a certain time, equilibrium is approached over the majority of the recycled binder film.

Recent studies evaluating the effect of rejuvenators on engineering and performance properties of mixtures and/or binders can be found in the literature (Elseifi et al., 2011; Zaumanis et al., 2013; Hajj et al., 2013; Hill et al., 2013). Shen et al. (2007) investigated the effects of a rejuvenator on properties of rejuvenated asphalt binders and mixtures by adding varying dosages. They found that the rejuvenator percentage significantly affected the properties of both rejuvenated aged binders and the mixtures. The authors also noted that the optimum percentages of the rejuvenator could be obtained by satisfying SHRP specifications through the blending charts. A similar study conducted by Booshehrian et al. (2013) reported that rejuvenators mitigated the stiffness of the resultant binder and improved the cracking resistance of the mixtures.

RESEARCH OBJECTIVE

The primary objective of this research is to investigate the impact of various rejuvenators on engineering properties of asphalt mixtures containing high content recycled materials.

RESEARCH METHODOLOGY

Figure 6 describes the research methodology employed in this chapter. A variety of laboratory tests were performed to investigate the performance of asphalt mixtures, including the Hamburg test, overlay test, dynamic modulus test, and repeated load test. Three different control mixtures with contents of RAS, RAP/RAS, and RAP were produced to compare the mixture performance and engineering properties to those of rejuvenated mixtures. Table 6 presents each laboratory test conducted in this study, listing its standard method and purpose.

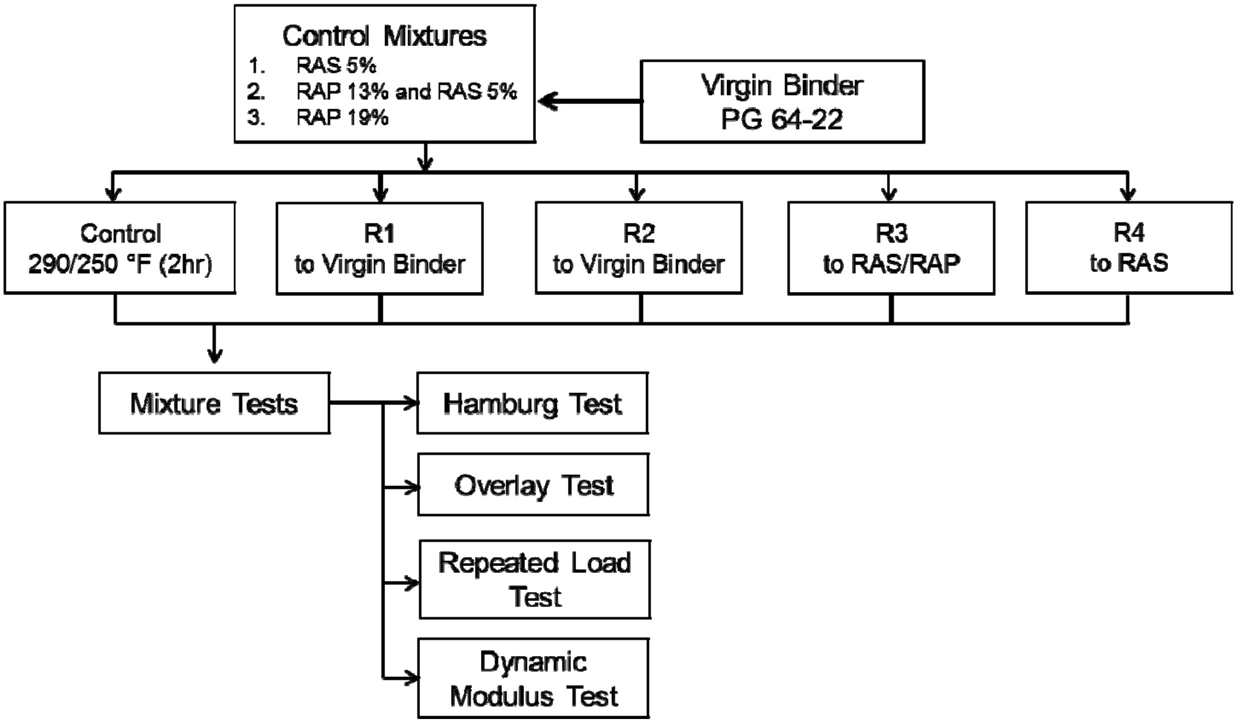


Figure 6. Research Methodology.

Table 6. Laboratory Tests Performed in This Research.

Test	Standard	Purpose
Mixture Design	AASHTO T312	Volumetric Characteristics
Hamburg Test	TEX-242-F	Rutting with Moisture Damage
Overlay Test	TEX-248-F	Fatigue and Reflective Cracking
Dynamic Modulus	AASHTO TP79-11	Viscoelastic Stiffness
Repeated Load	AASHTO TP79-11	Rutting

MATERIALS SELECTION

In this chapter, local aggregates used at three different field projects were collected to produce asphalt mixtures in the laboratory. The field projects are FM 973, Loop 820, and APT 119, respectively. Tables 7, 8, and 9 illustrate gradation of the aggregates and asphalt contents used in the mix design for each field project. As shown in the tables, each project used different contents of RAP and/or RAS, i.e., 5 percent RAS only, 13 percent RAP and 5 percent RAS, and 19 percent RAP only, respectively. Note that these three mixes were designed following TxDOT's standard mix design procedure Tex-204-F.

Table 7. Gradation of Aggregates and Asphalt Contents Used in FM 973 Project.

Combination of Materials		**Sieve Analysis**						
Aggregate Sources	**%**	**3/4"**	**3/8"**	**#4**	**#8**	**#30**	**#50**	**#200**
Limestone (Type C)	26	100	56.4	10.9	4.7	3.3	2.6	2.2
Limestone (Type D)	19	100	70.7	14.3	6.3	3.7	3.3	2.7
Limestone (Type F)	21	100	100	76.4	20.6	6.2	4.8	3.9
Manufactured Sand	22	100	100	99.9	89.8	40.3	24.2	7.6
Field Sand	7.8	100	100	99.8	98.1	90.5	66.9	3.7
RAS	**5**	100	100	99.7	98.9	62.8	53.7	23.4
Combined Gradation	100	100	83.1	55.5	38.3	21.4	15.1	4.8
Asphalt Binder		**Total asphalt content (%)**						
PG 64-22		5.2						

Table 8. Gradation of Aggregates and Asphalt Contents Used in Loop 820 Project.

Combination of Materials		**Sieve Analysis**						
Aggregate Sources	**%**	**1/2"**	**3/8"**	**#4**	**#8**	**#30**	**#50**	**#200**
Limestone (Type D)	51	100	96.7	39.1	8.6	3.5	3.0	2.6
Screenings	25	100	100	99.0	78.5	27.5	16.0	4.3
Sand	6.7	100	100	100	99.7	99.3	85.3	8.7
RAP	**13**	100	98.7	69.3	41.0	27.2	20.9	7.0
RAS	**5**	100	100	100	100	67.5	51.1	14.5
Combined Gradation	100	100	98.1	64.7	40.3	21.8	16.2	4.5
Asphalt Binder		**Total asphalt content (%)**						
PG 64-22		5.1						

Table 9. Gradation of Aggregates and Asphalt Contents Used in APT 119 Project.

Combination of Materials		**Sieve Analysis**						
Aggregate Sources	**%**	**1/2"**	**3/8"**	**#4**	**#8**	**#30**	**#50**	**#200**
Limestone (Type D)	46	100	99.2	40.1	10.1	6.2	3.1	1.5
Manufactured Sand	29	100	100	99.3	83.6	39.1	19.9	3.0
Field Sand	6	100	100	100	99.0	96.0	73.0	3.0
RAP	**19**	100	96.5	66.3	43.8	27.7	22.8	7.0
Combined Gradation	100	100	99.0	65.8	43.2	25.2	15.9	3.1
Asphalt Binder		**Total asphalt content (%)**						
PG 64-22		4.8						

Four different rejuvenators were chosen in this study. A dosage recommended by the manufacturers of the rejuvenators was added to the virgin asphalt binder or to directly recycled materials (RAP and/or RAS). Table 10 summarizes the information on the rejuvenators used in this chapter.

Table 10. Summary of Information on Rejuvenators Used.

Rejuvenators	**Description**
R1	➢ Added 0.6% of total asphalt binder by weight ➢ Used for both HMA and WMA mixture production
R2	➢ Added 1.5% of total asphalt binder by weight for HMA mixture production ➢ Added 1.2% of total asphalt binder by weight for WMA mixture production along with an Evotherm of 0.3%
R3	➢ Added 2% heated agent at 150°F by dry weight of the material to RAS/RAP material ➢ Used for HMA mixture production
R4	➢ Added 1% heated agent at 180°F by dry weight of the material to RAS material ➢ Used for HMA mixture production

LABORATORY TESTS

As mentioned earlier, the researchers performed various laboratory tests in this study. A total of 176 specimens were prepared to complete multiple tests for the whole study. Table 11 shows the matrix for the whole laboratory tests performed in this study. No rejuvenator is added to the control mixtures. This study also attempted to further investigate the impact of rejuvenators on properties of warm mix asphalt (WMA) mixtures containing RAS as well as the impact of curing time and temperature. Due to limited time, the WMA mixtures were prepared and tested only for FM 973 materials as shown in Table 11. Following TxDOT's specification, HMA mixtures were mixed at 290°F, cured for 2 hours at 250°F, and then compacted at 250°F. Following the recommendation from the manufacturer, WMA mixtures were mixed at 260°F and cured either for 2 hours at 250°F or 4 hours at 275°F as described in Table 11.

Table 11. Testing Matrix for Each Mix.

Mix	Tests	Control Mix (*HMA)	R1			R2		R3 (*HMA)	R3 (*HMA)
			*HMA	WMA		*HMA	**WMA + (E)		
				Case-I	Case-II				
FM973	Hamburg	2	2	2	2	2	2	2	2
	Overlay	5	5	5	5	5	5	5	5
	Dynamic Modulus	2	2	2	2	2	2	2	2
	Repeated Load	2	2	2	2	2	2	2	2
Loop820	Hamburg	2	2	-	-	2	-	2	-
	Overlay	5	5	-	-	5	-	5	-
	Dynamic Modulus	2	2	-	-	2	-	2	-
	Repeated Load	2	2	-	-	2	-	2	-
APT119	Hamburg	2	2	-	-	2	-	2	-
	Overlay	5	5	-	-	5	-	5	-
	Dynamic Modulus	2	2	-	-	2	-	2	-
	Repeated Load	2	2	-	-	2	-	2	-

*HMA: Mix/Cure/Compact 290/250/250°F (2 hours)
WMA:
Case-I: Mix/Cure/Compact 260/250/250°F (2 hours)
Case-II: Mix/Cure/Compact 260/275/275°F (4 hours)
E: Evotherm

Hamburg Test

Hamburg testing was conducted at a temperature of 122°F (50°C) in accordance with TEX-242-F, *Test Procedure for Hamburg Wheel-Tracking Test (HWTT)*. A Superpave gyratory compactor was used to produce cylindrical specimens with a diameter of 6 inches (150 mm) and a height of

2.4 inches (62 mm). A masonry saw was used to cut along the edge of the cylindrical specimens. The target air void of specimens was 7 percent ± 1 percent. To evaluate the rutting susceptibility and moisture resistance, the researchers submerged the specimens under water at a temperature of 122°F (50°C) during the test, and a linear variable differential transducer (LVDT) device measured deformations. The stop criterion was rut depth of 0.5 inches (12.5mm) or 20,000 passes.

Table 12 summarizes the rut depth of each test, and Figure 7 shows images of specimens after testing. The following observations are made from Table 12 and Figure 7:

- **FM 973 WMA Mixtures**: The HWTT result of the WMA-R1 (case-I) mixture was similar to the FM 973 control mixture. However, increasing the oven curing temperature from 250°F to 275°F and increasing the oven curing time from two hours to four hours (WMA-R1 case-II mixture) resulted in significant decrease in the HWTT rut depth. On the other hand, the WMA-R2 dramatically improved HWTT results compared to the FM 973 control mixture.
- **FM 973 HMA Mixtures**: R2 and R3 rejuvenating agents resulted in significant decrease in rut depth results, while the HMA-R1 mixture and the HMA-R4 mixture exhibited similar HWTT results compared to the FM 973 control mixture.
- **Loop 820 HMA Mixtures**: There were no significant effects observed from these mixtures: No rejuvenated mixtures were better than the Loop 820 control mixture.
- **APT 119 HMA Mixtures**: R1 and R2 rejuvenating agents improved HWTT results for APT 119 mixtures but not significantly.

Based on the limited test results, the incorporation of rejuvenators with RAP and/or RAS improved the rutting resistance and moisture susceptibility of HMA and WMA mixtures although a clear trend from all test cases was not observed.

Table 12. Hamburg Testing Results (units: mm).

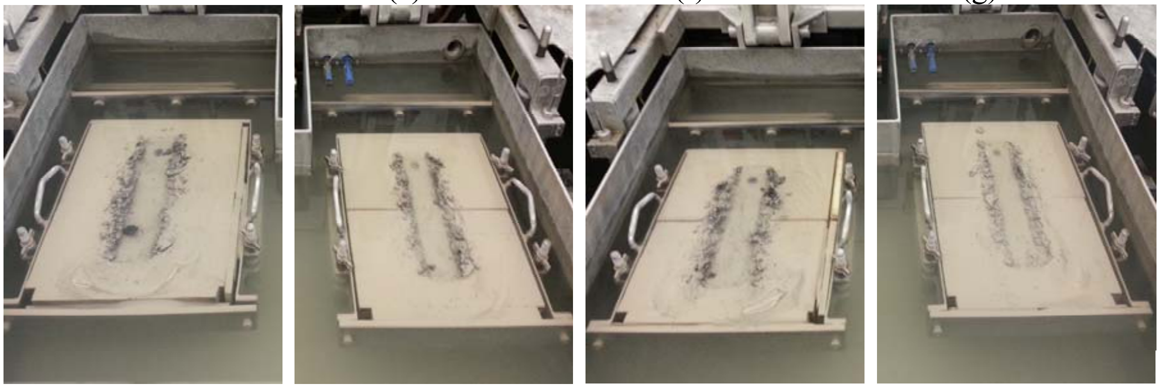
Mix	Pass #	Control Mix (*HMA)	R1			R2		R3 (*HMA)	R4 (*HMA)
			*HMA	WMA		*HMA	**WMA + (E)		
				Case-I	Case-II				
FM973	5,000	3.40	5.08	3.63	2.68	2.59	2.85	3.48	3.15
	10,000	6.23	9.73	7.00	3.41	3.14	3.55	4.29	8.86
	15,000	12.33	12.82 *(11,700)	12.77 *(12,850)	5.21	3.56	4.34	5.42	12.64 *(13,750)
	20,000	N/A	N/A	N/A	7.63	4.02	5.40	9.88	N/A
Loop820	5,000	1.97	5.12	-	-	3.81	-	3.07	-
	10,000	11.22	12.65 *(8,000)	-	-	12.71 *(9,150)	-	11.91	-
	15,000	12.60 *(10,950)	N/A	-	-	N/A	-	12.61 *(10,350)	-
	20,000	N/A	N/A	-	-	N/A	-	N/A	-
APT119	5,000	12.55 *(4,800)	9.54	-	-	6.05	-	12.54 *(3,800)	-
	10,000	N/A	12.71 *(5,700)	-	-	13.00 *(8,550)	-	N/A	-
	15,000	N/A	N/A	-	-	N/A	-	N/A	-
	20,000	N/A	N/A	-	-	N/A	-	N/A	-

*Parentheses indicates the actual failure passes

(a) FM 973 Control (b) R1 (c) R2 (d) R3

FM 973
WMA
Mixtures

(e) R1 (f) R2 (g) R3



(h)Loop820 Control (i) R1 (j) R2 (k) R3

Image not available

(l)APT119 Control (m) R1 (n) R2 (o) R3

Figure 7. Pictures of Each Mix after HWTT.

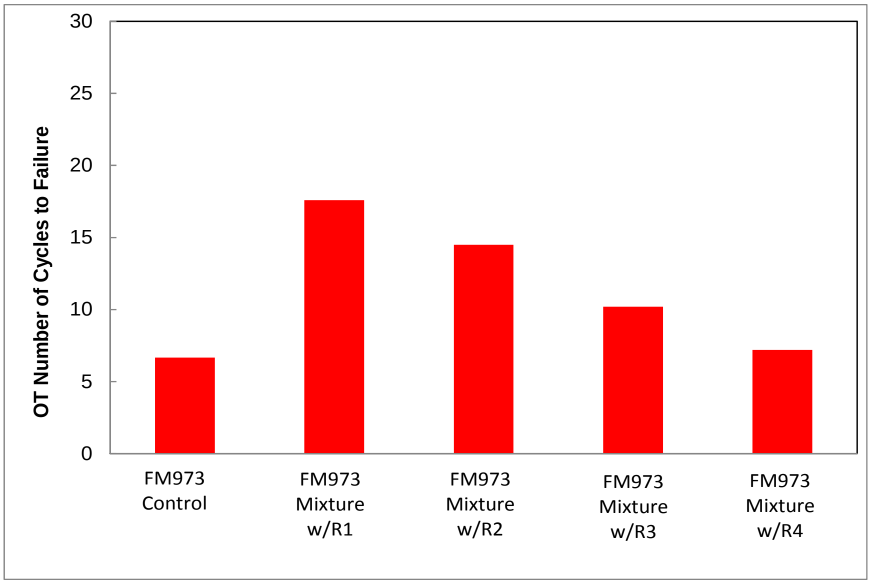
Overlay Test

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

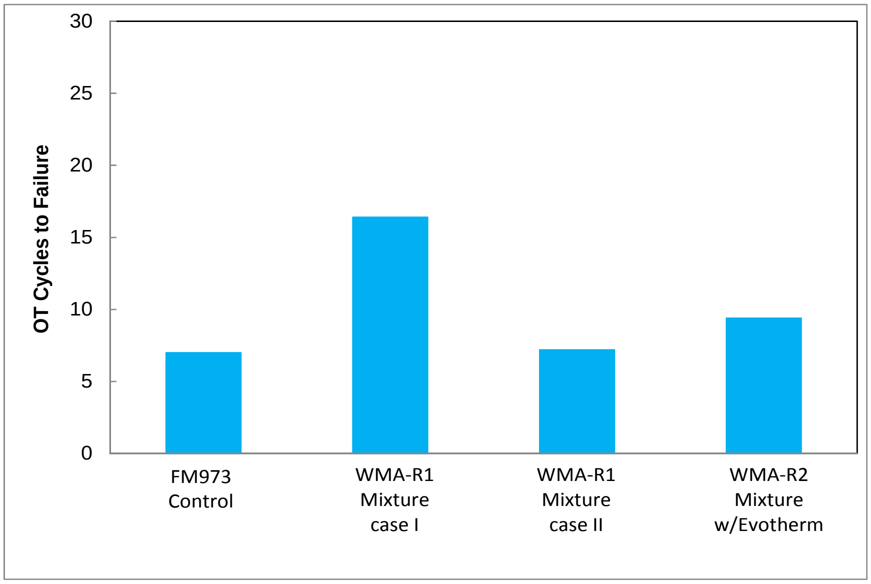
The reflective cracking life (average loading cycles of the five specimens) from each mix tested is presented in Figure 8 through Figure 10.

- **FM 973 HMA Mixtures**: R1 rejuvenating agent exhibited the best performance, followed by R2, R3, and then R4 rejuvenating agents, respectively. The control mixture showed the lowest value of cracking life.
- **FM 973 WMA Mixtures**: the WMA-R1 (case-II) mixture did not show improved the cracking resistance, while that of the WMA-R1 (case-I) mixture improved approximately up to 230 percent. Also, the WMA-R2 mixture exhibited improved the cracking resistance but not significantly.
- Similar results were observed for both the Loop 820 mixtures and the APT 119 mixtures, but the performance ranking of the rejuvenators were changed as shown in Figures 9 and 10.

In summary, all of the mixtures with rejuvenators exhibited higher OT cycles than the control mixtures. This observation implies that the rejuvenators reduced the stiffness of the aged binder from the recycled materials so that they improved cracking resistant of mixtures. Similar test results can be found in the study conducted by Booshehrian et al. (2013). In terms of the effect of the oven curing temperature and increasing the oven curing time to the cracking resistance of WMA mixtures, the researchers recommend further investigation with extended laboratory tests.



(a) FM 973 HMA Mixtures



(b) FM 973 WMA Mixtures

Figure 8. Overlay Test Results of FM 973 Mixtures with Rejuvenators.

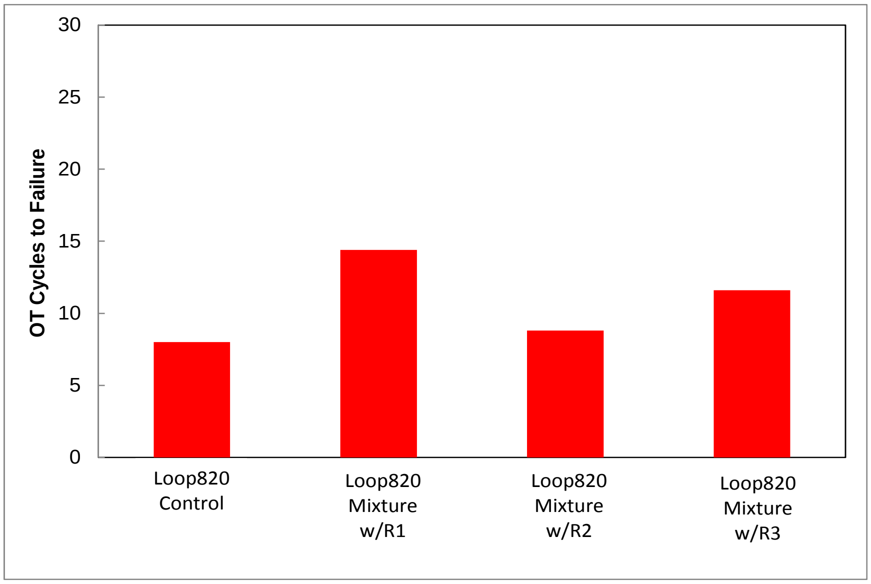


Figure 9. Overlay Test Results of Loop 820 Mixtures with Rejuvenators.

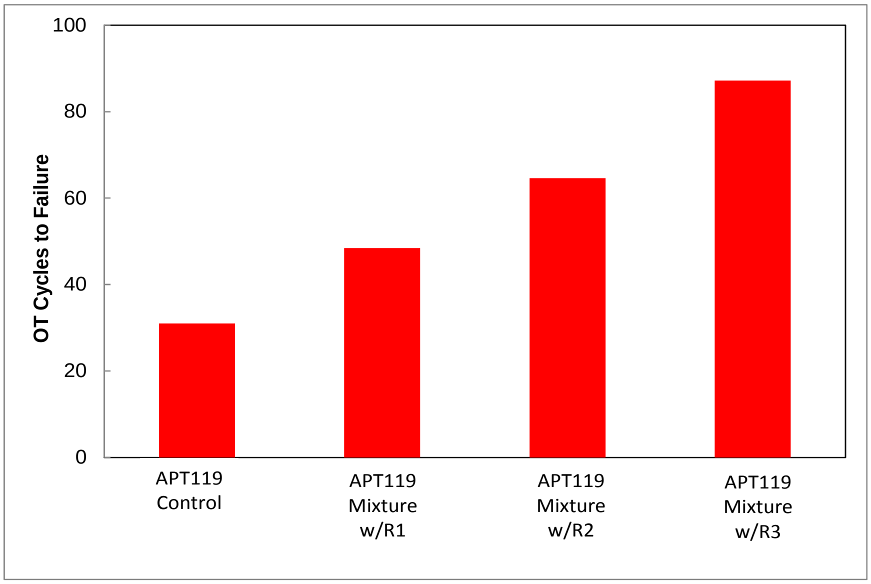


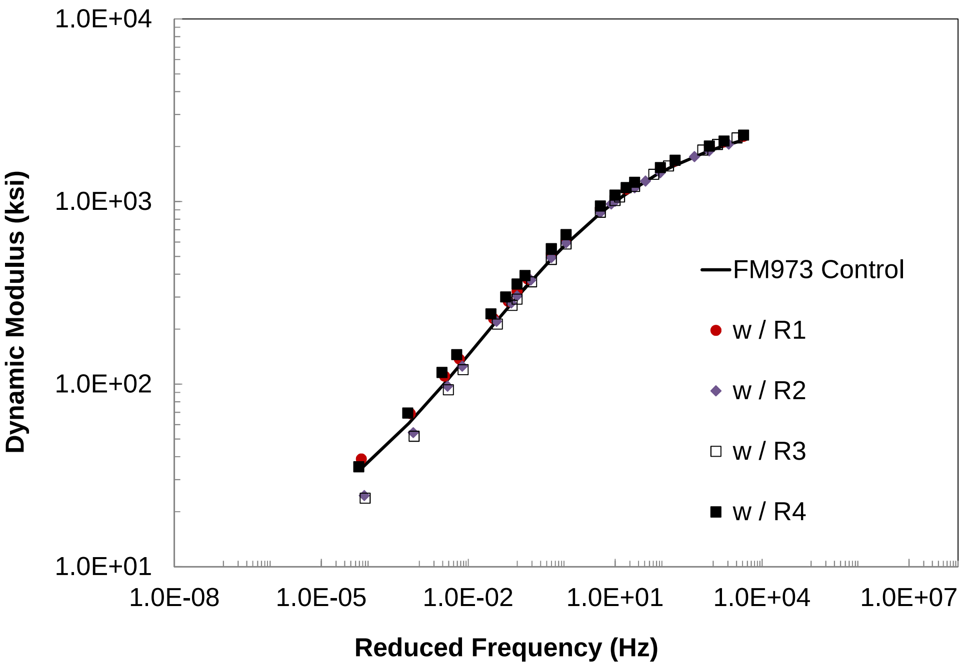
Figure 10. Overlay Test Results of APT 119 Mixtures with Rejuvenators.

