

Evaluation of Use of Recycled Asphalt Shingles in HMA

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This comprehensive study focused on best use of recycled asphalt shingles (RAS) in hot mix asphalt (HMA). Consistency of processed RAS is discussed. It was found that, in Texas, the processed RAS, including both tear-off asphalt shingles (TOAS) and manufacturing waste asphalt shingles (MWAS), have very low variability in terms of gradation and RAS binder content. Furthermore, the authors characterized RAS binder performance grade (PG). RAS binders are very stiff, and TOAS binders, with an average of high-temperature grade of 178°C, are much stiffer than MWAS binders that have an average of high-temperature grade of 131°C. Properties of blended virgin and extracted/recovered RAS binders were investigated. Generally, the properties of blended virgin and RAS binders are non-linear. However, for practical applications, the linear blending chart can still be used if the RAS binder percentage is below 30%. Further, compared to TOAS binders, MWAS binders have less impact on PG temperatures of virgin binders. Thus, it is important to consider differentiating MWAS from TOAS when used in asphalt mixes. This study also evaluated the impact of TOAS and MWAS on engineering properties of asphalt mixes. The use of RAS has no significant influence on dynamic moduli of HMA mixes, but improves their resistance to rutting/moisture damage. Meanwhile, adding RAS generally increases optimum asphalt content (OAC) of HMA mixes and higher OAC correspond to higher RAS content. However, RAS mixes typically exhibit very poor cracking resistance, compared to the 0% RAS mixes with either PG 64-22 or PG 70-22, even though the RAS mixes have higher OAC. Therefore, cracking resistance can be a significant concern for RAS mixes. This paper explored two approaches for improving cracking resistance of RAS mixes in the laboratory and the field. Laboratory test results clearly indicated that both using soft binder and increasing design density can improve cracking resistance of RAS mixes. When considering rutting resistance of RAS mixes, using soft binder is superior to decreasing design air voids. The effectiveness of decreasing design air voids was confirmed through two field test pavements on US 87 near Amarillo, Texas; the four soft binder test pavements on FM 973, near Austin, are still being monitored

Keywords: RAS, Binder Blending, Overlay Test, Rutting, Cracking, Dynamic Modulus

1. Introduction

Reclaimed asphalt pavement (RAP) has been one of the most often used recycling materials in the asphalt industry. With increases in the price of asphalt cement and subsequent price fluctuations, the industry has further amplified its recycling efforts. Most recently, with the drastic increases in cost of asphalt cement, the use of recycled asphalt shingles (RAS) in hot-mix asphalt (HMA) has become another 'black gold' to the asphalt paving industry, since RAS contains approximately 20-30% asphalt binder of its total mass. In addition to conserving energy and protecting the environment, the use of RAS can significantly reduce the cost of HMA production and paving. There are two basic types of RAS scraps: tear-off asphalt shingles (TOAS) and manufacture waste asphalt shingles (MWAS). In United States, around 10 million tons of TOAS and 1 million tons of MWAS are available for recycling (Newcomb et al. 1993). Specifically, there are several nation-wide, large roofing shingle manufacturers in

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Texas, such as Owens Corning, GAF, TAMKO, Certain Teed, etc. Significant markets exist for both the recycling and paving industries.

More than 30 years ago, some of the original pioneers established the first shingle recycling plants, investigated mix designs containing RAS, and then published the first technical literature in the late 1980s (Epps and Paulsen, 1986; Paulsen et al., 1986; and Shepherd et al., 1989). More recently, HMA producers, Departments of Transportation (DOTs), and researchers further expanded the expertise in shingle recycling in HMA (Grzybowski, 1993; Newcomb et al., 1993; Button et al., 1996; Janisch and Turgeon, 1996; Foo et al., 1999; NAHB, 1999; Dykes, 2002; Lum, 2006; Brock 2007; McGraw et al., 2007; Schroer, 2007, Johnson et al., 2010; Williams et al. 2011, and more on the website: www.shinglerecycling.org). All these efforts paved the way for more DOTs to use RAS in HMA.

In February 2009, the Texas Commission on Environmental Quality (TCEQ) issued an Authorization Memo to allow HMA plants to include either MWAS or TOAS under the TCEQ air quality standard permit for permanent HMA plants. Since then, RAS has been widely used in Texas. Meanwhile, some concerns on consistency of processed RAS, stiffness of RAS binder, and durability of RAS pavements were raised. To address these concerns, in 2010, the Texas Department of Transportation (TxDOT) initiated a research study at the Texas A&M Transportation Institute (TTI) with an overall objective of improving the use of RAS in HMA. To achieve this main objective, the following steps were undertaken by the researchers:

- Investigate consistency of processed RAS
- Characterize RAS binder properties
- Produce virgin binder/RAS binder blending charts
- Identify the impact of RAS on engineering properties of paving mixtures
- Evaluate approaches for improving durability of RAS mixes in the lab, and
- Validate the approaches for improving durability of RAS mixes in the field.

Details of each of these are presented below. This is followed by the summary and conclusions at the end of the paper.

2. Consistency of Processed RAS in Texas

Researchers visited different contractors and recyclers around Texas, and sampled 10 different types of processed RAS stockpiles: 4 MWAS and 6 TOAS. For simplicity, these are named MWAS-A, MWAS-B, MWAS-C, MWAS-D, TOAS-A, TOAS-B, TOAS-C, TOAS-D, TOAS-E, and TOAS-F. For each processed RAS stockpile, seven replicates of the processed RAS were collected and brought back to TTI for laboratory testing.

2.1 Dry Sieve Analysis Results

Currently, TxDOT's specification requires 100 percent passing the ½-inch sieve and 95 percent passing ¾ -inch sieve. All 10 processed RAS stockpiles tested met the specification and they are very consistent in terms of gradation. Due to space limitation, Table 1 only presents the dry sieve analysis test results for 4 processed RAS materials sampled in this study. In fact, three processed RAS (TOAS-C, TOAS-F, and MWAS-C) had 100 percent passing the ¾-inch sieve.

Table 1. Dry Sieve Analysis Results of Four Processed RAS Materials.

RAS	Sieve No.	#1	#2	#3	#4	#5	#6	#7	Average	Standard deviation
TOAS-C	1/2"	100	100	100	100	100	100	100	100	0.1
	3/8"	99	100	99	100	100	100	99	100	0.2
	# 4	81	86	82	84	88	86	84	84	2.3
TOAS-F	1/2"	100	100	100	100	100	100	99	100	0.4
	3/8"	100	100	100	100	100	100	98	100	0.9
	# 4	94	93	95	94	93	94	89	93	2.2
MWAS-A	1/2"	100	100	98	99	100	100	100	100	0.6
	3/8"	99	98	96	99	99	99	99	98	1.1
	# 4	91	82	87	91	88	88	90	88	3.1
MWAS-C	1/2"	100	100	100	100	100	100	100	100	0.0
	3/8"	100	100	100	100	100	100	100	100	0.1
	# 4	85	80	89	93	87	89	90	87	4.1

2.2 Ignition Oven Test and Associated Results

Normally, 1300 grams of representative material of HMA or RAP is required for an ignition oven test to determine the asphalt content and a washed sieve analysis. However, since RAS has very high asphalt content (more than 20 percent), the binder in 1300 grams of RAS could not be completely burned even if the specimen is burned more than three times. After many trials, researchers found that approximately 500-700 grams of RAS material provides complete burning and consistent results in terms of RAS binder content and RAS aggregate (solids) gradation. Following this practice, researchers performed the ignition oven test on all seven selected RAS materials and then a wet sieve analysis on the RAS aggregates; and for each selected RAS, seven replicates were tested. Due to limited space, only two representative test results are presented below: one for TOAS (see Table 2) and one for MWAS (Table 3).

