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16. Abstract

The use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) can significantly reduce the increasing cost of hot-mix asphalt paving, conserve energy, and protect the environment. However, the premature cracking problem has been a serious concern. This report presents the latest work on RAP/RAS mix design and performance analysis including field performance of a variety of RAP/RAS test sections around Texas, and the proposed RAP/RAS mix design and performance evaluation system for project-specific service conditions.

RAP/RAS mixes can have better or similar performance than virgin mixes if they are well designed with balancing both rutting/moisture damage and cracking requirements. Cracking performance of RAP/RAS mixes is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. It is obvious that a single cracking requirement does not apply to all asphalt overlay applications. Instead, a project-specific service conditions based mix design system should be developed. Based on the relationship between Overlay Test (OT) cycles and fracture properties (*A* and *n*) established under this study, a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions is proposed, and it includes a balanced mix design procedure and a performance evaluation system in which the Hamburg wheel tracking test and associated criteria are used to control rutting/moisture damage and the OT, and the required OT cycles determined from S-TxACOL cracking prediction with consideration of climate, traffic, pavement structure and existing pavement conditions. Additionally, the impacts of soft binder on engineering properties of RAP/RAS mixes in terms of dynamic modulus, HWTT rut depth, and OT cycles are investigated. The test results clearly indicated that the use of soft and modified asphalt binder (i.e., PG xx-28, PG xx-34) can effectively improve cracking resistance of RAP/RAS mixes without sacrificing much rutting/moisture damage resistance. Dynamic modulus is not a good indicator as cracking resistance of RAP/RAS mixes. Researchers highly recommend that the proposed RAP/RAS mix design and performance evaluation system for project-specific service conditions be implemented statewide.

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

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

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CHAPTER 1. INTRODUCTION

The asphalt paving industry has always advocated recycling. The earliest reclaimed asphalt pavement (RAP) dates back to 1915 (*1*). However, significant use of RAP in hot-mix asphalt (HMA) really started in the mid-1970s due to extremely high asphalt binder prices as the result of the oil embargo. In addition to RAP, recycled asphalt shingles (RAS) have recently been used in Texas. The use of RAP/RAS can significantly reduce the cost of HMA paving, conserve energy, and protect the environment. However, RAP/RAS binders are often much stiffer than virgin binders. Blending these very stiff materials with virgin materials makes the designed mixes prone to cracking and leading to durability problem, which is one of the major concerns on RAP/RAS mixes. It is critical to address the premature cracking distress in order to most effectively use these recycled materials.

Furthermore, historical data (*2, 3*) showed that the RAP mixes could have the same or similar performance as well as virgin HMA mixes. In some other cases, RAP mixes did not perform as well as expected. The controversial performance of RAP/RAS mixes could be caused by many factors, such as design, construction, etc. But one of the factors to which has not been paid enough attention, is the project-specific service conditions. It is obvious that the same mix could perform completely different when placed under two conditions: cold and heavy traffic loading vs. warm and light traffic loading. Therefore, it is important to design asphalt mixes, with and without RAP/RAS, based on project-specific service conditions. Additionally, it is necessary to identify different approaches for improving cracking resistance in case that RAP/RAS mixes cannot meet the requirement for project-specific service conditions.

This report presents field performance of RAP/RAS test sections in different climatic zones in Chapter 2, which strongly supports the necessity of establishing mix design and performance evaluation system for project-specific service conditions. Chapter 3 documents the proposed mix design and performance evaluation system for project-specific service conditions. Chapter 4 discusses the approaches for improving cracking resistance of RAP/RAS mixes. Finally, Chapter 5 presents a summary and conclusions from this project. Additionally, several other documents listed below are presented in the Appendices.

- Appendix A: RAP Quality, Processing and Construction Draft Specification.
- Appendix B: Balanced Mix Design Procedure for HMA Mixes Using High RAP.
- Appendix C: Pavement Type Selection Guidelines for the Use of High RAP in HMA Mixes.
- Appendix D: Guidelines for Use of the High RAP in HMA Mixes.

CHAPTER 2. FIELD PERFORMANCE OF RAP/RAS TEST SECTIONS

A series of field test sections with RAP/RAS have been constructed around Texas under Project 0-6092, as shown Figure 1. Table 1 lists detailed information of the field test sections. These field test sections covers different applications of RAP/RAS mixes, as listed below:

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

Performance of these test sections is very valuable to this and other projects. Specifically, the observed field performance of these test sections strongly indicates the importance and need of developing a mix design and performance evaluation system for project-specific service conditions. This chapter describes each of these field test sections and associated field performance.

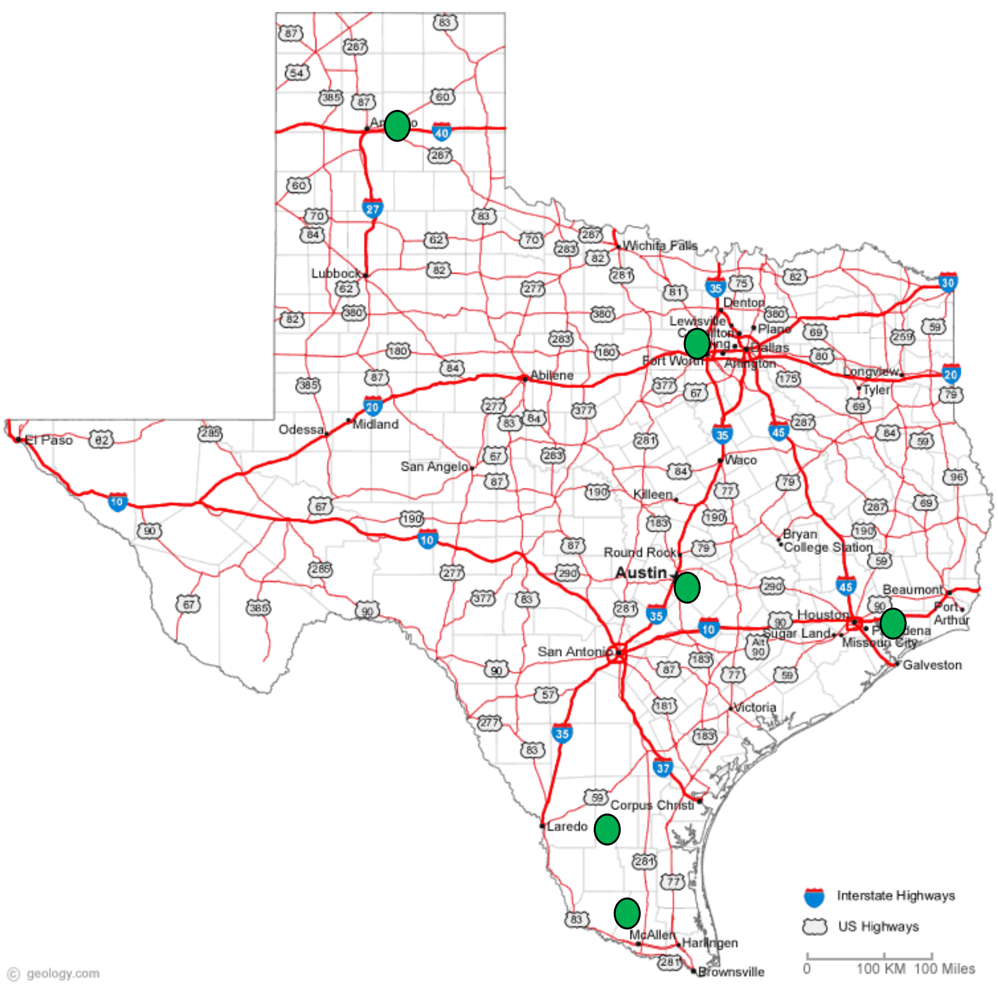


Figure 1. RAP/RAS Field Test Sections.

Table 1. Field RAP/RAS Test Sections.

Test Section				District	Weather	Traffic (mESAL/ 20 Years)	Overlay/new construction	Existing condition if overlay
Highway	RAP/RAS	Virgin binder	HMA/ WMA					
IH40	20% RAP	PG64-28	HMA	Amarillo	Very cold	30	4 inch overlay	Severe transverse cracking
	0% RAP	PG64-28						
	20% RAP	PG64-28						
	35% RAP	PG58-28						
FM1017	0% RAP	PG76-22	HMA	Pharr	Very hot	0.8	New construction, 1.5 inch surface layer	N/A
	20% RAP	PG70-22						
	35% RAP	PG70-22						
SH359	20% RAP	PG70-22	HMA	Laredo	Hot	1.0	3 inch overlay	Severe transverse cracking
SH146	15% RAP/ 5% RAS	PG64-22	HMA	Houston	Hot	1.5	New construction, 2 inch surface layer	N/A
FM973	0% RAP	PG70-22	HMA	Austin	Hot	3.0	2 inch overlay	Fine longitudinal cracking
	30% RAP	PG64-22	HMA					
	15% RAP/ 3% RAS	PG64-22	HMA					
	5% RAS	PG64-22	HMA					
	30% RAP	PG58-28	HMA					
	15% RAP/ 3% RAS	PG58-28	HMA					
	0% RAP	PG70-22	WMA Foaming					
	0% RAP	PG70-22	WMA Evotherm					
	15% RAP/ 3% RAS	PG64-22	WMA Evotherm					

RAP TEST SECTIONS ON IH40 AND OBSERVED FIELD PERFORMANCE

The four RAP test sections shown in Figure 2 were constructed on Interstate Highway (IH) 40 near Amarillo, Texas, on August 11, 2009. The existing pavement has a total of 8 inches (200 mm) of existing HMA with severe thermal-related transverse cracking that extends the full depth of the HMA (Figure 3). The reason for choosing these four sections was to permit the rapid determination of field performance of sections designed by both the current mix design method and the balanced RAP mix design method. Table 2 lists all mix design information of these four test sections, including optimum asphalt content (OAC), Hamburg wheel tracking test (HWTT), and Overlay test (OT). The pavement design called for a 4 inch (100 mm) milling and 4 inch (100 mm) overlay section. Amarillo's climate is a temperate semi-arid climate characterized by numerous freeze-thaw cycles and occasional blizzards during the winter season. Average daily high temperatures of Amarillo range from 48°F (9°C) in January to 92°F (33°C) in July. Furthermore, the traffic on IH40 is extremely heavy with over 50 percent heavy loaded trucks in the traffic stream. The cold weather, heavy traffic loading, and severe existing pavement cracking make this a good case study to rapidly evaluate the impact of different RAP layers on pavement performance.

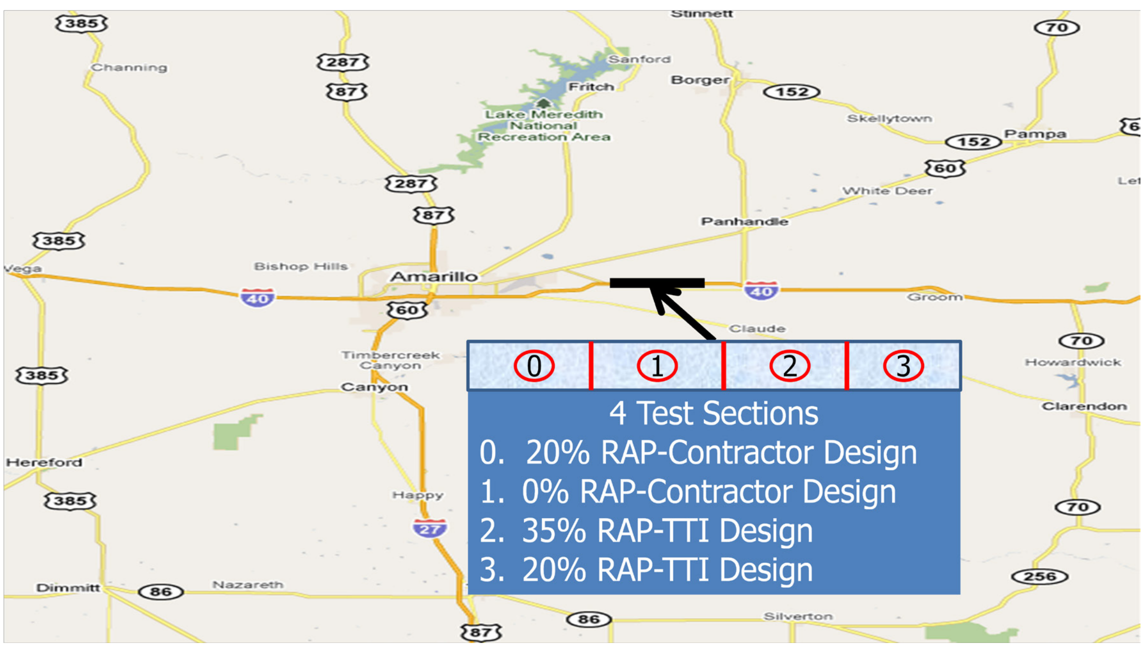


Figure 2. Four RAP Test Sections on IH40 near Amarillo, Texas.

Figure 3. Existing Pavement Conditions of IH40 after Milling.

Table 2. Mix Design Information of the Four RAP Test Sections on IH40 near Amarillo, Texas.

Section	RAP (%)	Virgin binder	Designer	Mix design method	OAC (%)	HWTT rut depth @ 20,000 passes	OT cycles
0	20	PG64-28	Contractor	TxDOT's Tex-204-F	5.0	3.72 mm	10
1	0	PG64-28	Contractor	TxDOT's Tex-204-F	4.8	4.38 mm	95
2	35	AC-10 (PG58-28)	TTI	Balanced mix design	5.5	8.00 mm	200
3	20	PG64-28	TTI	Balanced mix design	5.3	7.40 mm	103

Since the construction on August 11, 2009, five field surveys have been conducted on April 22, 2010, September 8, 2010, April 5, 2011, December 15, 2011, and May 30, 2012, respectively. So far, no rutting has been observed, but reflective cracking was observed on all four test sections on the third survey. Detailed reflective cracking observations for each section are tabulated in Table 3. Prior to placing the overlay the number of pre-existing cracks in each section was documented and mapped. The reflective cracking rate is therefore defined as the ratio of the number of reflective cracks to the original number of cracks before the 4 inch (100 mm) overlay. It is clear that the higher the lab OT cycles of the RAP mix, the lower reflective cracking rate, which further validates the effectiveness of OT for reflective cracking. It also clearly indicates that the 35 percent RAP test section with 200 OT cycles performed the best among the four sections. The overall conclusion from these four sections is that high RAP mix can have better or similar performance to the virgin mix, but it must be well-designed following appropriate mix design methods, such as the balanced RAP mix design methodology.

Table 3. Field Performance Survey: Reflective Cracking Rate (%).

Sections	8/11/2009	4/22/2010	9/8/2010	4/5/2011	12/15/2011	5/30/2012
20% RAP-contractor	0	0	36	83	97	97
0% RAP-contractor	0	0	20	53	65	80
35% RAP-TTI	0	0	0	29	38	57
20% RAP-TTI	0	0	4	50	83	96

RAP TEST SECTIONS ON FM1017 AND OBSERVED FIELD PERFORMANCE

Three RAP sections were constructed in south Texas on FM1017 near Pharr on April 6, 2010. It was a new construction with a 1.5 inch (37 mm) surface asphalt layer. The three RAP mixes are all dense-graded, fine Type D mixes. Again, two RAP mixes were designed by the contractor using TxDOT's standard mix design procedure, and one mix with 35 percent RAP was designed at TTI following the balanced mix design method. Table 4 presents the mix design information of these three RAP test sections and associated engineering properties.