Dynamic Modulus Test

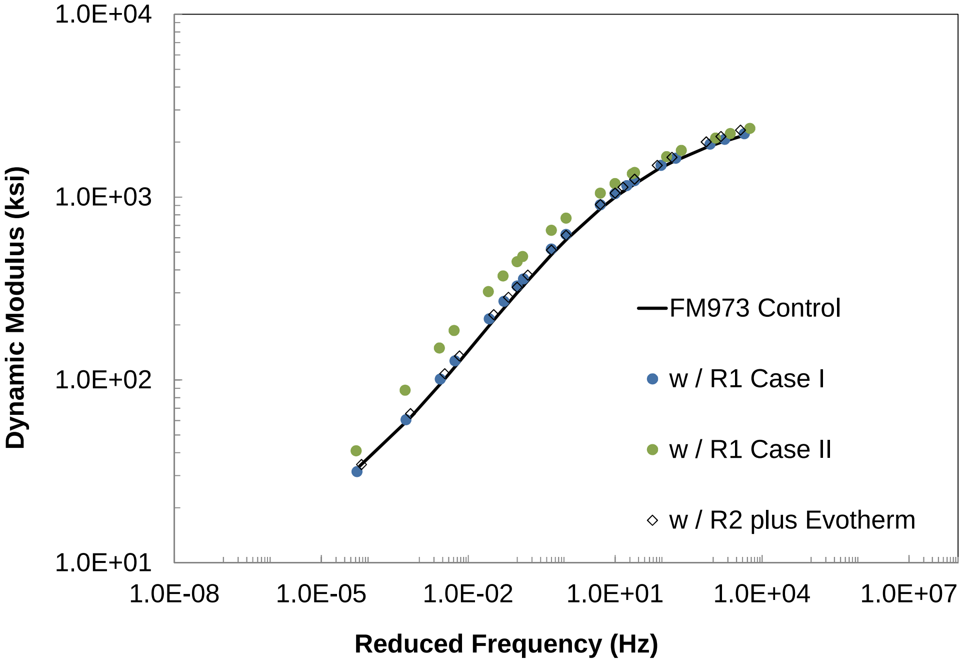
The dynamic modulus test measured changes in the viscoelastic stiffness of the asphalt mixtures due to the impact of rejuvenators. The test was conducted following the standard, AASHTO TP79-11, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The Superpave gyratory compactor was used to produce cylindrical samples with a diameter of 6 inches (150 mm) and a height of 6.7 inches (170 mm). The samples were then cored and cut to produce cylindrical specimens with a diameter of 4 inches (100 mm) and a height of 6 inches (150 mm). The target air void of the cored and cut specimens was 7 percent ± 1 percent. To measure the axial displacement of the testing specimens, the researchers glued mounting studs to the surface of the specimens so that three linear variable differential transformers (LVDTs) could be installed on the surface of the specimens through the studs at 120° radial intervals with a 2.8 inch (70 mm) gauge length. Three temperatures of 40, 68, and 104°F (4, 20, and 40°C, respectively) and either six and or seven loading frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz, and 0.01 Hz (104°F only) were used, and the frequency-temperature superposition concept was applied to obtain the linear viscoelastic master curves at a target reference temperature of 68°F. Two replicates were tested, and average values of dynamic modulus at each different testing temperature over the range of loading frequencies were obtained. Figures 11 through 13 present the master curves at the reference temperature of 68°F. Table 13 summarizes the shift factors obtained from each master curve.

- **FM 973 WMA Mixtures**: the WMA-R1 mixture (case-II) showed much stiffer than the FM 973 control mixture, while the WMA-R1 (case-I) and the WMA-R2 mixtures were similar to the FM 973 control mixture. It can be postulated that longer curing time would have affected the increased stiffness. Thus, the mixture with R1 (case-II) showed significant decrease in rut depth results, and the cracking resistance was not improved. It the future, various curing temperature and time conditions for WMA mixtures with other rejuvenators should be evaluated to confirm this conclusion.
- For other HMA mixtures tested, regardless of the rejuvenator type, it is interesting to note that there were no significant difference between the control mixtures and their counterparts for most of the master curves (40°F and 68°F zone). However, most counterparts showed the decreased stiffness characteristics at the low frequency (or high temperature 104°F zone) except for two cases: the Loop 820 mixtures with R1 and R3 rejuvenating agents. For example, the APT 119 control mixture exhibited the highest dynamic modulus values with R1 mixture was second followed by the R3 and R2 mixtures, respectively.

Based on the dynamic modulus test results obtained from this study, it can be concluded that rejuvenators may affect the stiffness characteristic of mixtures only over lower loading frequency levels (or hot temperature ranges).



(a) FM 973 HMA Mixtures



(b) FM 973 WMA Mixtures

Figure 11. Dynamic Modulus Test Results of FM 973 Mixtures with Rejuvenators.

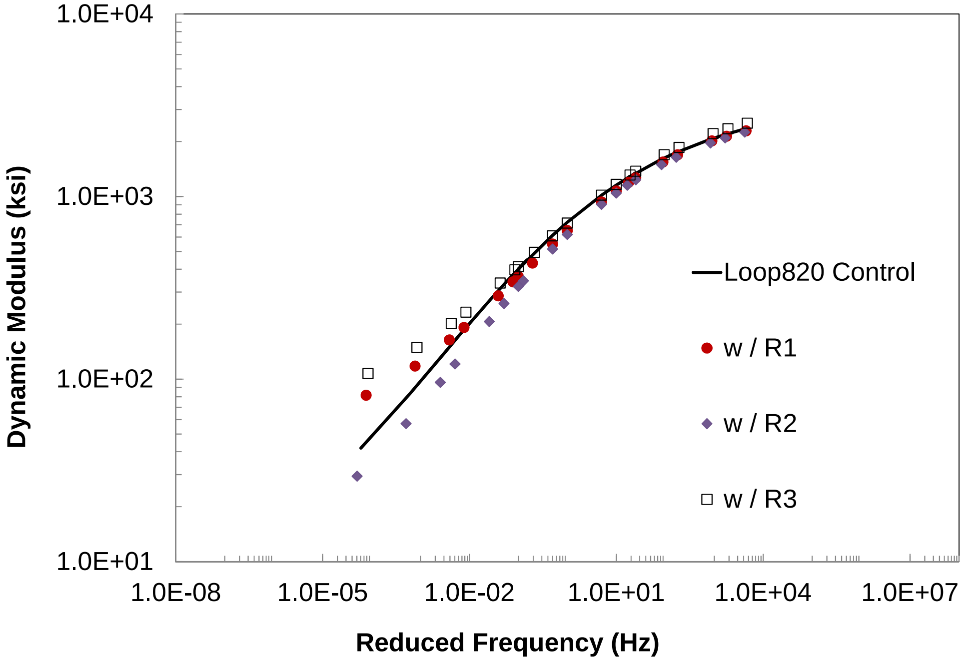


Figure 12. Dynamic Modulus Test Results of Loop 820 Mixtures with Rejuvenators.

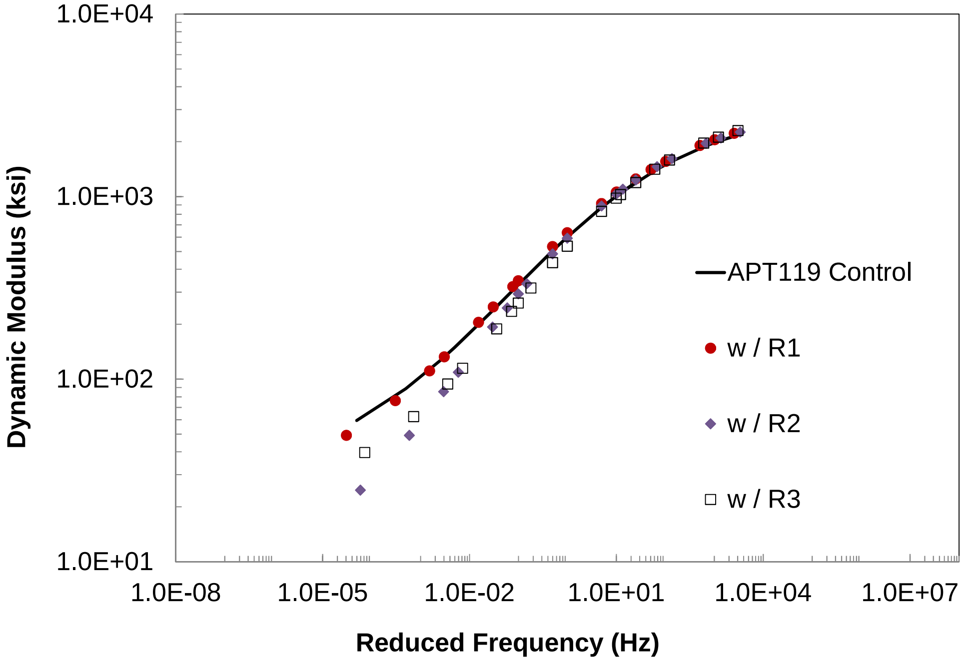


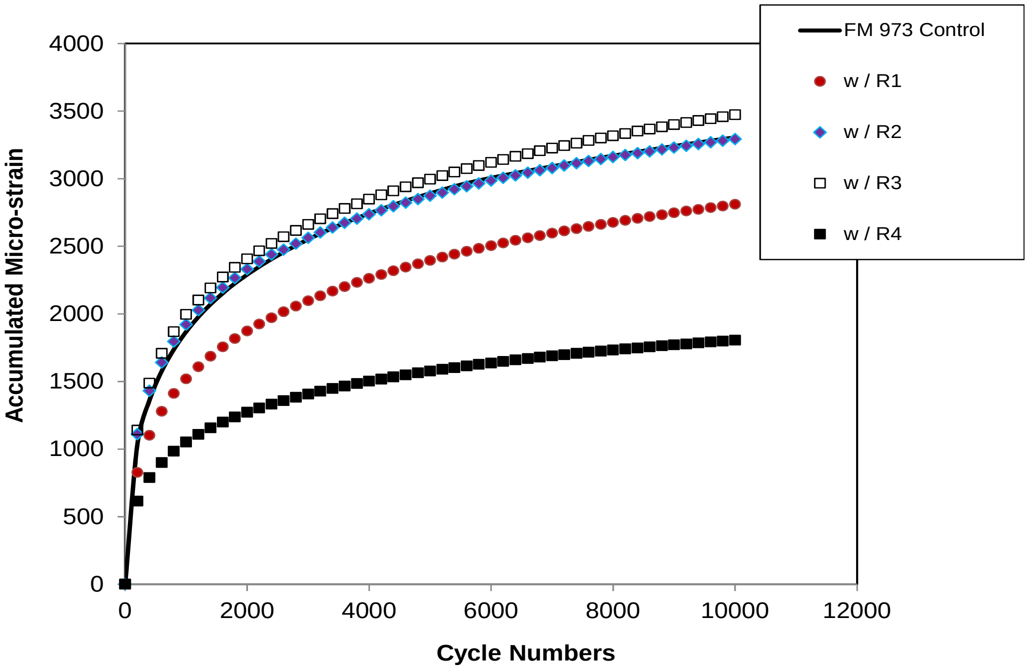
Figure 13. Dynamic Modulus Test Results of APT 119 Mixtures with Rejuvenators.

Table 13. Temperature Shift Factors of Each Test Case.

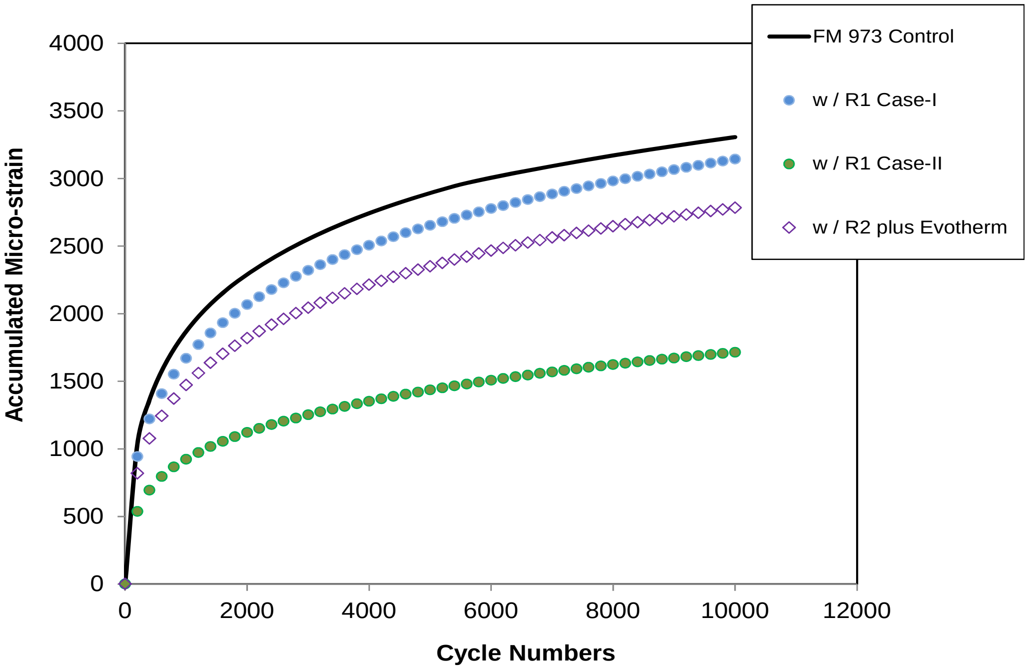
Mix	Log a_T	Control Mix (*)	R1			R2		R3 *(HMA)	R4 (*)
			(*)	WMA		*HMA	**WMA + (M1)		
				Case-I	Case-II				
FM973	Log a(40)	2.152	2.224	2.239	2.351	1.922	2.162	2.092	2.225
	Log a(68)	0	0	0	0	0	0	0	0
	Log a(104)	−2.213	−2.182	−2.270	−2.287	−2.122	−2.179	−2.103	−2.236
Loop820	Log a(4)	2.190	2.254	-	-	2.225	-	2.279	-
	Log a(20)	0	0	-	-	0	-	0	-
	Log a(40)	−2.217	−2.111	-	-	−2.295	-	−2.071	-
APT119	Log a(4)	2.144	2.010	-	-	2.134	-	2.087	-
	Log a(20)	0	0	-	-	0	-	0	-
	Log a(40)	−2.303	−2.513	-	-	−2.227	-	−2.141	-

Repeated Load Test

The unconfined, repeated load test was performed under a loading stress level of 138 kPa at 104°F. A loading stress level of 138kPa was selected based on the studies performed by Zhou et al (2002, 2003). The 138 kPa loading stress is applied in the form of a haversine curve with a loading time of 0.1 second and a rest period of 0.9 second in one cycle. Loading stress is repeatedly applied to the specimen until it exhibits a tertiary flow and reaches either 5 percent permanent strain level or 10,000 loading cycles. Two replicates from each mixture were prepared as with the dynamic modulus test specimens. Figures 14 through 16 present plots of the measured accumulative permanent strain against the number of loading cycles. The result of the repeated load test strongly relates to the stiffness of that mixture, which is the dynamic modulus—the stiffer the mixture, the more rut resistance and less accumulative permanent strain. For example, the ranking of the rut resistance of mixtures is very similar to the dynamic modulus test results of the same mixtures as presented in a later section of this study. Some mixtures with rejuvenators (i.e., FM 973 mixture-R2 and -R3, Loop 820 mixture-R3) exhibited similar rut resistance characteristics, while the others showed less or better rut resistance characteristics compared to their control mixtures.



(a) FM 973 HMA Mixtures



(b) FM 973 WMA Mixtures

Figure 14. Repeated Load Test Results of FM 973 Mixtures with Rejuvenators.

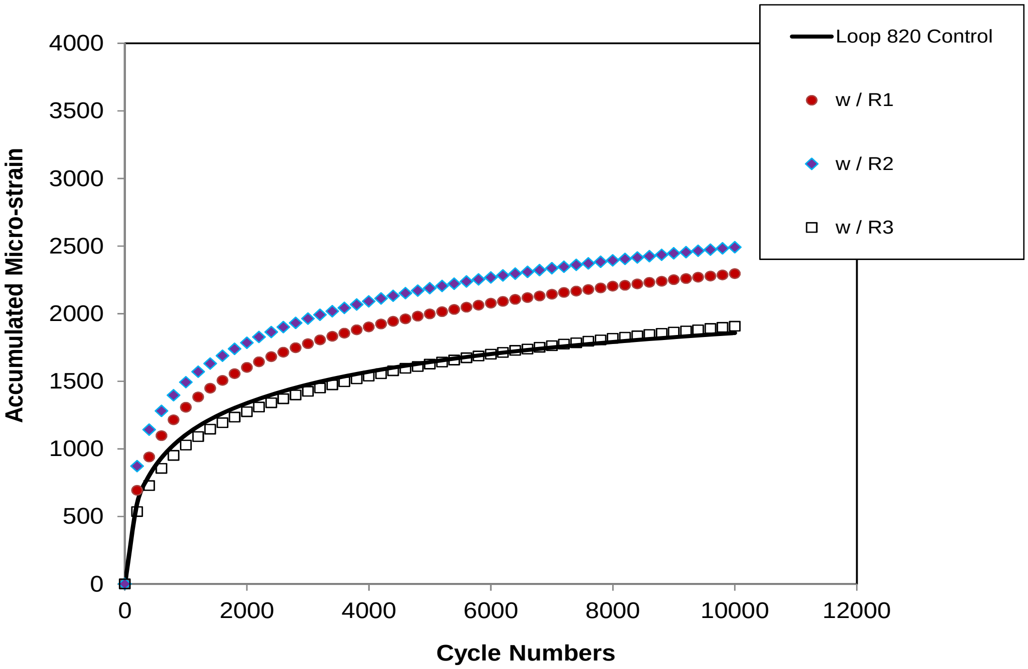


Figure 15. Repeated Load Test Results of Loop 820 Mixtures with Rejuvenators.

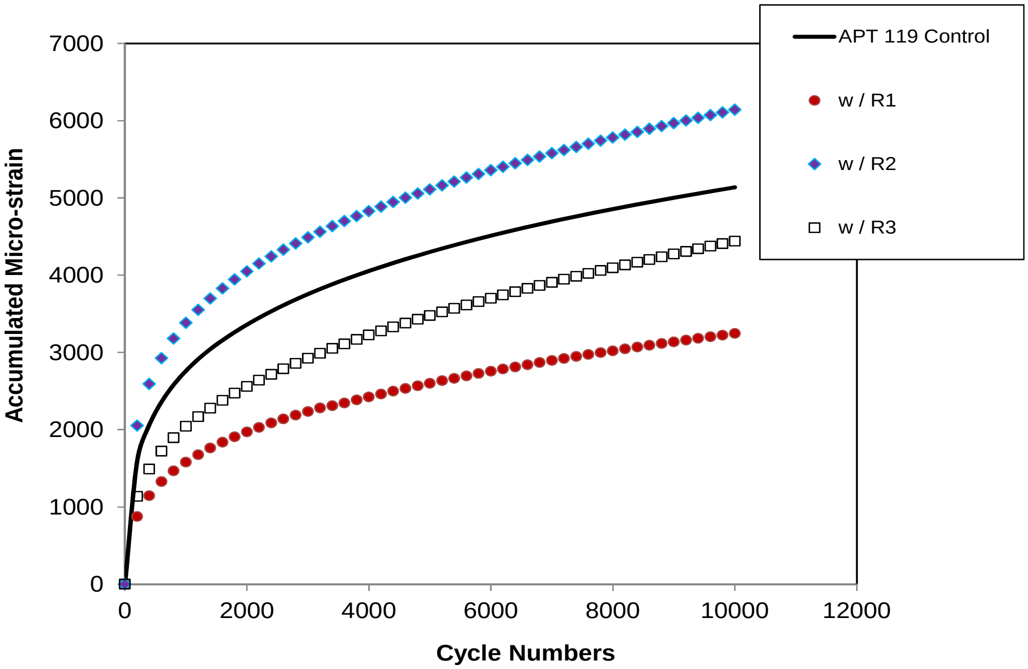


Figure 16. Repeated Load Test Results of APT 119 Mixtures with Rejuvenators.

Discussion of Test Results

Table 14 summarizes the performance ranking of the mixtures from each test. A lower numerical value in Table 14 is indicative of a better performance result from the HWTT, OT, dynamic modulus test, and repeated load test. In addition, the lower numerical number used for the dynamic modulus test indicates the ranking of the mixtures' stiffness. The results shown in the table indicate that the rejuvenators improve the mixture performance in terms of rutting resistance and cracking resistance. However, the ranking of the rejuvenators, based on the test results obtained from this study, depends on the engineering properties and mixture types.

Table 14. Summary of Performance Ranking.

Mix Type	Tests	Control Mix	R1	R2	R3	R4
FM 973 (HMA)	HWTT	3	5	1	2	4
	OT	5	1	2	3	4
	Dynamic Modulus	3	2	4	5	1
	Repeated Load	4	2	3	5	1
Loop 820 (HMA)	HWTT	1	4	3	2	-
	OT	4	1	3	2	-
	Dynamic Modulus	3	2	4	1	-
	Repeated Load	1	3	4	2	-
APT 119 (HMA)	HWTT	3	2	1	4	-
	OT	4	3	2	1	-
	Dynamic Modulus	1	2	4	3	-
	Repeated Load	3	1	4	2	-

COST ANALYSIS

The researchers conducted a simple cost analysis to see the cost benefits of HMA mixtures containing recycled materials incorporated with and without rejuvenators. According to Copeland (2011), there are four cost categories for asphalt production: Material, Plant production, Trucking, and Lay down. Among them, the most expensive production cost category is materials, comprising 70 percent of the cost to produce HMA. In this study, the cost related only to materials was considered, including asphalt binder, rejuvenator, recycled materials, and virgin aggregates. The cost of each material was simply assumed based on the literature and the actual cost of the rejuvenator (R1) was used for the calculation. Based on the mix design information on the APT 119 control mixture, the cost to produce a HMA batch of 2000 lb was calculated as follows and presented in Table 15:

- Virgin aggregates = 0.0068 ($/lb).
- Virgin Binder = 0.3107 ($/lb).
- RAP = 0.0023 ($/lb).
- R1 = 0.75 ($/lb).

Table 15. Example of Cost Saving Using R1.

Case 1. Virgin aggregates and virgin binder	
Total weight of asphalt mixture	2,000 (lb)
4.8% asphalt by total weight (virgin binder)	96 (lb)
Total weight of aggregate (virgin aggregates)	1,904 (lb)
Total cost = (1,904×0.0068)+(96×0.3107)	42.8 ($/US ton)
Case 2. Virgin aggregates plus 19% RAP and virgin binder	
Total weight of asphalt mixture	2,000 (lb)
19% RAP	380 (lb)
Asphalt content of RAP (5%) =(380×0.05)	19 (lb)
4.8 % asphalt by total weight (virgin binder)	96 (lb)
Actual virgin binder needed = (96-19)	77 (lb)
Total weight of aggregate (virgin aggregates)	1,543 (lb)
Total cost = (1,543×0.0068)+(380×0.0023)+(77×0.3107)	35.3 ($/US ton)
Case 3. Virgin aggregates plus 19% RAP and virgin binder plus 0.6% R1	
Total weight of asphalt mixture	2,000 (lb)
19% RAP	380 (lb)
Asphalt content of RAP (5%) =(190×0.05)	19 (lb)
4.8 % asphalt by total weight (virgin binder)	96 (lb)
0.6% R1 on total binder	0.576 (lb)
Actual virgin binder needed = (96-19-0.576)	76.4 (lb)
Total weight of aggregate (virgin aggregates)	1,543 (lb)
Total cost =(1,543×0.0068)+(380×0.0023)+(77×0.3107) +(0.576×0.75)	35.7 ($/US ton)

As shown in Table 15, using RAP can significantly reduce the cost of asphalt mixtures up to17.5 percent (comparison of case 1 and case 2) as expected. Even though the price of the rejuvenator (R1) is very high compared to other materials, the total cost associated with the rejuvenator (case 3) is actually no higher than that of case 2. As shown in the table, it is because the same amount of virgin binder is backed out as the amount of rejuvenator added, since it becomes the malthenes phase of the binder and remains there as such as a rejuvenator. The cost analysis results presented in the table do not show significant cost savings using the rejuvenator. However, it can be concluded that the incorporation of rejuvenators is a cost effective way to enhance the overall performance of the asphalt mixtures, as this paper presented.