The results listed in Tables 2 and 3 indicate that TOAS has higher binder content than MWAS. MWAS generally has a consistent 20 percent binder content; TOAS has various binder contents, ranging from 23 percent to 28 percent. Overall, RAS variability, in terms of asphalt binder content and gradation, are low for both MWAS and TOAS. MWAS exhibited a slightly lower variability.

Table 2. Gradations and Binder Contents from Ignition Tests: TOAS-B.

Sieve Size	Cumulative % Passing of RAS Samples							Average	Standard Deviation
	#1	#2	#3	#4	#5	#6	#7		
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.1
#4	98	91	98	99	94	98	99	97	2.7
#8	95	86	96	96	86	93	95	92	4.1
#16	75	65	76	80	66	72	74	73	5.0
#30	53	44	53	64	48	49	52	52	5.8
#50	48	38	47	60	43	43	46	46	6.2
#100	41	31	39	54	36	35	38	39	6.6
#200	30	22	28	46	28	25	27	30	7.2
Binder content (%)	25	24	28	28	28	28	28	27	1.5

Table 3. Gradations and Binder Contents from Ignition Tests: MWAS-A.

Sieve Size	Cumulative % Passing of RAS Samples							Average	Standard deviation
	#1	#2	#3	#4	#5	#6	#7		
1/2"	100	100	100	100	100	100	100	100	0.0
3/8"	100	100	100	100	100	100	100	100	0.0
#4	100	100	100	100	99	98	99	99	0.5
#8	99	98	99	99	98	95	97	98	1.5
#16	85	83	85	86	83	80	83	83	2.0
#30	66	63	64	65	63	59	61	63	2.1
#50	57	53	54	55	52	50	51	53	2.3
#100	45	42	42	43	37	37	37	40	3.1
#200	33	30	30	32	27	27	28	30	2.2
Binder content (%)	21	19	21	19	20	20	19	20	0.7

3. RAS Binder Characterization and Virgin/RAS Binder Blending Charts

It is a known fact that the extracted/recovered RAS binders, regardless of MWAS or TOAS, are very stiff, and they are far stiffer than any PG 76-22 binder. But their true PG is not well known due to the temperature limitations of commonly used dynamic shear rheometer (DSR). Since RAS binder properties have significant influence on virgin binder selection and the allowable maximum amount of RAS used in asphalt mixes, it is critical to determine the true performance grade of RAS binder. This study sampled, extracted/recovered, and characterized a variety of RAS binders. Detailed information is provided below.

3.1 Selection RAS Samples

The same 10 processed RAS products described previously were used: 4 MWAS (MWAS-A, MWAS-B, MWAS-C, and MWAS-D) and 6 TOAS (TOAS-A, TOAS-B, TOAS-C, TOAS-D, TOAS-E, and TOAS-F).

3.2 RAS Binder Extraction and Recovery

The following two methods to extract and recover RAS binder were used with trichloroethylene as the solvent.

- Tex-210-F - Determining Asphalt Content of Bituminous Mixtures by Extraction: Part I-Centrifuge Extraction Method Using Chlorinated Solvent
- ASTM D 5404 - Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator

The authors validated these two methods, first, through comparing both rheological properties (measured by DSR and BBR) and chemical components (measured by Fourier transform infrared spectroscopy) of one original shingle binder before and after the extraction and recovery process (Zhou et al., 2012). Then, the 10 RAS binders were extracted and recovered following the validated extraction and recovery methods. Upon completion of the extraction process, there was some difficulty in "pouring out the recovered TOAS binders, because they were so stiff, and just did not flow out of the beaker even at 165°C. In one case, the oven temperature was raised to 200°C to successfully drain out the TOAS binder.

3.3 RAS Binder Characterization

Both DSR and BBR were used to determine the PG grade of the 10 extracted/recovered RAS binders. Difficulties were encountered in grading the RAS binders using the BBR. There are two criteria (S and m) for determining the low-temperature grade of asphalt binders. RAS binders easily met the S (<300 MPa) criteria, but the measured m values were always less than 0.3. The authors even tried to perform the BBR test at higher temperatures (i.e., 18°C and even 24°C), but the measured m values are still less than 0.3, and in some cases, the beam deformation reached the limit of BBR machine within a very short of period of time. The reason for such a small m value is that RAS binders have much less capability to relax. Therefore, no reliable results from BBR test were obtained for any of the 10 recovered RAS binders. Alternative test (such as Asphalt Binder Cracking Device test) should be explored.

To measure the high-temperature grades of those extremely stiff binders, a high-temperature DSR was purchased by TTI. Nine of the 10 RAS binders were successfully graded following the Superpave PG system. The high-temperature grade of one TOAS binder was beyond the upper limit of the purchased DSR, which is 200°C, thus extrapolation was used to estimate its high-temperature grade. For each extracted/recovered RAS binder, both original and rolling thin-film oven (RTFO) aged residue were evaluated. The high-temperature grades of the 10 RAS binders are shown in Figure 1. At least two observations can be made from Figure 1:

- TOAS binders, with an average high-temperature grade of 178°C, are much stiffer than MWAS binders, with an average of high-temperature grade of 131°C.
- MWAS binder exhibited smaller variation in the high-temperature grade, compared with TOAS binder, varying from 159°C to 214°C.

These two observations may indicate that MWAS is different from TOAS so that it is necessary and important to differentiate MWAS from TOAS when using in asphalt mixes. For example, DOTs may desire to allow smaller amount of TOAS in the specification when compared with MWAS.

In summary, the RAS binders are very stiff. Thus, it is critical to investigate the impact of these extremely stiff binders on rheological properties of the combined binder after blending with virgin binders, which is discussed next.

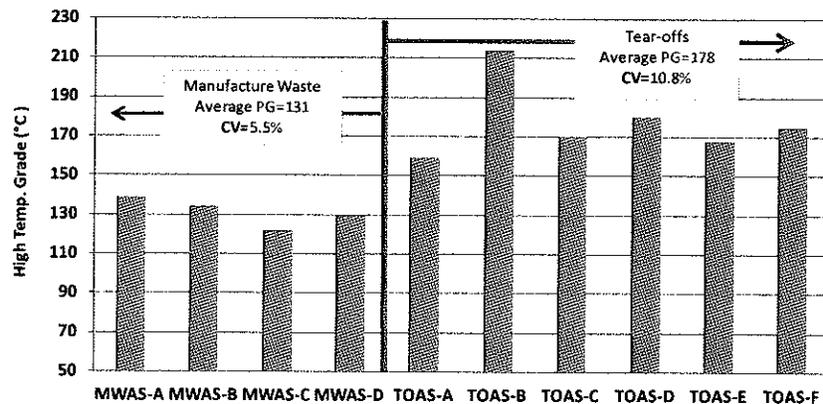


Figure 1. High PG Temperatures of both Manufacture Waste and Tear-off Shingles.