Since the completion of construction, four field surveys have been conducted. Figure 4 shows the pavement conditions of the three RAP sections surveyed on May 25, 2012. So far no rutting was observed, and only limited, fine cracking occurred.

After reviewing the low OT cycles of these three RAP mixes and comparing with those RAP mixes on IH40, one would wonder why these sections lasted one year without cracking. These three RAP test sections are in complete contrast to those on IH40 described previously, as noted in Table 4. It must also be recalled that 1) FM1017 is new construction with a stiff base, 2) there is no pre-existing cracks to initiate reflection cracks, 3) the traffic is very light on this highway, 4) the climate is very mild with no cold weather, and 5) this area has received very little rainfall since construction. Performance data observed on IH40 and FM1017 clearly indicated that it is not reasonable to set a cracking requirement for all applications. Instead, the cracking requirement of any mixes should be defined based on the project-specific service conditions, including climate, traffic, pavement structure, etc.

Table 4. Mix Design Information of the Three RAP Test Sections on FM1017 near Pharr.

Section	RAP (%)	Virgin binder	Designer	Mix design method	OAC (%)	HWTT rut depth @ 20,000 passes	OT cycles
1	20	PG64-22	Contractor	TxDOT's Tex-204-F	5.0	3.4 mm	6
2	35	PG64-22	TTI	Balanced mix design	6.4	9.3 mm	7
3	0	PG76-22	Contractor	TxDOT's Tex-204-F	4.9	2.2 mm	28

Figure 4. RAP Test Sections on FM1017 on May 25, 2012.

Table 5. RAP Sections on FM1017 vs. IH40.

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

RAP TEST SECTION ON SH359 AND OBSERVED FIELD PERFORMANCE

A RAP field test section with 3 inch milling and inlay was constructed on SH359, Laredo District on March 10, 2010. The existing pavement had fatigue cracking that can be seen even after 3 inch (75 mm) milling (Figure 5). A dense-graded Type C mix with 20 percent RAP designed by the contractor had an excellent rutting but poor cracking resistance: 2.3 mm Hamburg rut depth after 20,000 passes and 3 OT cycles. The main features of this section are 1) 3 inch (75 mm) milling and inlay with poor support, 2) both RAP and RAS in the mix, 3) excellent rutting/moisture damage resistance but poor cracking resistance of the RAP/RAS mix, 4) low traffic, and 5) warm weather.

Since the completion of construction on March 10, 2010, this test section has been monitored four times. The latest survey was conducted in May 2012. The test section was in perfect condition: no rutting and cracking, as shown in Figure 6. The researchers will continue to monitor this test section.

Figure 5. Observed Cracking after 3 inch Milling on SH359.

Figure 6. Perfect Condition of RAP/RAS Test Section on SH359.

RAP/RAS TEST SECTION ON SH146 AND OBSERVED FIELD PERFORMANCE

A field test section was constructed on SH146 in Houston area where the weather is warm. Again, the test section on SH146 was a new construction 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 OT cycles of 3. The main features of this section are 1) new construction, 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) warm weather.

Since the completion of construction on Oct. 8, 2010, this test section has been monitored three times. The latest survey was conducted in May 2012. The test section was in perfect condition: no rutting and cracking, as shown in Figure 7. The researchers will continue to monitor this test section.

Figure 7. Perfect Condition of RAP/RAS Test Section on SH146, Houston.

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 Austin area is warm. Different from US87, 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. Part of the objectives of the test sections on FM973 was to evaluate the effectiveness of using soft binder on improving cracking resistance of RAP/RAS mixes. Table 6 lists all the mixes used in field test sections. The main features of these nine sections are:

- HMA vs. RAP/RAS mixes.
- HMA vs. WMA.
- WMA: Foaming vs. Evotherm additive.
- PG64-22 vs. PG58-28.

Therefore, these test sections provided an opportunity for comparing the 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, and some areas had a low severity level of longitudinal cracking along the wheel passes. The overall deflection measured using falling weight deflectometer is around 11 mils (0.28 mm). So the 2 inch (50 mm) asphalt overlay is sitting on a solid foundation.

Since the completion of construction, up to now these nine test sections have been trafficked for six months. The latest survey was conducted in July 2012, and neither rutting nor cracking was observed on any test section. As one example, Figure 8 shows the conditions of Sections 3 and 6 in July 2012. Apparently, more time is needed for these test sections to show the difference among these nine test sections in terms of rutting and cracking. TTI researchers will continue to monitor the performance of these RAP/RAS test sections.

Table 6. Nine Test Sections on FM973, Austin.

Section No.	Type	Virgin Binder	RAP	RAS
1	HMA	70-22	0	0
2	HMA	64-22	30	0
3	HMA	64-22	15	3
4	HMA	64-22	0	5
5	HMA	58-28	30	0
6	HMA	58-28	15	3
7	WMA Foaming	70-22	0	0
8	WMA Evotherm	70-22	0	0
9	WMA Evotherm	64-22	15	3

Figure 8. Pavement Conditions of RAP/RAS Test Sections 3 and 6 on FM973 in July 2012.

SUMMARY AND DISCUSSION

When comparing the observed performance data of all the field test sections (Table 7), one may get conflicting results. RAP/RAS mixes with low OT cycles performed well on SH359, SH146, and FM1017. However, those RAP mixes on IH40 performed very poorly, although these mixes had higher OT cycles. After carefully considering all the information presented in Table 7, several important observations can be made:

- Cracking performance of asphalt mixes, different from rutting, is strongly connected with pavement structure. It is extremely difficult to propose a single cracking requirement for all applications.
- Cracking performance is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness.
- There is a terrible need to develop a RAP/RAS mix design and performance evaluation system for project-specific service conditions, including traffic, climate, existing pavement conditions, etc.

The observed observations are further supported by performance data of high RAP test sections on the NCAT 2006. Seven RAP sections were built in 2006, as reported by Kvasnak at the RAP ETG meeting in October 2008 (*4*). The mixes used on the NCAT sections were 1) virgin control mix with PG 67-22, 2) 20 percent RAP with PG 67-22 virgin binder, 3) 20 percent RAP with PG 76-22 virgin binder, 4) 45 percent RAP with PG 52-28 virgin binder, 5) 45 percent RAP with PG 67-22 virgin binder, 6) 45 percent RAP with PG 76-22 virgin binder, and 7) 45 percent RAP with PG 76-22 virgin binder + Sasobit. After two years, 10 million ESALs traffic, only the section with 45 percent RAP mix with PG 76-22 + Sasobit had cracks and all other six sections have almost no cracks at all. Further investigation found that the cracks observed were reflective cracking. The seven RAP test sections on NCAT test sections were milling and inlays that were sitting on more than 15 inch (375 mm) thick existing asphalt layer. The RAP test sections under this study and those at NCAT 2006 test track clearly indicate the importance of developing RAP/RAS mix design and performance evaluation system for project-specific service conditions.

Table 7. Field RAP/RAS Test Sections and Observed Performance.

Test Section				Weather	Traffic (mESAL/ 20 Years)	Overlay/new construction	Existing condition if overlay	OT cycles	Performance
Highway	**RAP/RAS**	**Virgin binder**	**HMA/ WMA**						
IH40	20% RAP	PG64-28	HMA	Very cold	30	4 inch overlay	Severe transverse cracking	10	100% reflect. cracking after 3 years
	0% RAP	PG64-28						90	
	20% RAP	PG64-28						103	
	35% RAP	PG58-28						200	57% reflect. cracking after 3 year
FM1017	0% RAP	PG76-22	HMA	Very hot	0.8	New construction, 1.5 inch surface layer	N/A	28	Limited, fine cracking after 2.5 years
	20% RAP	PG70-22						6	
	35% RAP	PG70-22						7	
SH359	20% RAP	PG70-22	HMA	Hot	1.0	3 inch overlay	Severe transverse cracking	3	No cracking after 2.5 years
SH146	15% RAP/ 5% RAS	PG64-22	HMA	Hot	1.5	New construction, 2 inch surface layer	N/A	3	No cracking after 2 years
FM973	0% RAP	PG70-22	HMA	Hot	3.0	2 inch overlay	Fine longitudinal cracking	90	No cracking after 10 months
	30% RAP	PG64-22						5	
	15% RAP/ 3% RAS							7	
	5% RAS							6	
	30% RAP	PG58-28						21	
	15% RAP/ 3% RAS							4	
	0% RAP	PG70-22	WMA Foaming					N/A	
	0% RAP	PG70-22	WMA Evotherm					N/A	
	15% RAP/ 3% RAS	PG64-22						30	

CHAPTER 3. BALANCED RAP/RAS MIX DESIGN AND PERFORMANCE EVALUATION SYSTEM FOR PROJECT-SPECIFIC SERVICE CONDITIONS

A balanced mix design for high RAP mixes has been proposed and documented in Report 0-6092-2 (*5*) in which the Hamburg wheel tracking test and Overlay test are used to evaluate rutting/moisture damage and cracking resistance, respectively. However, cracking requirement could not be developed due to limited field at that time. Currently, TxDOT has established the rutting/moisture damage requirements for mixes with different binders. For example, rut depth of a mix with PG76-22 binder should be less than 0.5 inch (12.5 mm) after 20,000 passes. But there is no OT requirement available. As clearly shown in Chapter 2, it may be difficult to establish a single cracking requirement, because cracking performance of asphalt mixes depends on traffic, climate, pavement structure, and existing pavement conditions for asphalt overlays. Therefore, a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions, rather than a cracking requirement, should be developed, and then implemented to ensure the mixes designed with acceptable field performance. Apparently, the new mix design system is an enhanced version of the balanced mix design for high RAP mixes. This chapter documents the development of such a mix design and performance evaluation system.

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

The proposed balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions is established on previous work on asphalt overlays under Project 0-5123: 1) The balanced mix design procedure proposed by Zhou et al. in Report 0-5123-1 (*6*) and 2) TxACOL: Asphalt overlay thickness design and performance analysis developed by Zhou et al. in Report 0-5123-3 (*7*). Therefore, it is a two-step process in which the asphalt overlay design and analysis system will take the mix design information as inputs, and then predict performance of the mix under project-specific service conditions. If the predicted performance meets the requirements, then the mix design process is done; otherwise one needs to change the virgin binder, RAP/RAS, or aggregates and repeat the mix design process.

Since rutting is not problem for RAP/RAS mixes, and it is well-controlled through the Hamburg wheel tracking test, the researchers believe that asphalt overlay performance analysis should focus on cracking (or reflective cracking), which is the main distress observed in the field. To evaluate the cracking performance of RAP/RAS mixes, the asphalt overlay design program, TxACOL, requires fracture cracking parameters (A and n) that can be determined from the Overlay test. However, in terms of mix design, it is much easier to use the number of OT cycles. Thus, in order to simplify and connect the mix design and cracking performance evaluation, the key issue becomes to establish a relationship between the number of OT cycles and fracture cracking parameters (A and n).

Relationship between the Number of OT Cycles and Fracture Cracking Parameters (*A* and *n*)

A variety of mixes including dense-graded, Superpave, and SMA was evaluated under the OT. For each mix, five replicates were tested, and an average of three of them with highest *n* values was selected for fracture properties (*A* and *n*) of that mix. The OT cycles and the determined fracture properties (*A* and *n*) for each mix are listed in Table 8. The established relationships among OT cycles, *A* and *n* are shown in Figures 9 and 10, respectively.

Table 8. 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 Cell 2 plant mix		356	1.1148E-08	5.7841
21	MnRoad Cell 16 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

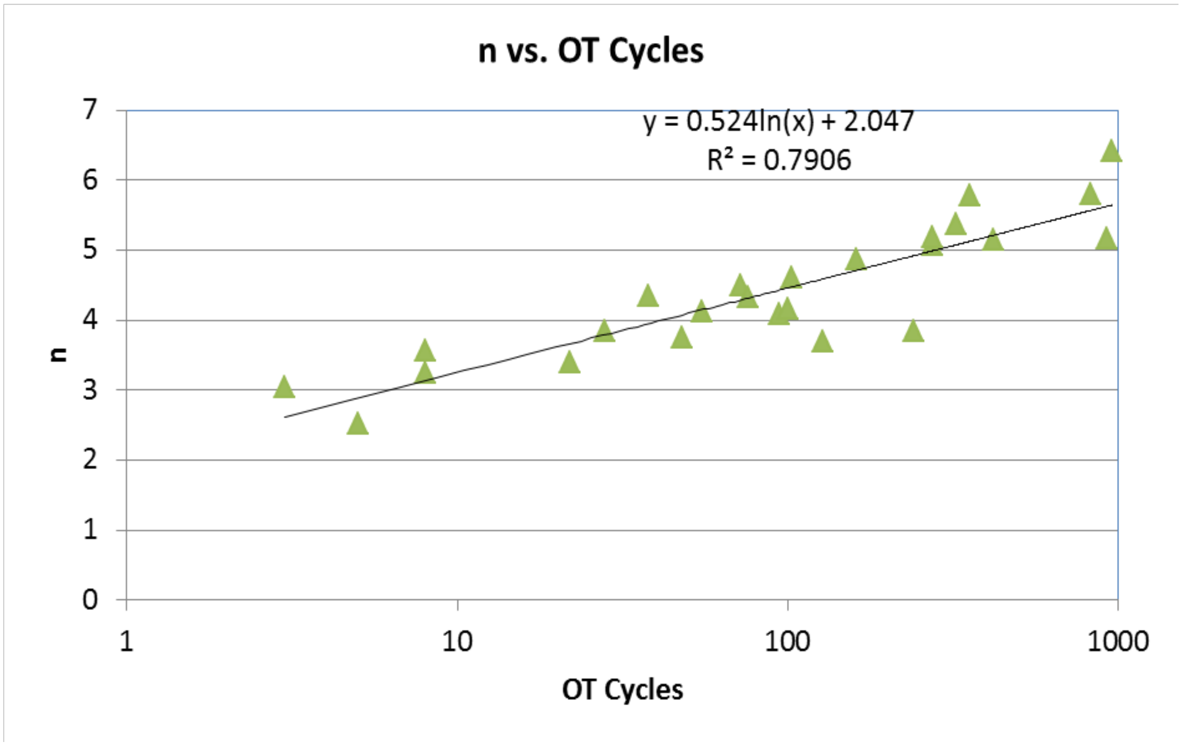


Figure 9. Relationship between OT Cycles and *n*.