This study evaluated various rejuvenators and their influence on the performance and engineering properties of HMA and WMA mixtures containing recycled materials. Various laboratory tests were employed to compare the performance and engineering properties of control asphalt mixtures (without rejuvenators) with those of asphalt mixtures incorporated with rejuvenators. In addition, a simple cost analysis was performed to investigate the cost benefits of using rejuvenators when HMA mixtures are produced along with recycled materials. Based on the test results, the following conclusions can be made.

- Due to limited time, the WMA mixtures were prepared and tested only for FM 973 materials. Based on the limited test results, higher curing temperature and longer curing time affected the performance of the WMA mixtures. It the future, various curing temperature and curing time conditions for WMA mixtures with other rejuvenators should be evaluated to confirm this conclusion.
- With respect to cracking resistance, all of the mixtures using rejuvenators exhibited improved cracking resistance when compared to the control mixtures. This clearly indicates that rejuvenators can reduce the stiffness of the aged binder from the recycled materials.
- Similarly, the incorporation of rejuvenators improved the moisture susceptibility and rutting resistance of the mixtures containing recycled materials.
- The performance ranking of the rejuvenators depends on mixture types and engineering properties evaluated. Two possible reasons for this can be speculated. The first one may be because of the degree of blending between the binder of recycled materials and virgin binder. The other reason may be due to different contents of recycled materials, different source of the aggregates, and the rejuvenator dosage. This study used the dosage recommended by each manufacturer. As mentioned in the introduction, the rejuvenator percentage significantly affects the properties of the mixtures (Shen et al. 2007). Thus, it may be necessary to determine the optimum dosage of each rejuvenator for each mixture if it is desired to properly improve the performance of the mixture.
- The simple cost analysis results showed that using rejuvenators may be a cost effective way to enhance the overall performance of the asphalt mixtures containing recycled materials.

Additional tests and analyses such as low temperature fracture performance tests, etc. are necessary. Specifically, field test sections with different types of rejuvenators should be constructed for further evaluation.

CHAPTER 4
SUMMARY AND CONCLUSIONS

This report documents field performance of RAS test sections in different climatic zones and impact of rejuvenators on engineering properties of RAS (/RAP) mixes. In addition, a simple cost analysis was performed to investigate the cost-benefits of using rejuvenators. Based on the research presented in this report, the following conclusions are made.

- Cracking performance is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, pavement structure, and layer thickness. It is extremely difficult to propose a single cracking requirement for all applications.
- There is a need to develop a RAP/RAS mix design and performance evaluation system for project-specific service conditions, including traffic, climate, existing pavement conditions, etc.
- Both increasing design density (leading to higher virgin binder content) and using soft virgin binders (e.g., PG XX-28) can improve cracking resistance.
- With respect to cracking resistance, all of the mixtures using rejuvenators exhibited improved cracking resistance, compared to the control mixtures. This clearly indicates that rejuvenators can reduce the stiffness of the aged binder from the recycled materials. Additionally, the incorporation of rejuvenators improved the moisture susceptibility and rutting resistance of the mixtures containing recycled materials.
- The simple cost analysis results showed that using rejuvenators may be a cost effective way to enhance the overall performance of the asphalt mixtures containing recycled materials.

Additional tests and analyses are necessary. Specifically, field test sections with different types of rejuvenators should be constructed for further evaluation.

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APPENDIX A
RAS CHARACTERIZATION AND BINDER BLENDING CHARACTERISTICS

The coating asphalt used for making new roof shingles is very stiff, but it is seldom known that such stiff asphalt is made from an asphalt flux (i.e., asphalt cement [AC]-5) by a process known as air blowing. During the process, air is bubbled through a large tank containing the hot flux. Heat and oxygen cause a chemical reaction that changes the characteristics of the asphalt. The whole process is monitored, and the blowing is stopped when the correct properties are reached. Thus the coating asphalt is highly oxidized in the beginning, and it becomes even stiffer and more oxidized after sitting on a roof for 20-30 years under the sun. Up to now the information on RAS binders, in terms of performance grade (PG), has been very limited. One of the reasons is that the roofing industry is still using Penetration and Ring and Ball soft point to grade the coating asphalt. Another reason is due to limitation of existing dynamic shear rheometer (DSR). This appendix will grade the binders extracted and recovered binders from Manufacture Waste Asphalt Shingles (MWAS) and Tear-off Asphalt Shingles (TOAS) following the Superpave PG system.

VALIDATION OF ASPHALT BINDER EXTRACTION AND RECOVERY METHODS

Solvent-based asphalt binder extraction and recovery become necessary if one needs to characterize the recovered binders. However, there are always concerns especially about the solvent-based asphalt binder recovery process. One of the concerns is that the properties of the recovered asphalt binder may be changed for two potential reasons: 1) some solvent remains in the recovered asphalt binder (note that solvent often softens asphalt binder), or 2) the recovered asphalt binder is stiffened due to over-cooking to remove the solvent. To address this concern and validate the extraction and recovery methods used, TTI researchers compared both rheological properties and chemical components of one original shingles binder with the extracted/recovered binder from the MWAS produced with the same original shingles binder tested. The researchers evaluated the rheological properties using DSR and bending beam rheometer (BBR) and measured the chemical property with Fourier transform infrared spectroscopy (FTIR). Note that the original shingles binder was directly received from a binder supplier, and no filler was added. Figure A1 shows the whole process. The solvent used in binder extraction is trichloroethylene. The extraction and recovery methods employed in this study are:

- Tex-210-F Determining Asphalt Content of Bituminous Mixtures by Extraction: Part I-Centrifuge Extraction Method Using Chlorinated Solvent.
- ASTM D5404 Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator.

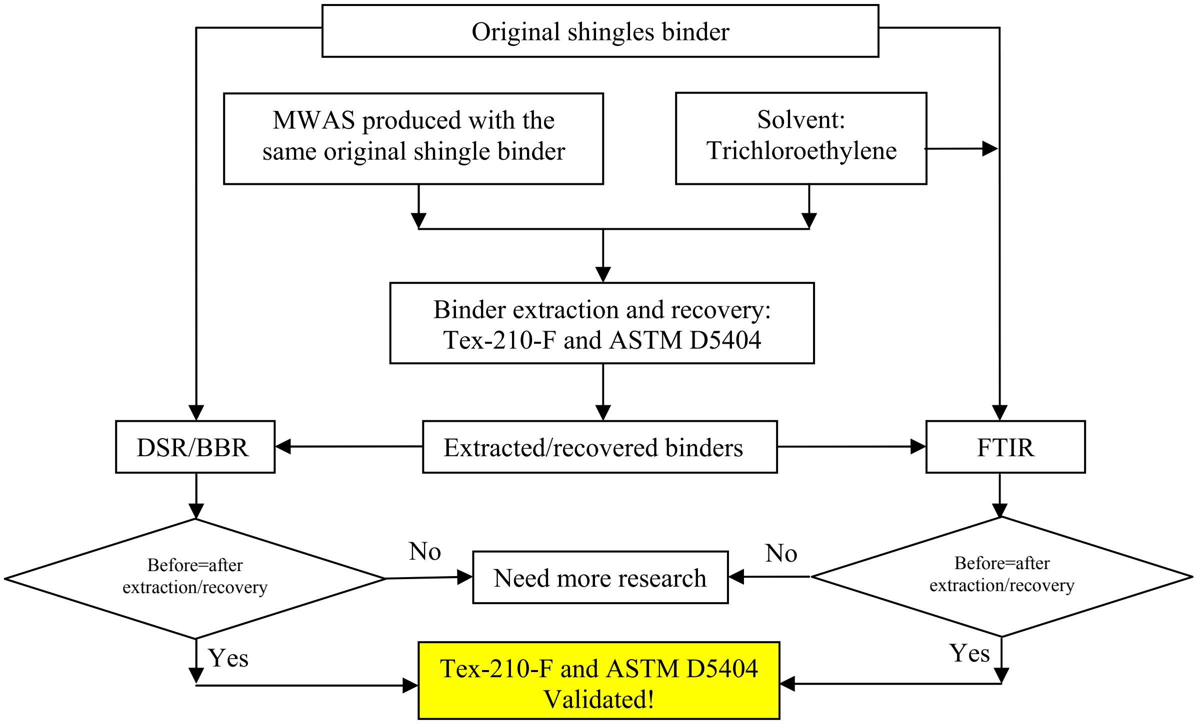


Figure A1. Flow Chart of Validation of Binder Extraction and Recovery Methods.

Chemical Property Comparison of RAS Binder before and after Extraction and Recovery

Figure A2 presents the FTIR test results of original shingles binder before and after the extraction and recovery. The chemical components of the original shingles binder are exactly the same as those of the extracted and recovered shingles binder. Furthermore, Figure A3 also shows the FTIR test result of the trichloroethylene solvent itself. Apparently, the trichloroethylene itself has large absorbance when wavelength is less than 1000 (cm-1). If there is any trichloroethylene left, the absorbance values of the recovered shingles binder will be different from those of original shingles binder in that wavelength range. Therefore, the trichloroethylene solvent was completely removed during the recovery process.

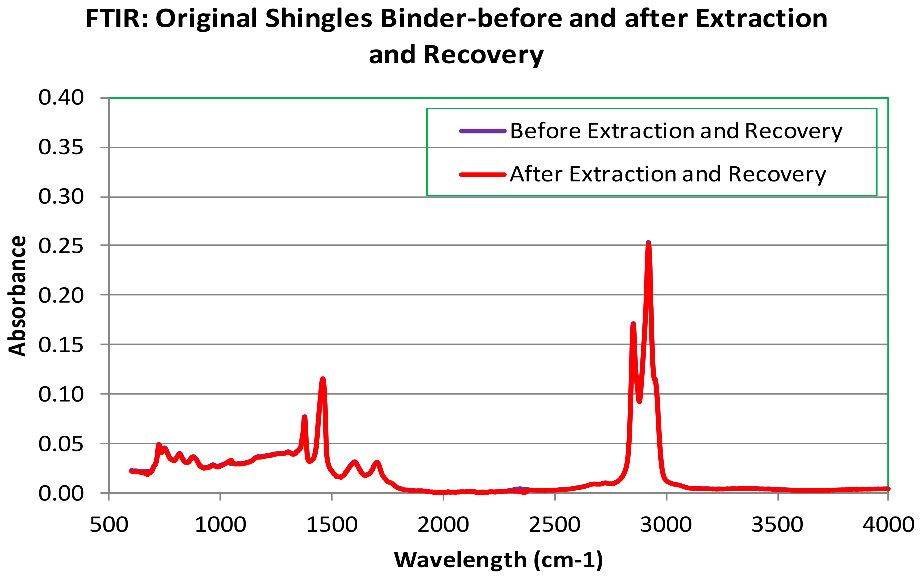


Figure A2. FTIR Test: Original Shingles Binder before and after Extraction and Recovery.

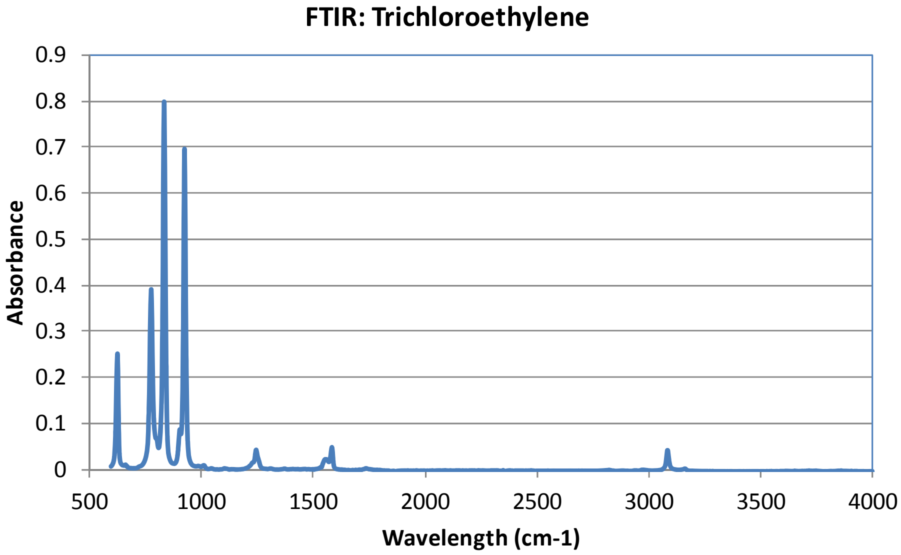


Figure A3. FTIR Test: Trichloroethylene.

Rheological Property Comparison of RAS Binder before and after Extraction and Recovery

Figure A4 illustrates the DSR and BBR test results of the original shingles binder before and after the extraction and recovery. Note that the BBR beams were prepared using the pressure aging vessel (PAV) aged asphalt binder residue. The rheological properties of the shingles binder, in terms of PG grade, do not change before and after the extraction and recovery. Note that the low temperature grade of the PAV-aged shingles binder is beyond the limits of the BBR test so no data are available (more discussion in a later section). Instead, the *S* and *m* values at

0°C were used for comparison. Again, the extraction and recovery process did not change the rheological properties of the shingles binder. With this validation, the authors conducted extensive shingles binder extraction and recovery following the Tex-210-F and ASTM D5404 and then evaluated the RAS binder properties, as discussed in the next section.

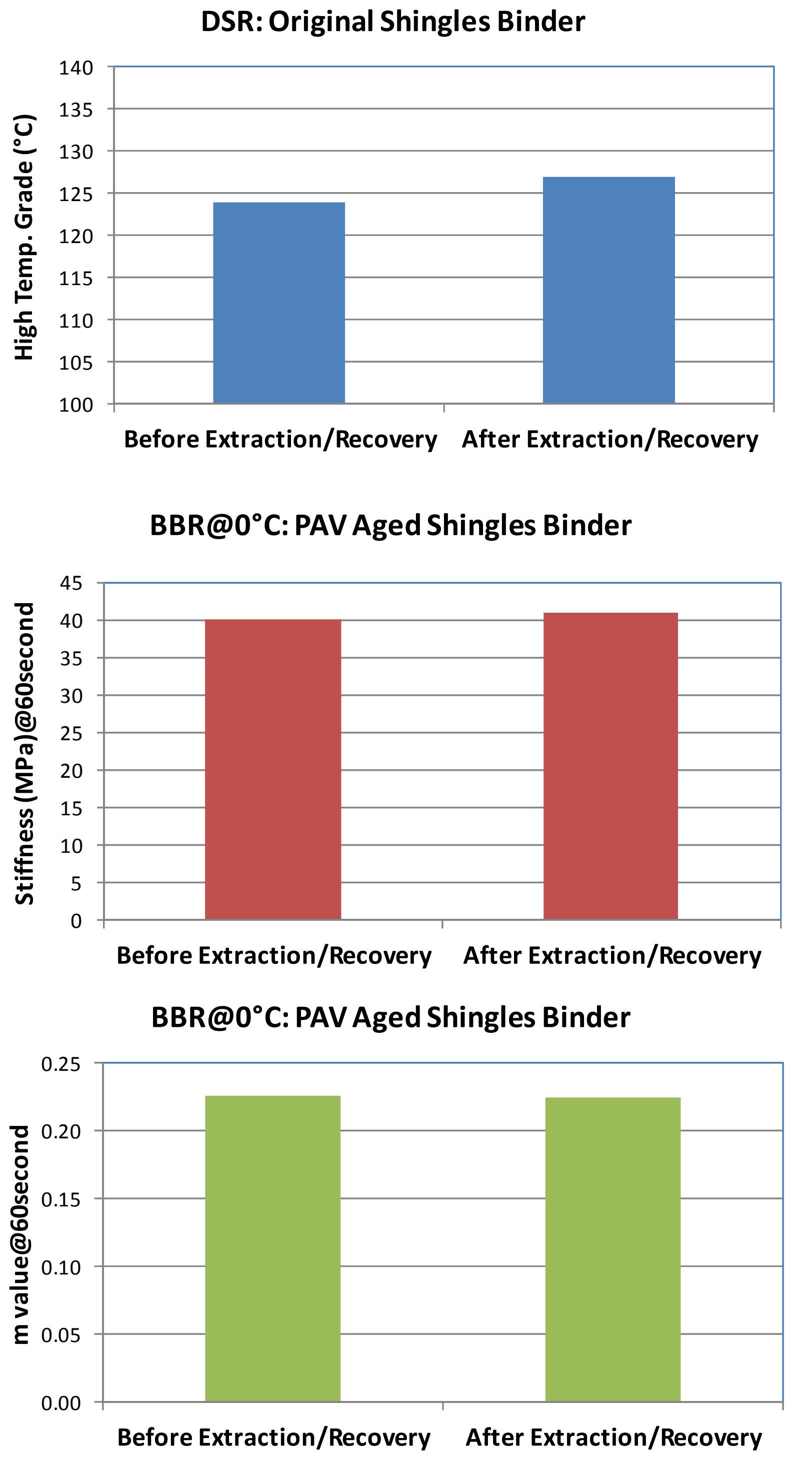


Figure A4. Rheological Properties of Shingles Binder: before/after Extraction/Recovery.

RAS BINDER CHARACTERIZATION

As discussed previously, roofing shingle binders, regardless of MWAS or TOAS, are very stiff, and they are far stiffer than any PG76-22 binder. Note that PG76-22 binders are the stiffest virgin binder used in Texas. It is important to know the true grade of the RAS binder since it has significant influence on virgin binder selection and then the allowable, maximum amount of RAS used in the asphalt mixes. This study sampled, extracted, recovered, and characterized a variety of RAS binders. Detailed information is presented below.

Selection of RAS Samples

A variety of processed RAS including both MWAS and TOAS were collected from contractors and shingles recyclers. In Texas, major shingles manufacturers are mainly located in the Dallas-Fort Worth and Houston areas. The contractors in these areas have been using MWAS collected from those shingles manufactories in the last three years. Four different types of MWAS often used in Texas were sampled from the processed MWAS stockpiles in this study and are designated as MWAS-A, MWAS-B, MWAS-C, and MWAS-D. Additionally, six TOAS types were also selected from different contractors and recyclers around Texas with the following designations: TOAS-A, TOAS-B, TOAS-C, TOAS-D, TOAS-E, and TOAS-F. In summary, a total of 10 processed RAS were selected and evaluated under this study.

RAS Binder Extraction and Recovery

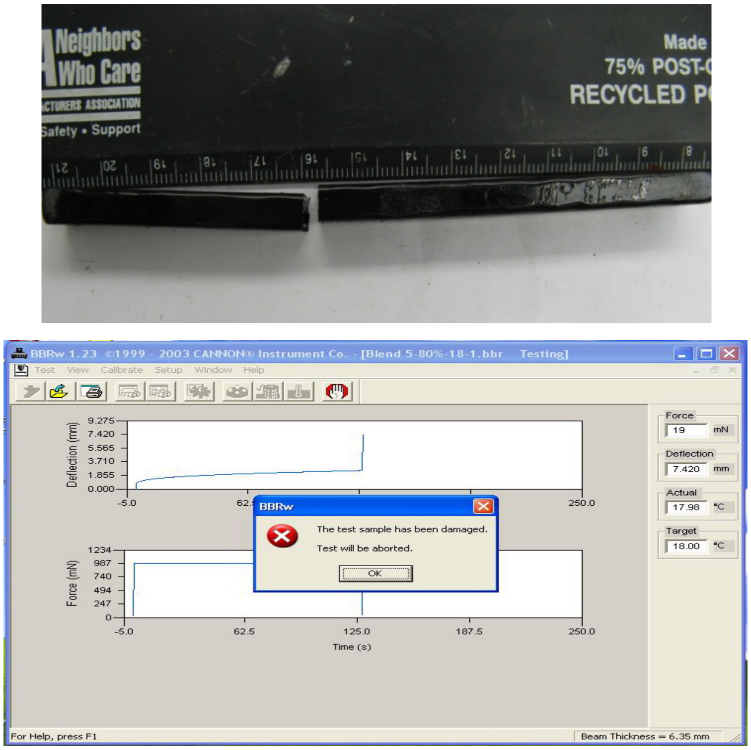
RAS binders were extracted and recovered from the 10 processed RAS selected above, following the validated extraction and recovery methods (Tex-210-F Part I and ASTM D5404). There was some difficulty in draining out of the recovered TOAS binders, which were so stiff that they did not flow out of the beaker even at 165°C (329°F) after finishing the recovery process. In one case, the oven temperature was raised to 200°C (392°F) in order to drain out the TOAS binder.

RAS Binder Characterization

Both DSR and BBR were used to grade the 10 extracted/recovered RAS binders. The results are discussed as follows.

- BBR test results

  As noted previously, the researchers had difficulty in grading PAV-aged shingles binder using BBR. There are two criteria (S and m) for determining the low temperature grade of asphalt binders. The RAS binders met the S (<300 MPa) criteria, but the measured m values were always less than 0.3. Some RAS binder beams fractured even before reaching 240 seconds (see Figure A5). The reason for having such a small m value is that RAS binders, including MWAS binders, have much less capability to relax under strain. Note that the original shingle binders are already substantially oxidized through the air blowing process. The researchers tried to run the BBR test at higher temperatures (i.e., 18°C and even 24°C), but the measured m values were still less than 0.3. In some cases the beam deformation reached the limit of BBR machine within a very short of period of time (see Figure A6). Therefore, no reliable results from BBR test were obtained for any one of the 10 recovered RAS binders. Alternative tests (such as the Asphalt Binder Cracking Device test) should be explored.



BBRw 1.23 ©1999 - 2003 CANNON® Instrument Co. - [Blend 5-80%-18-1.bbr Testing]

BBRw

The test sample has been damaged.

Test will be aborted.

OK

Force 19 mN

Deflection 7.420 mm

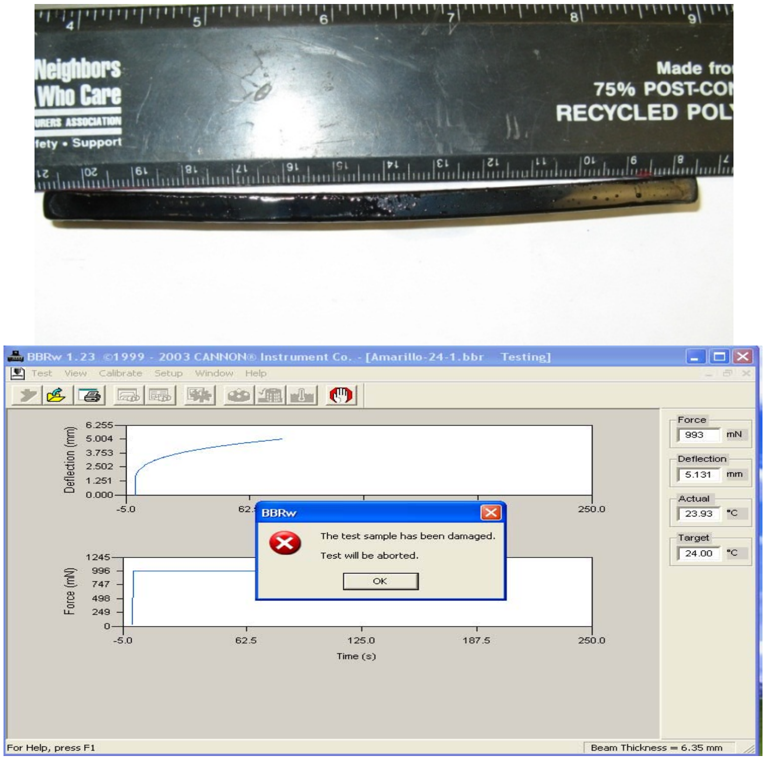
Actual 17.98 °C

Target 18.00 °C

For Help, press F1

Beam Thickness = 6.35 mm

Figure A5. BBR Test: Early Fractured RAS Binder Beam.