3.4 Virgin/RAS Binder Blending

Compared to virgin/RAP binder blending, very little work was reported on virgin/RAS binder blending in the literature. Nevertheless, AASHTO PP 53, *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 also be used with virgin/RAS binders. This study selected three virgin binders (PG 64-22-A, PG 64-22-B, and PG 64-28) and four RAS binders (TOAS-A, TOAS-E, MWAS-A, and MWAS-C) for investigating virgin/RAS binder blending. With these binders, a total of 4 combinations of virgin/RAS binders, as listed below, were tested. These 4 combinations were used in field test pavements that will be described later.

- Virgin Binder: PG 64-22-A and RAS Binder: TOAS-E
- Virgin Binder: PG 64-28 and RAS Binder: TOAS-A
- Virgin Binder: PG 64-22-B and RAS Binder: MWAS-A
- Virgin Binder: PG 64-22-B and RAS Binder: MWAS-C

For each combination, different percentages of virgin binder and RAS binder were blended and then evaluated through DSR and BBR testing in terms of the high and low PG temperatures. Test results for these four combinations are presented in Figures 2, 3, 4, and 5, respectively. The following observations are made from these figures.

- Generally, virgin and RAS binder blending is non-linear.
- For practical application, the linear blending chart can still be used if the RAS binder percentage is below 30%. Below 30% 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 ends of the PG grade of the blended binder.
- Increasing RAS binder content 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 about cracking resistance of the blended binder. Adding 20% RAS binder can make a PG xx-22 binder become a PG xx-16 (or even a PG xx-10 [Figure 2]) binder after blending. Additionally, Use of a PG xx-28 virgin binder to obtain a PG xx-22 when 20% RAS binder is added is achievable. Note that 20% RAS binder corresponds to 5% RAS by mass of the total mix with the assumptions that the optimum asphalt content of a RAS mix is 5% and RAS contains 20% asphalt binder.
- Impact of MWAS binder on the high and low PG temperatures of virgin binder is different from that of TOAS binder. Compared to the TOAS binders (Figures 2 and 3), the MWAS binders (Figures 4 and 5) have less impact on PG temperatures of virgin binders, which makes sense, since MWAS binders are significantly softer than TOAS binders (see Figure 1).

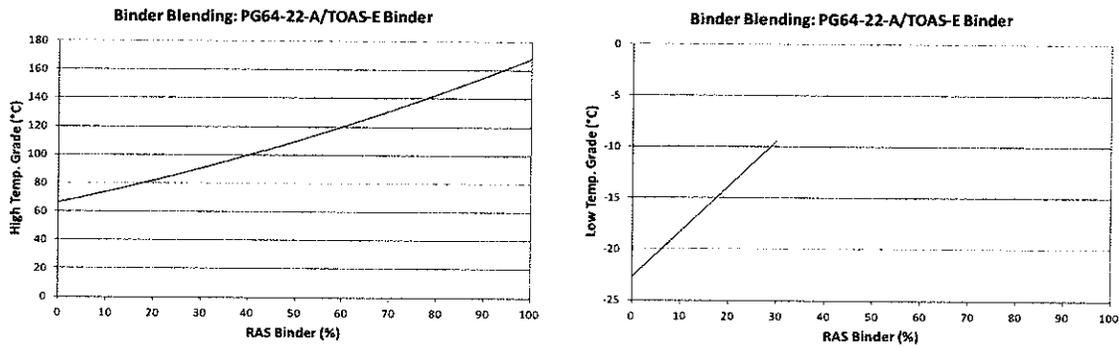


Figure 2. Binder Blending between PG 64-22-A and TOAS-E Binder.

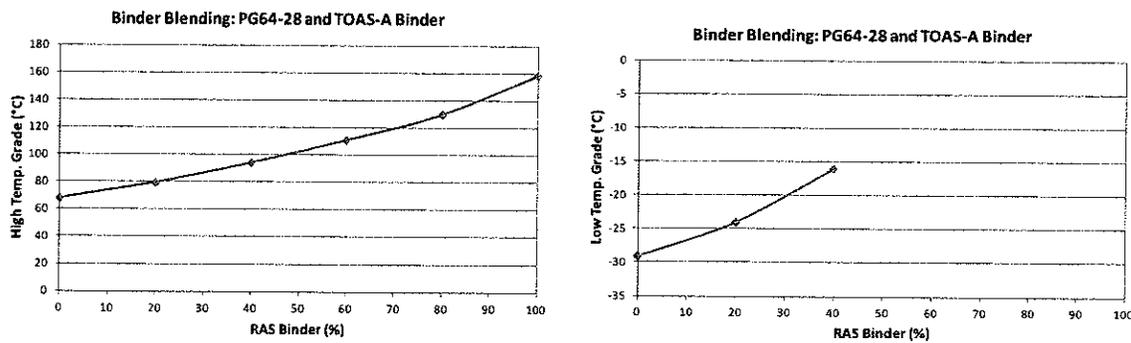


Figure 3. Binder Blending between PG 64-28 and TOAS-A Binder.

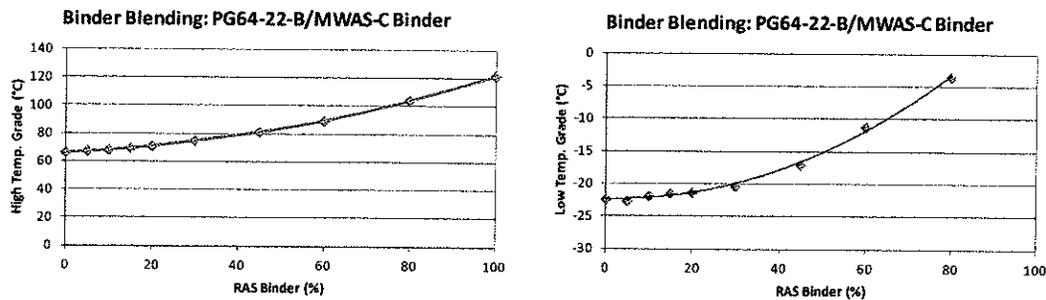


Figure 4. Binder Blending between PG 64-22-B and MWAS-C Binder.

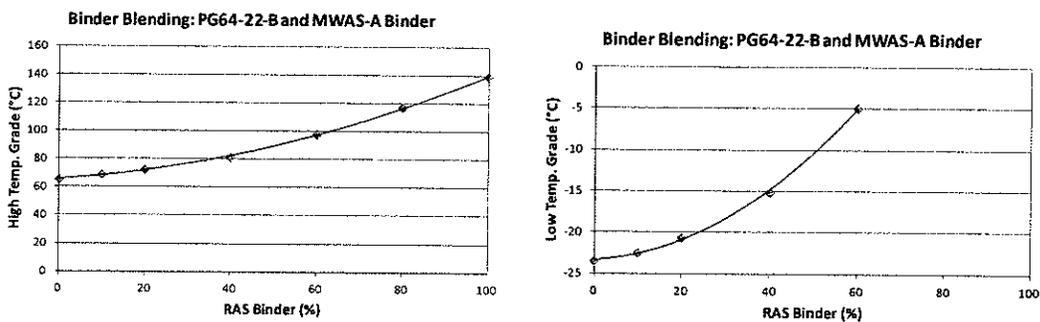


Figure 5. Binder Blending between PG 64-22-B and MWAS-A Binder.

