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16. Abstract

Recycled asphalt shingles (RAS) often containing more than 20 percent asphalt binder has become another black gold in the asphalt industry. There are two basic types of RAS scraps in the market: tear-off asphalt shingles (TOAS) and manufacture waste asphalt shingles (MWAS). Both TOAS and MWAS have been used in hot-mix asphalt (HMA) paving in Texas. Since RAS binder is very stiff, lots of concerns have been raised on using RAS in HMA. The researchers conducted a comprehensive investigation on HMA mixes containing RAS, including RAS binder characterization and blending charts for virgin/RAS binders, impact of RAS content on optimum asphalt content (OAC) and engineering properties of RAS mixes, and approaches for improving cracking resistance of RAS mixes. Furthermore, a variety of RAS field test sections were constructed to validate the approaches for improving cracking resistance of RAS mixes. Additionally, this report discusses the environmental and economic benefit of using RAS in HMA. Based on the research performed, it was found that TOAS binders with an average of high temperature grade of 175°C are much stiffer than MWAS binders, which have an average of high temperature grade of 131°C. Impact of MWAS binder on the high and low PG temperatures of virgin binder is different from that of TOAS binders. Thus it is important to consider differentiating MWAS from TOAS when used in asphalt mixes. The use of RAS has no significant influence on dynamic moduli of HMA mixes, but improves their rutting/moisture damage. However, RAS mixes have very poor cracking resistance, compared with the 0 percent RAS mixes with PG64-22 or PG70-22, even though the RAS mixes have higher OAC. Two approaches for improving cracking resistance of RAS mixes were explored in the laboratory. The test results clearly indicated that both using soft binder and increasing design density can improve cracking resistance of RAS mixes. When considering rutting/moisture damage of RAS mixes, using soft binder is superior to increasing design density. Furthermore, a series of field test sections have been constructed around Texas. The observed field performance of the test sections indicated that RAS mixes can be successfully used as surface layer of new construction with strong foundation. It also has been observed that the use of extra virgin asphalt binder (or increasing design density) can effectively improve cracking performance of RAS mixes. Apparently, more work is also needed to investigate the performance of RAS/RAP mixes produced at the warm mix temperatures.

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CHARACTERIZATION AND BEST USE OF RECYCLED ASPHALT SHINGLES IN HOT-MIX ASPHALT

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- Jerry Peterson.
- Steve Smith.
- Gisel Carrasco.
- Woody Raine.
- Mike Wittie.
- Mary Fletcher.

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CHAPTER 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, 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 usually 20–30 percent asphalt binder of its total weight. In addition to conserving energy and protecting the environment, the use of RAS can significantly reduce the increasing cost of HMA paving.

There are two basic types of RAS scraps in the market: 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. Specifically, there are several national wide, large roof shingles manufactories in Texas, such as Owens Corning, GAF, TAMKO, Certain Teed, etc. Significant markets exist for both recycling and paving industries.

More than 30 years ago, some of the original pioneers established the first shingles 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; Shepherd et al., 1989). More recently, additional 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, 1998; Dykes, 2002; Lum, 2006; Brock 2007; McGraw et al., 2007; Schroer, 2007, Johnson et al., 2010; Williams et al. 2011). 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 mixes were raised. To address these concerns, in 2010 the Texas Department of Transportation (TxDOT) initiated a research study (Project 0-6614) 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:

- Develop best practices for use of RAS in HMA.
- Characterize RAS binder properties.
- Develop virgin/RAS binders blending charts.
- Identify the impact of RAS on mix engineering properties.
- Evaluate approaches for improving durability of RAS mixes in the lab.
- Construct field test sections to validate the approaches for improving durability of RAS mixes.

Except the best practices for using of RAS in HMA documented in Report 0-6614-1, details of all others are presented in Chapters 2, 3, 4, 5, and 6 of this report, respectively.

Additionally, the environmental and cost impacts of RAS on asphalt mixes are discussed in Chapter 7. This is followed by summary and conclusions at the end of the report.

CHAPTER 2
RAS BINDER CHARACTERIZATION: MWAS VS. TOAS

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

VALIDATION OF ASPHALT BINDER EXTRACTION AND RECOVERY METHODS

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

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

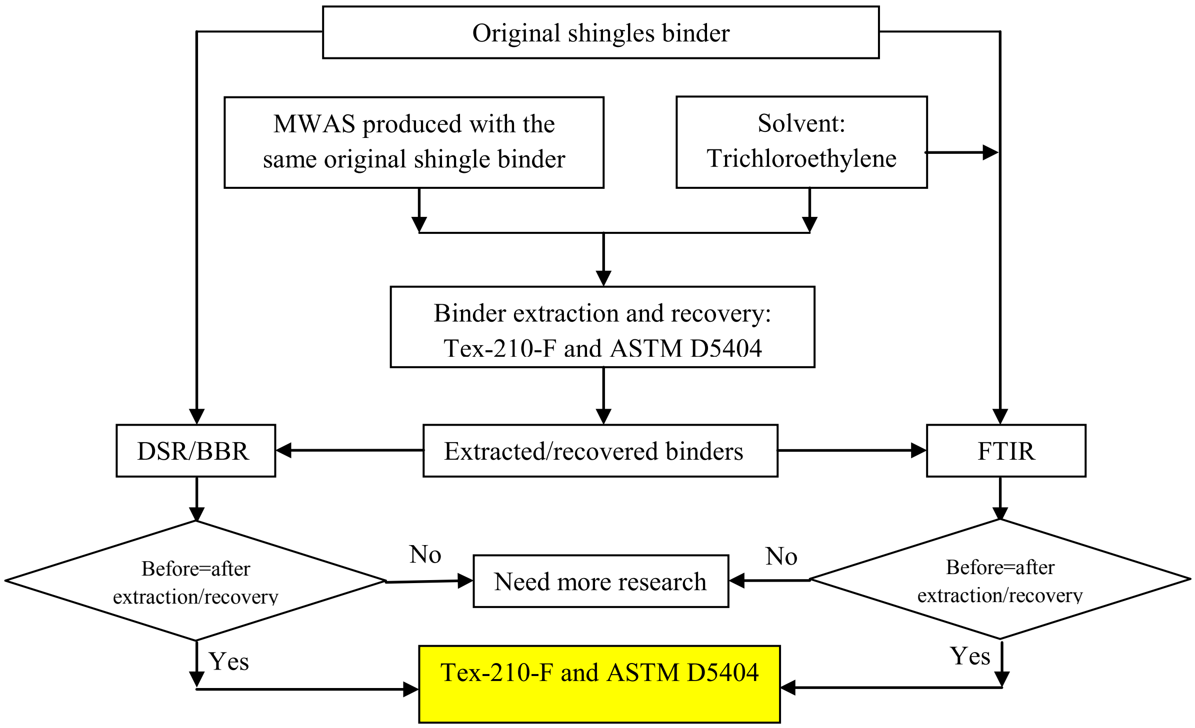


Figure 1. Flow Chart of Validation of Binder Extraction and Recovery Methods.

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

Figure 2 presents the FTIR test results of original shingles binder before and after the extraction and recovery. The chemical components of the original shingles binder are exactly the same as those of the extracted and recovered shingles binder. Furthermore, Figure 3 also shows the FTIR test result of the trichloroethylene solvent itself. Apparently, the trichloroethylene itself has large absorbance when wavelength is less than 1000 (cm-1). If there is any trichloroethylene left, the absorbance values of the recovered shingles binder will be different from those of original shingles binder in that wavelength range. Therefore, the trichloroethylene solvent was completely removed during the recovery process.