BBRw 1.23 ©1999 - 2003 CANNON® Instrument Co. - [Amarillo-24-1.bbr Testing]

BBRw

The test sample has been damaged.

Test will be aborted.

OK

Force 993 mN

Deflection 5.131 mm

Actual 23.93 °C

Target 24.00 °C

For Help, press F1

Beam Thickness = 6.35 mm

Figure A6. BBR Test: Overly Deformed RAS Binder Beam.

•DSR test results

To measure the high temperature grades of those extremely stiff binders, a high temperature DSR was specifically purchased for this study. Nine of the 10 RAS binders were successfully graded following the Superpave binder PG system. The high temperature grade of one TOAS binder was beyond the upper limit of the purchased DSR, which is 200°C, so extrapolation was used to estimate its high temperature grade. For each extracted/recovered RAS binder, the researchers evaluated both original and rolling thin-film oven-aged residue. The high temperature grades of the 10 RAS binders are shown in Figure A7.

Several observations can be clearly made from Figure A7:

- TOAS binders with an average high temperature grade of 175°C (347°F) are much stiffer than MWAS binders, which have an average of high temperature grade of 131°C (268°F).
- Compared to the TOAS varying from 159°C (318°F) to 214°C (417°F), the MWAS has a smaller variation in terms of the high temperature grade.

These two observations clearly indicate that the MWAS is different from the TOAS. It is necessary and important to differentiate the MWAS from the TOAS when used in asphalt mixes. For example, TxDOT may consider allowing smaller amount of TOAS in the specification when compared with MWAS.

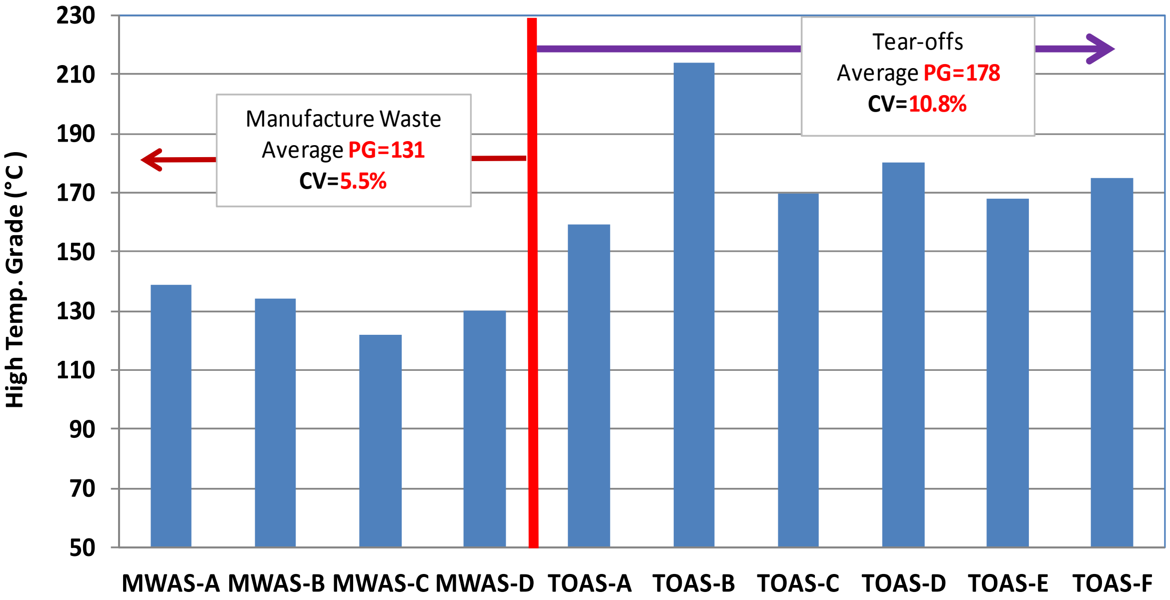


Figure A7. High Temperature Grades of RAS Binders: MWAS and TOAS.

INVESTIGATION OF VIRGIN AND RAS BINDER BLENDING

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

Virgin and RAS Binders

Three virgin binders selected for blending were: 1) PG64-22-A, 2) PG64-22-B, and 3) PG64-28. Four RAS binders were selected: TOAS-A, TOAS-E, MWAS-A, and MWAS-C. With these selected binders, a total of four combinations of virgin/RAS binders, as listed below, were evaluated under this study. Note that these four combinations have been used in the field test sections.

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

Laboratory Testing, Results, and Analysis

For each combination, different percentages of virgin and RAS binders were blended and then evaluated through DSR and BBR testing in terms of the high and low PG temperatures. The test results for these four combinations are presented in Figures A8, A9, A10, and A11, respectively.

The following observations are made from Figures A8 through A11.

- Generally the virgin and RAS binders blending is non-linear.
- For practical application, the linear blending chart can still be used if the RAS binder percentage is less than 30 percent. Within 30 percent RAS binder, not only is the linear blending chart applicable, but the regular DSR and BBR can also be used to evaluate the high and low PG temperatures of the blended binders.
- Increasing RAS binder will improve the high temperature grade of virgin binder and also warm up its low temperature grade, which is good for rutting resistance but causes concerns on cracking resistance of the blended binder. Adding 20 percent RAS binder can make a PGxx-22 binder become a PGxx-16 (or even a PGxx-10 as shown in Figure A8) binder after blending. Additionally, the necessity of using PGxx-28 virgin binder can also be seen in order to get a PGxx-22 combined binder when 20 percent RAS binder is added (Figure A9). Note that 20 percent RAS

binder corresponds to 5 percent RAS in weight of the total mix with the assumption that the optimum asphalt content of a RAS mix is 5 percent and RAS contains 20 percent asphalt binder.

- The impact of MWAS binders on the high and low PG temperatures of virgin binders is different from that of TOAS binders. Compared to the TOAS binders (Figures A8 and A9), the MWAS binders (Figures A10 and A11) have less impact on PG temperatures of virgin binders, which makes sense because TOAS binders are much stiffer than MWAS binders (see Figure A7). Therefore, it is necessary to consider differentiating the MWAS from the TOAS when designing HMA containing RAS.

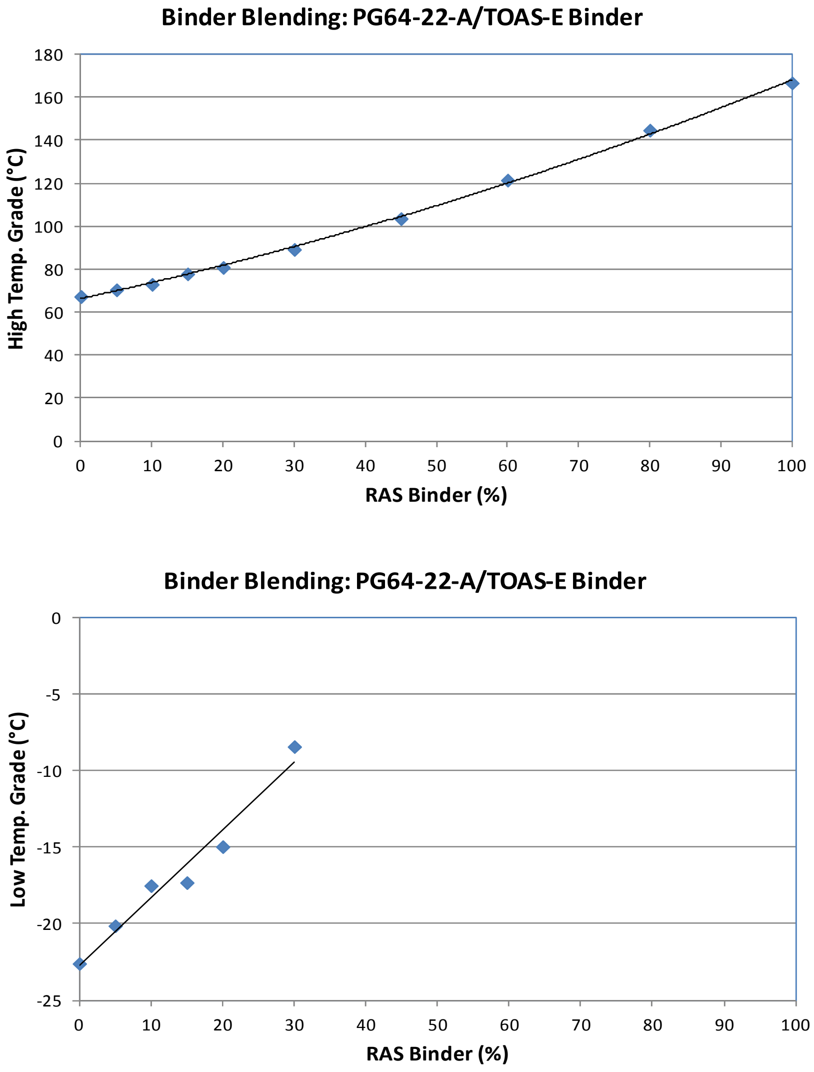


Figure A8. Binder Blending between PG64-22-A and TOAS-E Binder.

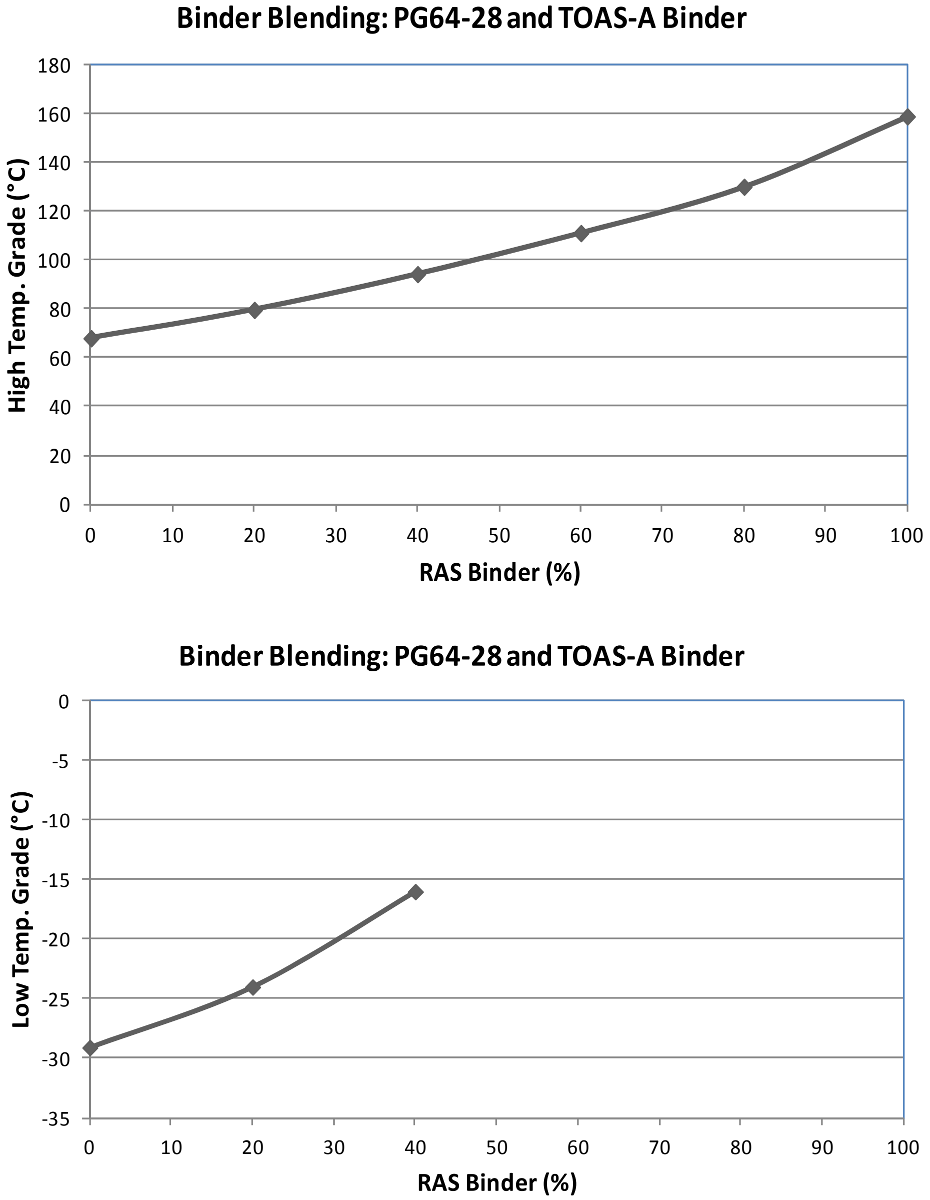


Figure A9. Binder Blending between PG64-28 and TOAS-A Binder.

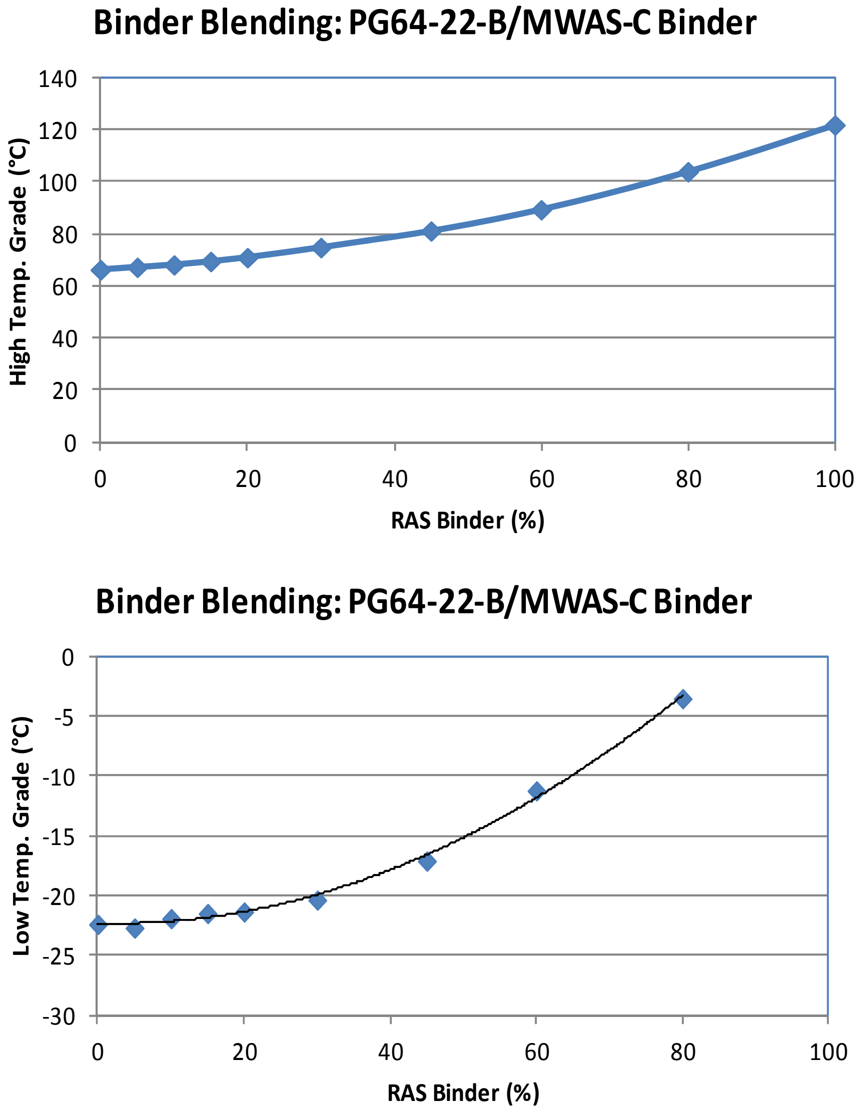


Figure A10. Binder Blending between PG64-22-B and MWAS-C Binder.

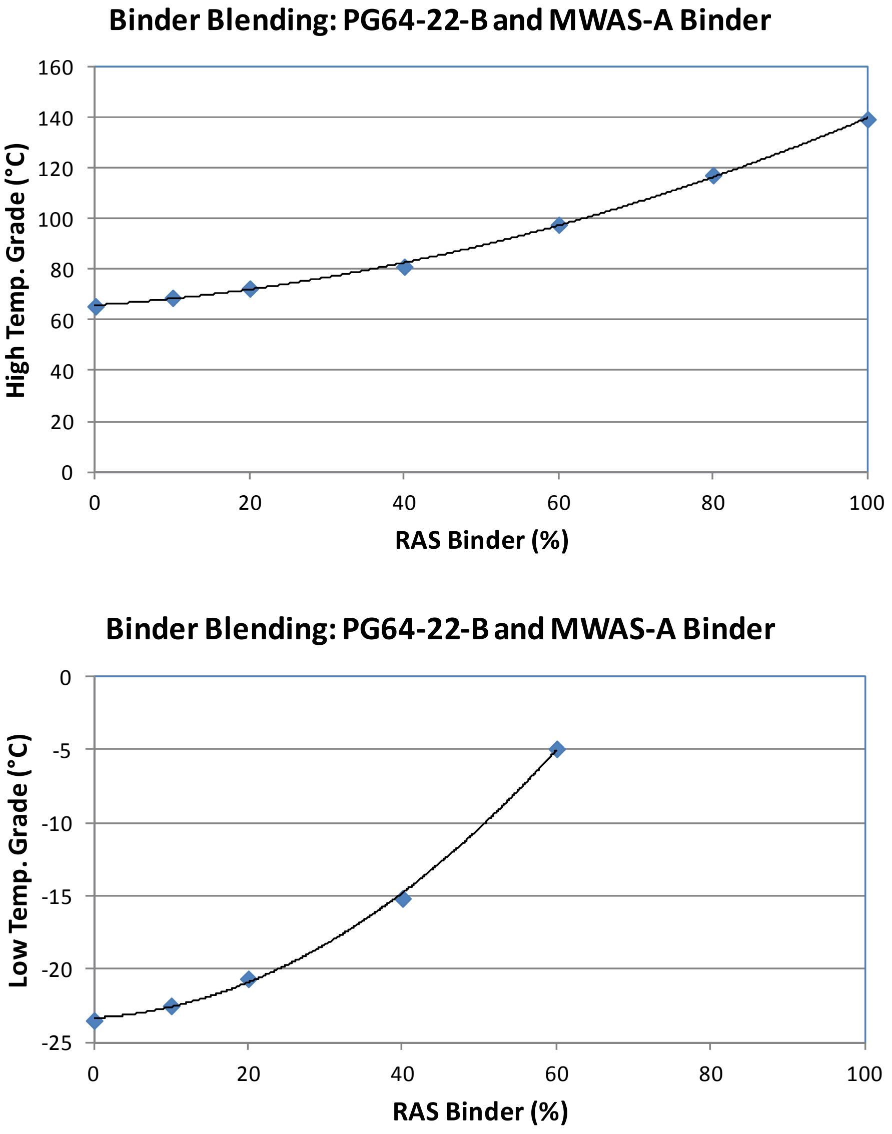


Figure A11. Binder Blending between PG64-22-B and MWAS-A Binder.

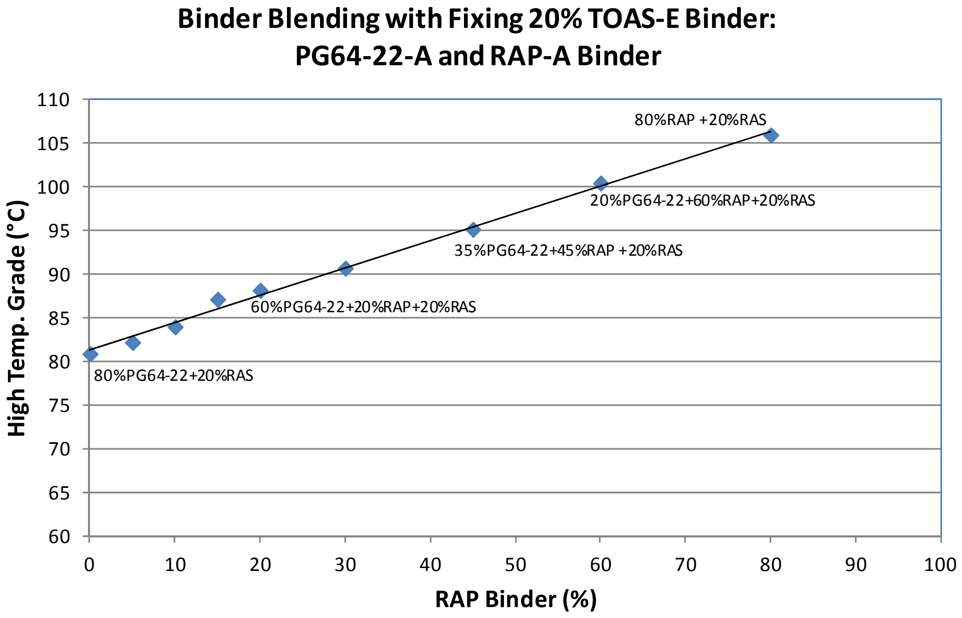
EVALUATION OF BLENDING AMONG VIRGIN, RAP AND RAS BINDERS

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

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

The DSR and BBR test results of these four combinations are shown in Figures A12, A13, A14, and A15, respectively. From these figures the following observations are made:

- As long as RAS binder content is fixed in the blending process, the virgin/RAP binders follows linear blending line, as seen in Figures A12 and A14. Both high and low PG temperatures of the combined binder increase linearly after adding RAP binder. When RAP binder content is fixed, the virgin/RAS binders blending, again, is non-linear (see Figures A11 and A13).
- When RAS binder is already blended with virgin binder, adding more RAP binder makes the blended binder even stiffer. For example, as shown in Figure A12, 20 percent RAS binder already modified the PG64-22-A binder to a PG81-15 binder. Adding RAP binder (even 5 percent RAP binder) will worsen the cracking resistance of the combined binder. Figures A13 through A15 show similar findings for fixed RAP binder with additional RAS binder added to the virgin binder.



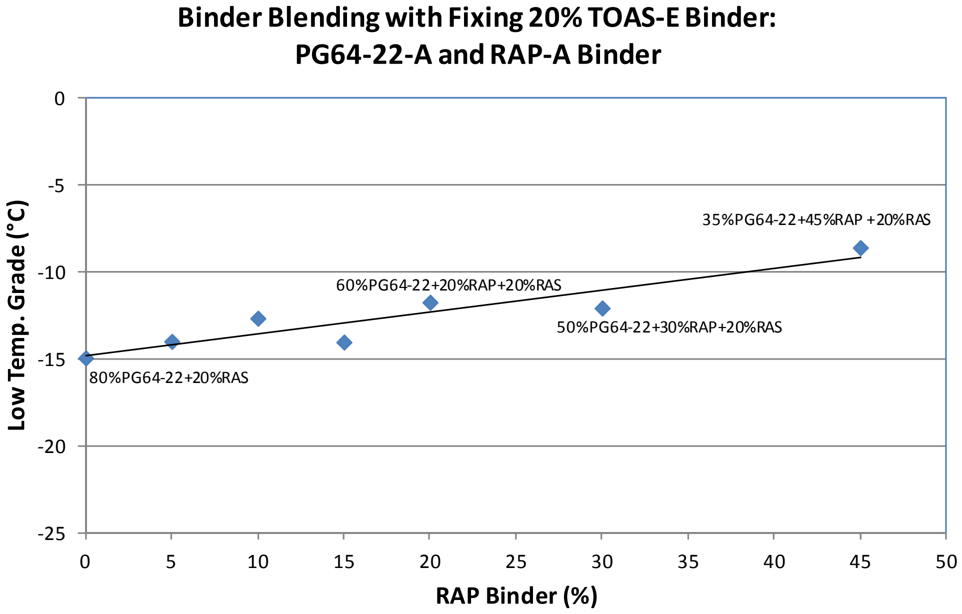
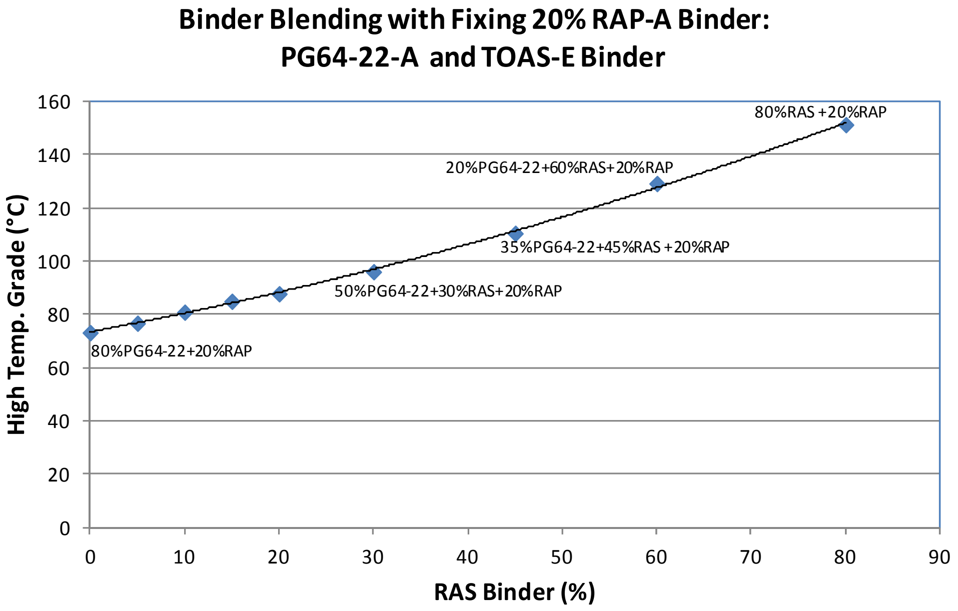


Figure A12. Binder Blending with Fixing 20 Percent TOAS-E Binder and Varying PG64-22-A and RAP-A Binder.