In addition to the influence of RAS binders on blended binders, RAS itself has significant impact on engineering properties of HMA mixes containing RAS, which is discussed in the next section.

4. Impact of RAS Content on Laboratory Mix Engineering Properties

Incorporation of RAS materials into asphalt mixes stiffens them and thus improves the resistance to rutting but may jeopardize resistance to cracking. Additionally, TOAS and MWAS may have different impacts; since these two are so different in terms of high-temperature grade (see Figure 1). Therefore, it is necessary to thoroughly investigate the impact of RAS content and RAS type (TOAS/MWAS) on mixture engineering properties in terms of dynamic modulus, rutting, and cracking. In this study, two RAS types (TOAS-E and MWAS-C) and three RAS percentages (0%, 3%, and 5%) were considered. Note that TOAS-E is very similar to MWAS-C in terms of RAS aggregate gradation and RAS binder content, and the main difference between them was RAS binder high-temperature PG: TOAS-E = 166°C vs. MWAS-C = 122°C. A total of six mixtures with the same aggregates and similar gradations, as listed in Table 4, were evaluated using the dynamic modulus test, Hamburg wheel tracking test (HWTT), and Texas Overlay test (OT). A 0% RAS/PG 64-22 mix was the control mix. A 0% RAS/PG 70-22 mix was added to compare with the mixes containing 5% RAS/PG 64-22, since many DOTs allow a one grade “dump” of the virgin binder when 5% RAS is used.

Table 4. Ignition Test Results: MWAS-A.

RAS Type	RAS Percentage ¹ and Virgin Binder			
	0% RAS/PG 70-22	0% RAS/PG 64-22	3% RAS/PG 64-22	5% RAS/PG 64-22
TOAS-E	X	X	X	X
MWAS-C	X	X	X	X

Note: 1- The percentage here is referred as to RAS rather than RAS binder.

The following steps were followed:

- Step 1: Fix the RAS content (i.e., 5%) and adjust virgin aggregate percentage to make the total aggregate gradation for each RAS mix as close to each other as possible (Figure 6).

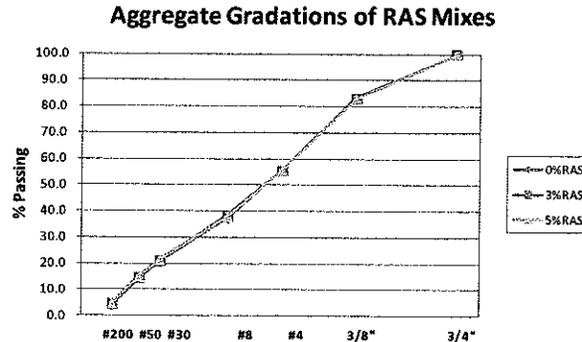


Figure 6. Gradations of HMA Mixes with varying RAS Contents.

- Step 2: Design the RAS mixes and select an optimum asphalt content (OAC) following standard TxDOT mix design procedure (Tex-204-F) for dense graded mixes, which are widely used in Texas (75% of all the HMA used in Texas).
- Step 3: Evaluate the dynamic modulus (or stiffness), rutting/moisture resistance, and cracking resistance of mixes with varying RAS content at its specific OAC.
 - Dynamic modulus of each mix was measured following the AASHTO TP 79, “Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT).” The 4-inch (100-mm) diameter by 6-inch (150-mm) tall specimens with 7 ± 0.5 percent air voids were fabricated in accordance with AASHTO PP 60, “Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC).” For each mix, two replicates were tested, and the average value is reported here.
 - Rutting/moisture resistance of RAS mixes was characterized using the Hamburg Wheel Tracking Test (Tex-242-F). The specimen size of the HWTT is 6-inch (150-mm) diameter by 2.5-inch (62-mm) height and its target air voids content is 7 ± 1 percent. The HWTT is conducted in a water bath at a constant temperature of 122°F (50°C). The specimens are tested under a rolling 1.85-inch (47-mm) wide steel wheel using a 158-lb (705-N) force. An average rut depth, measured at several locations including the center of the wheel travel path, is reported at end of the test.
 - Cracking resistance of RAS mixes was determined using Texas Overlay Tester (Tex-248-F). The standard specimen size for OT is 6-inch (150-mm) long by 3-inch (75-mm) wide by 1.5-inch (38-mm) high, and its target air voids content is 7 ± 1 percent after cutting. The OT is conducted in a displacement controlled mode with a maximum opening displacement of 0.025 inches (0.63 mm) at test temperature of 77°F (25°C). The number of cycles to failure (failure defined as 93 percent reduction of the cyclic maximum load from the one measured at the first load cycle) is used as an indicator for cracking resistance. Note that five replicates of OT specimens were tested for each mix, and the average value of OT cycles was used for comparison. The correlation between OT result and field cracking performance has been well documented (Zhou and Scullion, 2005, Zhou et al., 2007) and the OT has been used for evaluating both reflective and fatigue cracking by different researchers (Bennert et al., 2008, Zhou et al., 2009, Zhou et al., 2010, Mogawer et al., 2011).

4.1. Impact of RAS on OAC of HMA Mixes

Three mix designs were performed for mixes with TOAS-E: 0% TOAS-E/PG 64-22, 3% TOAS-E/PG 64-22, and 5% TOAS-E/PG 64-22. The OAC for each mix was determined based on 97% density (or 3% air voids) and is presented in Table 5. Mix designs for mixes containing 3% MWAS-C/PG 64-22, and 5% MWAS-C/PG 64-22 were conducted as well. It was found that the OACs for the mixes containing 3% and 5% MWAS-C are very close to

those of the mixes containing 3% and 5% TOAS-E. Thus, the same OAC was selected for the mixes with the same amount of RAS, regardless of TOAS-E or MWAS-C. Additionally, the OAC of the mix containing 0% RAS/PG 70-22 was kept the same as that of the mix with 0% RAS/PG 64-22, since these two mixes have exactly the same raw aggregates and gradation and the influence of binder type is considered through mixing and compaction temperatures. In summary, Table 5 lists the OAC of each RAS mix evaluated in this section.

It can be seen clearly that, with the higher RAS content, the OAC increases. The reason for this is that the increasing RAS content increases the composite PG grade of the blended RAS/virgin binder. (Note that it may also be due to incomplete use of all the binder in the RAS as binder in the mix. That is, the RAS binder is extracted and counted as binder, but it is not really active as binder in the mix). Therefore, with the higher composite PG grade, the mixing and compaction temperatures should be increased for high RAS mixes. When the mixing and compaction temperatures are kept the same for each RAS mix, higher RAS mixes will need more asphalt binder to achieve the same density. The higher OAC somehow offsets the impact of higher RAS content on engineering properties of RAS mixes, as discussed next.