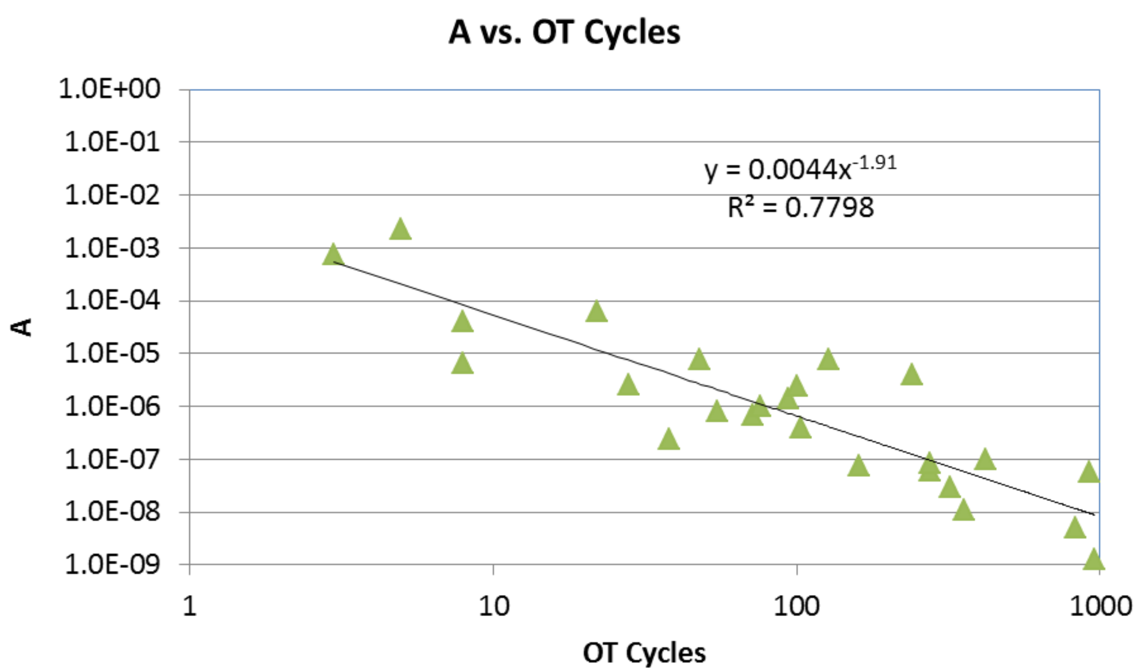


Figure 10. Relationship between OT Cycles and *A*.

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

Figure 11 shows the proposed RAP/RAS mix design and performance evaluation system for project-specific conditions. 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 12.

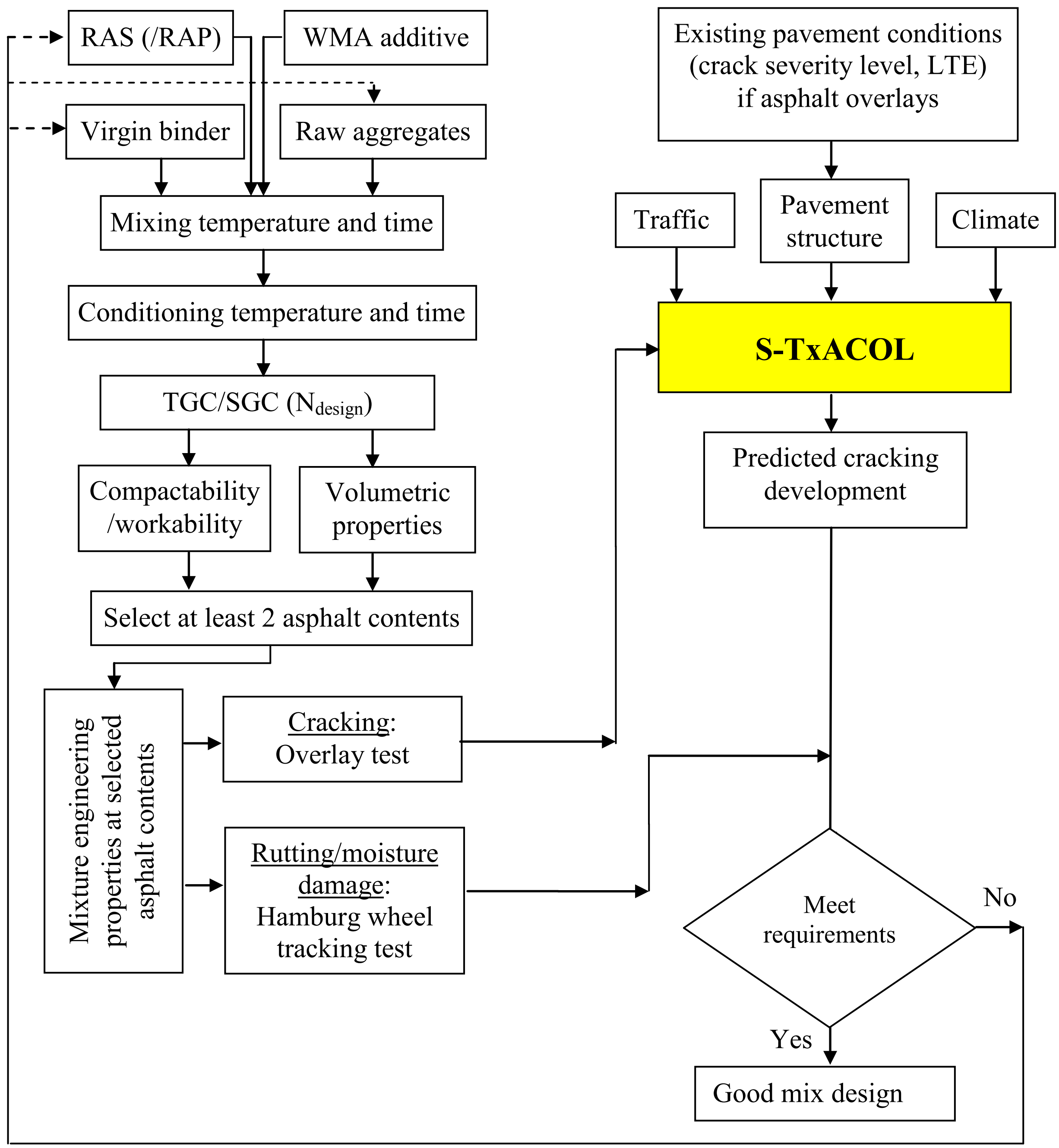


Figure 11. Balanced RAP/RAS Mix Design and Performance Evaluation System for Project-Specific Service Conditions.

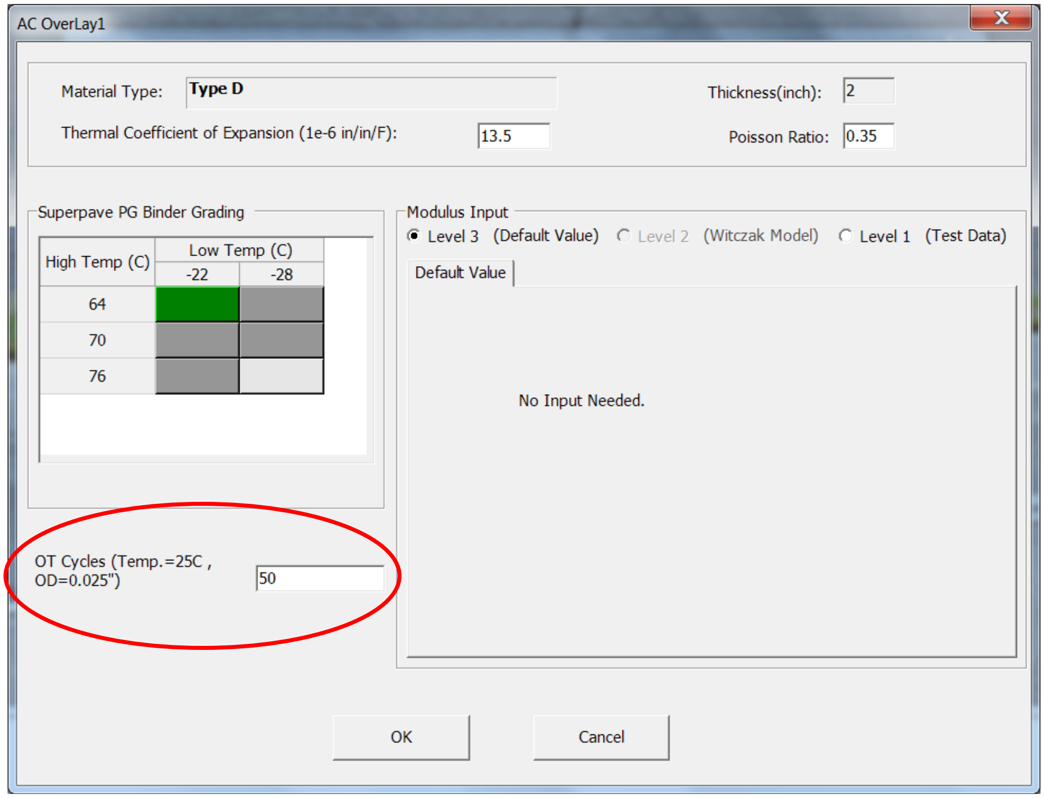


Figure 12. OT Cycles Input Interface for S-TxACOL.

DEMONSTRATION OF VARIOUS CRACKING REQUIREMENTS FOR PROJECT-SPECIFIC SERVICE CONDITIONS

Two series of case studies were performed using the simplified TxACOL: S-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 13 and 14.

- 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 13 and 14 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.

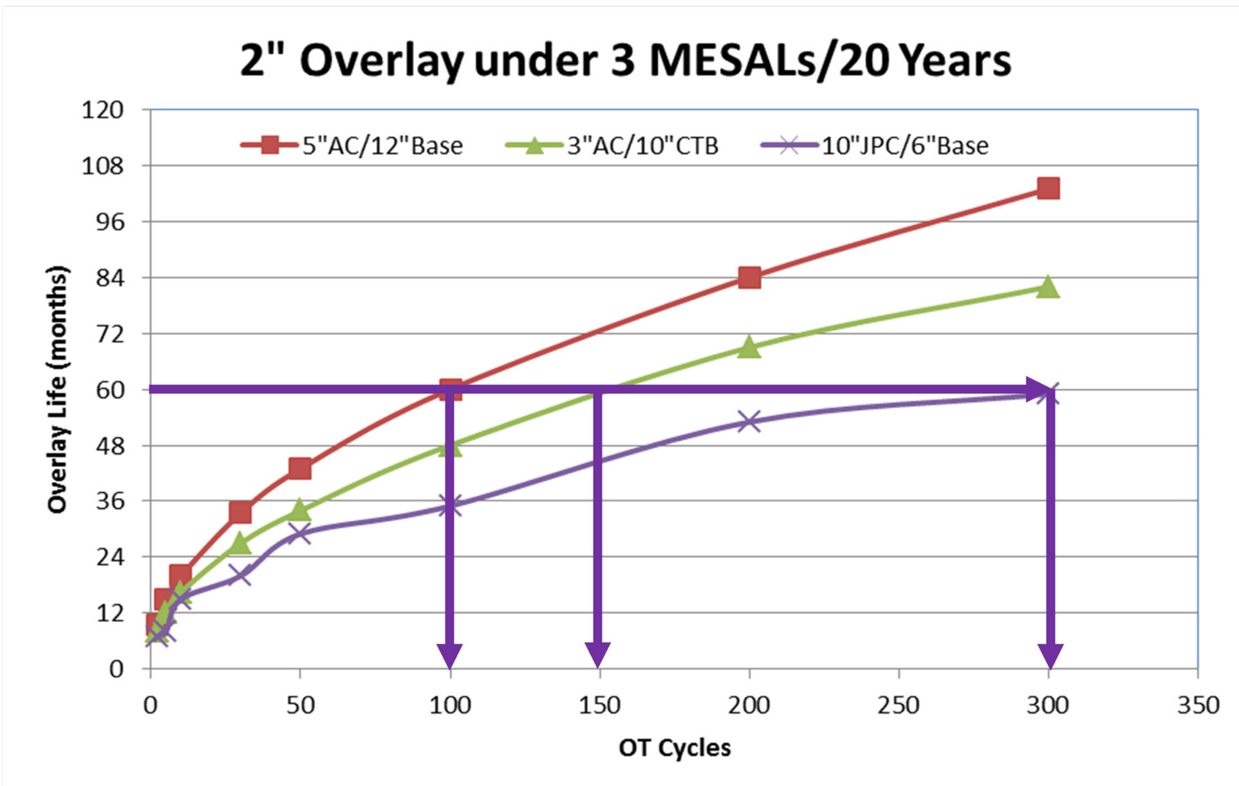


Figure 13. Relationships between OT Cycles and Cracking Development for Three Applications with Medium Cracking Severity.

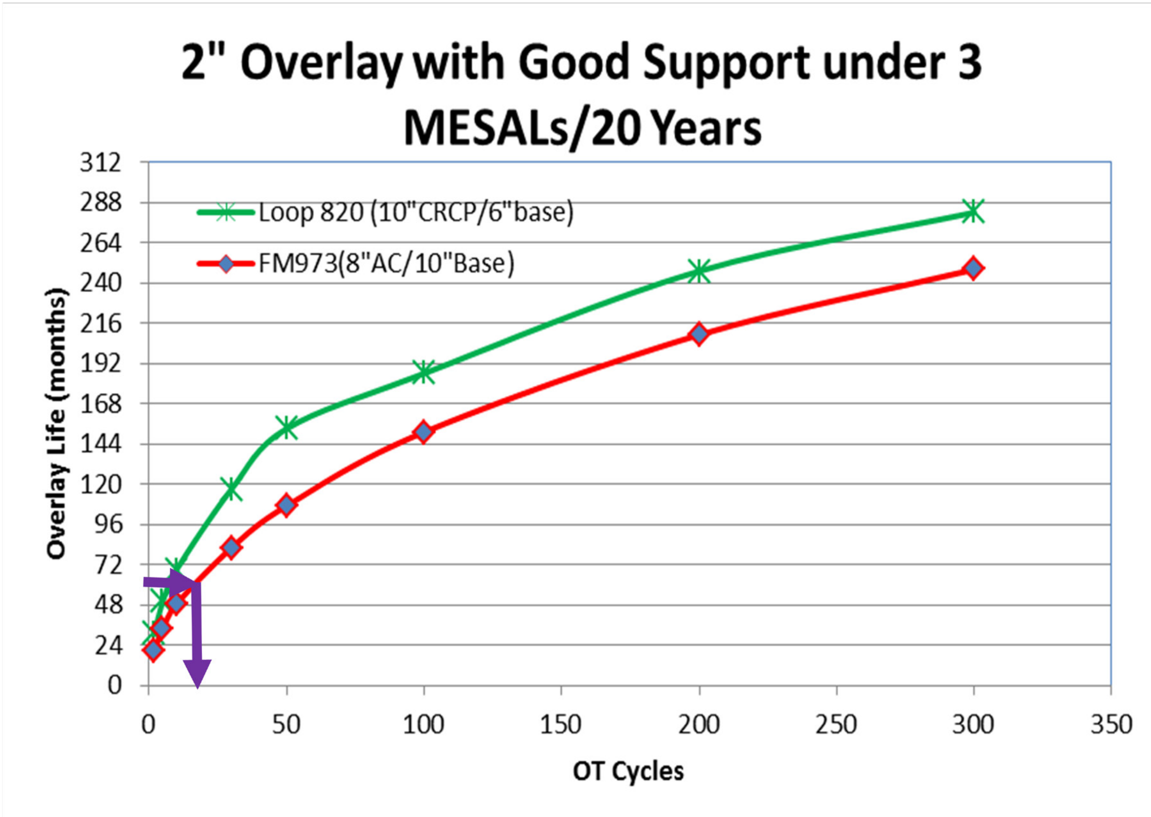


Figure 14. Relationships between OT Cycles and Cracking Development for Two Applications with Very Good LTE.