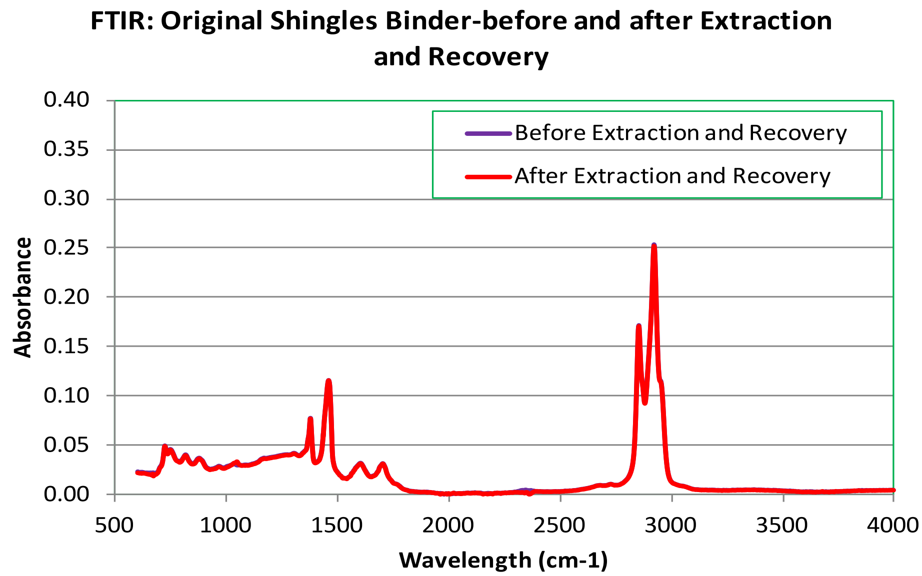


Figure 2. FTIR Test: Original Shingles Binder before and after Extraction and Recovery.

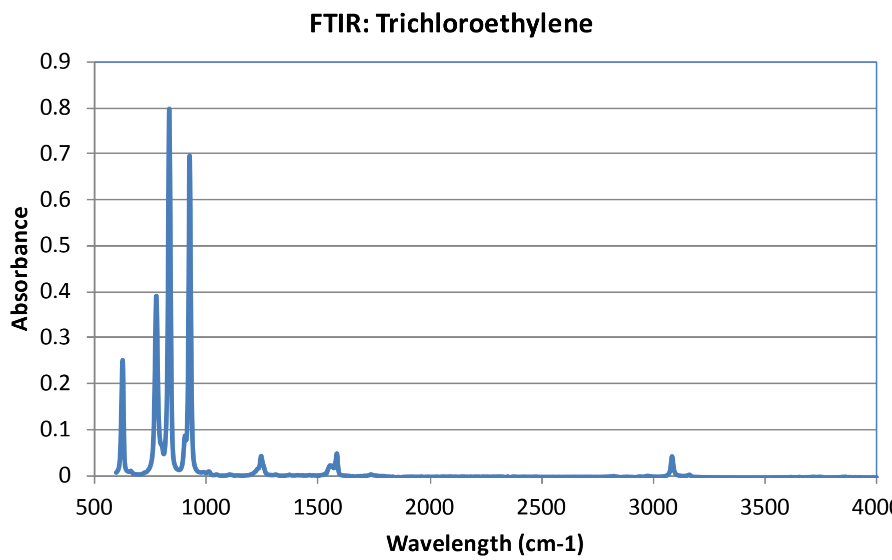


Figure 3. FTIR Test: Trichloroethylene.

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

Figure 4 illustrates the DSR and BBR test results of the original shingles binder before and after the extraction and recovery. Note that the BBR beams were prepared using the pressure aging vessel (PAV) aged asphalt binder residue. The rheological properties of the shingles binder, in terms of PG grade, have no change before and after the extraction and recovery. Note that the low temperatures grade of the PAV aged shingles binder are beyond the limits of BBR test so no data are available (more discussion in later section). Instead, the *S* and *m* values at 0°C were used for comparison. Again, the extraction and recovery process did not change the rheological properties of the shingles binder. With this validation, the authors conducted extensive shingles binder extraction and recovery following the Tex-210-F and ASTM D5404, and then evaluated the RAS binder properties, as discussed in next section.

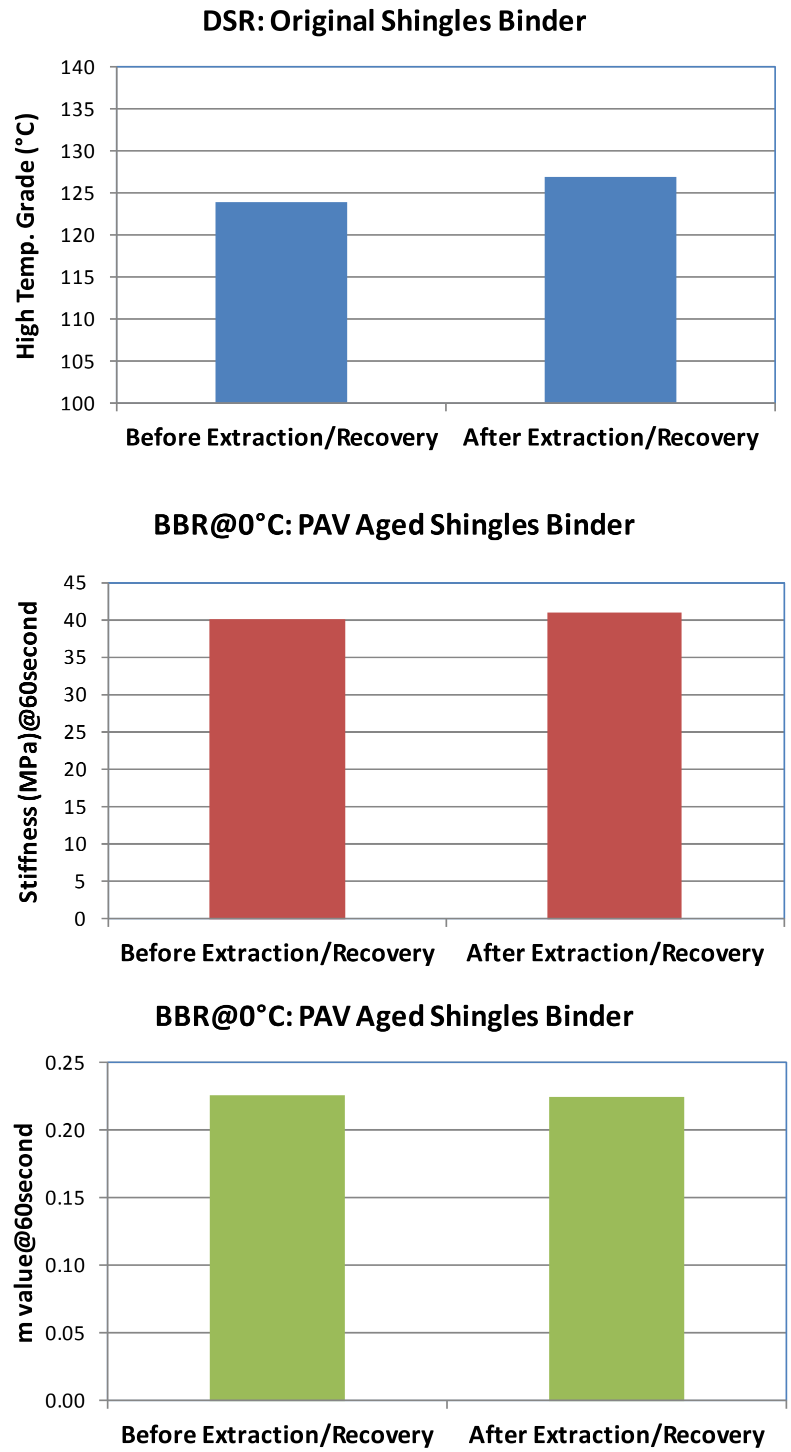


Figure 4. Rheological Properties of Shingles Binder: before and after Extraction/Recovery.