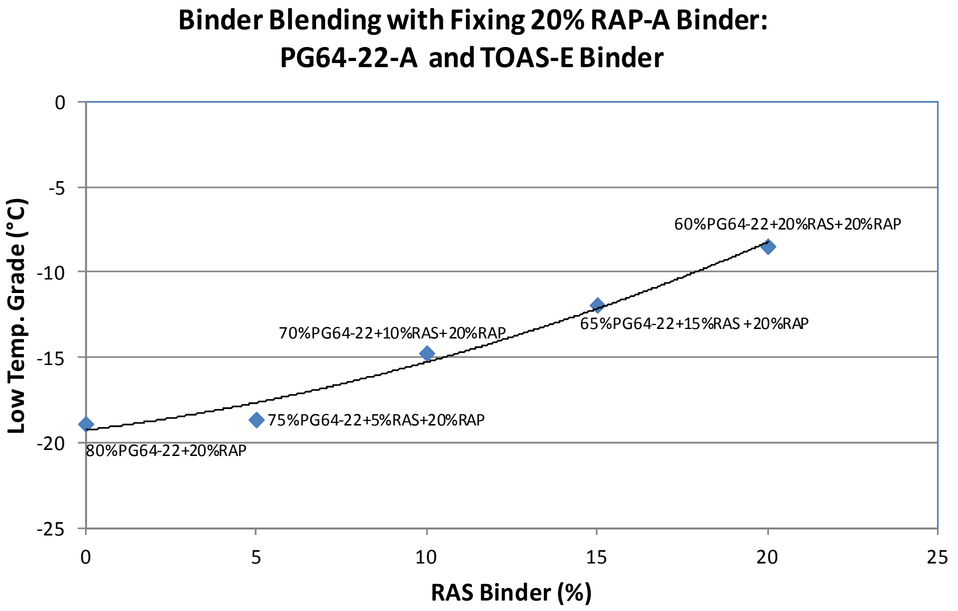
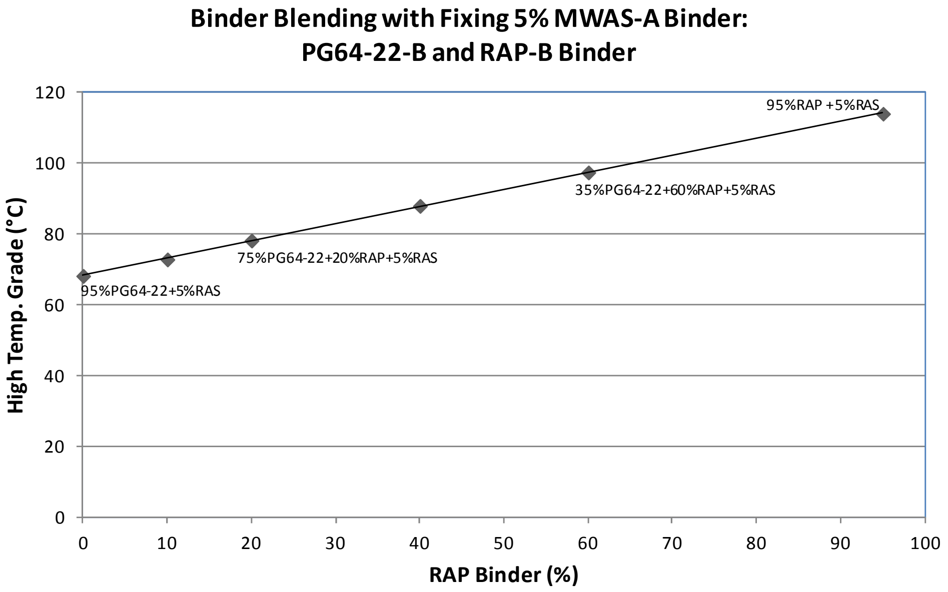


Figure A13. Binder Blending with Fixing 20 Percent RAP-A Binder and Varying PG64-22-A and TOAS-E Binder.


Binder Blending with Fixing 5% MWAS-A Binder:
PG64-22-B and RAP-B Binder

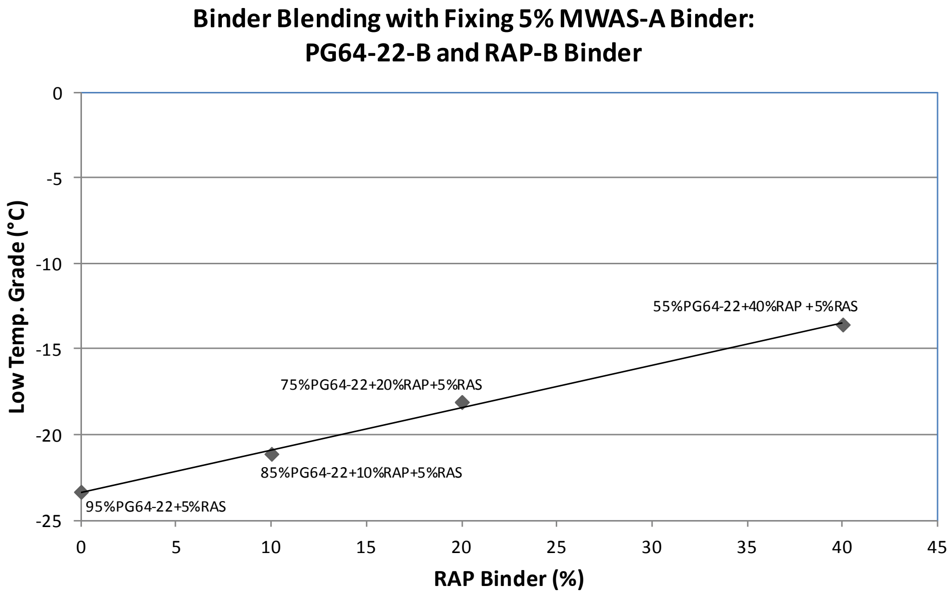
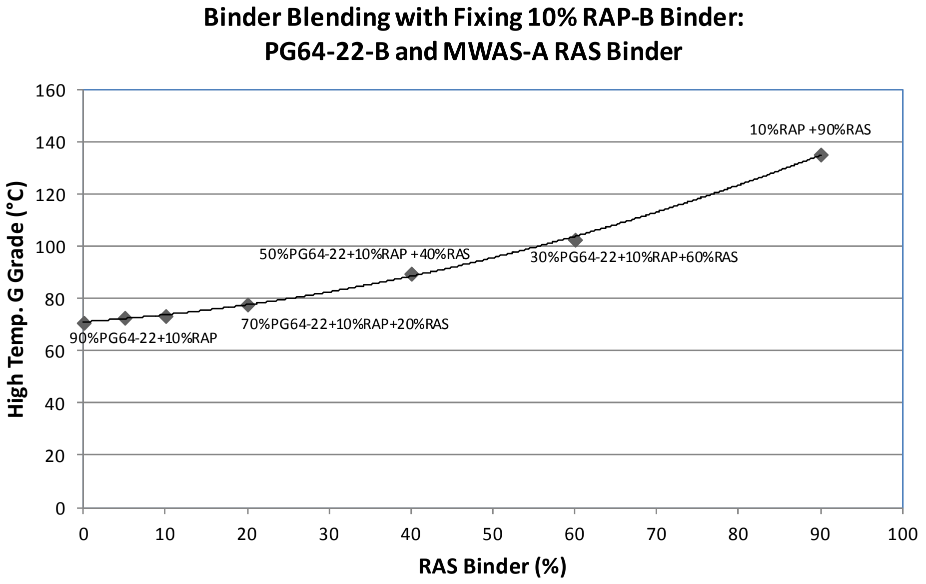

Binder Blending with Fixing 5% MWAS-A Binder:
PG64-22-B and RAP-B Binder

Figure A14. Binder Blending with Fixing 5 Percent MWAS-A Binder and Varying PG64-22-B and RAP-B Binder.



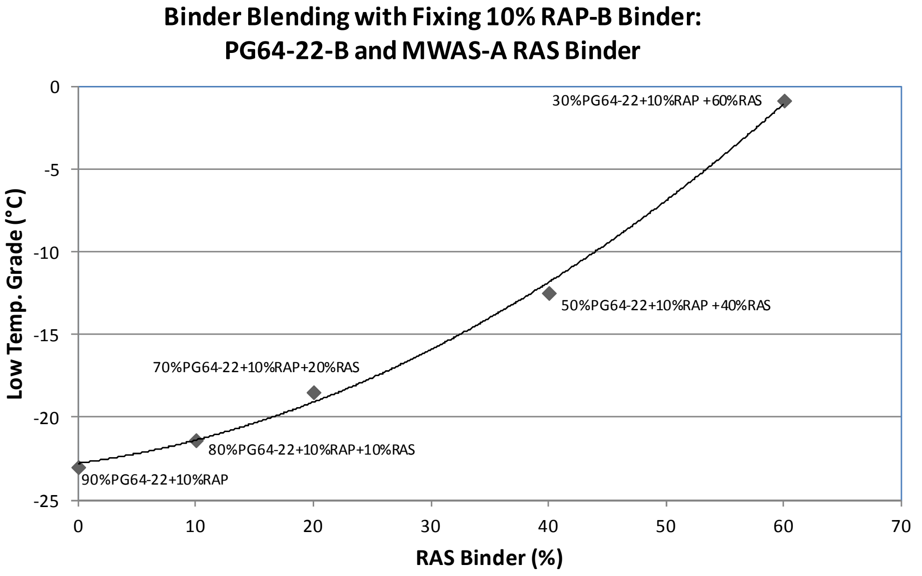


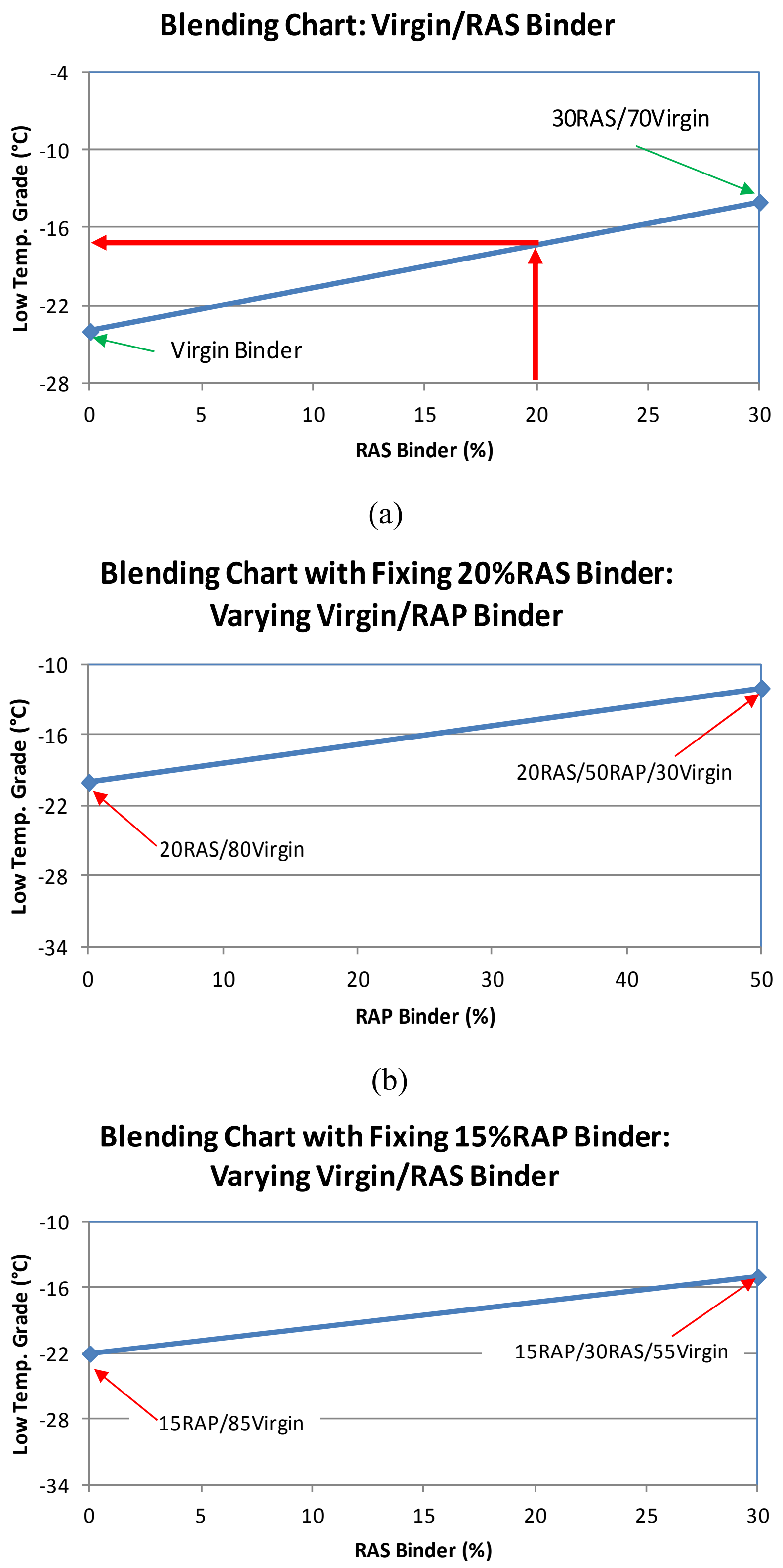
Figure A15. Binder Blending with Fixing 10 Percent RAP-B Binder and Varying PG64-22-B and MWAS-A Binder.

DISCUSSION ON MAXIMUM ALLOWABLE ASPHALT BINDER REPLACEMENT

The DSR and BBR test results presented above clearly indicate that RAS binders significantly influence both high and low PG temperatures of the blended binder with positive effect on high temperature property (or rutting resistance) and negative effect on low temperature property (or cracking resistance). Thus the maximum allowable RAS binder replacement is controlled by the influence of RAS binder on the low temperature property of the blended binder. The virgin/RAS binders blending charts shown in Figures A5 and A6 clearly indicate that the maximum allowable binder replacement for MWAS should be different from that for TOAS. It seems OK to use a maximum of 20 percent MWAS binder replacement, but for TOAS binders, the binder replacement should be significantly reduced depending on the combination of virgin and TOAS binders.

When both RAP and RAS are used, the maximum allowable recycled binder (RAP binder plus RAS binder) replacement is influenced by many factors (such as virgin binder, RAP binder, RAS binder, pavement layers [surface or base layer], climate, traffic, etc.). It will be safe to directly evaluate the blending chart for virgin, RAP, and RAS binders. Reviewing the impact of RAS binder on low temperature property of the blended binders shown in Figures A8, A9, A10, A11, A13, and 15, RAS binders, for practical applications, should be limited to 30 percent of the total binder. If this is the case, the blending chart for virgin/RAP/RAS can be significantly simplified:

- A linear blending chart is practically applicable to estimate the high and low PG temperatures of the blended virgin/RAS binders or virgin/RAP/RAS binders, which significantly reduces the DSR/BBR testing workload because only the properties of blended binders at two ends are required. Anything in between can be linearly interpolated. For virgin/RAS binders blending (see Figure A16a), one only needs to determine the PG temperatures of virgin binder and the 30 percent RAS/70 percent virgin binders, respectively. Then one can determine the continuous PG temperatures of any blending through linear interpolation. For virgin/RAP/RAS binders blending (see Figures A16b and A16c), a similar approach can be used for 1) fixing RAS binder replacement (say 20 percent) and varying virgin/RAP binders and 2) fixing RAP binder replacement (15 percent) and varying virgin/RAS binders. Note that RAS/RAP binder replacements shown in Figure A16b/c are just for demonstration only and can be replaced with real numbers.
- Additionally, the use of the linear blending chart and practical amount of RAP/RAS binders makes it possible to employ regular DSR and BBR test equipment to evaluate the properties of the blended virgin/RAP/RAS binders.



Blending Chart: Virgin/RAS Binder

(a)

Blending Chart with Fixing 20%RAS Binder: Varying Virgin/RAP Binder

(b)

Blending Chart with Fixing 15%RAP Binder: Varying Virgin/RAS Binder

(c)

Figure A16. Illustration of Linear Blending Charts for Virgin/RAP/RAS Binders.

SUMMARY AND FINDINGS

Based on the data presented previously, the following summary and findings are offered:

- The asphalt binder extraction and recovery procedures (Tex-210-F Part I and ASTM D5404) are validated in this study. No solvent was detected through FTIR testing, and the binder rheological properties, in terms of PG high and low temperatures, were almost the same before and after going through the extraction and recovery processes.
- TOAS binders with an average of high temperature grade of 175°C (347°F) are much stiffer than MWAS binders, which have an average high temperature grade of 131°C (268°F). Compared to the TOAS binders, which vary from 159°C (318°F) to 214°C (417°F), the MWAS has smaller variation in terms of the high temperatures grade. These two observations clearly indicate that the MWAS is different from the TOAS. It is necessary and important to differentiate the MWAS from the TOAS when used in asphalt mixes.
- Increasing RAS binder will improve the high temperature grade of virgin binder and warm up its low temperature grade, which is good for rutting resistance but causes concerns on cracking resistance of the blended binder. Adding 20 percent RAS binder can make a PGxx-22 binder become a PGxx-16 (or even a PGxx-10 in Figure A8) binder after blending. Additionally, the necessity of using PGxx-28 virgin binder can also be seen in order to get a PGxx-22 combined binder when 20 percent RAS binder is added (Figure A9). Note that 20 percent RAS binder corresponds to 5 percent RAS in weight of the total mix with the assumption that the optimum asphalt content of a RAS mix is 5 percent and RAS contains 20 percent asphalt binder.
- The impact of MWAS binders on the high and low PG temperatures of virgin binders differs from that of TOAS binders. Compared to the TOAS binders (Figures A8 and A9), the MWAS binders (Figures A11 and A12) have less impact on PG temperatures of virgin binders, which makes sense since TOAS binders are much stiffer than MWAS binders (see Figure A7). Therefore, it is necessary to consider differentiating the MWAS from the TOAS when designing HMA containing RAS.
- Different from virgin/RAP binders blending, the virgin/RAS binder blending is generally non-linear. However, for practical application, the linear blending chart can still be used for estimating continuous grade (high and low temperatures) of both virgin/RAS blended binders and virgin/RAP/RAS blended binders, if the RAS binder is limited to within 30 percent of the total binder. In this way, the DSR/BBR testing is significantly reduced. Furthermore, within 30 percent RAS binder, not only is the linear blending chart applicable, but the regular DSR and BBR can also be used to evaluate the high and low PG temperatures of the blended binders.

APPENDIX B
BALANCED MIX DESIGN METHOD FOR DENSE-GRADED AND SMA MIXES CONTAINING RAS/RAP

INTRODUCTION

As clearly observed from field performance of RAS test sections described in Chapter 2, rutting has not been a significant problem with TxDOT's current RAP/RAS mixes, since it is well controlled through the Hamburg wheel tracking test (or other tests) and associated criteria. The cracking issue observed in the field should be the main focus when designing mixes containing RAP/RAS. Therefore, the philosophy on developing a mix design and performance evaluation procedure is to focus on meeting both volumetric and cracking requirements while ensuring that acceptable rutting and moisture damage resistance is also achieved. Table B1 lists potential cracking distresses when mixtures containing RAP/RAS are used for different applications.

Table B1. 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 construction pavement	Surface layer	Thermal cracking, fatigue cracking (top-down)
	Intermediate layer	
	Bottom layer	Fatigue cracking

Currently, asphalt mix design in Texas is based on volumetric properties of asphalt mixes plus checking potential rutting and moisture damage. Texas and other states have already established the rutting/moisture damage requirements for mixes with different binders. For example in Texas, the rut depth of a mix with PG76-22 binder should be less than 0.5 inches (12.5 mm) after 20,000 passes. However, there is no cracking requirement on dense-graded and/or Superpave mixes in the current TxDOT specification. As clearly observed in the field and discussed previously, it may be difficult to establish a single cracking requirement for all scenarios 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 system for project-specific service conditions, rather than a single cracking requirement, should be developed and implemented to ensure the mixes are designed with acceptable field performance. A two-step process is envisioned. In Step 1 the site conditions will be investigated and the performance model will be run to predict pavement performance for a range of different materials properties (different OT cycles): the designers then select the OT requirement to meet the design performance goal (for example less than 50 percent reflection cracking after 8 years).

In Step 2 a lab mix design is run to design a mix with the required OT cycles. If this does not work, the process will be redesigned, this time changing overlay thicknesses or virgin binder (or others).

In the last several years, the researchers at TTI have made significant progresses toward the goal of balanced RAP/RAS mix design for project-specific service conditions, as noted below:

- Balanced mix design for overlay mixes developed under Project 0-5123 and documented in Report FHWA/TX-06/0-5123-1 (*Zhou et al. 2006*).
- Mechanistic-empirical asphalt overlay thickness design and analysis system (TxACOL) developed under Project 0-5123 and documented in Report FHWA/TX-09/0-5123-3 (*Zhou et al. 2009*).
- High RAP mixes design methodology with balanced performance developed under Project 0-6092 and documented in Report FHWA/TX-11/0-6092-2 (*Zhou et al. 2011*).

TxACOL is an overlay design program used to predict both rutting and reflection cracking of asphalt overlays. The inputs required for this program include both rutting and fracture parameters (*A* and *n*). In order to make this into a practical tool for our sponsors (i.e., TxDOT) and to accelerate implementation, a simpler methodology for determining the fracture parameters (*A* and *n*) has to be developed, as described below. This work led to the development of a simplified performance prediction model called S-TxACOL. The rutting prediction is removed from S-TxACOL as rutting appears to be controlled by TxDOT's current Hamburg wheel track test requirement. For reflective cracking, a relationship between the fracture parameters (*A* and *n*) and the routine OT test results (the number of OT cycles) has been established, and detailed information is described in the following section.

RELATIONSHIP BETWEEN THE NUMBER OF OT CYCLES AND THE FRACTURE PARAMETERS

In Texas there are two OT test procedures: Tex-248-F: *Test Procedure for Overlay Test* and the modified version of Tex-248-F: *Test Procedure for Overlay Test (TxDOT 2009).* Tex-248-F is a routine test for asphalt mix design to evaluate cracking resistance of asphalt mixes. In the process of asphalt mix design, the OT test is often run at 77°F with a maximum opening displacement of 0.025 inches. The modified Tex-248-F is used to determine fracture properties (*A* and *n*) of asphalt mixes. These two test procedures are identical except for the maximum opening displacement. The modified version is run at a reduced maximum opening displacement: 0.017inches. (Note that details of the modified Tex-248-F and the steps to determine fracture properties (*A* and *n*) are documented in reference *Zhou et al. 2009*.) Therefore, in order to develop the relationship, the same mix must be evaluated under these two test procedures.

A total of 25 mixes, including dense-graded, Superpave, and SMA, were selected in this study. For each mix, 10 OT specimens with 7±1 percent air voids were prepared for each mix. Five OT specimens were tested under the standard Tex-248-F with a 0.025 inch maximum opening displacement, and the rest five OT specimens were used for the modified Tex-248-F with a 0.017-inch maximum opening displacement. The average values of the OT cycles to failure and fracture properties (*A* and *n*) for each mix are listed in Table B2. Figures B1 and B2 show the relationships among OT cycles *A* and *n*, respectively. With these relationships, the balanced

RAP/RAS mix design for project-specific service conditions is proposed and described in the next section.

Table B2. OT Test Results of 25 Mixes.