Table 5. OAC of Each RAS Mix.

RAS Type	Optimum Asphalt Content (%)			
	0% RAS/PG 70-22	0% RAS/PG 64-22	3% RAS/PG 64-22	5% RAS/PG 64-22
TOAS-E	4.7	4.7	4.9	5.2
MWAS-C				

4.2. Impact of RAS on Dynamic Modulus

Dynamic moduli of each mix measured at different temperatures are shifted following the time-temperature superposition principle and presented in master curve format. Figure 7 shows master curves for all six mixes. Overall, the dynamic modulus master curves of these six mixes are similar, except that the 0% RAS/PG 70-22 mix has a little bit higher moduli. Higher RAS content does not always mean higher stiffness. Additionally, in terms of dynamic moduli of HMA mixes, the TOAS-E and MWAS-C have very similar impact.

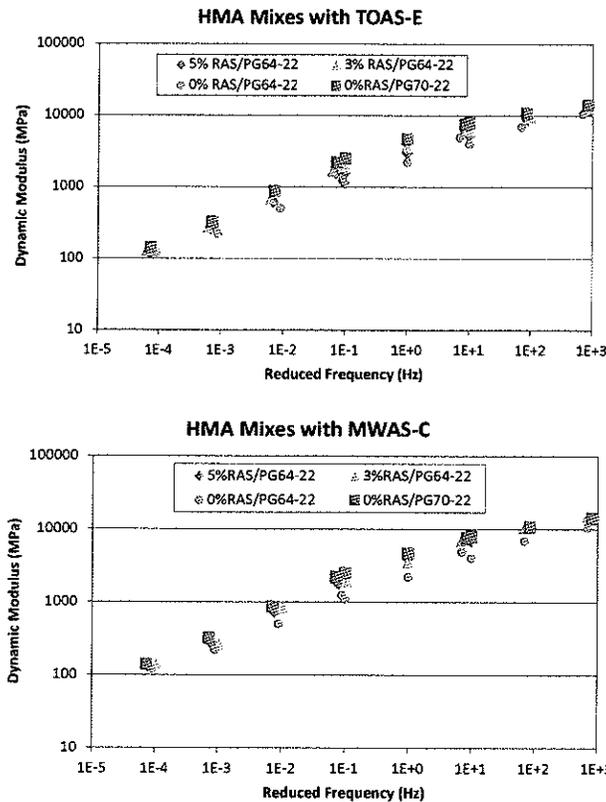


Figure 7. Impact of RAS on Dynamic Moduli of HMA Mixes.

4.3. Impact of RAS on Rutting Resistance

Figure 8 presents the HWTT test results. For those mixes containing PG 64-22, adding RAS improved rutting/moisture damage, whether TOAS-E or MWAS-C. However, such improvement is not significant enough to match the impact of the 0% RAS/PG 70-22 binder. This observation implies that the degree of blending between PG 64-22 virgin binder and RAS binder in the mixing and curing process before compaction is different from the blending of pure PG 64-22 binder and extracted/recovered RAS binders (see Figures 2 and 4). One may take the mix with 5% RAS (TOAS-E)/PG 64-22 as an example. If complete (or 100%) blending occurs, like those shown Figure 2, the blended binder becomes PG 80-15, which is far stiffer than PG 70-22 binder, and accordingly, the mix containing 5% TOAS-E should exhibit less rutting. Surely, complete (100%) blending in the mixing, curing, and compaction processes did not occur, since the high-temperature grade of the TOAS-E binder is 166°C.

Additionally, Figure 8 shows that the mixes containing TOAS-E have less rut depths than those containing MWAS-C, which is reasonable, since the TOAS-E binder is stiffer than the MWAS-C binder (see Figure 1).

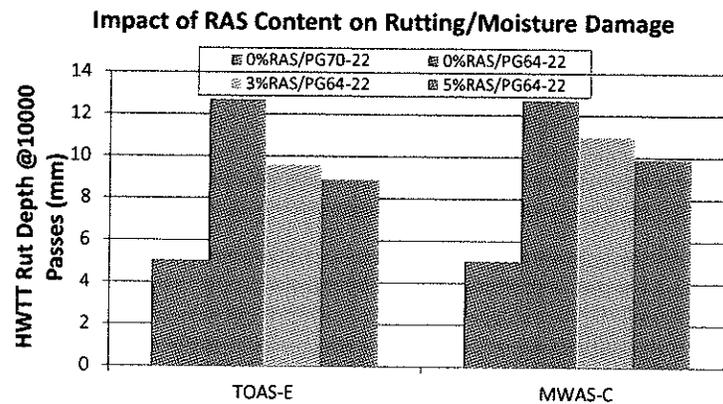


Figure 8. Impact of RAS on Rutting/Moisture Damage of HMA Mixes.

4.4. Impact of RAS on Cracking Resistance

Figure 9 shows the impact of RAS on cracking resistance of HMA mixes. For those mixes containing PG 64-22, the use of RAS decreases cracking resistance of the HMA mixes, whether TOAS-E or MWAS-C. The TOAS-E has a worse effect than the MWAS-C, which implies that blending between the virgin PG 64-22 and the TOAS-E binder (or the MWAS-C binder) actually occurred. If there is no blending at all, both of the mixes containing TOAS-E should have the same OT cycles as those containing MWAS-C. Although it is unknown how much blending actually occurred, one known thing is that the mixes containing MWAS-C had much better cracking resistance than those containing TOAS-E. This finding is consistent with the binder blending charts presented previously, in which the impact of the MWAS-C on the low-temperature grade of blended binder is much less than that of the TOAS-E (see low-temperature grades of Figures 2b and 4b).

Compared with the 0% RAS/PG 70-22 mix, those PG 64-22 mixes with either 3% or 5% RAS have worse cracking resistance. This is not a surprise because, if blending between virgin PG 64-22 and RAS binder occurs, the low-temperature grade would become warmer (i.e., PG xx-15 shown in Figure 2); Conversely, if there is no or very limited blending, the total effective asphalt binder amounts within those RAS mixes would be much less than the 0% RAS mixes with PG 70-22 or PG 64-22 binder. Regardless, the cracking resistance is a big concern for RAS mixes.

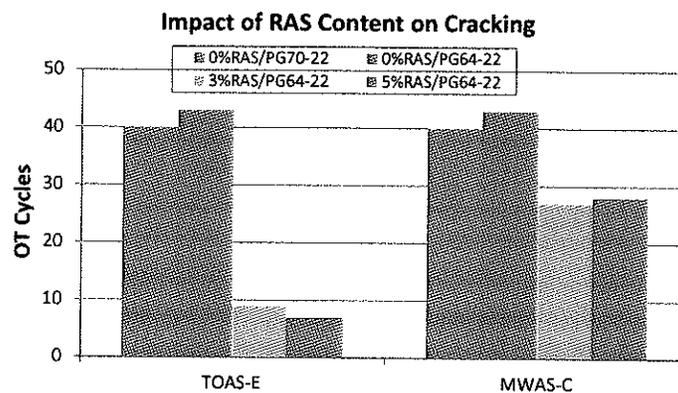


Figure 9. Impact of RAS on Cracking Resistance of HMA Mixes.