RAS BINDER CHARACTERIZATION

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

Selection of RAS Samples

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

RAS Binder Extraction and Recovery

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

RAS Binder Characterization

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

- BBR test results

  As noted previously, the researchers had difficulty in grading PAV aged shingles binder using BBR. There are two criteria (*S* and *m*) for determining the low temperature grade of asphalt binders. It is no problem for RAS binders to meet the *S* (<300 MPa) criteria, but the measured *m* values were always less than 0.3. Some RAS binder beams fractured even before reaching 240 seconds (see Figure 5). The reason for having such a small *m* value is that RAS binders including MWAS binders have much less capability to relax under strain. Note that the original shingles binders are already substantially oxidized through air blowing process. The researchers even tried to run 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 reaches the limit of BBR machine within a very short of period of time (see Figure 6). Therefore, no reliable results from BBR test were obtained for any one of the 10 recovered RAS binders. Alternative tests (such as Asphalt Binder Cracking Device test) should be explored.

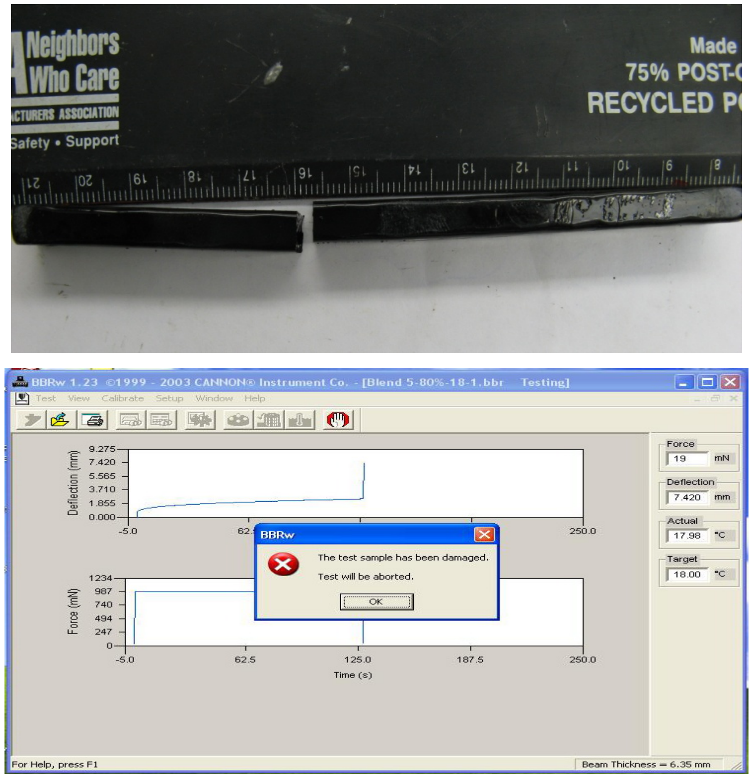


Figure 5. BBR Test: Early Fractured RAS Binder Beam.

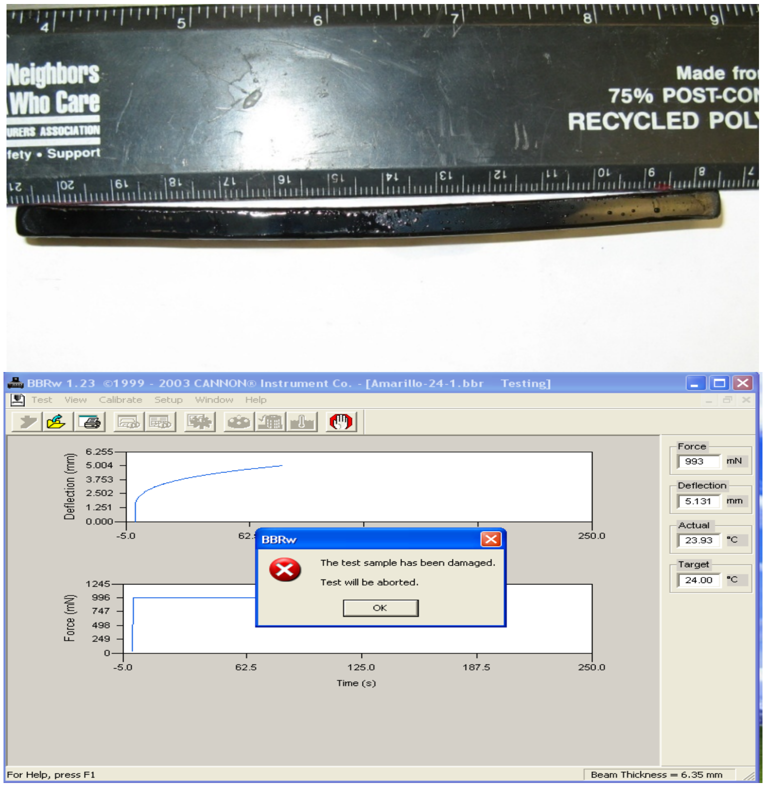


Figure 6. BBR Test: Overly Deformed RAS Binder Beam.

- DSR test results

  To measure the high temperature grades of those extremely stiff binders, a high temperature DSR was specifically purchased under this study. Nine of the 10 RAS binders were successfully graded following Superpave binder PG system. The high temperature grade of one TOAS binder is beyond the upper limit of the purchased DSR, which is 200°C, so that extrapolation was used to estimate its high temperature grade. For each extracted/recovered RAS binder, both original and rolling thin-film oven aged residue were evaluated. The high temperature grades of the 10 RAS binders are shown in Figure 7.

  Several observations can be clearly made from Figure 7:

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

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

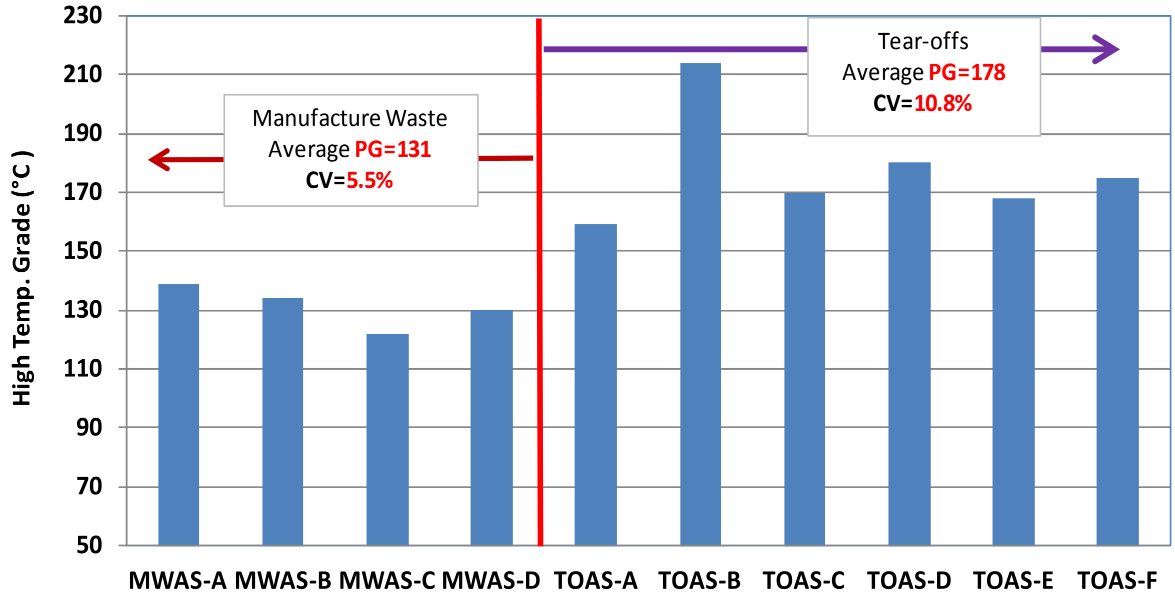


Figure 7. High Temperature Grades of RAS Binders: MWAS and TOAS.