No.	Mixes		OT Cycles @0.025"	Fracture Properties	
	Description	Mix type		A	n
1	US87 S1-RAS mix	Dense-graded mix	94	1.3677E-06	4.0833
2	US87 S2-RAS mix		48	7.8997E-06	3.7445
3	SH143-RAP mix		5	2.2461E-03	2.5136
4	SH359-RAP mix		3	7.6451E-04	3.0370
5	Loop820-RAP/RAS/WMA		8	3.9572E-05	3.2465
6	Dallas-Ty B mix		22	6.2163E-05	3.3900
7	Dallas-Ty C mix		128	7.9056E-06	3.7014
8	PG64-34-5% TamKo RAS mix		322	2.9004E-08	5.3648
9	PG58-34-5% TamKo RAS mix		420	1.0015E-07	5.1560
10	Odessa Plant Mix S4		161	7.3597E-08	4.8755
11	PG64-34-5% Buda RAS mix		72	6.6989E-07	4.4910
12	Buda PG58-34-5% RAS mix		274	6.1648E-08	5.0803
13	PG64-22 15%RAP mix		76	1.0020E-06	4.3220
14	PG64-28 15%RAP mix		240	3.9073E-06	3.8385
15	PG64-34 15%RAP mix		926	5.8813E-08	5.1721
16	Paris-PG58-34 15%RAP mix		274	8.3199E-08	5.1880
17	Amarillo-20%RAP-I40 plant mix		103	3.8371E-07	4.6076
18	NCAT N9-1 plant mix	Superpave mix	55	8.1553E-07	4.1200
19	NCAT N9-2 plant mix		8	6.4143E-06	3.5650
20	MnRoad Cell2 plant mix		356	1.1148E-08	5.7841
21	MnRoad Cell16 plant mix		100	2.4601E-06	4.1542
22	NCAT S6-1 plant mix		28	2.6396E-06	3.8433
23	NCAT N10-1 plant mix		38	2.4574E-07	4.3536
24	Lubbock PG70-28 mix	SMA	827	5.1984E-09	5.7962
25	Lubbock PG70-28 mix		957	1.2871E-09	6.4071

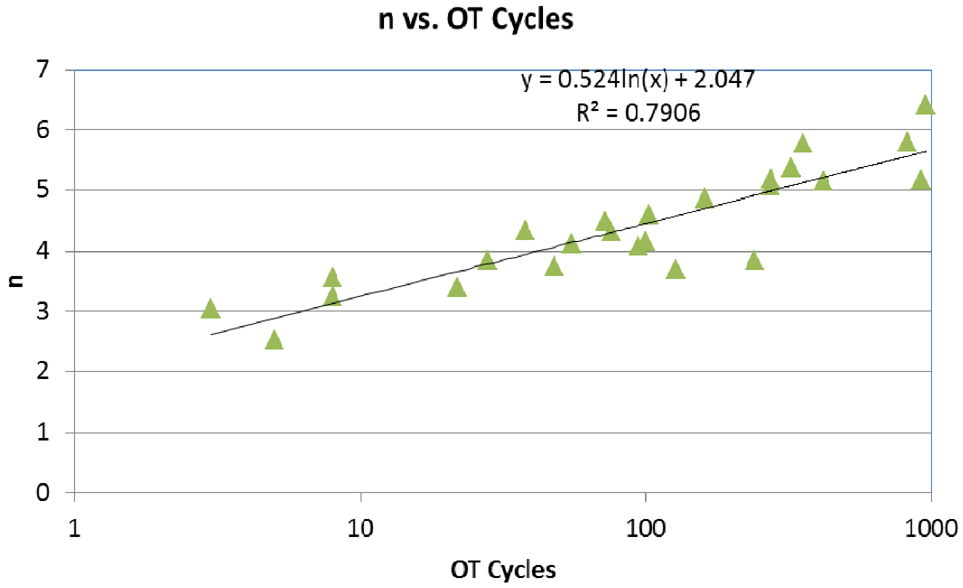


Figure B1. Relationship between OT Cycles and *n*.

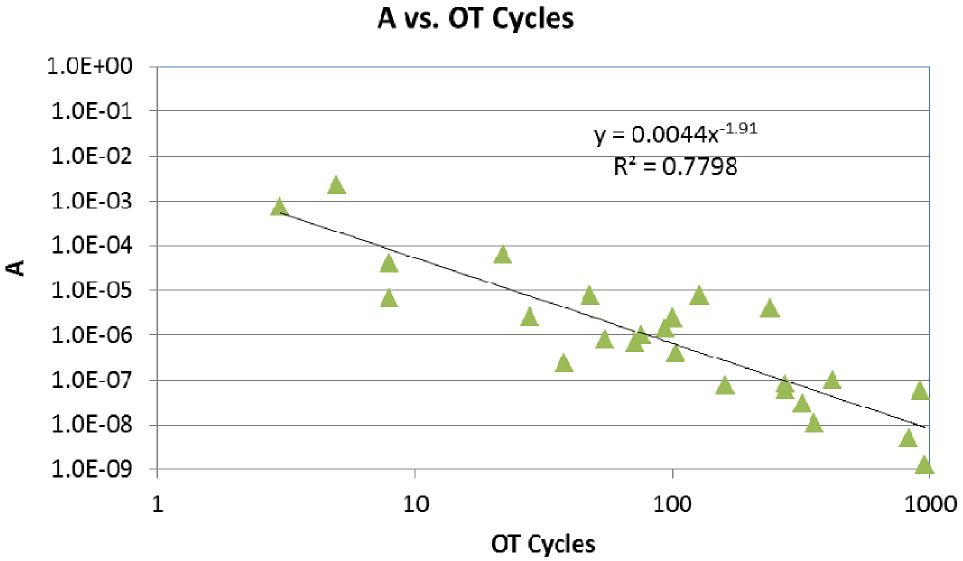


Figure B2. Relationship between OT Cycles and *A*.

PROPOSED BALANCED RAP/RAS MIX DESIGN FOR PROJECT-SPECIFIC SERVICE CONDITIONS

Figure B3 shows the proposed RAP/RAS mix design system for project-specific service conditions. This system integrates both mix design and pavement structure design, which has been pursued for a long time. Basically, the proposed system is an expanded balanced 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 B4. Note that S-TxACOL uses exactly the same reflective cracking models as those in

TxACOL (*Zhou et al. 2010*). Three mechanisms (shearing, bending, and daily thermal movement) of reflective cracking are all modeled through fracture mechanics. These models have recently been re-validated through an implementation study with independent field test sections in Texas (*Hu et al. 2013*).

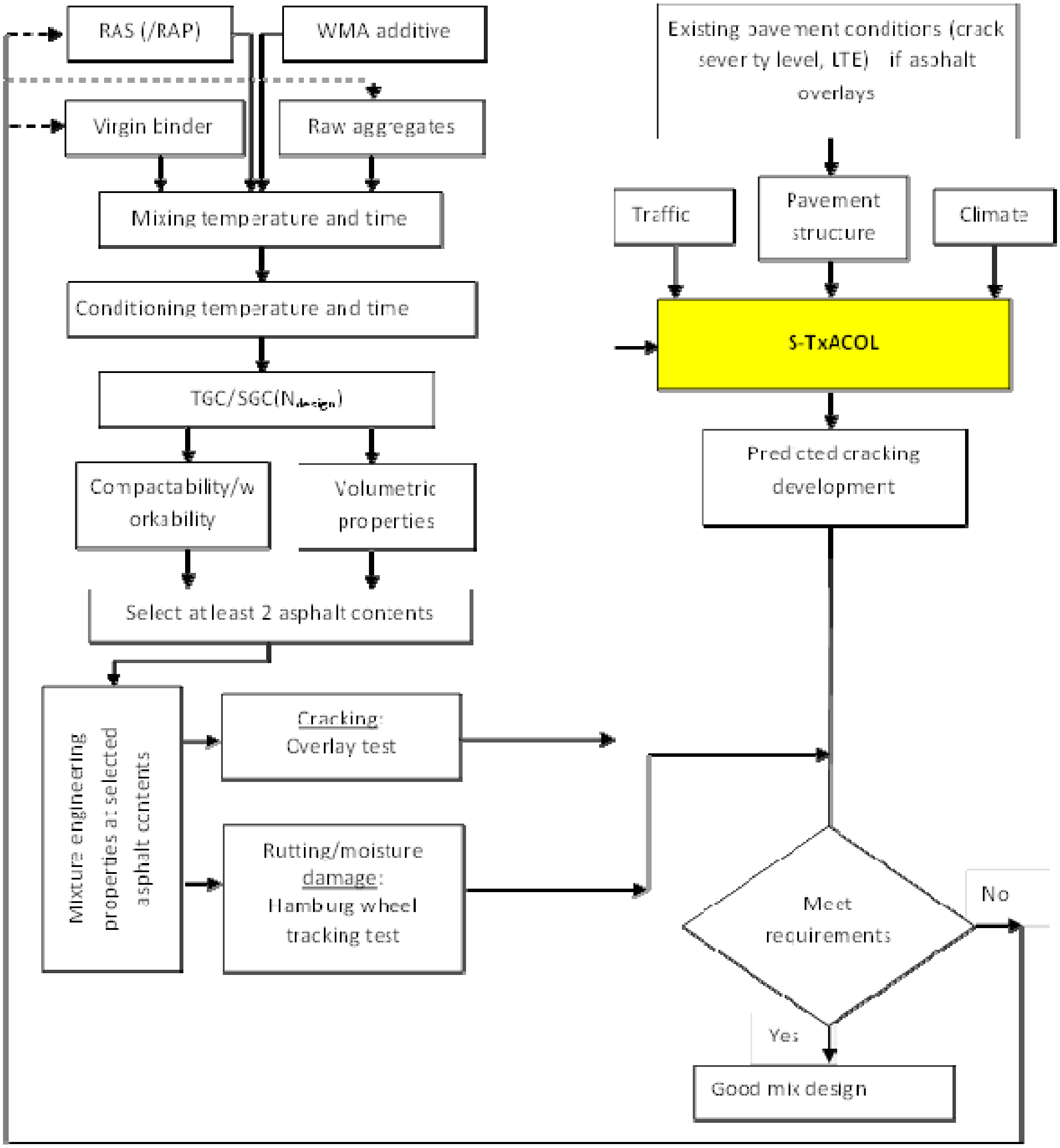
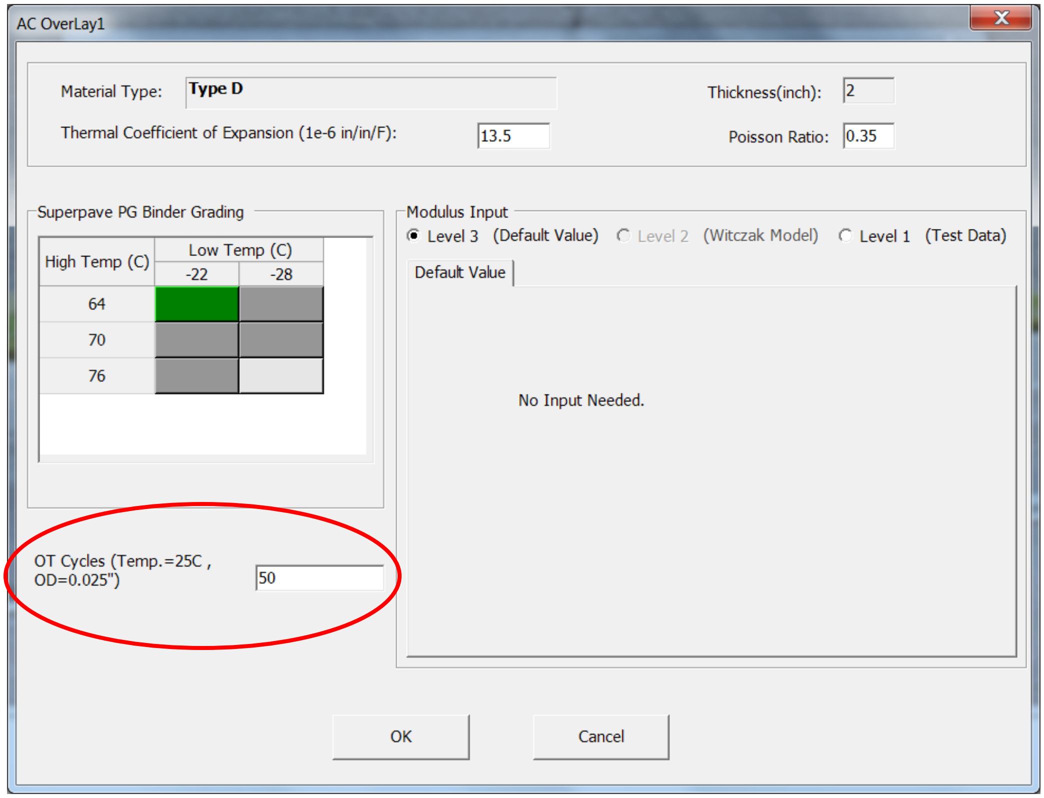


Figure B3. Balanced RAP/RAS Mix Design and Performance Evaluation System for Project-Specific Service Conditions.



Material Type: **Type D**

Thickness(inch): 2

Thermal Coefficient of Expansion (1e-6 in/in/F): 13.5

Poisson Ratio: 0.35

Superpave PG Binder Grading

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

Modulus Input

● Level 3 (Default Value) ○ Level 2 (Witczak Model) ○ Level 1 (Test Data)

Default Value

No Input Needed.

OT Cycles (Temp.=25C, OD=0.025"): 50

Figure B4. OT Cycles Input Interface for S-TxACOL.

In summary, this section described the balanced RAP/RAS mix design and simplified performance evaluation system for project-specific service conditions. In this system the Hamburg wheel tracking test and associated criteria are used to control rutting/moisture damage. The S-TxACOL prediction model with the input of the OT cycles computes the amount of reflective cracking development with time with consideration of climate, traffic, pavement structure, and existing pavement conditions. The next section includes case studies presented to demonstrate this approach.

DEMONSTRATION OF VARIOUS CRACKING REQUIREMENTS FOR PROJECT-SPECIFIC SERVICE CONDITIONS

Two series of case studies were performed using the simplified TxACOL to demonstrate the importance of varying cracking requirements for different applications. Detailed information is described below.

Case 1: Impact of Different Existing Pavement Conditions on Cracking Requirements

A 2-inch (50 mm) asphalt overlay with PG 70-22 binder is applied to the following existing pavements with different load transfer efficiency (LTE) in Bastrop County, Austin District. The traffic level is 3 million ESALs within 20 years. The relationship between OT cycles and cracking development for each application predicted from S-TxACOL is shown in Figures B5 and B6.

- 10-inch (250 mm) Jointed Portland Concrete Pavement (JPCP) over 6-inch (150 mm) base with LTE=70 percent.
- 3-inch (75 mm) asphalt pavement over 10 inch (250 mm) cement stabilized base (CTB) with LTE=70 percent.
- 5-inch (125 mm) asphalt layer over 12-inch (300 mm) granular base with medium severity cracking (LTE=70 percent).
- 10-inch (250 mm) Continuous Reinforced Concrete Pavement (CPCP) over 6-inch (150 mm) base with LTE=90 percent.
- 8-inch (200 mm) asphalt layer over 10-inch (250 mm) very stiff base with low severity level (LTE=50 percent).

The results shown in Figures B5 and B6 clearly indicate that varying OT cycles (or cracking requirement) are necessary for different applications. In order to have the same overlay life, the mix being used for asphalt overlay over JPCP should have higher OT cycles when compared to asphalt overlay over CRCP. Clearly, it is much safer to use RAP/RAS mixes for asphalt overlay over CRCP.

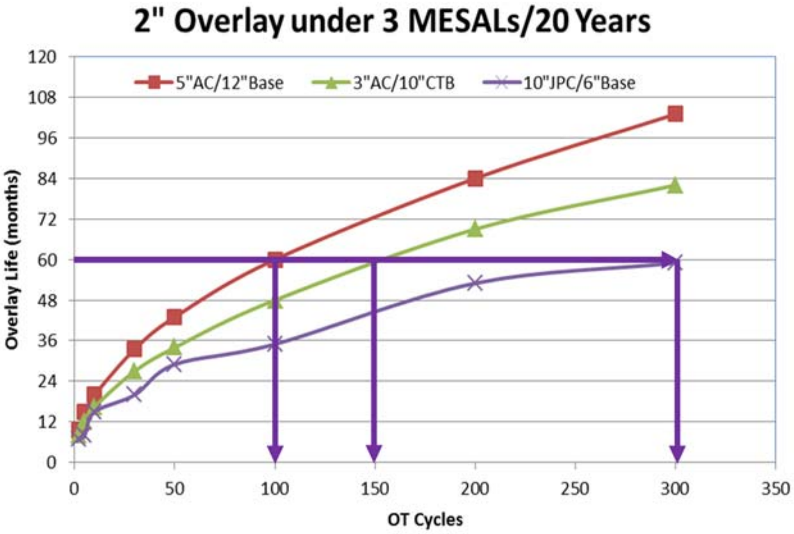


Figure B5. Relationships between OT Cycles and Cracking Development for Three Applications with Medium Cracking Severity.

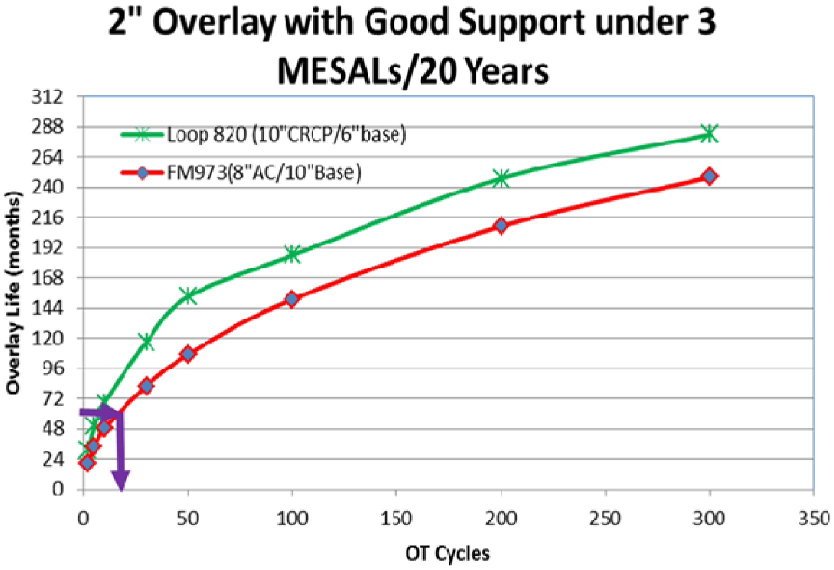


Figure B6. Relationships between OT Cycles and Cracking Development for Two Applications with Very Good LTE.

Case 2: Impact of Climate on Cracking Requirements

Again, the same 2-inch (50 mm) asphalt overlay with PG 70-22 binder is applied to the following existing pavements at three climatic zones: Amarillo, Austin, and McAllen. Amarillo has severe winter conditions with lots of freeze-thaw cycling, and McAllen has a very mild winter with no freeze-thaw cycle. The same traffic level of 3 million ESALs within 20 years is assumed. The relationship between OT cycles and cracking development for each application predicted from S-TxACOL is shown in Figures B7, B8, and B9. The overlay life is defined as time until 50% return of reflective cracking. It is obvious that climate has significant influence on cracking development and consequently on cracking requirement.

- 10-inch (250 mm) Jointed Portland Concrete Pavement over 6-inch (150 mm) base with LTE=70 percent.
- 3-inch (75 mm) asphalt pavement over 10 inch (250 mm) cement stabilized base with LTE=70 percent.

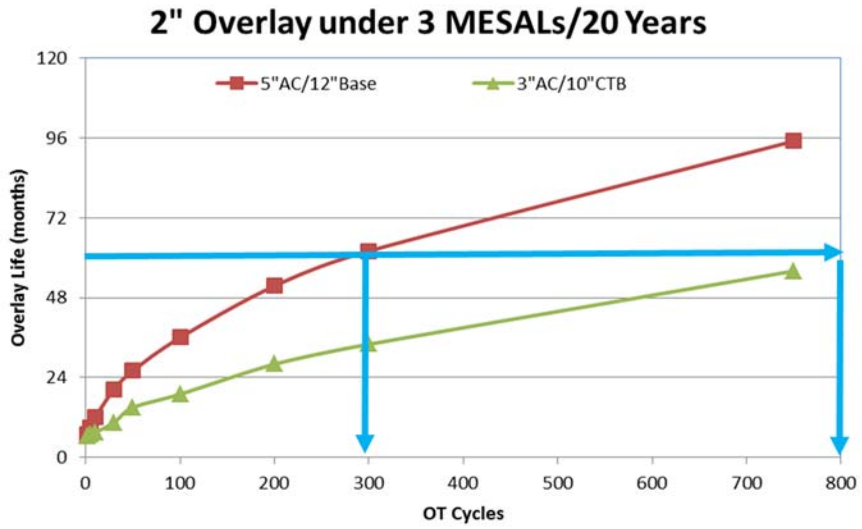


Figure B7. Amarillo: Relationships between OT Cycles and Cracking Development.

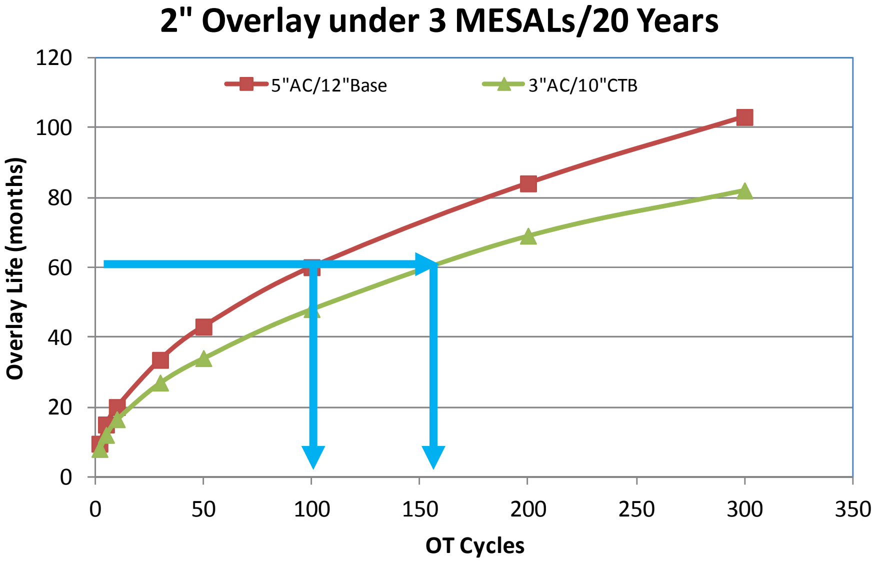


Figure B8. Austin: Relationships between OT Cycles and Cracking Development.

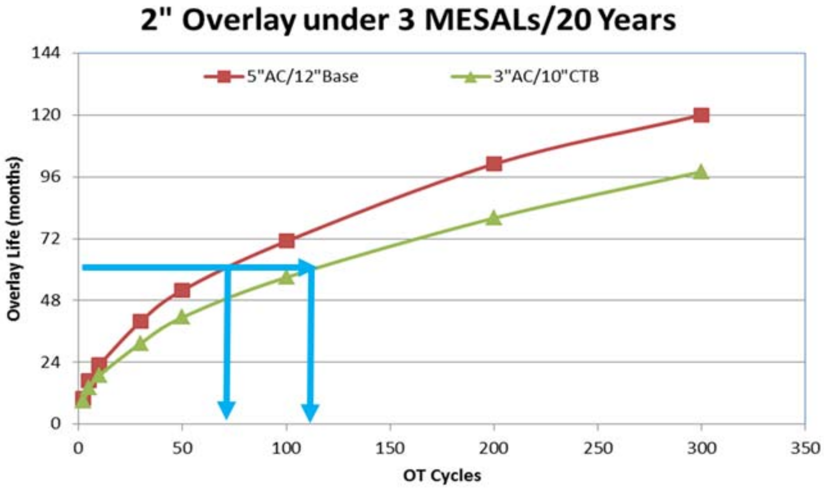


Figure B9. McAllen: Relationships between OT Cycles and Cracking Development.

In summary, all things else being equal, to get equivalent life until reflective cracking returns different OT requirements are needed for these three zones. For the flexible pavement design, the OT requirement changes from 65 to 300 cycles with a change from mild to cold climates. This section further demonstrates that a single cracking requirement does not apply to all asphalt overlay applications and the necessity of performing S-TxACOL analysis for project-specific service conditions.

SUMMARY

The researchers developed a RAP/RAS mix design system for project-specific service conditions. The developed design system includes a balanced mix design and a performance evaluation system in which the Hamburg wheel tracking test and associated criteria are used to control rutting/moisture damage, and the Overlay test and the required OT cycles determined from S-TxACOL cracking prediction with consideration of climate, traffic, pavement structure, and existing pavement conditions are employed for controlling cracking. It is recommended that the developed mix design system for project-specific service conditions should be implemented in TxDOT's districts for designing both dense-graded and SMA mixes containing RAP/RAS.