4.5. Summary and Discussion

Findings and discussions from the results presented above are provided below:

- RAS has no significant influence on dynamic moduli of HMA mixtures, but improves their rutting resistance and moisture damage. RAS generally increases OAC of HMA mixes. However, RAS mixes exhibit very poor cracking resistance, compared to the mixes containing only PG 64-22 or PG 70-22, even though the RAS mixes have higher OAC. Therefore, cracking resistance is a big concern for the RAS mixes.
- Impact of the TOAS-E is different from that of the MWAS-C in terms of cracking resistance, as the MWAS-C mixes offer much better cracking resistance. This finding is consistent with results from binder blending discussed previously.
- Both the HWTT and OT results indicated that some blending occurs between virgin binder and RAS binder during the HMA mixing and curing (or short-term aging) processes. But the blending is not 100%, and this is no surprise, since the high-temperature grades of the TOAS-E and the MWAS-C binders are 166°C and 122°C, respectively. It is well known that the mixing temperature for a PG 64-22 binder is around 143°C (290°F). Extremely, impractically high temperature is required in order to make the RAS binder flow and comeingle with virgin binder, whether using TOAS or MWAS. Although the degree of blending is still unknown, one known fact is that the use of RAS increases cracking of HMA mixes, and some remedies need to be explored, as discussed in next section.

5. Laboratory Evaluation of Approaches for Improving Cracking Resistance of RAS Mixes

RAS has significant impact on cracking resistance and, consequently, on the durability of HMA mixes. Some approaches need to be pursued to balance the performance of RAS mixes. In general, there are at least 4 potential approaches:

- Reduce RAS content (i.e., from 5% to 3%),
- Rejuvenate RAS binder in the mix design process,
- Use soft virgin binders, especially on the low-temperature grade (i.e., PG XX-28, PG XX-34), and
- Decrease design air voids.

Naturally, the first choice is to use less RAS. However, the previous results shown in Figure 9 indicated that reducing RAS from 5% to 3% does not have significant improvement on cracking resistance. Further reducing RAS usage quantities will minimize the economic and environmental benefit. The second choice is to rejuvenate RAS binder by using a rejuvenating agent. This may sound a good idea and should improve cracking resistance of RAS mixes (Tran et al., 2012), but there are practical and technical issues when applied to normal asphalt plant operations. Apparently, more research is needed in the area of rejuvenating agents and their practical application. Thus, this paper focused on the last two approaches: using soft binder and decreasing design air voids. The researchers evaluated the effectiveness of these two approaches in improving cracking resistance of RAS mixes.

5.1. Use of Soft Binders

The same 5% RAS/PG 64-22 mixes containing TOAS-E and MWAS-C that were previously designed were used as “control” mixes. Two soft binders were selected: PG 64-28 and PG 64-34. A total of six mixes (2 RAS using 3 virgin binders), listed in Table 6, were evaluated using the dynamic modulus test (AASHTO TP 79), HWTT (Tex-242-F), and OT (Tex-248-F). The same 5.2% OAC was used for all six mixes, since the purpose is to investigate the influence of soft binders. Figures 10, 11, and 12, show the test results.

Table 6. RAS Mixes with Soft Virgin Binders.

RAS	5%RAS/PG 64-22	5%RAS/PG 64-28	5%RAS/PG 64-34
TOAS-E	X	X	X
MWAS-C	X	X	X

It can be seen from Figure 10 that RAS mixes with softer binders have slightly lower moduli, but the differences among these 6 mixes is very small. Meanwhile, compared with the 5% RAS/PG 64-22 mix, the use of softer binders

improved rutting/moisture damage, as indicated in Figure 11. One reason for the improvement is that both PG 64-28 and PG 64-34 are polymer-modified binders. As expected, the mixes containing MWAS-C have deeper rut depth than those containing TOAS-E. Figure 12 clearly indicates that using soft (modified) binders is an effective method to improve cracking resistance of RAS mixes. 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 (modified) binders has little impact on dynamic moduli of RAS mixes; whereas, it can improve both rutting and cracking resistance of RAS mixes, particularly cracking resistance.

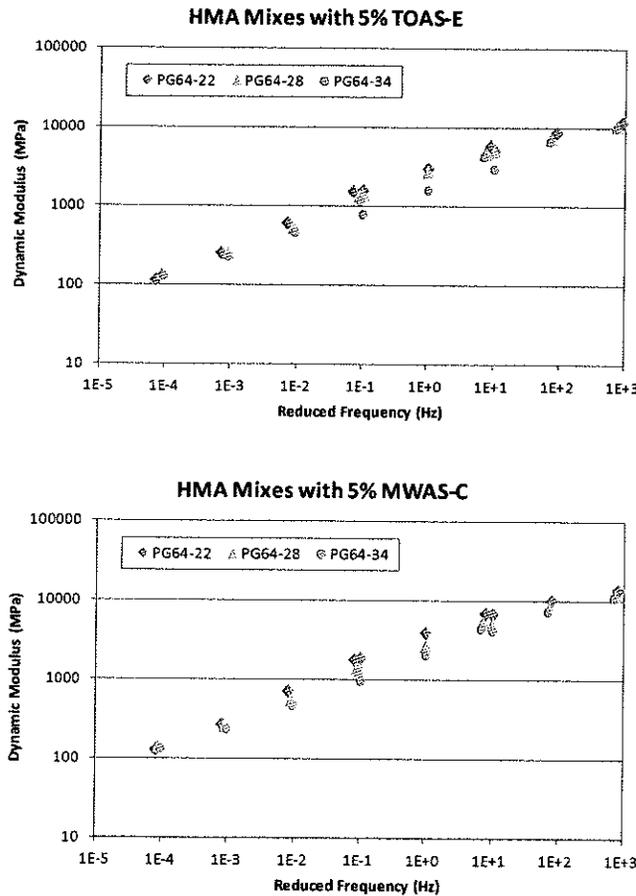


Figure 10. Impact of Soft Binders on Dynamic Modulus of 5% RAS Mixes.

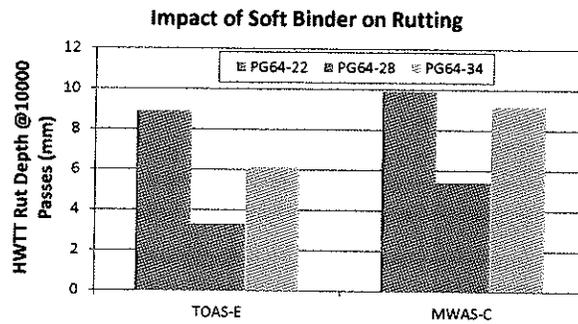


Figure 11. Impact of Soft Binders on Rutting/Moisture Damage of 5% RAS Mixes.