DISCUSSION ON PRODUCTION TEMPERATURES OF RAS MIXES

Production temperature of asphalt mixes depends on the viscosity of asphalt binders and how well the asphalt binder coats the aggregates. For all virgin mixes without RAP/RAS, general rules have been well established. For example, the production temperature for a virgin mix with a PG64-22 binder is around 143°C (290°F) at which the virgin binder PG64-22 can easily flow and then coat virgin aggregates. However, the mixing (or production) temperature for RAS (or RAP) mixes has not well established. This study explored how mixing (or production) temperature affects RAS binder melting and coating virgin aggregates. The researchers blended white limestone aggregates with a MWAS and a TOAS at different temperatures, respectively. Four mixing (or production) temperatures used in the lab are 143°C (290°F), 149°C (300°F), 163°C (325°F), and 200°C (392°F). The process of the mixing temperature investigation is described below:

- Step 1: Sieve limestone aggregates and keep the aggregates passing 1/2 inch sieve and retaining on 3/8 inch sieve.
- Step 2: Wash the aggregates and dry them up in oven.
- Step 3: Weight the dried limestone aggregate and RAS (either MWAS or TOAS) in a ratio of 80:20.
- Step 4: Load the shallow pan with the limestone aggregates into an oven with pre-set temperature (i.e., 143°C [290°F]) and store them overnight; Meanwhile, store the RAS in a hot room with the temperature of 60°C (140°F) overnight.
- Step 5: In the second morning, manually blend the aggregates with RAS and then store them together for 2 hrs at the same oven with the same pre-set temperature as that for aggregates. The purpose of this step is to heat up the RAS and make sure that the RAS and limestone aggregates have the same pre-set temperature (i.e., 143°C [290°F]).

- Step 6: Without adding any virgin binder, blend the aggregates and RAS using bucket mixer for 2–3 minutes. Then put the mixed RAS/limestone aggregates back to the same oven and store for another 2 hrs at the same pre-set temperature.
- Step 7: Separate the RAS from limestone aggregate through sieving with a 3/8 inch sieve.
- Step 8: Take photos to the limestone aggregates and see the change of color of the limestone.

Figure 8 shows the limestone aggregates after mixing at four different mixing temperatures. Extremely high mixing (or production) temperature is needed in order to have MWAS binder (around PG130) to melt and coat virgin aggregates more and better. However, the TOAS even at the temperature of 200°C (392°F) did not show much melting and coating effect.

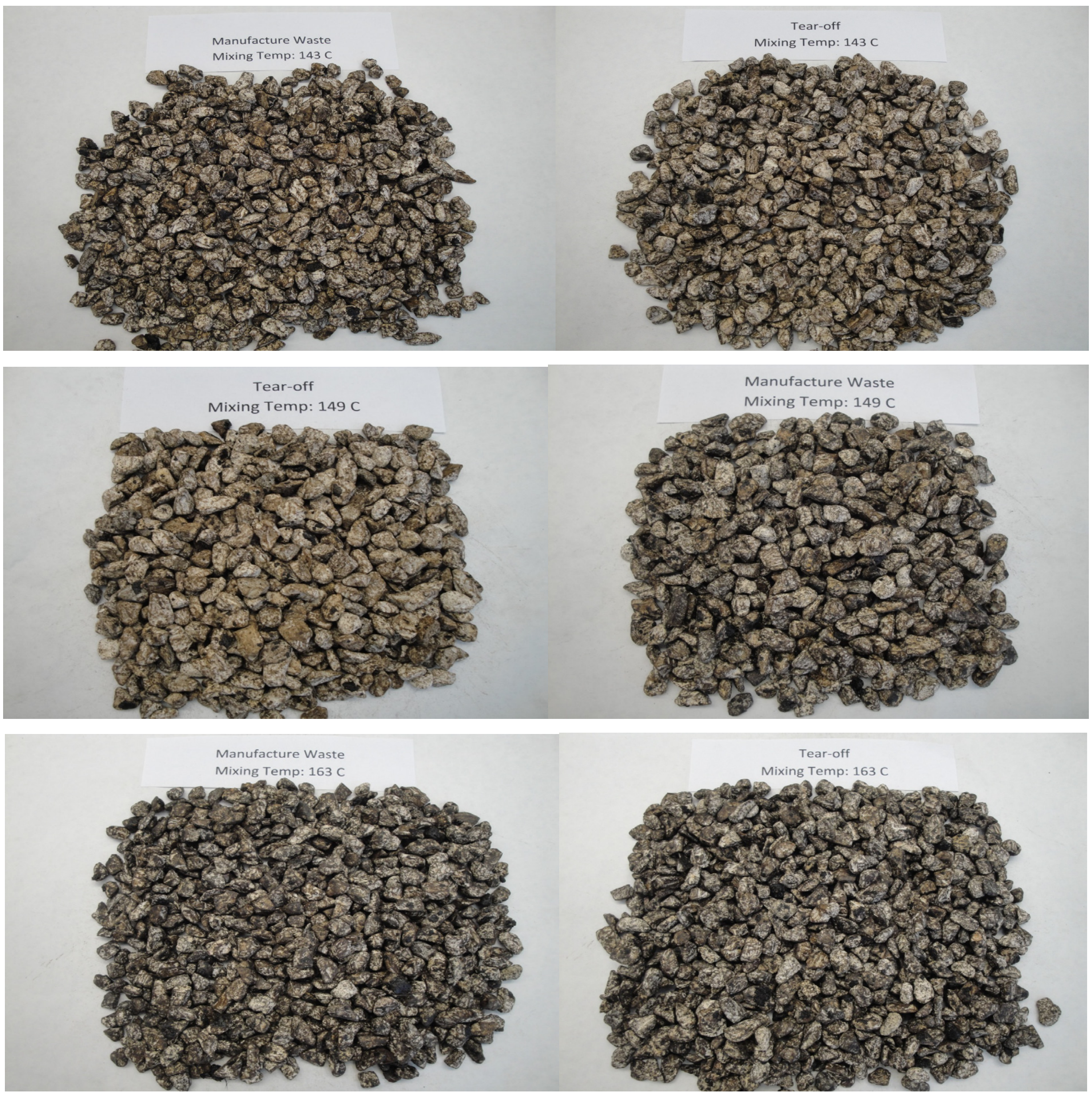


Figure 8. RAS Binder Transfer to Limestone Aggregates at Four Different Temperatures.