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Hu, S., F. Zhou, and T. Scullion. *Implementation of Texas Asphalt Concrete Overlay Design System*, FHWA/TX-12/5-5123-03-1, Texas Transportation Institute, College Station, TX, 2013.

TxDOT Designation: TEX-248-F. Overlay Test. Construction Division, Texas Department of Transportation, 2009.

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Zhou, F., Hu, S., and Scullion, T. "Advanced Asphalt Overlay Thickness Design and Analysis System", *Journal of Association of Asphalt Paving Technologists (AAPT)*, Vol. 79, Sacramento, CA, 2010.

APPENDIX C
GUIDELINES AND APPROACHES FOR IMPROVING CRACKING RESISTANCE OF RAS MIXES

It is well known that the use of RAS can improve rutting resistance of asphalt mixes, but it causes poor cracking resistance of the mix and, consequently, the poor durability of asphalt mixes. Therefore, some approaches need to be taken to balance the performance of RAS mixes. Following are three approaches:

- Rejuvenating RAS binder in the mix design process.
- Using soft virgin binders especially on the low temperature grade (i.e., PGXX-28, PGXX-34).
- Increasing design density (lowering design air voids) or reducing N_{design}.

The use of rejuvenators discussed in Chapter 3 is an effective way to improving cracking resistance of RAS mixes. This appendix focused on the last two approaches—using soft binder and increasing design density—and evaluated the effectiveness of these two approaches in improving cracking resistance of RAS mixes.

USE OF SOFT BINDERS

The same RAS mix with 5-percent RAS/PG64-22 used on FM973 test section No. 4 was used here. In addition to TOAS-E, MWAS-C was also used in this study for comparison between TOAS and MWAS. Two soft binders selected in this study are PG64-28 and PG64-34. A total of six mixes (2 RAS and 3 virgin binders) listed in Table C1 were evaluated under dynamic modulus test (AASHTO TP79), HWTT (Tex-242-F), and OT (Tex-248-F). Note that the same 5.2-percent OAC was used for all six mixes since the purpose is to investigate the influence of soft binders. Figures C1, C2, and C3 show the test results.

Table C1. RAS Mixes with Soft Virgin Binders.

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

Figure C1 shows that RAS mixes with softer binders have slightly lower moduli, but the difference among these six mixes is very small in terms of dynamic modulus. Meanwhile, compared with the 5-percent RAS/PG64-22 mix, the use of softer binders improved rutting/moisture damage, as indicated in Figure C2. The reason for the improvement is that both PG64-28 and PG64-34 are polymer-modified binders. As expected, the mixes with the MWAS-C have deeper rut depths than those with TOAS-E. Figure C3 clearly indicates 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 little impact on the dynamic moduli of RAS mixes, whereas, it can improve both rutting and cracking resistance of RAS mixes, especially cracking resistance.

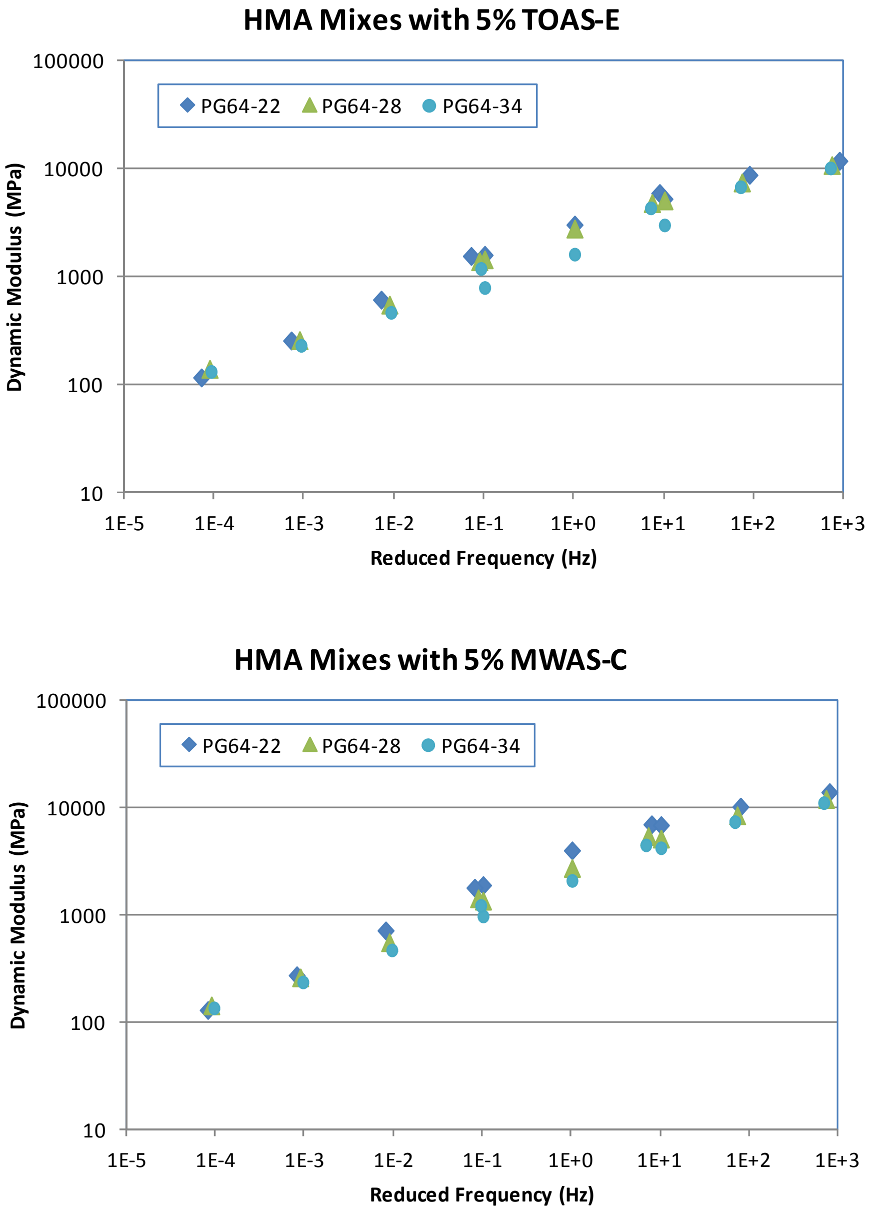


Figure C1. Impact of Soft Binders on Dynamic Modulus of 5-Percent RAS Mixes.

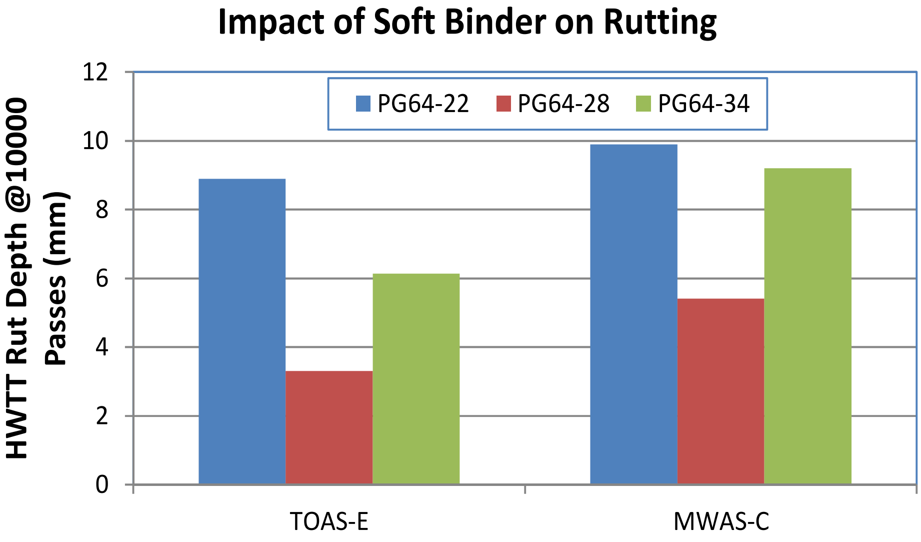


Figure C2. Impact of Soft Binders on Rutting/Moisture Damage of 5-Percent RAS Mixes.

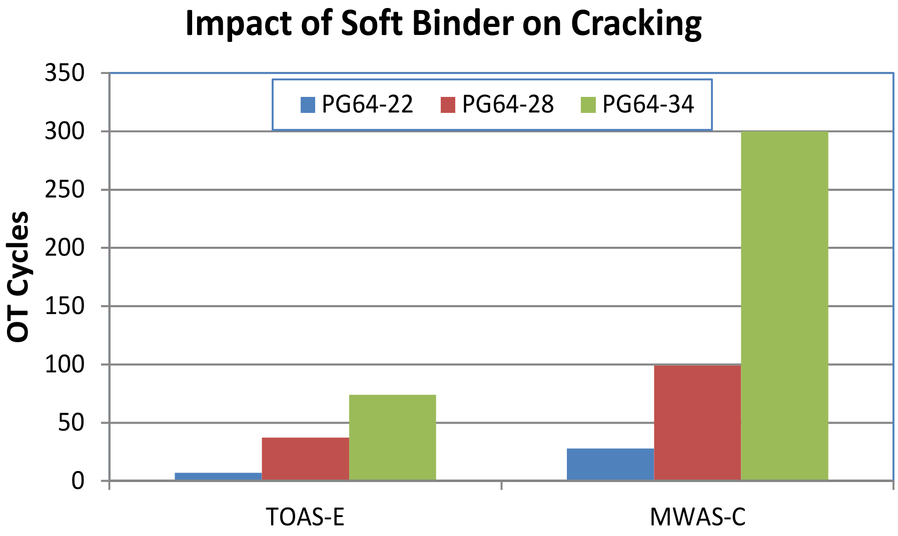


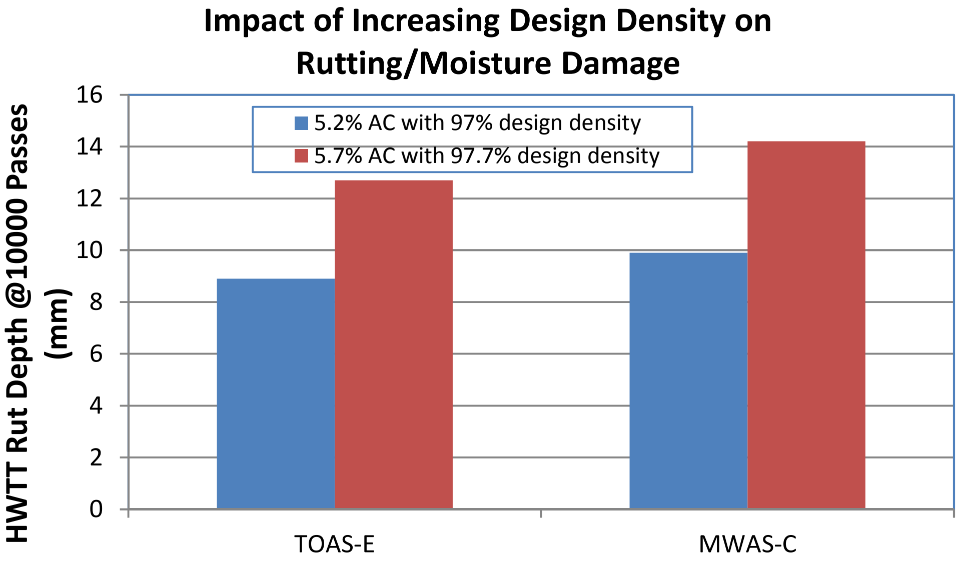
Figure C3. Impact of Soft Binder on Cracking Resistance of 5-Percent RAS Mixes.

INCREASING DESIGN DENSITY

Another simple way to improve cracking resistance of RAS mixes is to add more virgin binder into the mixes through increasing design density (or lowering the design air voids) when selecting OAC (alternatively, one can reduce N_{design}). Currently the design density for selecting OAC of RAP/RAS mixes is 97 percent. To avoid bleeding problem, the maximum design density should be less than 98 percent. Again, the same 5-percent RAS/PG64-22 mixes with TOAS-E and MWAS-C previously designed were used here. Two design densities, 97 percent and 97.7 percent, were used. The corresponding OACs are 5.2 percent and 5.7 percent, respectively.

Only the HWTT (Tex-242-F) and OT (Tex-248-F) testing were performed, and the dynamic modulus test was omitted since the previous results did not show much difference among different RAS mixes. Figure C4 shows the test results.

Figure C4 shows that the higher OAC corresponding to increased design density significantly improves cracking resistance, which is desirable. Meanwhile the higher OAC makes the RAS mixes more susceptible to potential rutting/moisture damage. Therefore, one must exercise caution when improving cracking resistance of RAS mixes through increasing design density.



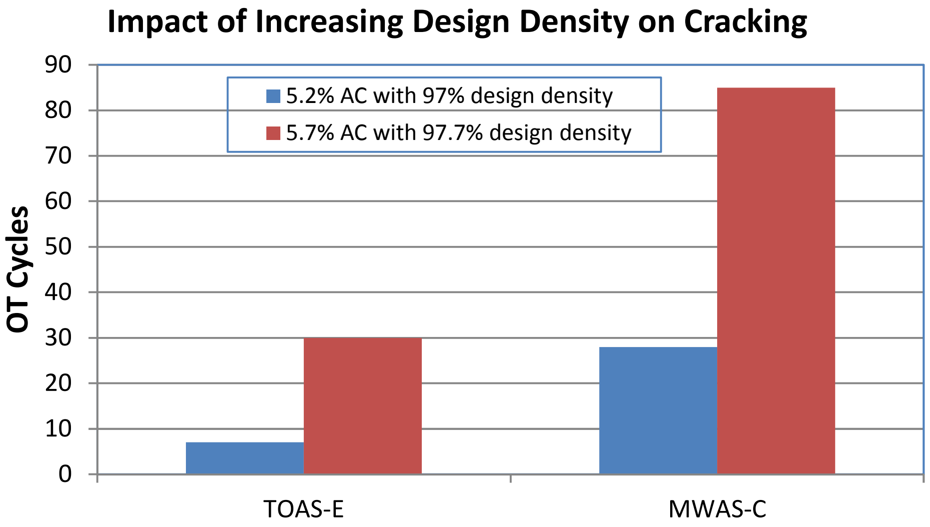


Figure C4. Impact of Increasing Design Density on Rutting/Moisture Damage and Cracking Resistance of RAS Mixes.

SUMMARY

Both laboratory and field performance (Chapter 2) clearly indicated that cracking performance of RAS mixes can be improved by employing the following approaches:

- Rejuvenating RAS binder in the mix design process.
- Using soft virgin binders especially on the low temperature grade (i.e., PGXX-28, PGXX-34).
- Increasing design density (lowering design air voids) or reducing N_{design}.

It is highly recommended that districts start to use these approaches for longer pavement life.

APPENDIX D
ENVIRONMENTAL BENEFITS AND COST IMPACTS OF RAS ON ASPHALT MIXTURES

INTRODUCTION

Pavement construction and rehabilitation are among the largest consumers of natural resources. Therefore, the use of recycled materials in pavements represents an important opportunity to conserve both materials and energy. However, neither asphalt paving contractors nor any other industry, for that matter, recycles materials simply to improve the environment. If the particular recycling process is not profitable, it is not likely to be sustainable. Considering the current and predicted future price of virgin asphalt cement, the use of RAS in asphalt paving mixtures offers significant economic as well as environmental benefits. The primary economic driver for asphalt shingle recycling is the AC cost savings derived by HMA producers (Krivit, 2005; Johnson et al., 2010). Thus, the main environmental benefits are avoiding deposition of millions of tons of non-biodegradable material in precious landfills along with conservation of fossil fuels and aggregates. Recycling of asphalt shingles is a growing industry that could foster business opportunities, create jobs, and generate revenue.

Many variables come into play when estimating potential cost savings when using RAS in asphalt mixtures, both HMA and WMA. Such variables include:

- Type of the asphalt mixture produced.
- Price of neat liquid asphalt.
- Amount (%) of RAS used in the paving mixture.
- Type of RAS used (post-consumer or manufacturing waste).
- Cost of aggregates alternative to those contributed by the RAS.
- Landfill tipping fees.
- Capital cost of equipment for grinding/handling RAS.
- Expenses for acquisition, transporting, processing, and handling RAS.

NAHB (1998) reported that roof installation annually generates an estimated 7 to 10 million tons of post-consumer or TOAS and construction debris. US shingle production plants generate another 750,000 to 1 million tons of MWAS. In 2011, 11 million tons of waste shingles is likely a very conservative estimate. Hansen (2009) pointed out that this represents more than 2 million tons of asphalt cement potentially available for use in asphalt paving mixtures or a replacement of almost 9 percent of the current national need for liquid asphalt in pavement construction. Assuming 5 percent AC in a paving mixture and a 1-inch thick layer, 2 million tons of HMA is enough to resurface 108,000 lane-miles of pavement—almost halfway to the moon or more than 4 times around the equator.

Regrettably, Rahim (2010) reported that only 5 percent of shingle waste is recycled in new construction. The ever-increasing amount of waste shingles poses a significant environmental and economic concern. As the price of crude petroleum, and thus liquid asphalt, increases, so will the value of RAS. If a suitable means of reusing most of these materials can be found, then their environmental liability could be significantly diminished.

According to Rahim (2010), AASHTO adopted a standard specification for asphalt shingle use in HMA in 2005. This national specification guides the use of RAS in HMA and enables HMA producers to design mixtures that satisfy typical specifications of state and local transportation agencies. The AASHTO specification permits the use of both MWAS and TOAS. In 2006, AASHTO adopted a recommended practice, PP 53, to supplement the standard specification and then updated it in 2009. These provide significant aid and encouragement for utilizing RAS in HMA.

ENVIRONMENTAL ISSUES

Current published information suggests that recycling of asphalt shingles, particularly in HMA, is technically feasible and is likely to offer economic, environmental, and maybe even engineering benefits.

Asbestos

Published literature suggests that asbestos is the number one concern related to the use of RAS (Hansen, 2009). This is primarily an air emission concern related to liberation of asbestos fibers during grinding and handling ground TOAS and, thus, creating a serious health hazard (Rahim, 2010). In fact, major impediments to the recycling of TOAS are environmental and regulatory concerns, predominantly with regard to asbestos (Marks and Gerald, 1997; NAHB, 1998; ARMA, 1998; Zickell, 2003; Lee et al., 2004; Krivit, 2007). The use of asbestos in residential shingles was discontinued in the late 1970s in the United States. Therefore, asbestos has not been used in the manufacture of asphalt shingles for about 30 years, and since the typical life of roofing shingles is from 12 to 25 years, asbestos is seldom encountered in TOAS or in other roofing products (Townsend et al., 2007; Krivit, 2007).

McMullin (2007) asserted that the content of asbestos in shingles in 1963 was only about 0.02 percent by weight. In 1977, the content of asbestos in shingles was only 0.00016 percent by weight. The chances of finding any asbestos in TOAS is a about 0.8 percent of shingles (roughly 0.5 percent show a trace, 0.17 percent show 2 percent, and 0.11 percent show 5 percent [based on 1770 samples reported by the Chelsea Center at the University of Massachusetts in 2003]). As a result of these findings, the State of Maine no longer requires asbestos testing. Grefe (2007) reported that, after hundreds of tests, less than 1 percent yielded presence of asbestos.

According to Schroer (2009), the National Emissions Standards for Hazardous Air Pollutants (NESHAP) under the United States Environmental Protection Agency (EPA) has an exemption based on these facts. In the Appendix of the Code of Federal Regulations, Section 40, Subpart M, shingles from 4-plex or smaller residential dwellings are exempt from asbestos testing, in accordance with local regulations. A few tests have indicated a trace of asbestos but no measurable levels. Experts believe that the asbestos was contained in mastics used for sealing joints in roofs and/or rolled roofing (Townsend et al., 2007).

Asbestos was once used in asphalt shingles to act as reinforcement (i.e., a fibrous mat) for the shingle and also acted as a fireproofing/insulating material. Asbestos was also used in certain other roofing products. Townsend et al. (2007) presented a summary of information published in the Federal Register along with data they collected by from other sources showing how asbestos was used in shingles and other roofing products (Table D1).

Table D1. Asbestos-Containing Asphalt Roofing Products (after Townsend et al., 2007).

Manufacturer	Years Manufactured	Product
Barber Asphalt Corporation	Information not available	Asphalt-asbestos roofing felt or mat
Carey Manufacturing Company	Information not available	Asphalt-asbestos shingles, asbestos finish felt, mastic
The Celotex Corporation	1906 through 1984	Asphalt roof coating and other miscellaneous materials
Fibreboard Corporation	1920 to 1968	Roof paint, roll roofing with asbestos-containing base sheets, caulking compounds, plastic cements, taping and finishing compounds
General Aniline and Film Corporation	Information not available	Roofing asphalt
Johns-Manville Corporation	1891 through 1983	Asphalt-asbestos shingles, rag-felt shingles, fibrous roof coating, shingle tab cement, roof putty
Kaylite Company	Information not available	Asbestos surface coating for shingles
National Gypsum Company	1941 through 1981	Roofing and shingles
Monroe Company	Information not available	Asbestos surface coatings for shingles
Rhone-Poulenc Ag Company	Early 1930s through 1976	Adhesives, coatings, sealants, and mastics
United States Gypsum Company	1930 through 1977	Paper and felt

Most shingle processors in Missouri document the source of the shingles but do not routinely test for asbestos, following the NESHAP guidance (Schroer, 2009). Hansen (2009) recaps that the occurrence of asbestos in TOAS from residential roofs will be minimal but that the recycling facility operator may expect to occasionally encounter asbestos-containing material and should be prepared to inspect and manage such materials.

Polycyclic Aromatic Hydrocarbons

Townsend et al. (2007) published an extensive review of environmental issues associated with use of RAS in HMA. They explained that since asphalt shingles contain a petroleum-derived product (i.e., asphalt), they contain polycyclic aromatic hydrocarbons (PAHs). PAHs comprise a group of more than 100 chemicals formed primarily during the incomplete burning of coal, oil, or gas (ARMA, 1998). Many PAHs are harmless. However, at elevated levels of exposure, some PAHs are known to have detrimental effects on human health (e.g., cataracts, kidney and liver damage, cancer).

The potential risk pathways for PAH compounds from RAS are not well understood (Rahim, 2010). Issues have been raised regarding PAH migration into ground water (e.g., leaching from stockpiles), direct exposure to humans via dust during grinding and handling RAS, and release during handling at HMA facilities. Therefore, do ground recycled asphalt shingles pose either a direct exposure risk or a leaching risk or does the use of RAS in HMA production impact PAH emissions? Leaching tests by Kreich et al. (2002) (leached using the toxicity characteristic leaching procedure [TCLP]) indicated that four different asphalt roofing materials yielded results that were below the detection limit (0.1 mg/L) for 29 selected PAHs. Townsend et al. (2007) reported two other TCLP leaching studies (using materials from Maine and Florida) with similar results. Wess et al. (2004) assessed the effects of runoff water from asphalt pavements in California. Samples collected from water-draining road surfaces were analyzed for PAHs and selected heavy metals (lead, zinc, cadmium). Results indicated that concentrations of the PAH analytes in all stream and road runoff samples were below the detection limit of 0.5 µg/L.

Townsend et al. (2007) stated that the question of PAH emissions from HMA plants using RAS has been raised, but no data exist to suggest that such practices would result in PAH emissions any different from HMA using virgin asphalt. They deduced that environmental risks associated with PAH migration appear to be small and comparable to that presented by any material containing asphalt. They further noted that, on a life-cycle basis, overall emissions may be reduced because of the energy offsets that using recycled asphalt shingles would provide versus using exclusively virgin asphalt materials.

Greenhouse Gas Emissions

Cochran (2007) conducted a preliminary analysis of reductions in greenhouse gas (GHG) emissions due to recycling TOAS. Her analyses indicated that the equivalent of about 0.27 to 0.29 lb of CO_2 equivalents are reduced for every ton of tear-off asphalt shingles recycled.

Canada produces about 36 million tons of HMA per year. According to Clapham (2007), if only 5 percent of this total annual production of HMA used recycled shingles, a reduction of 108,000 tons of CO_2 emission could be achieved.

Other Air Emissions

Hughes (1997) pointed out that there is occasional consternation that asphalt mixtures containing recycled materials may not be able to be recycled in the future. A particular concern is whether air emissions from the HMA facility will thereby be increased. However, since the generic composition of RAS is essentially the same as that of asphalt mixtures, the recyclability and air emissions of mixtures containing RAS are not concerns. Since the asphalt in RAS is typically harder than that in HMA or RAP, particularly that in TOAS, one could argue that HMA or RAP containing RAS will release fewer volatile organic compounds than conventional HMA or RAP.