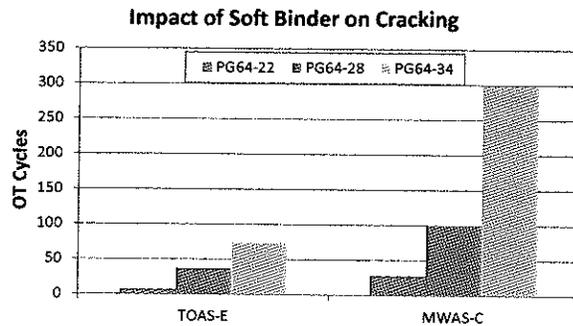


Figure 12. Impact of Soft Binder on Cracking Resistance of 5% RAS Mixes.

5.2. Decreasing Design Air Voids

Another simple way to improve cracking resistance of RAS mixes is to add more virgin binder with a lower low-temperature grade into the mixes through decreasing design air voids when selecting OAC. Currently, the TxDOT design density for selecting OAC of RAP/RAS mixes is 97%. To avoid bleeding problems, the maximum design density should be less than 98%. Again, the same 5% RAS/PG 64-22 mixes with the TOAS-E and MWAS-C, that were previously designed, were used here. Two design densities: 97% and 97.7% were used, and accordingly, the corresponding OACs were 5.2% and 5.7%, respectively. Only the HWT (Tex-242-F), and OT (Tex-248-F) testing was performed. The dynamic modulus test was omitted, since the previous results showed little difference among different RAS mixes. Figure 13 shows the test results.

It can be seen from Figure 13 that the higher OAC corresponding to decreased design air voids significantly improves cracking resistance. Conversely, the higher OAC makes the RAS mixtures more susceptible to potential rutting. Therefore, one must exercise caution when improving cracking resistance of RAS mixes through decreasing design air voids.

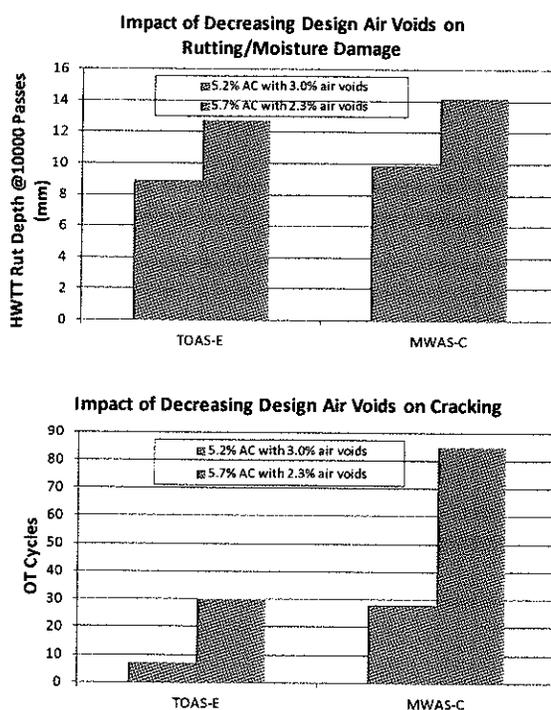


Figure 13. Impact of Decreasing Design Air Voids on Rutting and Cracking Resistance of RAS Mixes.

5.3. Discussion

The OT results presented above clearly indicated that both using soft binder and decreasing design air voids can improve cracking resistance of RAS mixes. When considering rutting of RAS mixes, using soft binder is superior to decreasing design air voids (see Figures 11 and 13). In order to validate these laboratory test results and these two approaches, field test pavements were constructed in Texas, which are discussed in next section.

6. Field Validation of Approaches for Improving Cracking Performance of RAS Mixes

Field test pavements were constructed to validate the two approaches for improving cracking performance of RAS mixes: using soft binder and decreasing design air voids. A total of 6 asphalt overlay test pavements using RAS mixes were built in two different areas of Texas. Field performance, to date, of these test pavements are presented below:

6.1. RAS Test Pavements on US 87, Amarillo, Texas

Two 3-inch thick asphalt overlay test pavements were constructed end to end in the same lane and travelling direction on US 87, Amarillo, Texas, in late October 2010. The main objective of these two test pavements was to validate the effectiveness of decreasing design air voids on improving cracking resistance of RAS mixes. The RAS mixes used on the two test pavements are exactly the same (aggregates, gradation, virgin binder, and RAS) except for the OAC; OAC for the control section was 4.6% while the other is 5.2%. Amarillo's climate is a temperate semi-arid climate characterized by numerous freeze-thaw cycles and occasional blizzards during the winter season. Average daily high temperatures for Amarillo range from 48°F (9°C) in January to 92°F (33°C) in July. US 87 in Amarillo has medium traffic with around 5 million ESALs in 20 years. The existing asphalt pavement exhibited severe transverse cracking. Cold weather and severe existing pavement cracking plus high traffic make these two pavements a good case study to rapidly validate the effectiveness of decreasing design air voids on improving cracking resistance of RAS mixes.

After completion of construction of these two RAS test pavements, three field surveys were conducted on Apr. 5, 2011, Dec. 15, 2011, and May 30, 2012. So far, no rutting has been observed, but reflective cracking occurred in both test pavements (Figure 14). The development history of the observed reflective cracking is shown in Figure 15. Prior to placing the overlay, the number of pre-existing cracks in each pavement was documented and mapped. 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. Apparently, decreasing design air voids significantly improved reflective cracking performance of the RAS mix on US 87, which is clearly shown in Figure 15.

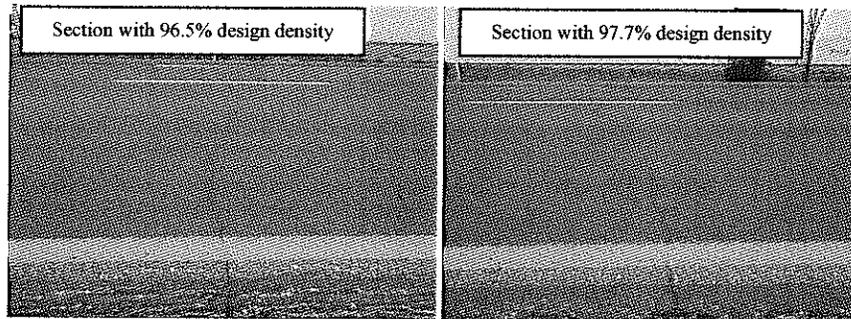


Figure 14. Observed Reflective Cracking of RAS Test Pavements on US 87, Amarillo, Texas.

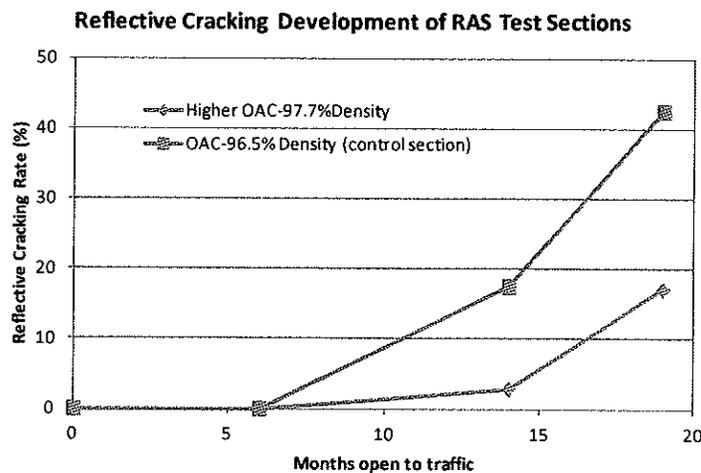


Figure 15. Reflective Cracking Development History of RAS Test Pavements on US 87, Amarillo, Texas.