Referring the mixing temperatures for virgin mixes with virgin binders (i.e., 143°C [290°F] for PG64-22, 149°C [300°F] for PG70-22, 163°C [325°F] for PG76-22), it seems that the mixing (or production) temperature needs to be at least two times of its high temperature grade in order to make the RAS binder flow and coating virgin aggregates. This means that the production temperature for a mix with a MWAS binder (PG130-XX) should be around 260°C (500°F). For those mixes with TOAS (PG175-XX) the production temperature may need to go up to 350°C (662°F). Such high production temperature is impractical. The actually mixing (or production) temperature for RAP/RAS mixes with PG64-22 binders used in Texas is around 149°C (300°F). Thus, it is unrealistic to expect that the binder in RAS, regardless of MWAS or TOAS, will melt down and flow out to coat virgin aggregates. The most possible scenario is that RAS acts like a black rock and has very little (if not none) contribution in the coating process. The reduced virgin binder (i.e., PG64-22) needs to coat both virgin binder and RAS, as illustrated in Figure 9. The major difference between virgin mix and RAS (RAP) mix is that the RAS mix often has thinner film thickness than virgin mix if the RAS binder is assumed to be 100 percent active. The good thing for RAS (or RAP) mix is that the virgin binder can activate as a rejuvenator to continue to soften the hard RAS binder in the period of pavement service.

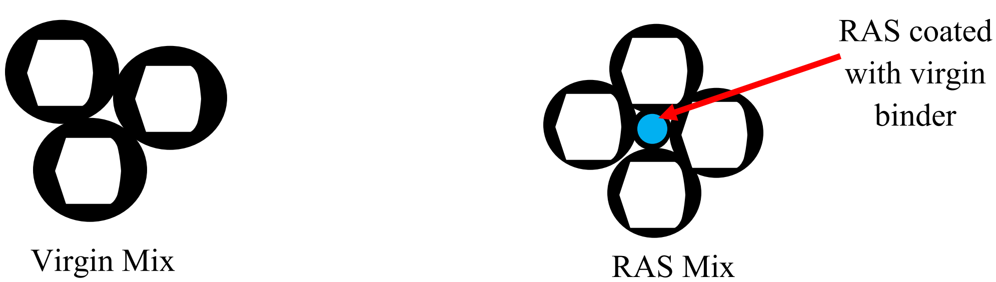


Figure 9. Illustration of Coating during Production: Virgin vs. RAS/RAP Mixes.

SUMMARY AND FINDINGS

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

- The asphalt binder extraction and recovery procedures (Tex-210-F Part I and ASTM D5404) are validated in this study. No solvent was detected through FTIR testing, and the binder rheological properties, in terms of PG high and low temperatures, were almost the same before and after going through the extraction and recovery processes.

- TOAS binders with an average of high temperature grade of 175°C (347°F) are much stiffer than MWAS binders, which have an average of high temperature grade of 131°C (268°F). Compared to the TOAS varying from 159°C (318°F) to 214°C (417°F), the MWAS has smaller variation in terms of the high temperatures grade. These two observations clearly indicate that the MWAS is different from the TOAS. It is necessary and important to differentiate the MWAS from the TOAS when used in asphalt mixes.

In general, the RAS binders are very stiff, and regular DSR and BBR could not characterize rheological properties of these extremely stiff binders. Therefore it is critical to investigate the impact of these stiff binders on rheological properties of the combined binder after blending with virgin binders, which is discussed in next section.

CHAPTER 3
DEVELOPMENT OF VIRGIN AND RAS BINDERS BLENDING CHARTS

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

INVESTIGATION OF VIRGIN AND RAS BINDERS BLENDING

Virgin and RAS Binders

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

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

Laboratory Testing, Results, and Analysis

For each combination, different percentages of virgin and RAS binders were blended and then evaluated through DSR and BBR testing in terms of the high and low PG temperatures. The test results for these four combinations are presented in Figures 10, 11, 12, and 13, respectively.

The following observations are made from Figures 10 through 13.

- Generally the virgin and RAS binders blending is non-linear.
- For practically application, the linear blending chart can still be used if the RAS binder percentage is less than 30 percent. Within 30 percent RAS binder, not only is the linear blending chart applicable, but the regular DSR and BBR can also be used to evaluate the high and low PG temperatures of the blended binders.
- Increasing RAS binder will improve the high temperature grade of virgin binder and also warm up its low temperature grade, which is good for rutting resistance but causes concerns on cracking resistance of the blended binder. Adding 20 percent RAS binder can make a PGxx-22 binder become a PGxx-16 (or even a PGxx-10 in Figure 9) binder after blending. Additionally, the necessity of using PGxx-28 virgin binder can also be

seen in order to get a PGxx-22 combined binder when 20 percent RAS binder is added (Figure 11). Note that 20 percent RAS binder is corresponding to 5 percent RAS in weight of the total mix with an assumption that the optimum asphalt content of a RAS mix is 5 percent and RAS contains 20 percent asphalt binder in it.

- Impact of MWAS binders on the high and low PG temperatures of virgin binders is different from that of TOAS binders. Compared to the TOAS binders (Figures 10 and 11), the MWAS binders (Figures 12 and 13) have less impact on PG temperatures of virgin binders, which makes sense since TOAS binders are much stiffer than those MWAS binders (see Figure 7). Therefore, it is necessary to consider differentiating the MWAS from the TOAS when designing HMA containing RAS.

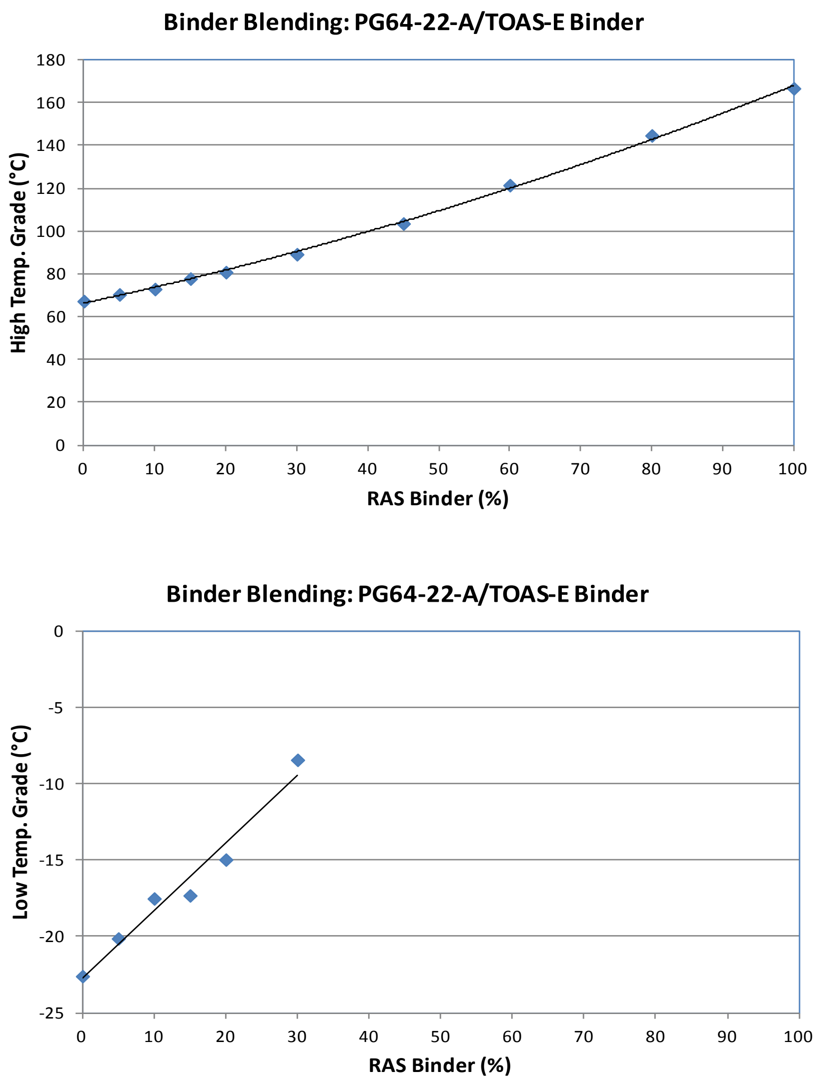
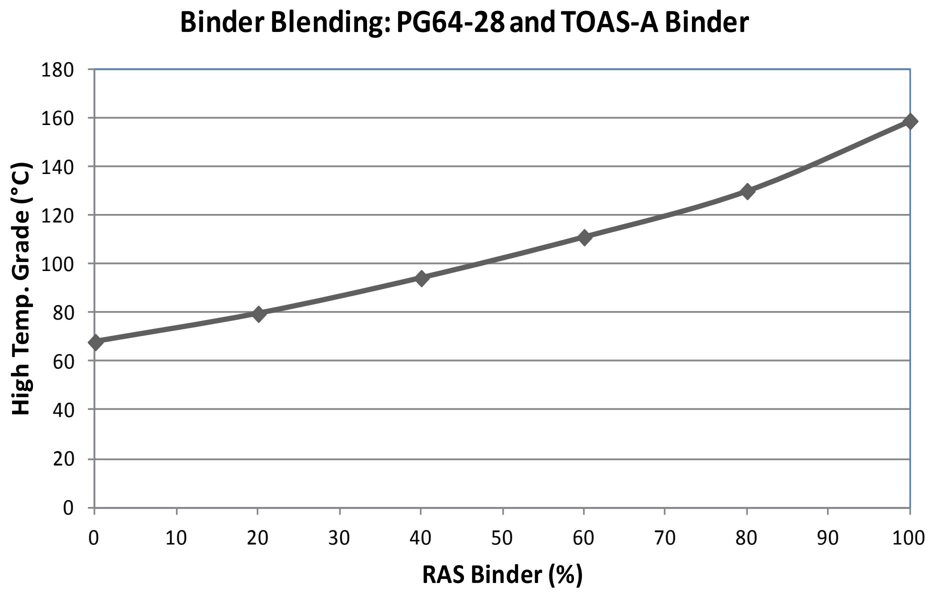