Case 2: Impact of Climate on Cracking Requirements

Again, the same 2 inch (50 mm) asphalt overlay with PG 70-22 binder is assumed to apply to the following existing pavements at three climatic zones: Amarillo, Austin, and McAllen. 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 15, 16, and 17. It is obvious that climate has significant influence on cracking development and consequently on cracking requirement.

- 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.

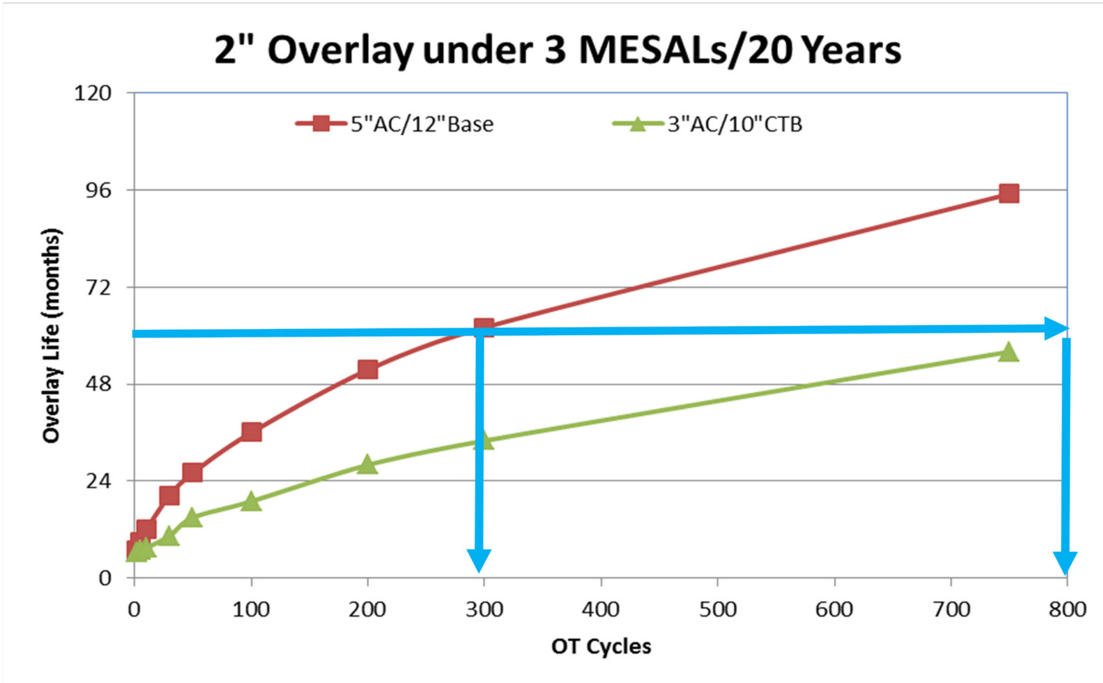


Figure 15. Amarillo: Relationships between OT Cycles and Cracking Development.

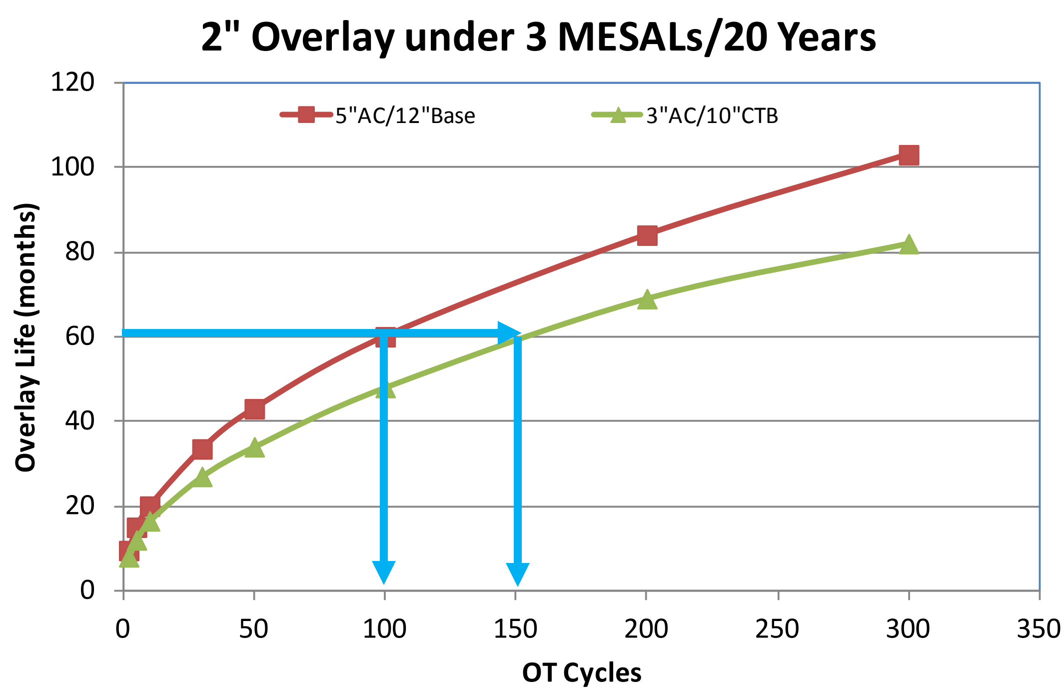


Figure 16. Austin: Relationships between OT Cycles and Cracking Development.

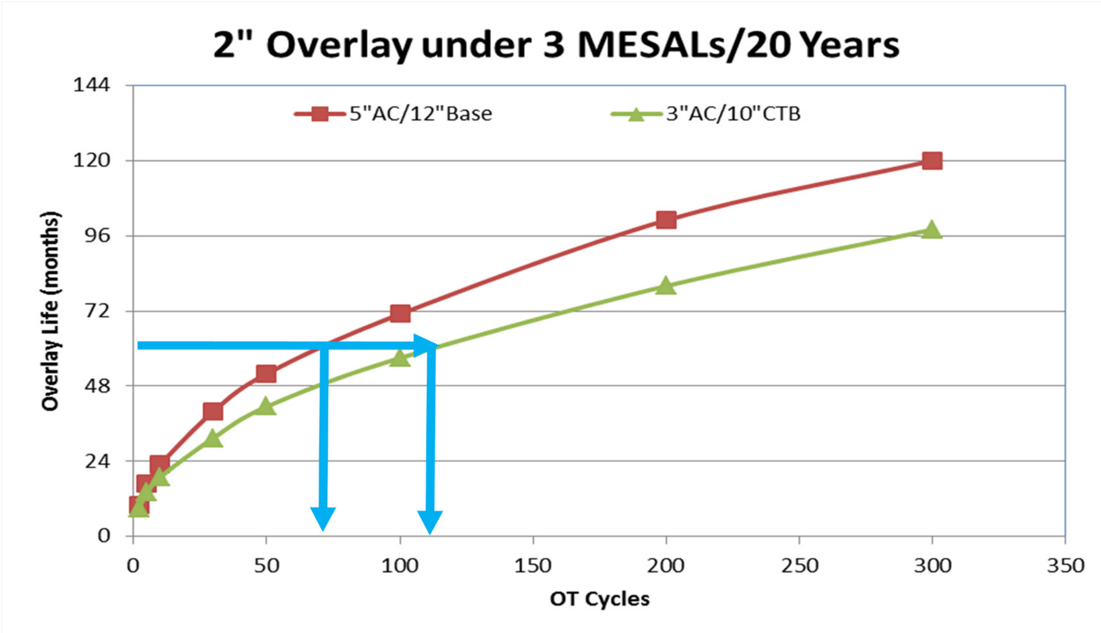


Figure 17. McAllen: Relationships between OT Cycles and Cracking Development.

SUMMARY

This chapter described the balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions 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 to control cracking. This chapter also demonstrated 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.

CHAPTER 4. APPROACHES FOR IMPROVING CRACKING RESISTANCE OF RAP/RAS MIXES

The use of RAP/RAS can improve rutting resistance of HMA mixes, but it causes poor cracking resistance of the mix and, consequently, premature cracking and durability problems. Thus, some approaches need to be taken to balance the performance of RAS mixes. In general, there are at least four approaches:

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

The first two approaches have been evaluated and well-documented in Report 0-6092-2 (*5*). Basically, these two approaches are effective to improve cracking resistance of RAP/RAS mixes. The third choice is to rejuvenate RAP/RAS binder using some rejuvenating agents. It sounds like a good idea and potentially improves cracking resistance of RAP/RAS mixes. However, there are many practical and technical issues when this approach would be applied to normal asphalt plant operations, and its effectiveness is being investigated under Project 0-6614. Thus, this study focused on the last approach: using soft binders. Detailed information is described below.

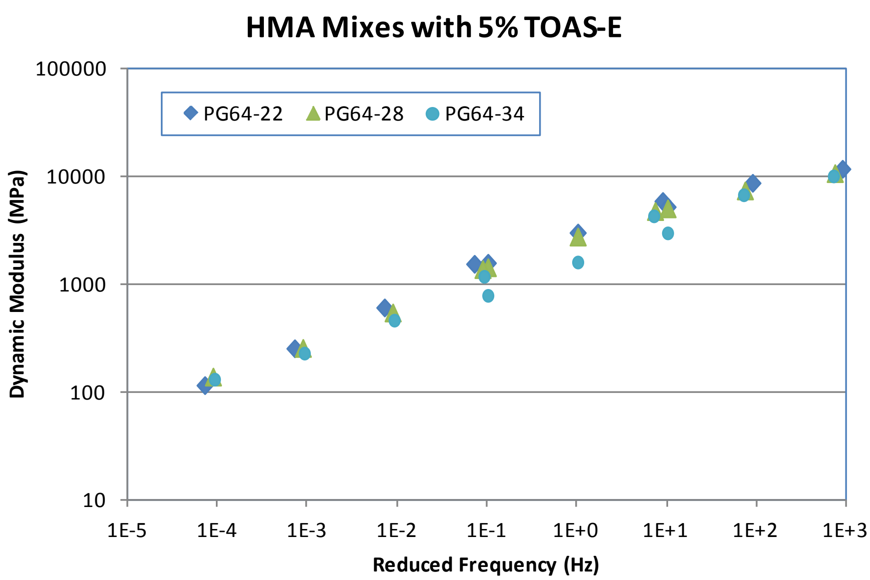
IMPACT OF SOFT BINDERS ON RAS MIX PROPERTIES

A dense-graded Type C mix with PG64-22 binder and 5 percent RAS was used in this study to evaluate the impact of soft binder on RAS mix properties. This Type C mix is a real mix placed on Section 4 of field test sections on FM973, and its design asphalt content is 5.2 percent. In addition to the virgin binder PG64-22, two more softer binders–PG64-28 and PG64-34–are evaluated here. Furthermore, two types of RAS–tear-off shingles–TOAS-E and manufacture waste shingle-MWAS-C–are included. A total of six mixes (2 RAS and 3 virgin binders) listed in Table 9 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 18, 19, and 20 show the test results.

Table 9. 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 18 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 19. The reason for the improvement is that both PG64-28 and PG64-34 are polymer modified binders. As expected, the mixes with the MWAS-C have deeper rut depth than those with TOAS-E. Figure 20 clearly indicated that it is very effective to improve cracking resistance of RAS mixes using soft virgin binders. For the cases presented here, one grade (−6°C) lower can triple the OT cycles of RAS mixes. Additionally, the mixes with the MWAS-C always have better cracking life than those with the TOAS-E. In summary, the use of soft binders has not much impact on dynamic moduli of RAS mixes; whereas, it can improve both rutting and cracking resistance of RAS mixes, especially on cracking resistance.



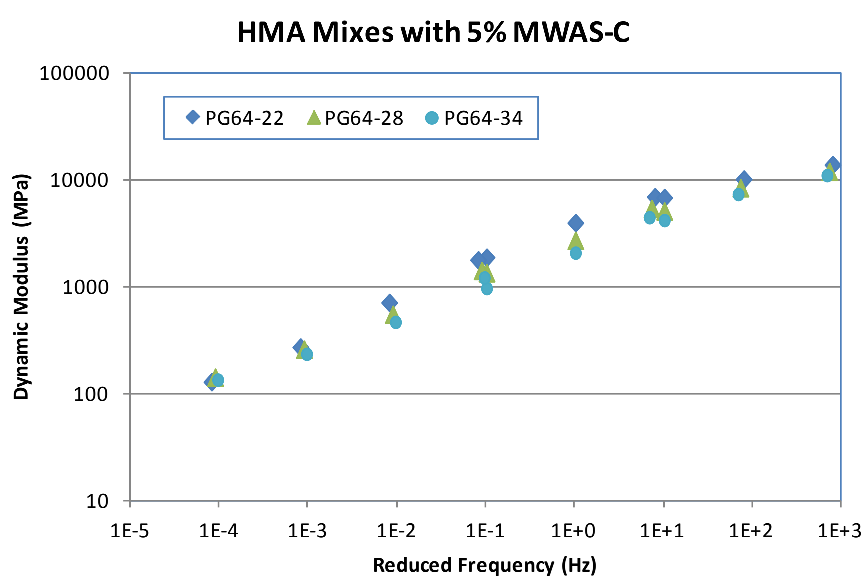


Figure 18. Impact of Soft Binders on Dynamic Modulus of 5 Percent RAS Mixes.

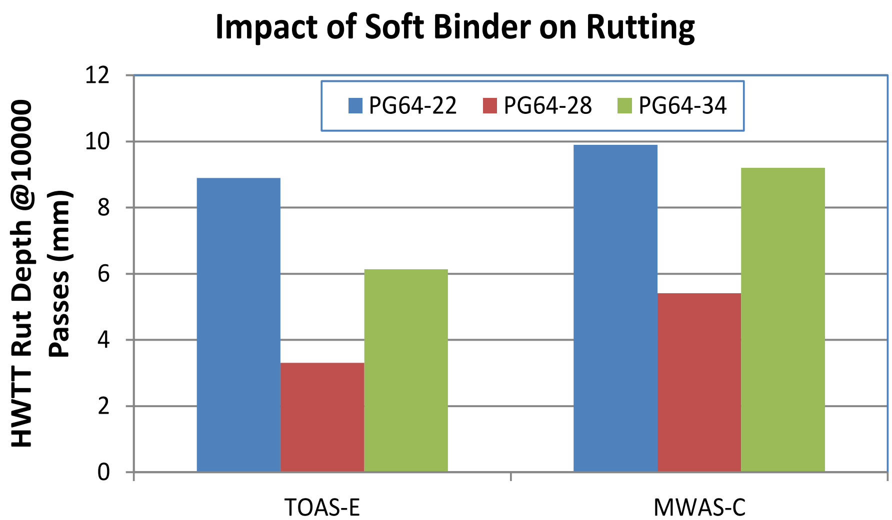


Figure 19. Impact of Soft Binders on Rutting/Moisture Damage of 5 Percent RAS Mixes.