Sengoz and Topal (2005) pointed out that shingle recycling may actually *reduce* emissions of potentially hazardous components associated with the mining, production, and transport of virgin materials (asphalt and aggregates) that they replace. Inevitably, regulatory agencies must provide regulations, policies, and permit conditions that (1) afford protection for human health and the environment, (2) are appropriate for the risk presented, and (3) are not unnecessarily severe (and thus inhibit recycling).

Energy Savings

According to Krivit (2007), using RAS in HMA plants results in energy savings from three sources:

- Reduced use of virgin asphalt cement.
- Reduced energy to dry/heat virgin aggregates in the HMA plant.
- Reduced electricity and other fuel to run the overall HMA plant.

Krivit (2007) further stated that, depending on the logistics of the specific shingle recycling system compared to the traditional HMA plant based solely on virgin materials, there could be additional energy savings due to reduced transportation (e.g., if shingles are processed and used near their source of generation).

Cochran (2007), of the US EPA, conducted a preliminary analysis of energy savings of recycling tear-off shingles and found that the equivalent of about 200 kilowatt-hours of electricity is saved for every ton of tear-off asphalt shingles recycled. She admitted that this analysis was very preliminary and should be refined.

Life-Cycle Environmental Impacts

Cochran (2006) conducted a comprehensive life-cycle analysis that compared recycling of asphalt shingles (separated at the job site or separated at a materials recovery facility) with disposal (in an unlined or lined landfill). This study evaluated environmental impacts from management methods and emissions to air, soil, and water. Impacts analyzed included global warming potential, human toxicity potential, abiotic (e.g., water, sand, or gravel) depletion potential, and acidification potential. According to her analysis, shingle recycling reduced the environmental and energy burden associated with the manufacture of asphalt from crude oil but, of course, added some burden as a result of the requirement for processing the shingles prior to reuse. She found that the net energy requirement associated with recycling shingles into HMA was less than the requirement associated with disposing of those shingles in a landfill and using all virgin materials for HMA production.

The University of California at Berkeley developed software (Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects® [PaLATE]) to assist with assessment of environmental and economic effects of pavements and roads. PaLATE takes user input for the design, initial construction, maintenance, equipment, and costs for a roadway and estimates life-cycle environmental effects and costs. Environmental effects that are investigated include (http://www.ce.berkeley.edu/~horvath/palate.html):

- Energy consumption.

- CO_2 emissions.
- NO_x emissions.
- PM_{10} emissions.
- SO_2 emissions.
- CO emissions.
- Leachate information.

Waste Reduction Model

The US EPA created a computer program called Waste Reduction Model (WARM) to help solid waste planners and organizations track and voluntarily report GHG emissions reductions from several different waste management practices including use of RAS. WARM is available free both as a web-based calculator and as a Microsoft Excel® spreadsheet at: http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html. The Excel-based version of WARM offers more functionality than the web-based calculator. WARM calculates and totals GHG emissions of baseline and alternative waste management practices, e.g., source reduction, recycling, combustion, composting, and landfilling. The model calculates emissions in metric tons of carbon equivalent, metric tons of carbon dioxide equivalent, and energy units (million BTU) across a wide range of material types commonly found in municipal solid waste.

ECONOMIC FACTORS

According to Krivit (2007), the economics of TOAS recycling are currently driven by three main factors: 1) prevailing landfill tipping fees; 2) price of virgin AC; and 3) cost of RAS production. The virgin AC price, as a world commodity, will generally follow national/international trends. The future of AC costs is expected to continue to increase over the long term. Figure D1 depicts an illustration of the price trend for AC (Peterson, 2011). Note that the prices in Figure D1 are rack prices; to estimate typical bid prices for asphalt, one should add about $100 or a little more to these values. The point here is that as the price of asphalt increases, so does the value of asphalt shingles.

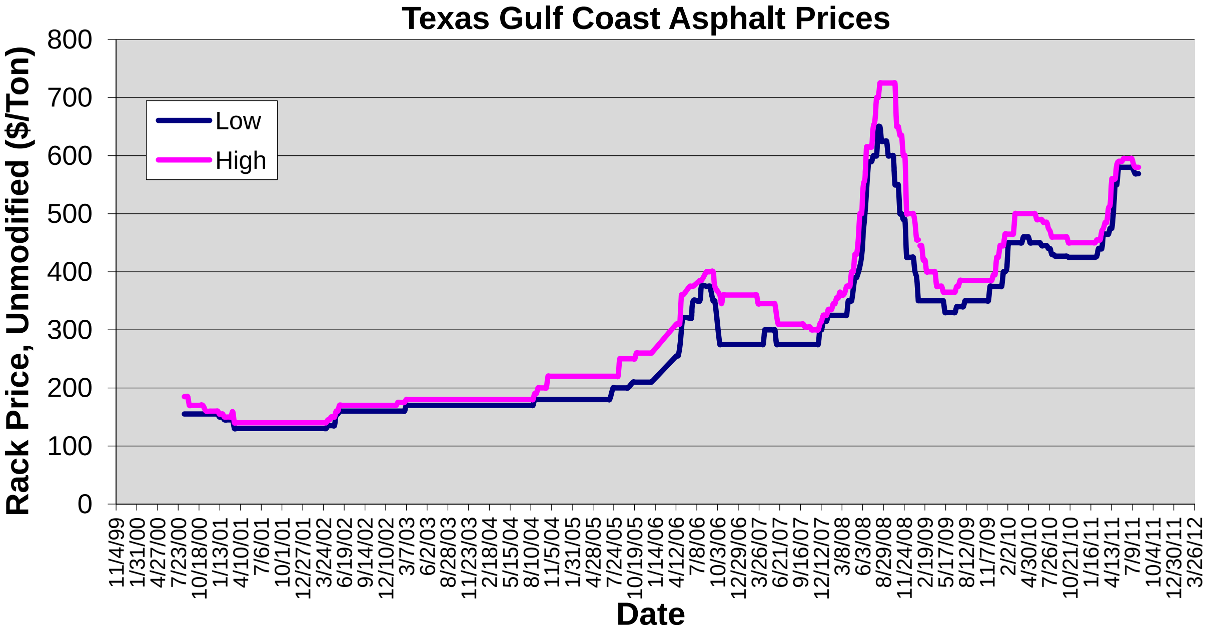


Figure D1. Price Trends for Liquid Asphalt from 1999 to 2011 (after Peterson, 2011).

Using conservative values, if one assumes RAS contains 20 percent recoverable AC, the use of only 2.5 percent RAS in HMA can reduce the virgin binder content by 0.5 percentage points. That is, one would use 4.5 percent virgin binder instead of 5.0 percent in a typical HMA. So, for each ton of HMA, 10 lb of virgin liquid AC would be saved. At a production rate of 300 tons per hour for 10 hours, 3000 tons of HMA is produced. Thus, in a day's production, one could save 15 tons of virgin AC. Using a cost of $600 per ton for virgin AC, this equates to a savings of $9000 per day minus the cost of 75 tons of ground shingles. Assuming a total cost of $40/ton for processing, transporting, and blending the RAS, 2.5 percent ground shingles in HMA will yield a net savings of $6000 per day or $2.00 per ton. If 5 percent RAS can be accommodated in the asphalt mixture, obviously, the net savings is double this value.

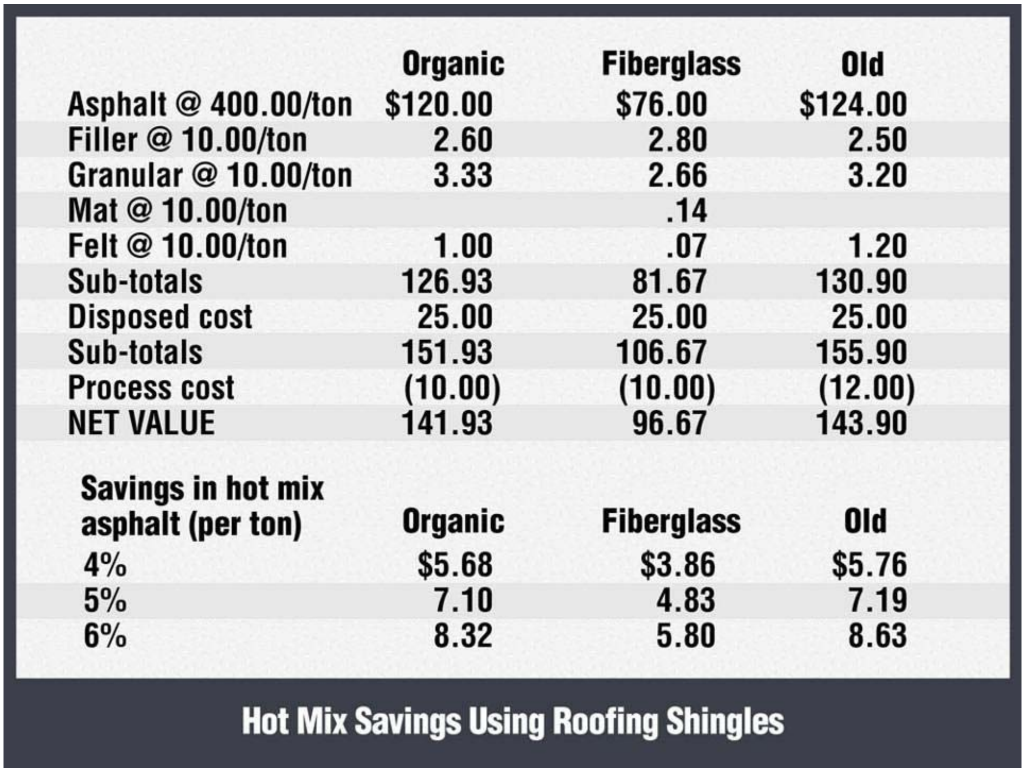
According to Krivit (2007), Bituminous Roadways, Inc. (BRI), in Missouri, indicated that the use of MWAS has become their standard practice with a large percentage of the HMA production incorporating RAS in the same manner as RAP is incorporated (Peterson, 2004). BRI realized savings of approximately $0.50 to $1.00 per ton of final HMA product with the use of 5 percent RAS. The average cost per ton for HMA was approximately $30 per ton in 2003 (Peterson, 2004). This is very similar to the savings reported by Allied Blacktop, based in Eau Claire, Wisconsin, who reported savings of about $0.50 per ton of HMA (Ayers, 2003). Maupin (2008) estimated a savings of $2.69 per ton of HMA containing 5 percent shingles. Other studies have indicated a savings of up to $3 per ton of final HMA (NAPA, 2000) back in 2000 when AC was less than $200/ton. With the current cost of AC at about $600 per ton, a savings of $3 per ton of HMA appears reasonable when using 5 percent shingles, and thus, a day's production of 3000 tons of HMA could save $9000.

Brock (2007), of Astec Industries, used the values for composition of three different types of shingles, shown in Table D2, and prepared a simplified economic analysis of RAS in HMA when the cost of liquid AC was \$400 per ton (Table D3). Therefore, in 2011, with the cost of AC around \$600/ton, the cost savings would be significantly greater. Although the value of RAS has surely increased with the price of AC, the price of RAS has probably not escalated to the same degree as virgin AC.

Table D2. Typical Shingle Composition (modified after Brock, 2007).

Item	**New Organic Shingles**		**New Fiberglass Shingles**		**Old Shingles (TOAS)**	
	lb/100 ft^2	%	lb/100 ft^2	%	lb/100 ft^2	%
Asphalt	68	30	38	19	73	31
Filler	58	26	83	40	58	25
Granules	75	33	79	38	75	32
Mat	--	--	4	2	--	--
Felt	22	10	--	--	28	12
Cut-Out	(2)	1	(2)	1	0	0
TOTAL	221	--	202	--	235	--

Table D3. Typical HMA Plant Economic Savings When Using RAS (after Brock, 2007).



	Organic	Fiberglass	Old
Asphalt @ 400.00/ton	$120.00	$76.00	$124.00
Filler @ 10.00/ton	2.60	2.80	2.50
Granular @ 10.00/ton	3.33	2.66	3.20
Mat @ 10.00/ton		.14	
Felt @ 10.00/ton	1.00	.07	1.20
Sub-totals	126.93	81.67	130.90
Disposed cost	25.00	25.00	25.00
Sub-totals	151.93	106.67	155.90
Process cost	(10.00)	(10.00)	(12.00)
NET VALUE	141.93	96.67	143.90

Savings in hot mix asphalt (per ton)	Organic	Fiberglass	Old
4%	$5.68	$3.86	$5.76
5%	7.10	4.83	7.19
6%	8.32	5.80	8.63

Hot Mix Savings Using Roofing Shingles

It currently appears that the price of liquid AC will increase at a faster rate than that of RAS. Therefore, the potential savings by using RAS in HMA is expected to increase. Investing in equipment and training necessary to incorporate RAS into HMA should be prudent. If landfill operators increased tipping fees for recyclable materials, such as asphalt shingles, economics would be further pushed in the direction of recycling. Grefe (2007) affirmed that the LaCrosse County, Wisconsin, landfill uses a differential fee structure to encourage contractors to supply separated shingles to a processing area.

Krivit (2007) stated that landfill tipping fees vary by region within the United States and concluded that the economics of shingle recycling are much more favorable on the North East region of the US, where landfill tipping fees can exceed $100 per ton. Most other parts of the country report tipping fees ranging from less than $10 per ton to about $45 per ton. According to the TCEQ (2007), the average state-wide tipping fee in Texas in 2006 was $25.70 per ton.

Therefore, Krivit (2007) concluded that shingle disposal is often cheaper than recovery for several reasons, including:

- Labor costs for sorting.
- Capital costs for processing equipment.
- Relatively low cost of disposal.
- Low market values for recovered products.
- Shingle transportation costs (particularly to rural areas).

The total volumes of recoverable construction and demolition material delivered to a recycling facility may be relatively low (particularly in Greater Minnesota). Furthermore, these tonnages and economies of scale are even lower when attempting to recover just one marketable material, such as RAS.

Hughes (1997) originally presented a very simplified economic analysis or worksheet for recycling RAS into HMA based on a generic cost-benefit model (Table D4). Krivit (2007) added Item G, in Table D4, to account for capital costs, as he contended that any specific net savings calculations must include calculations for the budgeted capital (e.g., land, buildings, and equipment) and operations/maintenance costs. He included additional items in Item H, stating that cost estimates should include labor, sales, and other marketing costs as well as utilities (including water) and transportation. Krivit (2007) further commented that all QA/QC costs related to RAS must be included, along with any laboratory costs for asbestos testing and final product engineering tests. A notable economic benefit to using MWAS over TOAS is that asbestos testing is not required.

Hansen (2009) illustrated potential savings of using RAS in an asphalt mixture by using the following values.

- RAS in mix = 5 percent.
- Effective (recoverable) AC content of RAS = 20%.
- Virgin AC = $600/ton.
- Fine aggregate in shingles = 30%.
- Value of fine aggregate = $10/ton.
- Tipping fee = $25/ton.
- Acquisition cost = $0/ton (assumes generator of waste pays this cost).
- Additional processing cost = $12/ton.
- Capital costs = $0 in this example.
- Miscellaneous costs = $0 in this example.

Using these above values with the original NAPA worksheet (Hughes, 1997), Hansen (2009) achieved a cost savings of $6.80 per ton of HMA. This clearly illustrates the value of RAS in asphalt mixtures (both HMA and WMA), with a majority of the savings coming from replacing virgin AC. The analysis should take into account the higher cost of AC when using quantities of RAS or RAS/RAP combinations that require a softer than normal grade of AC. In this case, the savings for Rows A and B would be based on the AC and aggregate content of the RAS or the combined RAP/RAS and the cost of the standard grade of AC. Then, an additional cost item would be needed to account for the higher cost of the softer AC. This higher cost would be the difference between the costs of the softer and standard grade of AC multiplied by the amount of virgin AC required.

Table D4. Method for Calculating the Value of RAS in Asphalt Mixtures (Modified after Hughes, 1997; Hansen, 2009; Krivit, 2007).

Calculation	**$/ton of Finished HMA**
Savings	
A. Savings from reduced need for new (virgin) asphalt cement (AC)	
New AC $/ton ( ) x %AC in RAS ( ) x % RAS in mix ( )	$__________
B. Savings from new (virgin) fine, bituminous aggregate	
New fine agg. $/ton ( ) x % fine agg. in RAS ( ) x % RAS in mix ( )	$__________
C. Savings from tipping fee	
Tipping fee $/ton ( ) x % RAS in mix ( )	$__________
D. Total Gross Savings per ton of hot mix (add: A + B + C) =	**$__________**
Costs	
E. Less acquisition cost of RAS (e.g., trucking cost):	
Acquisition cost $/ton ( ) x % of RAS in mix ( )	$__________
F. Less additional processing costs (e.g., sorting, crushing, screening):	
Processing cost $/ton ( ) x % of RAS in mix ( )	$__________
G. Less capital costs (e.g., equipment, land, improvements)	
Capital costs $/ton ( ) x % of RAS in mix ( )	$__________
H. Other miscellaneous costs of testing, engineering design (e.g., asbestos monitoring, mix design, other QC/QA)	
Costs $/ton ( ) x % RAS in mix ( )	$__________
I. Total costs (add: E + F + G + H) =	**$__________**
Net savings per ton of hot mix asphalt (Subtract: D − I) =	**$__________**

Rand (2011) deduced that proper use of unmodified binders (e.g., PG 64-22 instead of PG 70-22 or PG 76-22) along with RAP and RAS can reduce the cost of asphalt pavement material by more than $15/ton. The assumptions shown in Table D5 were used to determine the HMA cost estimates in Table D6 and Figure D2. Note that the cost estimates in Table D6 and Figure D2 represent material costs only. These do not reflect the total as-constructed cost of HMA and are based on 2011 cost data in Texas. Costs can vary significantly with circumstances.

Table D5. Assumptions Used for Asphalt Pavement Cost Estimates.

Material	Cost Per Ton	Notes
Aggregate	$22	Includes processing & freight
PG 76-22	$538	Based on September 2009* Index (freight not included)
PG 70-22	$480	Based on September 2009* Index (freight not included)
PG 64-22	$377	Based on September 2009* Index (freight not included)
RAP	$15	Contains 5% AC, includes processing & freight
RAS	$20	Contains 20% AC, includes processing & freight

*Source: Louisiana Asphalt Pavement Association

Table D6. Asphalt Pavement Cost Estimates.

Binder Grade	Virgin Mix	20% RAP Only	5% RAS Only	15% RAP + 5% RAS	*One Grade Softer Binder
PG 76-22	47.80	41.24	42.54	37.64	35.74
PG 70-22	44.90	38.92	40.22	35.74	32.39
PG 64-22	39.75	34.80	36.10	32.39	NA

*Includes 15% RAP and 5% RAS

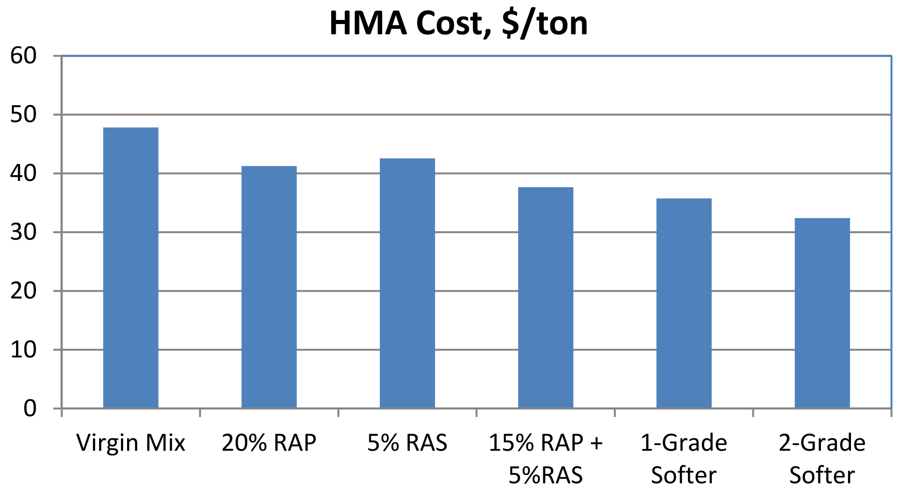


Figure D2. HMA Cost in Dollars per Ton for Type D (1/2-inch NMAS) Mix Containing PG 76-22.

TxDOT typically uses 5 million to 15 million tons of asphalt mix annually. Assuming TxDOT could save $10/ton by using RAP, RAS, and unmodified binders, an annual savings of $50 to $150 million is achievable (Rand, 2011). Robinette and Epps (2010) agree that the value of RAP and RAS depends on local market conditions, e.g., price of virgin asphalt binder, crushed virgin aggregate, and processing RAP and/or RAS. Because the price of asphalt binder fluctuates, the value of RAP and RAS changes almost daily.

PERTINENT ACTIVITIES TO ENCOURAGE RECYCLING

Various government agencies are creating regulations to encourage recycling of shingles. These activities usually come under the general heading of construction and demolition (C&D) debris. For example, in 1990, the Massachusetts Department of Environmental Protection (MassDEP) introduced its first bans on landfilling and combustion of easy-to-recycle and toxic materials. Additional waste bans have been phased in over time. A few of the materials prohibited from disposal in Massachusetts that have been used in pavements are:

- Asphalt shingles.
- Asphalt pavement, brick, and concrete.
- Glass and metal containers.
- Whole tires (banned from landfills only; shredded tires acceptable).

Since the first waste bans were introduced, Massachusetts municipalities and businesses, often supported by MassDEP grants and technical assistance, have developed new infrastructure to collect banned items and other discarded materials and to divert them from disposal to reuse and/or recycling (http://www.mass.gov/dep/recycle/solid/wastebans.htm).

In 2006, the US Army published a memorandum titled *Requirements for Sustainable Management of Waste in Military Construction, Renovation and Demolition Activities*. Briefly stated, this policy mandates that all new construction, renovation, and demolition projects include contract performance requirements to divert, as a minimum, 50 percent of non-hazardous C&D debris from landfill disposal. The Army's goal for C&D debris diversion is based partly on levels considered achievable by other public agencies responsible for solid waste management. California, the City of Chicago, and Nova Scotia (Kenney, 2007) require diversion of at least 50 percent of C&D waste from construction, remodeling, reproofing, and demolition projects. The City of Halifax requires 75 percent diversion of C&D (Kenney, 2007). Many other jurisdictions have enacted ordinances to require C&D waste diversion or exclude C&D materials from landfill disposal. The Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding and Guiding Principles require that at least 50 percent of C&D debris be recycled or salvaged. So, while the Army's C&D waste management policy is progressive, it is not without precedent in the public sector.

http://www.erdc.usace.army.mil/pls/erdcpub/www_org_info.show_page?f_id=2364657&f_parent=55174

SUMMARY AND CONCLUSIONS

These conclusions are based on findings from this review of published information.

- Discarded asphalt shingles may consist of MWAS or TOAS. Recycling of MWAS has been widely accepted because of its relatively homogeneous nature, lower oxidation, and freedom from asbestos. TOAS recycling is technically feasible, but the practice has been limited in some areas because of concerns about asbestos and, to a lesser extent, PAHs.
- Using 5 percent RAS in HMA and assuming a cost of $600 per ton for virgin AC, a contractor can save about $4.00 to $7.00 per ton of HMA, depending on the cost to acquire the RAS.
- The net energy requirement associated with recycling shingles into HMA is less than the requirement associated with disposing of those shingles in a landfill and using all virgin materials for HMA production.
- Use of RAS in HMA should provide environmental benefits by offsetting the use of virgin asphalt and by reducing the volume of debris in landfills.
- The occurrence of asbestos in TOAS from residential reroofing projects will be very limited (and will decrease with time), but the recycling facility operator should expect to encounter asbestos on occasion and, thus, should be adequately prepared to monitor and manage such material.
- Risks associated with polycyclic aromatic hydrocarbons migration appear to be small and comparable to that encountered when handling any asphalt-containing material. Data do not exist to suggest that incorporating RAS into HMA should be limited because of PAH concerns.
- Using RAS in HMA to conserve virgin asphalt instead of disposing of shingles in landfills will reduce greenhouse gas emissions.
- Models are available for estimating energy savings, greenhouse gas emissions as well as life-cycle costs and environmental effects when using RAS in HMA. Some of these models are identified in this document.
- Future recyclability and air emissions of pavements containing RAS are not concerns. Asphalt in RAS is typically harder (less volatile) than that in HMA or RAP, particularly that in TOAS, and therefore HMA or RAP containing RAS should liberate fewer volatile organic compounds than conventional HMA or RAP.
- Selected public agencies now mandate that all new construction, renovation, and demolition projects include contract performance requirements to divert some minimum percentage of non-hazardous C&D debris from landfill disposal.

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