Figure 10. Binder Blending between PG64-22-A and TOAS-E Binder.



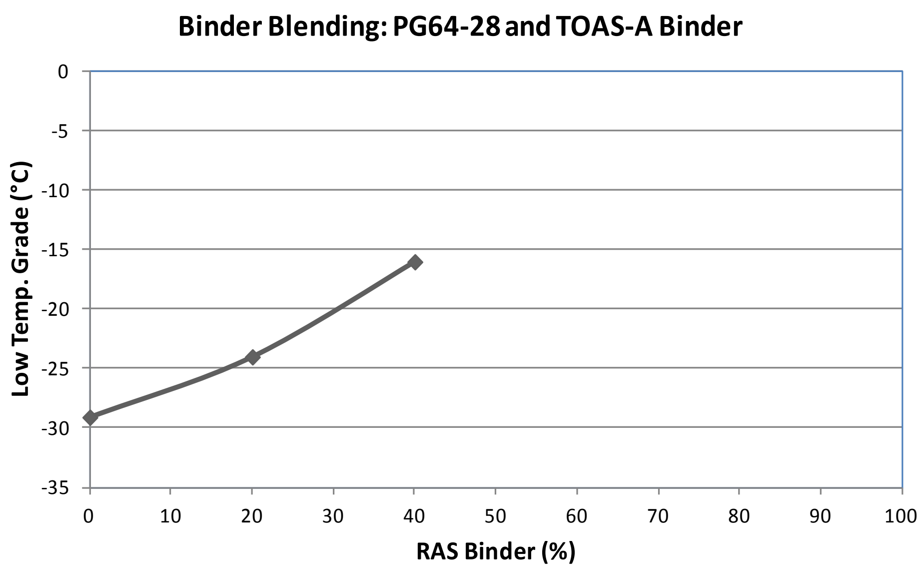
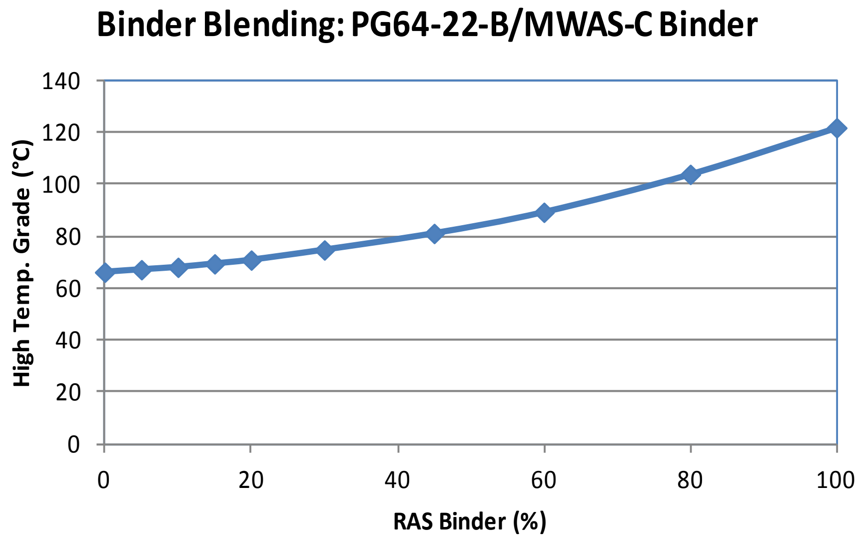


Figure 11. Binder Blending between PG64-28 and TOAS-A Binder.



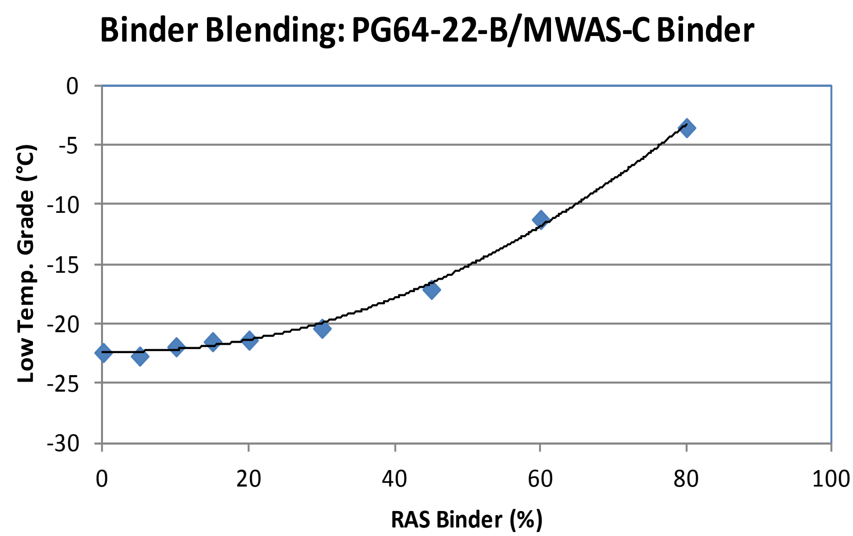
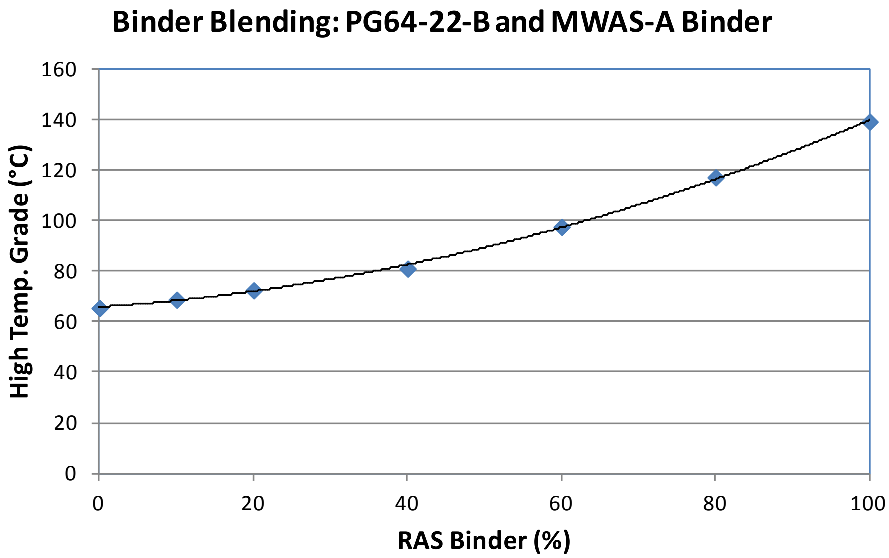


Figure 12. Binder Blending between PG64-22-B and MWAS-C Binder.