6.2. Field Test Pavements on FM 973, Austin, Texas

A comprehensive series of experimental asphalt overlay test pavements were constructed on FM 973 near the Austin Bergstrom International Airport. Compared to the cold weather in Amarillo, the weather in Austin area is fairly warm. This roadway experiences very heavy truck traffic, as it carries traffic from several aggregate quarries and concrete batch plants. A total of 9 test pavements were built between December 2011 and January 2012. One objective of these test pavements was to evaluate the effectiveness of using soft binder on improving cracking resistance of RAP/RAS mixes. Table 7 lists four HMA test sections related to this study. In addition to the virgin PG 70-22 mix (control mix), three other mixes were evaluated. Prior to the 2-inch asphalt overlay, the overall pavement condition was good. Some areas exhibited longitudinal cracking along the wheel paths. After completion of construction, these four RAP/RAS test pavements were trafficked for six months. One survey was conducted in July 2012, and neither rutting nor cracking was observed on any test section. Figure 16 shows current conditions of

Pavements 3 and 6. Apparently, more time is needed for these test sections to show differences in rutting or cracking. TTI researchers will continue to monitor performance of these pavements.

Table 7. Four Test Pavements on FM 973, Austin, Texas.

Mix	Virgin Binder Grade	RAS (%)	RAP (%)	
			0	15
HMA	PG 70-22	0	Section 1	
	PG 64-22	3		Section 3
		5	Section 4	
	PG 58-28	3		Section 6

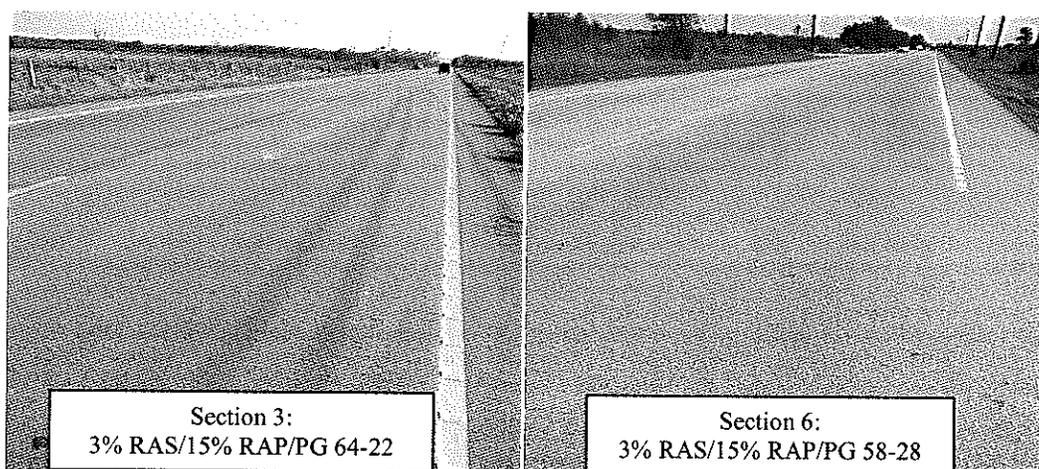


Figure 16. Conditions of RAP/RAS Test Pavements 3 and 6 on FM 973, Austin, Texas, in July 2012.

7. Summary and Conclusions

This paper presents a comprehensive study on HMA mixes containing RAS, including RAS consistency, RAS binder characterization and blending charts for virgin/RAS binders, impact of RAS content on OAC and engineering properties of RAS mixes, and approaches for improving cracking resistance of RAS mixes. Six RAS field test pavements were constructed to validate the approaches for improving cracking resistance of RAS mixes. Based on the research presented in this paper, the following conclusions are offered:

- All 10 processed RAS materials tested in this study, whether TOAS or MWAS, met the specification and are consistent in terms of gradation. TOAS had a higher binder content than MWAS. MWAS had a consistent 20 percent binder content, while TOAS yielded binder contents, ranging from 23 percent to 28 percent. Overall, RAS variability in terms of binder content and gradation are low for both MWAS and TOAS. MWAS exhibited slightly lower variability.

- RAS binders are very stiff. TOAS binders, with an average high-temperature grade of 175°C, are much stiffer than MWAS binders, which had an average of high-temperature grade of 131°C. MWAS has smaller variation in the high-temperatures grade, compared to the TOAS, which varied from 159°C to 214°C.
- Generally, virgin and RAS binder blending is non-linear. For practical application, the linear blending chart can still be used if the RAS *binder* percentage is below 30%. Below 30% RAS binder, not only is the linear blending chart applicable, but the regular DSR and BBR can be used to evaluate the high and low ends of the PG grade of the blended binder.
- Compared with the TOAS binders, the MWAS binders have less impact on PG temperatures of virgin binders, which is reasonable, since MWAS binders are much softer than TOAS binders. Thus, it is important to consider differentiating MWAS from TOAS when used in asphalt mixes.
- RAS has no significant influence on dynamic moduli of HMA mixtures, but improves their rutting resistance.
- Adding RAS generally increases OAC of HMA mixes, depending on compaction temperature, curing time, and other factors.
- RAS mixes exhibited very poor cracking resistance, compared with the 0% RAS mixes containing PG 64-22 or PG 70-22, even though the RAS mixes have higher OAC. Therefore, cracking resistance is of concern for the RAS mixes.
- Two approaches for improving cracking resistance of RAS mixes were explored in the laboratory. Test results clearly indicated that both using soft binder and decreasing design air voids can improve cracking resistance of RAS mixes. When considering rutting of RAS mixes, using soft (modified) binder is superior to decreasing design air voids. Six field test pavements were built to validate these two approaches. The effectiveness of increasing design density was confirmed through field test pavements on US 87, Amarillo, Texas; the soft binder test pavements on FM 973, in Austin, are being monitored.

When using the softer binder and low air void approaches, one should be aware that, if the RAS is not well blended into the mixture or, if segregation occurs during mixing and/or placement, there will be spots on the pavement with "softer" mix, which may fail due to rutting.

The findings from this study need to be further validated with field performance data from different test pavements under various scenarios. More work is also needed to investigate the performance of RAS/RAP mixes produced at warm mix temperatures. Additionally, more research should be performed in two more areas:

- Degree of blending between virgin binder and RAS binder in laboratory mixing and compaction as well as plant production and, possibly, even after field compaction: the degree of blending has significant influence on volumetric properties of asphalt mixes and, thus the resulting OAC.
- Intermediate temperature binder property: This study focused on high- and low-temperature binder properties. Fatigue cracking is influenced more by the intermediate temperature binder property.

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Disclaimer

The contents and opinions of this paper reflect the views of the authors, who are solely responsible for the facts and the accuracy of the data presented herein. The contents of this paper do not necessarily reflect the official views or the policies of any agencies.

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