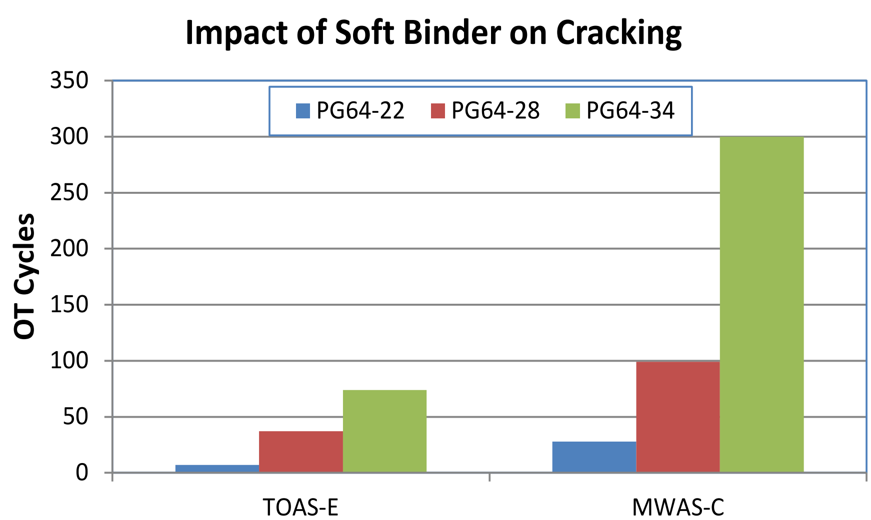


Figure 20. Impact of Soft Binders on Cracking Resistance of 5 Percent RAS Mixes.

IMPACT OF SOFT BINDERS ON RAP MIX PROPERTIES

A dense-graded Type D mix with 15 percent RAP from Paris District was used here for evaluating the impact of soft binders on RAP mix properties. Four virgin binders–PG64-22, PG58-28, PG64-28, and PG64-34–were selected for this study. The same aggregates gradation and OAC were utilized for all four mixes, and the only variable was the type of virgin binder. Only the HWTT (Tex-242-F) and OT (Tex-248-F) tests were performed, since the dynamic modulus test did not show much difference among different RAS mixes. Figure 21 shows the HWTT and OT test results.

Similar to previous results shown in Figures 19 and 20, the RAP mixes with modified soft binders have significantly better cracking resistance than the mix with PG64-22 virgin binder, as seen in Figure 21. Meanwhile, the mix with regular PG58-28 binder without any modification has a little bit better cracking resistance, but its HWTT result is too poor. Therefore, it is highly recommended that soft but highly modified binder rather than straight run soft binders (i.e., PG58-28) be used for improving cracking resistance of RAP mixes.

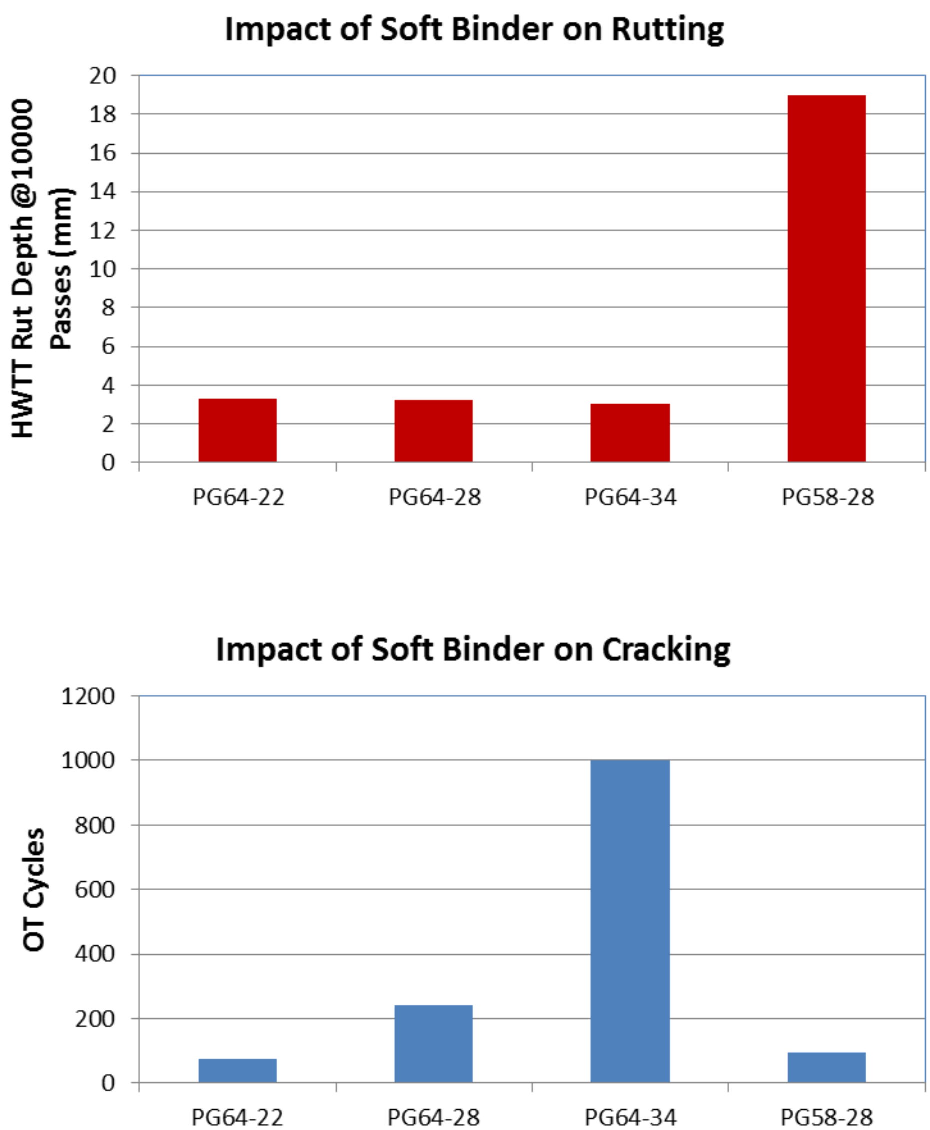


Figure 21. Impact of Soft Binders on Rutting/Moisture Damage and Cracking Resistance of RAP Mixes.

SUMMARY

This chapter investigated the impact of soft binders on the engineering properties of RAP/RAS mixes in terms of dynamic modulus, HWTT rut depth, and OT cycles. The test results clearly indicated that the use of soft and modified asphalt binders (i.e., PG xx-28, PG xx-34) can effectively improve cracking resistance of RAP/RAS mixes without sacrificing much rutting/moisture damage resistance. Dynamic modulus is not a good indicator as cracking resistance of RAP/RAS mixes.

CHAPTER 5. SUMMARY AND CONCLUSIONS

This report presents the latest work on RAP/RAS mix design and performance analysis including field performance of a variety of RAP/RAS test sections around Texas and the proposed RAP/RAS mix design and performance evaluation system for project-specific service conditions. Additionally, this report discusses approaches for improving cracking resistance of RAP/RAS mixes. Based on the research presented in this report, the following conclusions and recommendations are offered:

1. RAP/RAS mixes can have better or similar performance than virgin mixes if they are well-designed with balancing both rutting/moisture damage and cracking requirements.
2. Cracking performance of RAP/RAS mixes is influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. This report clearly demonstrates that a single cracking requirement does not apply to all asphalt overlay applications. Instead, a project-specific service conditions -based mix design system should be developed.
3. A relationship between OT cycles and fracture properties (*A* and *n*) is developed under this study. Such a relationship makes it possible to directly input OT cycles into S-TxACOL and make prediction of reflective cracking development of asphalt overlays. Consequently, it is possible to combine the mix design with asphalt overlay structure performance analysis into a mix design and performance evaluation system.
4. A RAP/RAS mix design and performance evaluation system for project-specific service conditions is proposed in this report. The proposed 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.
5. Researchers recommend that the statewide implementation of the proposed RAP/RAS mix design and performance evaluation system be pursued.
6. The impacts of soft binders on engineering properties of RAP/RAS mixes in terms of dynamic modulus, HWTT rut depth, and OT cycles are investigated. The test results clearly indicated that the use of soft and modified asphalt binder (i.e. PG xx-28, PG xx-34) can effectively improve cracking resistance of RAP/RAS mixes without sacrificing much rutting/moisture damage resistance. It was also found that dynamic modulus is not a good indicator as cracking resistance of RAP/RAS mixes.

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7. F. Zhou, S. Hu, X. Hu, and T. Scullion, Mechanistic-Empirical Asphalt Overlay Thickness Design and Analysis System, Research Report FHWA/TX-09/0-5123-3, Texas Transportation Institute, College Station, TX, October 2009.

APPENDIX A
RAP QUALITY, PROCESSING, AND CONSTRUCTION DRAFT SPECIFICATION

This appendix describes RAP quality in Texas, guidelines for RAP processing, and RAP mix field construction draft specification (or guidelines). Detailed information is presented below.

RAP QUALITY IN TEXAS

RAP quality (or variability) has always been a cause for concern to many pavement/material engineers. To investigate this issue, the authors visited and surveyed three RAP stockpiles that TxDOT owned and eight RAP stockpiles that contractors owned around Texas. One observation during the visits was that both TxDOT and the contractors generally kept different stockpiles for RAP taken from different sources. During each visit, RAP samples were collected when visiting each individual RAP stockpile. A front-end loader was used to make the sampling platform and then the bag samples were collected (Figure A1). In most cases, seven RAP samples were collected around the RAP stockpile and then brought back to TTI for laboratory evaluation. The RAP quality in terms of aggregates gradation and asphalt binder contents was evaluated through the ignition oven test. Tables A1 to A12 show the ignition oven test results of RAP that both TxDOT and contractors owned.

Figure A1. Sampling RAP Stockpiles.

Tables A1–A12 show that, in terms of aggregate gradation and asphalt content, there is little variability in the RAP materials collected during the field visits. For example, the largest standard deviation on passing #8 sieve size for all RAP samples is 5.0 percent and most of them are below 4.0 percent, which is better than the national survey results (average = 4.32 percent and ranging from 0.78 to 9.0 percent) that West reported (*1*). The standard deviations of passing #200 sieve size in this study range from 0.5 to 2.3 percent, which is a little better than the national survey results ranging from 0.3 to 3.0 percent (*1*). As for the asphalt content, the standard deviations ranging from 0.1 to 0.5 percent are much smaller than the national results, which are between 0.1 to 1.5 percent (*1*). Apparently, these laboratory test results show that both TxDOT and contractors' RAP materials, in terms of aggregate gradation and asphalt content, are consistent. Therefore, it is reasonable to expect that produced RAP mixes will be consistent as well. However, as discussed previously, consistent and good quality RAP does not always equal good performing RAP mixes. All RAP mixes should be designed following the balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions.

Table A1. TxDOT-Owned Stockpile #1: Unfractionated RAP.

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

Table A2. TxDOT-Owned Stockpile #2: Unfractionated RAP.

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

Table A3. TxDOT-Owned Stockpile #3: Lab Fractionated RAP (1/2 inch–1/4 inch).

Sieve Size	Cumulative % Passing of RAP Samples					Ave	Stdev
	#1	#2	#3	#4	#5		
1/2	100.0	100.0	99.9	99.7	100.0	99.9	0.1
3/8	87.1	86.3	84.6	88.8	88.4	87.1	1.7
#4	39.3	31.6	38.2	41.4	38.9	37.9	3.7
#8	25.6	17.4	24.9	27.8	25.5	24.3	4.0
#16	21.0	14.1	20.3	23.0	21.1	19.9	3.4
#30	17.9	11.9	17.1	19.6	18.0	16.9	2.9
#50	14.3	9.5	13.5	15.9	14.5	13.5	2.4
#100	9.3	6.0	8.3	10.8	9.3	8.7	1.8
#200	5.3	3.3	6.3	6.7	5.2	5.4	1.3
AC (%)	3.52	2.62	3.5	3.6	3.34	3.3	0.4

Table A4. TxDOT-Owned Stockpile #3: Lab Fractionated RAP (Passing 1/4 inch).

Sieve Size	Cumulative % Passing of RAP Samples					Ave	Stdev
	#1	#2	#3	#4	#5		
1/2	100.0	100.0	100.0	100.0	100.0	100.0	0.0
3/8	100.0	100.0	100.0	100.0	100.0	100.0	0.0
#4	100.0	100.0	99.9	99.9	100.0	99.9	0.0
#8	79.3	81.4	78.7	77.9	84.4	80.4	2.6
#16	60.1	59.6	60.7	59.6	67.7	61.5	3.5
#30	46.1	42.4	47.0	47.2	53.8	47.3	4.1
#50	33.7	28.4	34.7	35.3	39.4	34.3	4.0
#100	21.1	16.3	21.8	22.0	24.7	21.2	3.0
#200	12.5	8.5	12.5	13.3	14.6	12.3	2.3
AC (%)	6.2	5.3	6.2	6.4	6.5	6.1	0.5

Table A5. Contractor-Owned Stockpile: C1-Crushed RAP.

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

Table A6. Contractor-Owned Stockpile: C2-Crushed RAP.

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

Table A7. Contractor-Owned Stockpile: C2-Crushed RAP+RAS.

Sieve Size	Cumulative % Passing of RAP Samples							Ave	Stdev
	#1	#2	#3	#4	#5	#6	#7		
3/4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
1/2	98.3	100	99.0	97.7	98.7	99.1	97.3	98.6	0.9
3/8	93.6	94.2	93.4	91.7	92.9	93.2	92.6	93.1	0.8
#4	75.0	75.2	73.6	70.6	70.3	72.8	73.6	73.0	2.0
#8	59.4	58.1	57.4	55.5	54.3	57.0	57.4	57.0	1.7
#16	45.9	45.6	44.9	45.1	43.6	45.7	44.9	45.1	0.8
#30	34.4	35.8	35.0	37.1	35.7	37.0	35.1	35.7	1.0
#50	25.4	28.3	27.7	31.0	29.9	30.6	27.4	28.6	2.0
#100	15.0	17.6	17.3	20.7	20.2	20.2	16.6	18.2	2.2
#200	8.6	10.5	10.5	13.0	13.0	13.0	10.2	11.3	1.8
AC (%)	7.5	8.1	7.7	8.6	8.2	8.0	7.4	7.9	0.4

Table A8. Contractor-Owned Stockpile: C3-Crushed RAP.