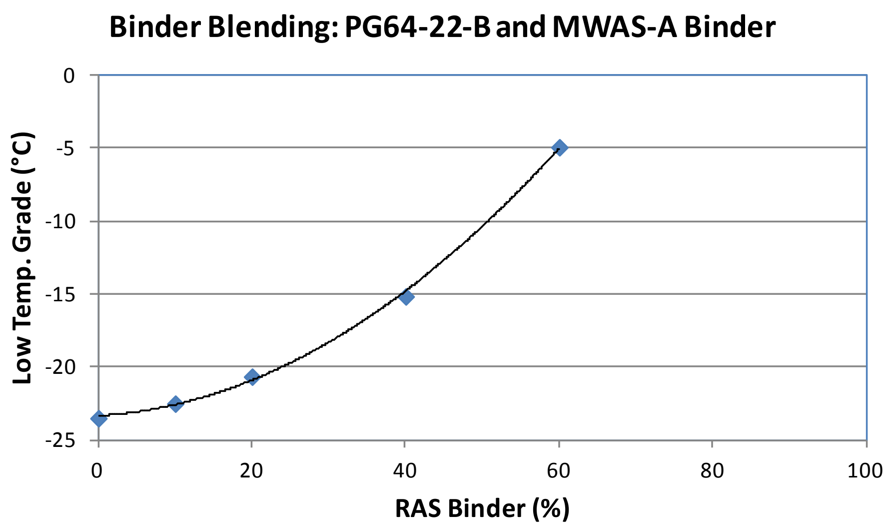


Figure 13. Binder Blending between PG64-22-B and MWAS-A Binder.

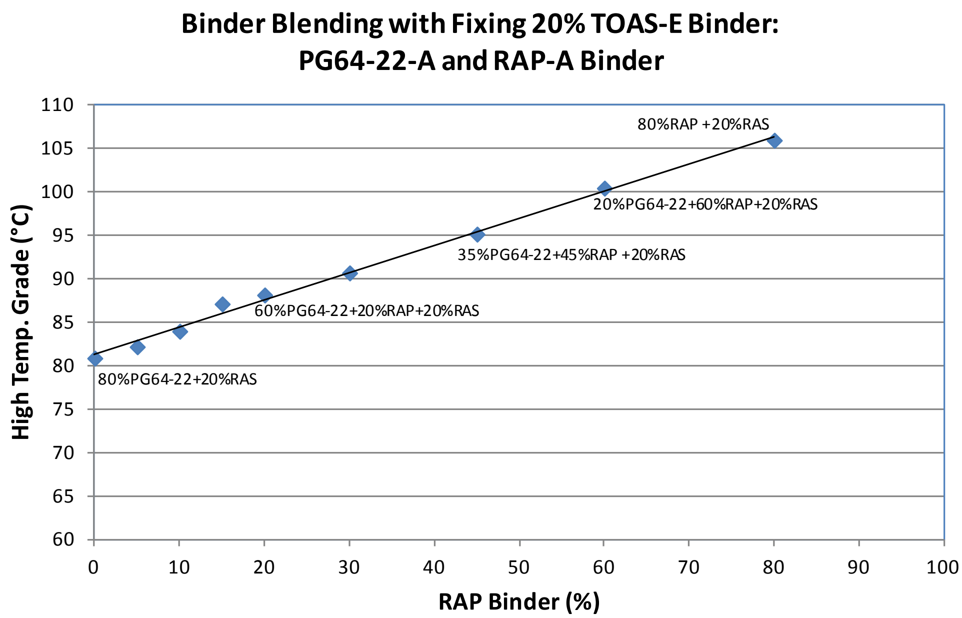
EVALUATION OF BLENDING AMONG VIRGIN, RAP AND RAS BINDERS

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

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

The DSR and BBR test results of these four combinations are shown in Figures 14, 15, 16, and 17, respectively. From these figures the following observations are made:

- As long as RAS binder content is fixed in the blending process, the virgin/RAP binders follows linear blending line, as seen in Figures 14 and 16. Both high and low temperatures of PG of the combined binder increases linearly with adding RAP binder. When RAP binder content is fixed, the virgin/RAS binders blending, again, is non-linear (see Figures 13 and 15).
- When RAS binder is already blended with virgin binder, adding more RAP binder makes the blended binder even stiffer. For example, as shown in Figure 14, 20 percent RAS binder itself already modified the PG64-22-A binder to a PG81-15 binder. Adding any RAP binder (even 5 percent RAP binder) will worsen the cracking resistance of the combined binder. The similar finding for fixing RAP binder but adding more RAS binder to the virgin binder can be observed in Figures 15, 16, and 17.



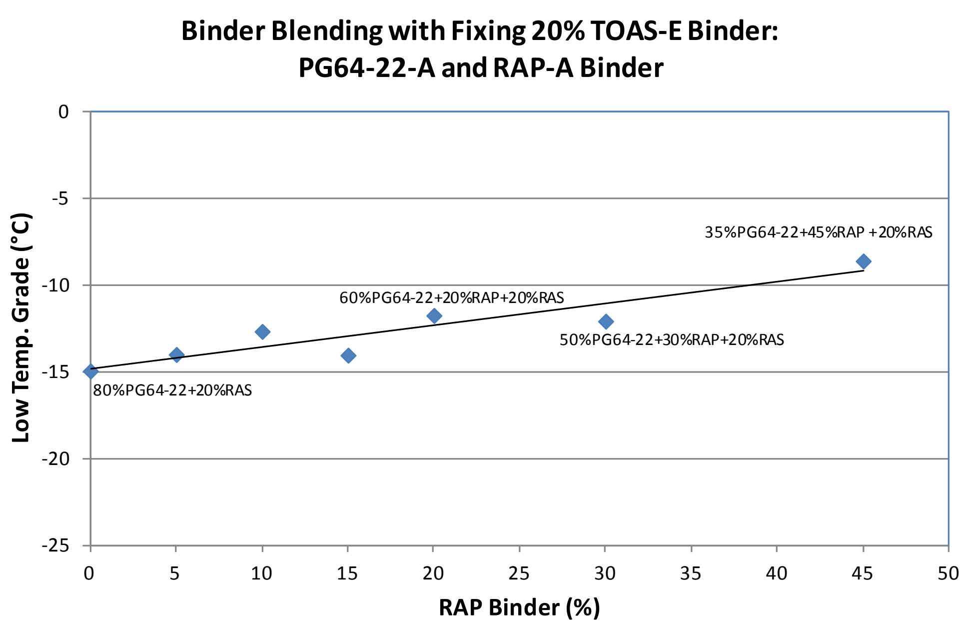
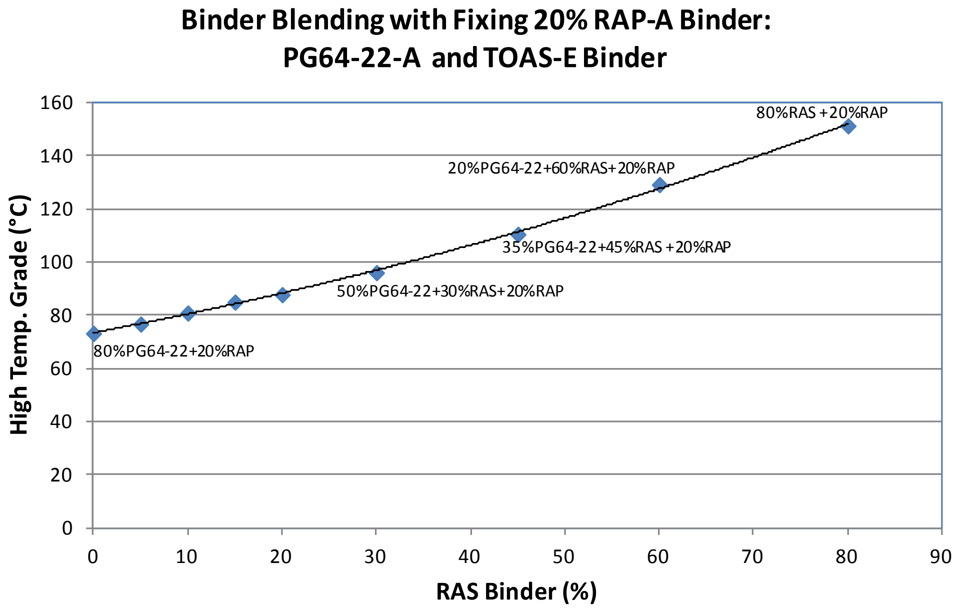