Sieve Size	Cumulative % Passing of RAP Samples			Ave	Stdev
	#1	#2	#3		
3/4	100.0	100.0	100.0	100.0	0.0
1/2	99.3	100.0	100.0	99.8	0.4
3/8	97.7	96.9	97.1	97.3	0.4
#4	79.6	77.7	77.1	78.2	1.3
#8	59.1	57.5	56.1	57.6	1.5
#16	48.0	47.1	45.9	47.0	1.0
#30	40.1	40.6	39.2	39.9	0.7
#50	26.3	28.9	27.7	27.6	1.3
#100	11.3	15.5	13.5	13.4	2.1
#200	5.9	8.9	7.4	7.4	1.5
AC (%)	4.0	4.2	4.3	4.2	0.1

Table A9. Contractor-Owned Stockpile: C4-Crushed Coarse RAP.

Sieve Size	Cumulative % Passing of RAP Samples						Ave	Stdev
	#1	#2	#3	#4	#5	#6		
¾	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
1/2	96.1	93.9	94.2	94.4	96.6	94.9	95.0	1.1
3/8	79.6	68.1	70.2	73.8	70.5	70.6	72.1	4.1
#4	30.2	21.1	19.2	22.6	23.2	18.9	22.5	4.1
#8	21.5	14.3	13.6	15.9	16.8	12.8	15.8	3.1
#16	17.2	11.2	11.8	13.2	14.4	10.9	13.1	2.4
#30	14.9	9.6	10.5	11.9	12.9	10.0	11.6	2.0
#50	13.1	8.2	9.3	10.6	11.5	9.0	10.3	1.8
#100	7.7	7.9	5.5	6.2	6.7	5.4	6.6	1.1
#200	4.4	5.2	3.1	3.4	3.6	2.9	3.8	0.9
AC (%)	2.7	2.3	2.1	2.4	2.7	2.3	2.4	0.2

Table A10. Contractor-Owned Stockpile: C4-Crushed Fine RAP.

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

Table A11. Contractor-Owned Stockpile: C5-Crushed Coarse RAP.

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

Table A12. Contractor-Owned Stockpile: C5-Crushed Fine RAP.

Sieve Size	Cumulative % Passing of RAP Samples							Ave	Stdev
	#1	#2	#3	#4	#5	#6	#7		
3/4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0
1/2	100.0	100.0	99.6	100.0	100.0	100.0	99.8	99.9	0.2
3/8	99.9	99.2	98.8	99.2	99.5	99.4	99.6	99.4	0.4
#4	91.0	88.2	89.8	89.2	90.4	90.6	88.2	89.6	1.1
#8	70.6	63.2	69.9	67.5	69.7	69.9	64.1	67.8	3.1
#16	54.0	47.5	54.6	51.7	53.5	52.4	45.5	51.3	3.5
#30	42.4	38.3	44.1	41.0	42.0	39.0	33.6	40.1	3.5
#50	29.9	27.7	32.2	28.5	28.5	25.5	22.8	27.9	3.0
#100	14.2	13.0	17.4	13.1	12.9	10.9	10.2	13.1	2.3
#200	6.7	5.7	10.4	5.7	5.5	4.4	4.3	6.1	2.1
AC (%)	4.7	4.9	5.0	5.3	5.0	4.6	4.3	4.8	0.3

PROPOSED GUIDELINES FOR RAP PROCESSING AND STOCKPILES MANAGEMENT

RAP processing and stockpiles management are key to having high-quality RAP and consistent RAP mixes. The authors proposed guidelines for RAP processing and stockpile management guidelines based on field observation and the interactions with TxDOT's personnel and contractors. The six-step RAP processing and stockpiles management guidelines are presented below:

1. **Eliminate contamination.**

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

   Contamination may occur from milled-up paving geosynthetics (fabrics, grid), reflective lane markers (yellow or white), and dumping general road debris with dirt and vegetation on the pile. In some cases, the multiple-source RAP stockpiles were believed to contain construction trash. Figure A1 shows an extreme example in which concrete trash and reinforced steel were mixed with RAP stockpile. Another type of contamination may be due to unstable, unconditioned, sunk earth surface. Any potential contamination to RAP stockpiles should be avoided in order to improve the RAP quality and, accordingly, pavement performance.

Figure A1. Contaminated RAP Stockpile.

2. **Separate RAP stockpiles from different sources.**

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

3. **Blend or mix before processing RAP stockpiles.**

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

4. **Process (crush or fractionate) RAP stockpiles.**

4.1. Crush or Fractionate RAP

There has been a lot of discussion about fractionating RAP, but the current practice for RAP processing is to crush all RAP materials to a single maximum size, in most cases, either 1/2 inch or 3/8 inch. Unlike crushing, fractionating the RAP involves simply screening RAP materials into two or more sizes. The fractionated RAP is often split into coarse and fine fractions. The coarse RAP stockpile will contain only the RAP material retained over a 3/8 inch screen or 1/2 inch screen; the fine RAP stockpile will contain only the RAP material passing the 3/8 inch screen or 1/2 inch screen. In comparing RAP fractionation with simply crushing RAP, there are benefits and some additional costs for fractionation. For example, RAP fractionation can provide designers more flexibility to choose different percentages of the coarse and fine RAP with virgin aggregates to meet both gradation and volumetric requirements. Generally speaking, it is easier to use more total fractionated RAP than crushed RAP.

4.2. Avoid over crushing

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

5. **Store the processed RAP using paved, sloped surface.**

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

5.1. Conical vs. horizontal stockpiles

As documented in "Recycling Hot-Mix Asphalt Pavements" (*2*), the RAP in the early days were piled in low, horizontal piles for fear that high, conical stockpiles would cause RAP to pack together with the weight of the pile. However, past experience indicated that this is not the case. Additionally, RAP has a tendency to hold water and the low, horizontal stockpiles often retain higher moisture accumulation than the tall, conical stockpiles. In general, tall, conical stockpiles are preferred.

5.2. Use paved, sloped surface area

While waiting for the contractors, the authors observed that at least one contractor already started using the paved, sloped surface to stockpile RAP materials. Using the paved surface under stockpiles not only can contribute to drainage from RAP stockpiles, but it also provides an even hard-surfaced area to minimize material loss and contamination of underlying materials. Meanwhile, providing a slope to the paved surface under the stockpile away from the side where the front-end loader moves RAP materials to cold feed bin, as Figure A2 shows, will allow rainwater to drain away, allowing drier RAP materials to go into the plant.

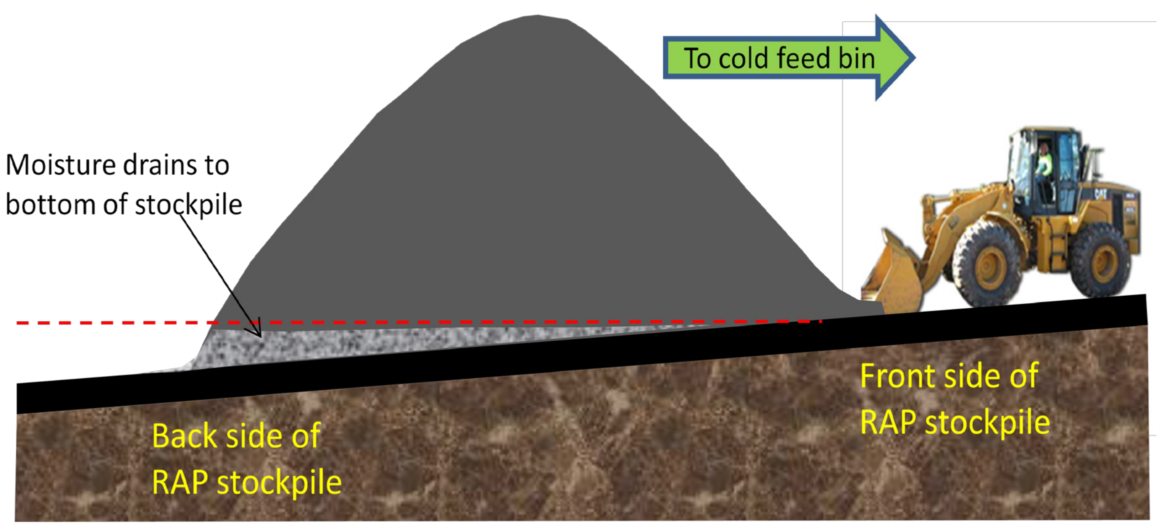

Figure A2. Illustration of Paved, Sloped Surface under RAP Stockpiles.

5.3. Cover RAP stockpiles if necessary

Currently, relatively few contractors cover any of their RAP stockpiles, but covering RAP stockpiles to minimize RAP moisture content is even more economical than covering virgin aggregate stockpiles. RAP should never be covered with a tarp or plastic, however. It is best to store RAP materials under the roof of an open-sided building (see Figure A3). Free air can pass over the RAP, but the RAP is protected from precipitation.

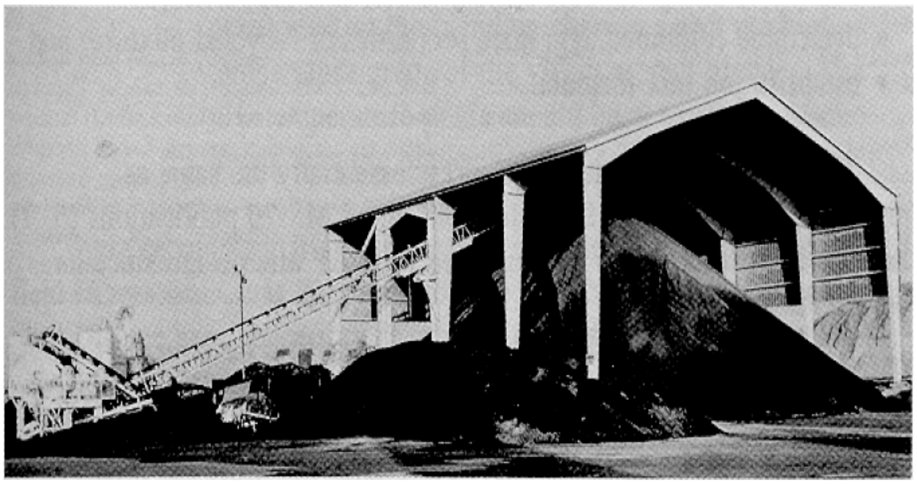

Figure A3. Storing RAP under a Covered Roof (*2*).

6. Characterize the processed RAP and mark stockpiles.

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

The guidelines proposed above may not completely solve the RAP variability problem, but they do provide a good starting point to have consistent RAP.

RAP MIX CONSTRUCTION SPECIFICATION

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

Conventional equipment, conventional techniques, and conventional indicators of a completed mat apply. Paving superintendents may claim that the RAP mixes are stiff. This means that the rollers and compactors must operate closer to the paver to get the job done. In some cases, they may need more passes over a given point in the pavement surface to obtain the desired air void content in the mat.

References

1. R. West, Summary of NCAT Survey on RAP Management Practices and RAP Variability, National Center for Asphalt Technology, Auburn, AL, July 2008.
2. National Asphalt Pavement Association, "*Recycling Hot-Mix Asphalt Pavements*." Information Series 123, Lanham, MD, 2007.

APPENDIX B
BALANCED MIX DESIGN PROCEDURE FOR HMA MIXES USING HIGH RAP

Although there is no significant difference between RAP mixes and virgin mixes in terms of production in the plant and placing and compacting in the field, designing RAP mixes is more complicated than virgin asphalt mixes. Not only does the virgin aggregates and virgin binder information have to be obtained, but RAP binder content and RAP aggregate gradation must also be determined through the ignition oven or asphalt binder extraction test. In addition, asphalt binder recovery tests may be needed to grade the RAP binder in order to use the blending chart. Furthermore, there are at least four more challenges when designing RAP mixes in the laboratory, especially for high RAP mixes (i.e., more than 25 percent):

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

There are no acceptable solutions for the first two challenges, but alternative approaches exist. One of them is to use the balanced mix design approach that Zhou et al. proposed (*3*) whereby the OAC is selected based on target air voids (or density) and rutting/moisture, and cracking resistances are determined using the HWTT and OT, respectively. The balanced mix design approach addresses challenges 1 and 2 through employing the OT to directly measure the cracking resistance of RAP mixes. Some ideas on the last two challenges were explored in this study and are described below.

RAP HANDLING

Proper RAP handling is one of the critical steps in the RAP mix design process. It is important to heat up RAP materials to ensure that the binder transfers from the RAP to the virgin aggregates. Basically there are two issues with RAP heating (or handling) in the laboratory: heating time and temperature. Different methods are available. Some designers preheat RAP materials at the target mixing temperature for a period of time before mixing with virgin aggregates. Others superheat the virgin aggregate and mix the RAP in at room temperature. Additionally, NCHRP Report 452 (*4*) recommends a preheating temperature of 230°F (110°C) for RAP and the 10°C above mixing temperature for virgin aggregates. Recently, the National Center for Asphalt Technology (NCAT) investigated different approaches of handling RAP in the laboratory, as Kvasnak (*5*) reported. After evaluating the four popular methods, Kvasnak (*5*) recommended that RAP be preheated at the same target mixing temperature as that of virgin aggregates, but with a timeframe of no less than 30 min. and no longer than 3 hr, depending on RAP amount. One target mixing temperature for both RAP and virgin aggregates is more practical for mix designers to implement, so the authors adopted the single temperature approach for this study.

Regarding the pre-heating time, after many trials and consulting several contractors' mix designers, a two-step preheating process is recommended:

- Warm up the RAP materials overnight (12–15 hr) at 140°F (60°C), which is the most used temperature to dry materials.
- Preheating the RAP at the mixing target temperature for 2 hr, which is often the time for preheating virgin binder.

This two-step preheating process combines NCAT's recommendations on one temperature for all and meanwhile fixes the preheating time. As the contractors in Texas have verified, this RAP handling process provides consistent results between laboratory mix design and plant-produced QC job formula.

MIXING AND COMPACTION TEMPERATURES

The mixing and compaction temperatures for high RAP mixes have not been well addressed in the literature, because this is not an issue when RAP contents are relatively low. As discussed previously, Kvasnak (*5*) recommended the same target mixing temperature for RAP materials and virgin aggregates, but the target mixing temperature was not clearly defined in that paper. Normally the virgin binder PG grade controls the mixing and compaction temperatures for virgin mixes. But for RAP mixes, there are at least three options for selecting the laboratory mixing and compaction temperatures:

- The mixing and compaction temperatures corresponding to the virgin binder.

- The mixing and compaction temperatures corresponding to the blended virgin/RAP binder.
- The mixing and compaction temperatures corresponding to the RAP binder.

Generally RAP binder is stiffer than virgin binder. The virgin binder will be overheated and consequently overaged if Option 3—the mixing and compaction temperatures corresponding to the RAP binder—is chosen. Since Option 3 is not a good choice, this study evaluated only Options 1 and 2.

The data presented in Report 0-9092-2 (*6*) indicated that increasing the mixing and compaction temperatures significantly lowered the optimum asphalt content (OAC). Consequently, cracking resistance of RAP mixes at the higher mixing and compaction temperatures becomes worse due to lower OAC and aging at high temperatures. Therefore, from the conservative point of view, it is proposed to use the mixing and compaction temperatures corresponding to virgin binder for RAP mixes design so that RAP mixes can have higher OAC, enough virgin asphalt binder, and better cracking resistance.

PROPOSED BALANCED MIX DESIGN PROCEDURE FOR HIGH RAP MIXES

Based on the discussion above and the previous work (*3*), a balanced mix design procedure for HMA mixes containing high RAP is proposed (see Figure B1). Basically it consists of the following 11 steps:

1. Evaluate RAP materials to determine RAP binder content and RAP aggregates gradation.
2. Select virgin binder, virgin aggregates, and total aggregates gradation.
3. Weigh the virgin aggregates and preheat these in an oven to the preselected mixing temperature based on virgin binder property.
4. Weigh then warm up RAP at 140°F (60°C) overnight (load the RAP materials in a dry oven or room just before the end of the day/office hours).
5. Manually mix the preheated RAP with hot virgin aggregates (on the morning of the second day).
6. Load virgin binder into the oven and wait around 2 hr to melt the virgin binder.
7. Mix virgin binder with the RAP/virgin aggregates blended in Step 5.
8. Lower the oven temperature to compaction temperature for short-term aging.
9. Compact the RAP mix samples by either TGC or Superpave gyratory compactor (SGC) for volumetric evaluation.
10. Meanwhile, compact the RAP mix samples by SGC for performance evaluation under HWTT and OT testing.

11. Select a balanced asphalt content meeting volumetric, rutting/moisture damage, and cracking requirements. Note that volumetric requirement refers to maximum density that is used to control potential bleeding. VMA is not considered here for two reasons:

- Without accurate RAP aggregate specific gravity and unknown amount of blending between RAP binder and virgin binder, it is difficult to calculate accurate VMA of the RAP mix.
- OT, instead of VMA, is used to directly evaluate cracking resistance of RAP mixes.

Field demonstration of the balanced RAP mix design procedure and detailed examples are presented in next section.

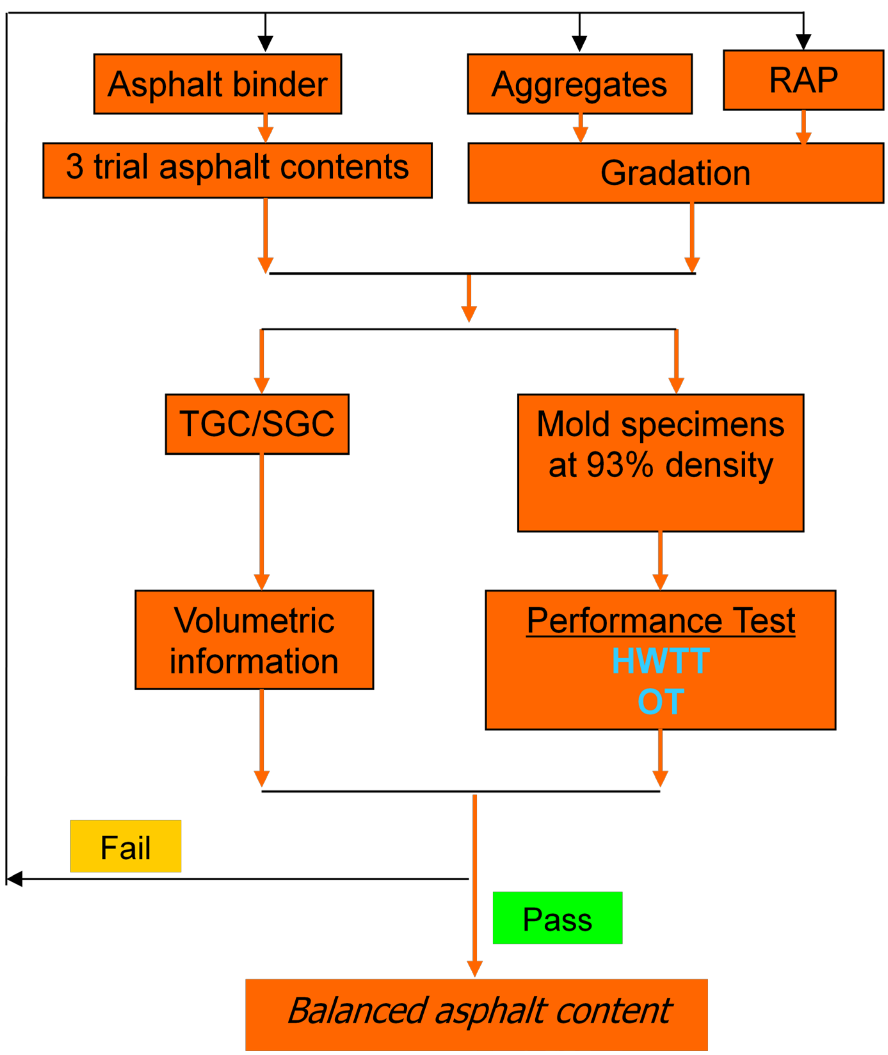

Figure B1. Balanced RAP Mix Design Flowchart.

DEMONSTRATION AND VALIDATION OF THE BALANCED MIX DESIGN PROCEDURE FOR HIGH RAP MIXES

This section demonstrates and validates the balanced mix design procedure for high RAP mixes through designing and constructing field test sections on Interstate Highway (IH) 40, Amarillo. The four RAP test sections shown in Figure B2 were constructed on IH40 near Amarillo, Texas, on August 11, 2009. The existing pavement has a total of 8 inches of existing HMA with severe thermal-related transverse cracking, which extends to the full depth of the HMA (see Figure B3). The reason for choosing these four sections is to permit the rapid determination of field performance of sections designed using both the current mix design method and the balanced RAP mix design method. The pavement design called for a 4 inch (100 mm) milling and 4 inch (100 mm) overlay section. Amarillo's climate is a temperate semi-arid climate with numerous freeze-thaw cycles and occasional blizzards during the winter season. Average daily high temperatures in Amarillo range from 48°F (9°C) in January to 92°F (33°C) in July. Furthermore, the traffic on IH40 is extremely heavy with over 50 percent heavy loaded trucks in the traffic stream. The cold weather, heavy traffic loading, and severe existing pavement cracking makes this a good case study to rapidly evaluate the impact of different RAP layers on pavement performance.

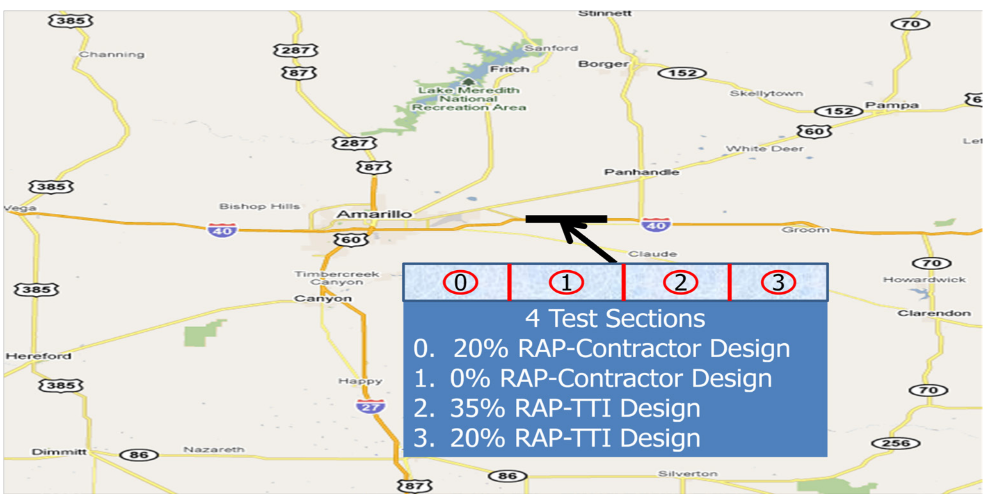

Figure B2. Four RAP Test Sections on IH40 near Amarillo, Texas.

Figure B3. Existing Pavement Conditions of IH40 after Milling.

RAP Mix Design Information of the Four Test Sections

The four RAP mixes used on IH40 are all dense-graded Type C mixes. As indicated in Figure B2, the 20 percent RAP mix and 0 percent RAP mix used in Sections #0 and #1, respectively, were designed by the contractor who followed TxDOT's standard mix design procedure (Tex-204-F) in which the OAC was selected based on a target 96.5 percent density and then checked to ensure the mix meets the HWTT 0.5 inch (12.5 mm) rutting requirement. Detailed mix design information about these two mixes and associated HWTT and OT results are tabulated in Table B1.

TTI designed the 35 percent RAP and 20 percent RAP mixes used in Sections #2 and #3 by following the balanced RAP mix design method (see the flow chart in Figure B1). As discussed previously, the final balanced asphalt content is determined by optimizing the maximum density, HWTT rut depth, and OT cycles. Based on past TxDOT experience with the TGC, the researchers chose a maximum density of 98 percent in this study. Figure B4 illustrates the asphalt content for the 98 percent maximum density line, rut depth (left vertical axis) and OT cycles (right axis) at different asphalt contents for the 35 percent RAP mix designed for Section #2. This section is different from the others since it used a softer PG58-28 virgin binder to compensate for the high RAP content. (Also, the initial trial mixes at 35 percent RAP with the PG 64-22 virgin binder yielded very poor OT results.) Figure B4 shows that based on the 98 percent maximum density requirement, the maximum asphalt content is 5.6 percent. As long as the asphalt content is below 5.6 percent, rutting/moisture requirement are automatically met. Therefore, the real control factor is the cracking requirement. Currently, there is no official cracking criteria in Texas for dense-graded mixes. Past experience with dense-graded asphalt mixes used on the LTPP sections on US175 near Dallas, Texas, showed that the good performance overlay mixes often have a minimum of 300 cycles. Apparently, the 35 percent RAP mix cannot meet such criteria. However, with these test sections the 300-cycle criteria can be further evaluated. For a factor of safety, 5.5 percent asphalt content was selected for the

35 percent RAP test section, which is 0.1 percent less than the maximum asphalt content (5.6 percent) for 98 percent density. The corresponding OT cycles to 5.5 percent asphalt content is 200 cycles for the 35 percent RAP mix. Table B1 provides more information on the 35 percent RAP mix.

Table B1. Mix Design Information of the Four RAP Test Sections on IH40 near Amarillo, Texas.

Section	RAP (%)	Virgin binder	Designer	Mix design method	OAC (%)	HWTT rut depth @ 20,000 passes	OT cycles
0	20	PG64-28	Contractor	TxDOT's Tex-204-F	5.0	3.72 mm	10
1	0	PG64-28	Contractor	TxDOT's Tex-204-F	4.8	4.38 mm	95
2	35	AC-10 (PG58-28)	TTI	Balanced mix design	5.5	8.00 mm	200
3	20	PG64-28	TTI	Balanced mix design	5.3	7.40 mm	103

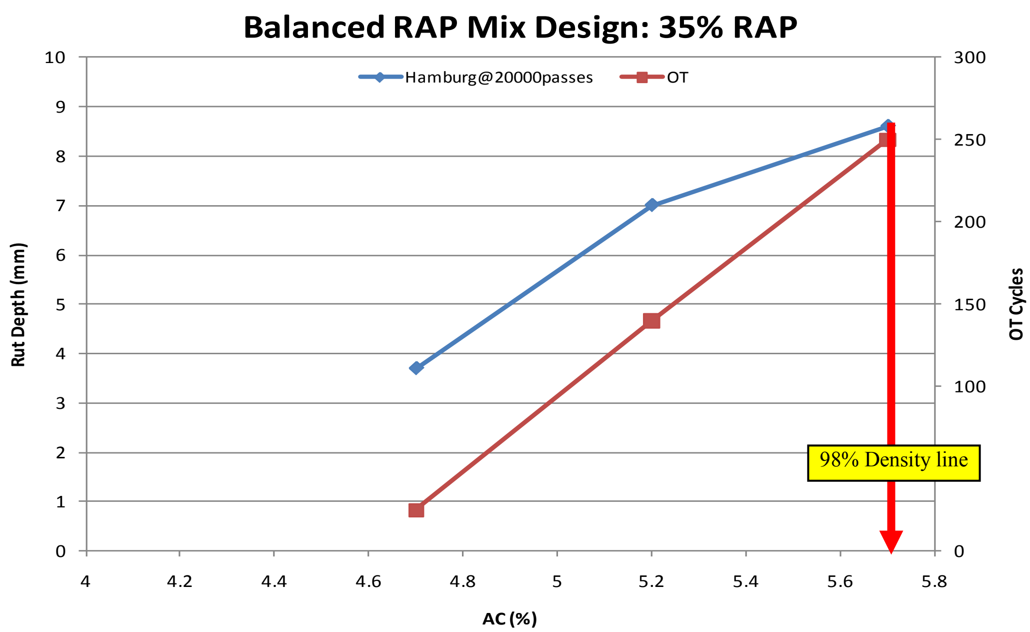

Figure B4. Balanced RAP Mix Design for 35 Percent RAP Mix of Section #2.

Similarly, the 20 percent RAP mix used in Section #3 was designed (see Figure B5). Again, rutting/moisture resistance is not a problem as long as asphalt content is below 5.4 percent, which corresponds to 98 percent density. But cracking resistance is not ideal. Similar to the 35 percent RAP mix, the asphalt content of 5.3 percent was recommended for 20 percent RAP mix, which is 0.1 percent less than the maximum asphalt content (5.4 percent) for 98 percent density. The corresponding OT cycles to 5.3 percent asphalt content is 125 cycles. Table B1 details the 20 percent RAP mix design information.

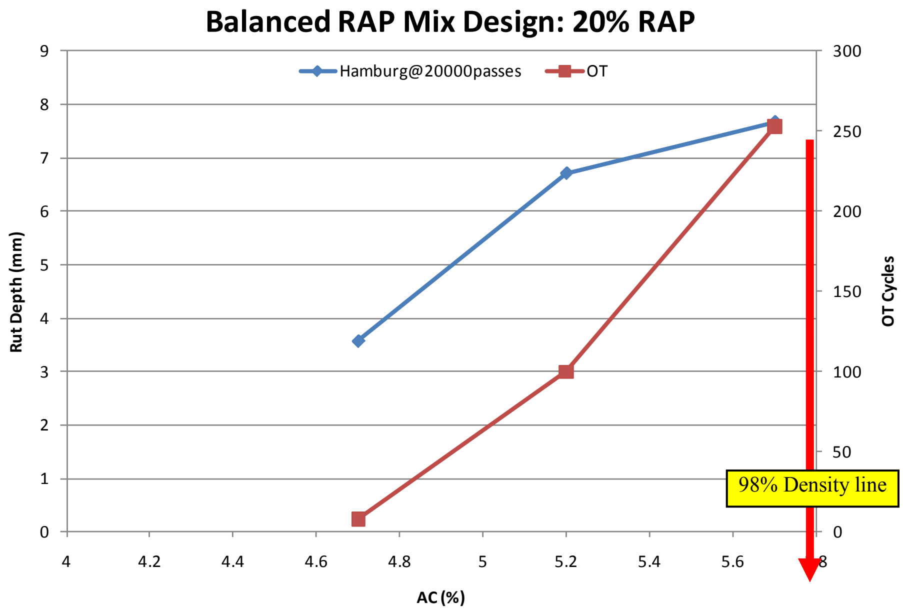

Figure B5. Balanced RAP Mix Design for 20 Percent RAP Mix of Section #3.

Field Performance of IH40 RAP Test Sections

Since the construction of IH40 on August 11, 2009, five field surveys have been conducted on April 22, 2010, September 8, 2010, April 5, 2011, December 15, 2011, and May 30, 2012, respectively. So far, no rutting has been observed, but reflective cracking was observed on all four test sections on the third survey. Detailed reflective cracking observations for each section are tabulated in Table B2. Prior to placing the overlay, the number of preexisting cracks in each section was documented and mapped. The reflective cracking rate is therefore defined as the ratio of the number of reflective cracks to the original number of cracks before the 4-inch (100 mm) overlay. It is clear that the higher the lab OT cycles of the RAP mix, the lower the reflective cracking rate, which further validates the effectiveness of OT for reflective cracking. It also clearly indicates that the 35 percent RAP test section with 200 OT cycles performed the best among the four sections. The overall conclusion from these four sections is that high RAP mix can have better or similar performance to the virgin mix, but it must be well designed following appropriate mix design methods, such as the balanced mix design procedure for HMA mixes containing high RAP.

Table B2. Field Performance Survey: Reflective Cracking Rate (%).

Sections	8/11/2009	4/22/2010	9/8/2010	4/5/2011	12/15/2011	5/30/2012
20% RAP-contractor	0	0	36	83	97	97
0% RAP-contractor	0	0	20	53	65	80
35% RAP-TTI	0	0	0	29	38	57
20% RAP-TTI	0	0	4	50	83	96

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1. R. Bonaquest, *New Approach for the Design of High RAP HMA*, Presented at 2005 Northeast Asphalt User/Producer Group Meeting, Burlington, VT, Oct. 19–20, 2005.
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3. F. Zhou, S. Hu, T. Scullion, M. Mikhail, and L. F. Walubita, "A Balanced HMA Mix Design Procedure for Overlays," *Journal of the Association of Asphalt Paving Technologists*, Vol. 76, 2007, pp. 823–850.
4. R. McDaniel and R. M. Anderson, *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician's Manual*, NCHRP Report No. 452, Transportation Research Board, Washington, D.C., 2001.
5. A. Kvasnak, "What to Consider when Designing a High RAP Content Mix," *Hot Mix Asphalt Technology*, National Asphalt Pavement Association, Vol. 18, July 2010, pp. 18–19, 21.
6. Zhou, F., S. Hu, G. Das, and T. Scullion (2011), High RAP Mix Design Methodology with Balanced Performance, Report FHWA/TX-11/0-6092-2, Texas Transportation Institute, College Station, TX, November 2011.

APPENDIX C
PAVEMENT TYPE SELECTION GUIDELINES FOR THE USE OF HIGH RAP MIXES

In general, pavement type selection often refers to the decision of selecting flexible pavement or rigid pavement. The topic discussed here is not about selecting a pavement type between flexible and rigid pavements. Instead, the focus is where to best use high RAP mixes with low risk. For example, a high RAP mix will have higher risk when it is used as an overlay over a jointed portland concrete pavement, compared with its use as an overlay over a continuously reinforced concrete pavement (CRCP). As discussed in Chapter 3, the best place for using high RAP mixes depends on many factors: traffic, climate, RAP mix properties, pavement structure, and existing pavement conditions. Without a pavement performance analysis system, it is very difficult (if not impossible) to make a rational decision. Recognizing the complexity of selecting the best application of high RAP mixes and the need for an asphalt overlay performance analysis system, the researchers integrated the balanced mix design procedure for high RAP mixes (*1*) and the asphalt overlay design and analysis system (S-TxACOL) into a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions. This integrated mix design and performance evaluation system is clearly described in Chapter 3. With the purpose of demonstration, the authors discuss the following case study to show the best application for a high RAP mix with an OT cycle of 50 and a 2-inch asphalt overlay.

A 2-inch (50 mm) asphalt overlay with PG 70-22 binder is applied to the following five potential applications in Bastrop County, Austin District. The traffic level is 3 million ESALs within 20 years.

1. 10-inch (250 mm) Jointed Portland Concrete Pavement (JPCP) over 6-inch (150 mm) base with LTE=70 percent.
2. 3-inch (75 mm) asphalt pavement over 10=inch (250 mm) cement stabilized base (CTB) with LTE=70 percent.
3. 5-inch (125 mm) asphalt layer over 12-inch (300 mm) granular base with medium severity cracking (LTE=70 percent).
4. 10-inch (250 mm) Continuous Reinforced Concrete Pavement (CPCP) over 6-inch (150 mm) base with LTE=90 percent.
5. 8-inch (200 mm) asphalt layer over 10-inch (250 mm) very stiff base with low severity level (LTE=50 percent).

The relationship between OT cycles and cracking development for each application predicted from S-TxACOL program is shown in Figures C1 and C2. Apparently, it is much safer to use the high RAP mix with an OT cycle of 50 as an overlay over CRCP (Case 4) or a thick asphalt pavement with low severity cracking (Case 5).

In summary, the balanced RAP/RAS mix design and performance evaluation system can be used as a tool to guide TxDOT's material and pavement engineers to best use high RAP mixes for project-specific service conditions.

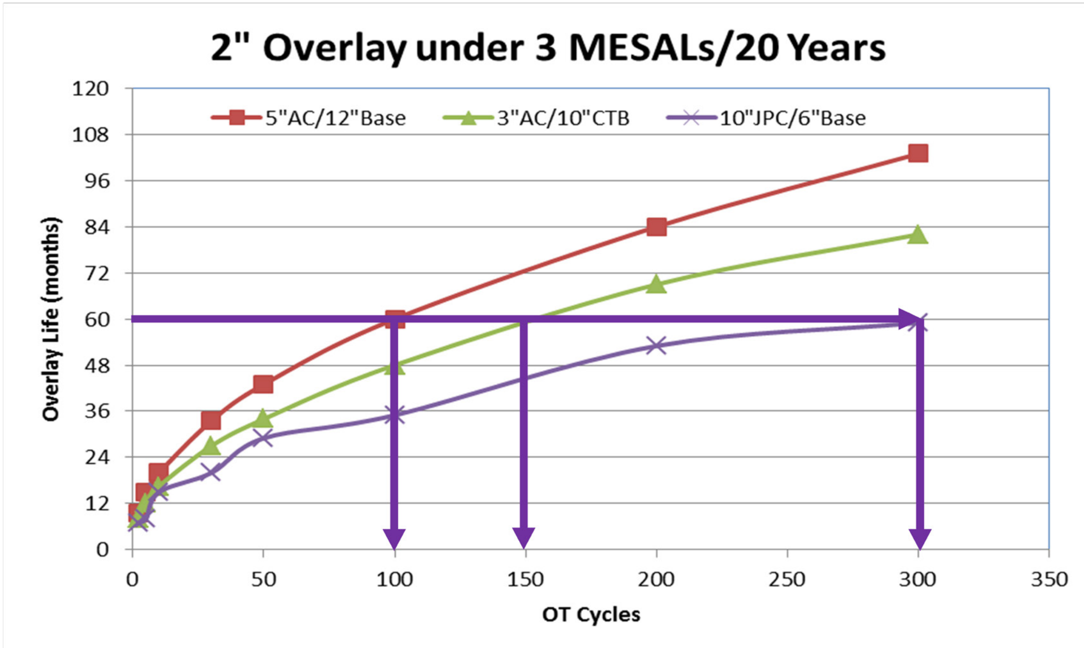

Figure C1. Relationships between OT Cycles and Cracking Development for Three Applications with Medium Cracking Severity.

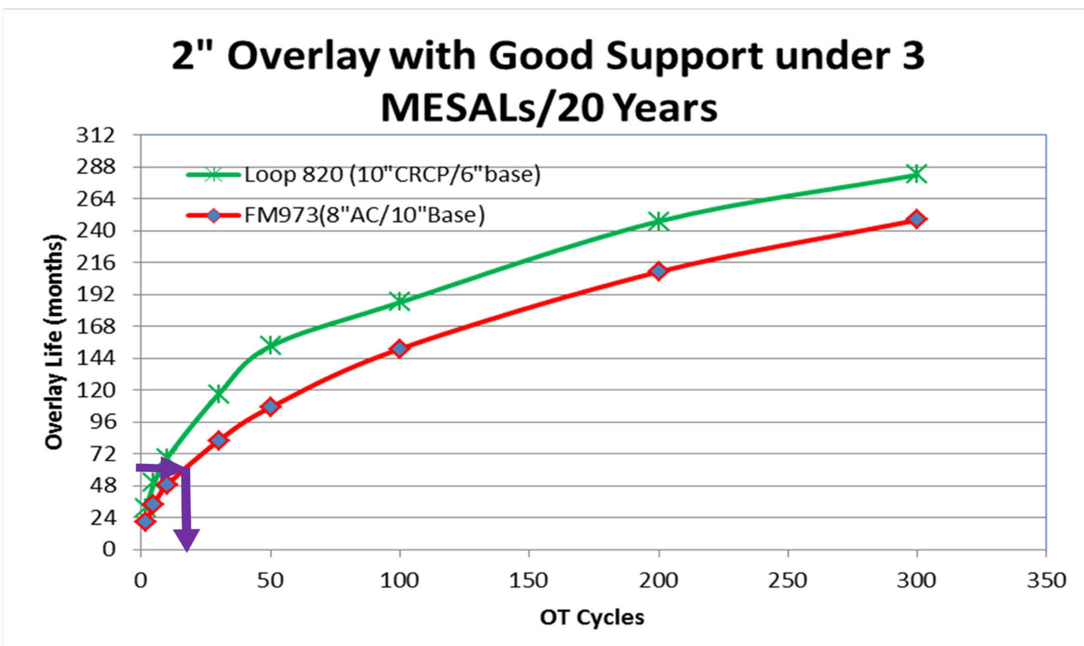

Figure C2. Relationships between OT Cycles and Cracking Development for Two Applications with Very Good LTE.

APPENDIX D
GUIDELINES FOR THE USE OF HIGH RAP IN HMA MIXES

A variety of field test sections with different RAP mixes have been constructed under Project 0-6092. Field performance of these test sections documented in Chapter 2 clearly indicated that high RAP mixes could have similar or better performance than virgin mixes. However, these RAP mixes must be designed for project-specific conditions. In order to best and successfully use the high RAP mixes, one must establish guidelines for each of the following four areas:

- RAP processing and stockpile management guidelines.
- Substitute binder and maximum allowable amount of recycled binder.
- High RAP mix design guidelines.
- Pavement type selection guidelines.

Apparently, the guidelines are established on existing TxDOT specifications and the research work performed under Project 0-6092 including this report and the other two published reports.

- F. Zhou, G. Das, T. Scullion, and S. Hu, *RAP Stockpile Management and Processing in Texas: State of Practice and Proposed Guidelines*, Research Report FHWA/TX-10/0-6092-1, Texas Transportation Institute, College Station, TX, November 2009.
- F. Zhou, S. Hu, G. Das, and T. Scullion, *High RAP Mixes Design Methodology with Balanced Performance*, Research Report FHWA/TX-11/0-6092-2, Texas Transportation Institute, College Station, TX, November 2011.

Detailed information about each of the four components is described in the following text.

RAP PROCESSIGN AND STOCKPILE MANAGEMENT GUIDELINES

RAP processing and stockpile management have significant impact on RAP quality (or variability), which is the first and crucial step to have a good RAP mix. To address this issue, the authors developed guidelines for RAP processing and stockpile management that are documented in Appendix A.

SUBSTITUTE BINDER AND MAXIMUM ALLOWABLE AMOUNT OF RECYCLED BINDER

When using high RAP in HMA, there are two things one needs to pay special attention to: maximum allowable amount of RAP and substitute binder. TxDOT's latest specification requires that the use of RAP cannot exceed the maximum allowable percentages of RAP shown in Table D1 for dense-graded mixes. The allowable percentages shown in Table D1 may be decreased or increased when shown on the plans. When RAP (or RAS) is used, calculate and ensure that the ratio of the recycled asphalt binder to total binder does not exceed the percentages shown in Table D2 during mixture design and HMA production. Note that surface, intermediate, and base mixes referenced in Tables D1 and D2 are defined as follows:

- **Surface mixes** are the final lift or riding surface of the pavement structure.
- **Intermediate mixes** are non-surface mixtures placed less than or equal to 8 inches from the riding surface.
- **Base mixes** are non-surface mixtures placed greater than 8 inches from the riding surface.

Specifically, when using substitute binders, one must ensure that the substitute PG binder and mixture made with the substitute PG binder meets the following:

- The substitute binder meets the specification requirements for the substitute binder grade in accordance with Section 300.2.J, "Performance-Graded Binders."
- The substitute binder has an unaged dynamic shear value less than or equal to 2.00 kPa and an RTFO aged dynamic shear value less than or equal to 5.00 kPa at the PG test temperature; and
- The mixture has less than 10.0 mm of rutting on the Hamburg Wheel test (Tex-242-F) after the number of passes required for the originally specified binder. Use of substitute PG binders may be allowed only at the discretion of the Engineer if the Hamburg Wheel test results are between 10.0 mm and 12.5 mm.

Note that the discussion here focuses on dense-graded mixes, since more than 70 percent HMA are dense-graded mixes. The specification also has other guidance on substitute binder and maximum allowable amount of RAP used in Superpave mixes, PFC, and SMA mixes.

Table D1. Maximum Allowable Amounts of RAP.[1]

Maximum Allowable Fractionated RAP[2] (%)			Maximum Allowable Unfractionated RAP[3] (%)		
Surface	**Intermediate**	**Base**	**Surface**	**Intermediate**	**Base**
20.0	30.0	40.0	10.0	10.0	10.0

1. Must also meet the recycled binder to total binder ratio shown in Table 5.
2. Up to 5% RAS may be used separately or as a replacement for fractionated RAP.
3. Unfractionated RAP may not be combined with fractionated RAP or RAS.

Table D2. Maximum Recycled Binder Ratios and Allowable Substitute PG Binders.

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

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

HIGH RAP MIX DESIGN GUIDELINES

As clearly demonstrated in Chapter 2, high RAP mixes can have similar or better performance than virgin mixes when these are designed using the balanced mix design procedure with consideration of project-specific service conditions. The authors developed a balanced RAP/RAS mix design and performance evaluation system for project-specific service conditions. Details of the balanced mix design and performance evaluation system are described in Chapter 3 and Appendix B. It is critical to use the developed mix design system to design acceptable RAP/RAS mixes meeting the requirements of project-specific service conditions.

PAVEMENT TYPE SELECTION GUIDELINES FOR THE USE OF HIGH RAP MIXES

Field performance of a RAP mix depends on traffic, climate, pavement structure, and pavement type. For example, a RAP mix will perform in a completely different manner when it is used in the two diverse service conditions: 1) an overlay mix over a CRCP, and 2) an overlay mix over JPCP with poor load transfer efficiency. The most important thing is to select and design high RAP mixes for project-specific service conditions by following the balanced RAP/RAS mix design and performance evaluation system. The previous Appendix C gives the detailed pavement type selection guidelines.