Figure 14. Binder Blending with Fixing 20 Percent TOAS-E Binder and Varying PG64-22-A and RAP-A Binder.



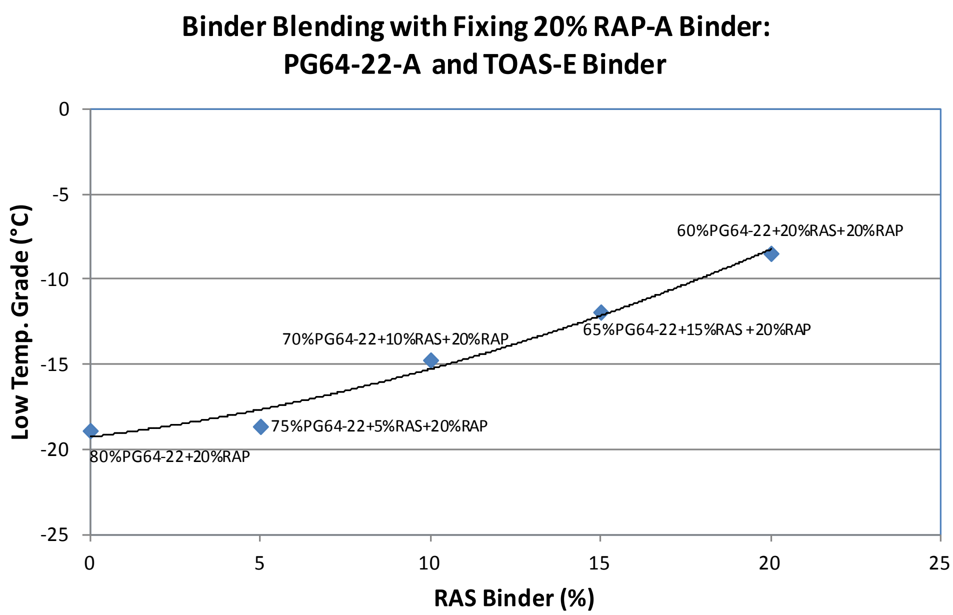
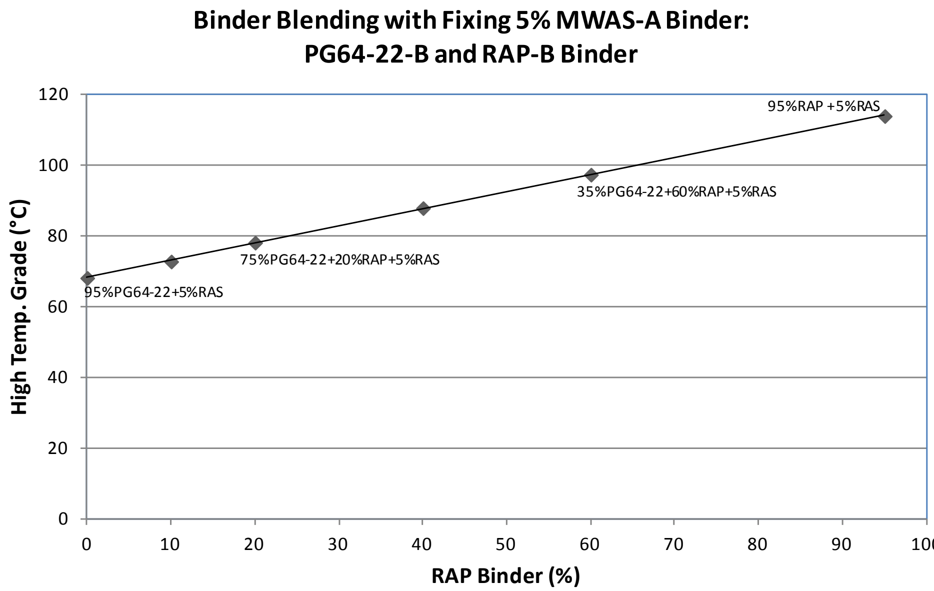


Figure 15. Binder Blending with Fixing 20 Percent RAP-A Binder and Varying PG64-22-A and TOAS-E Binder.



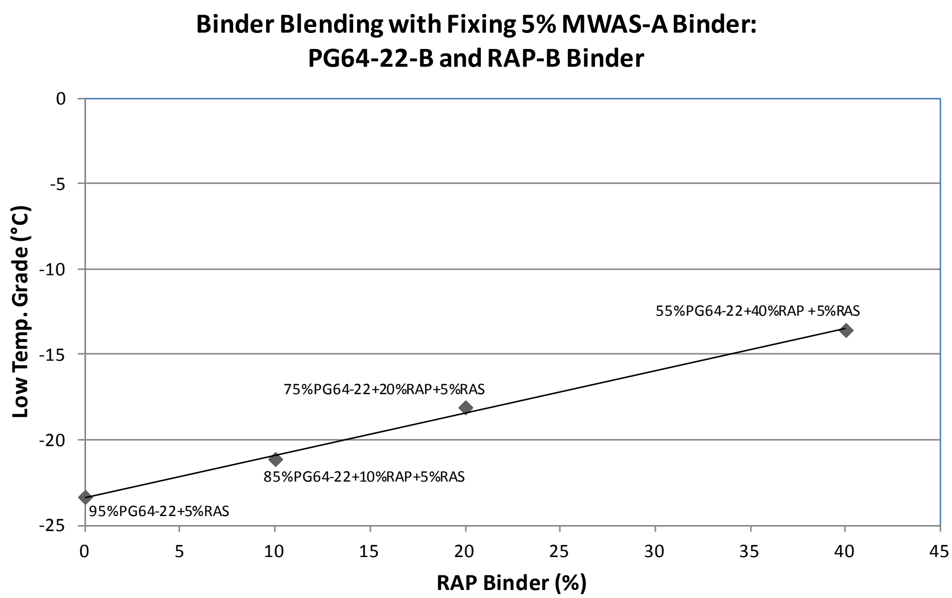
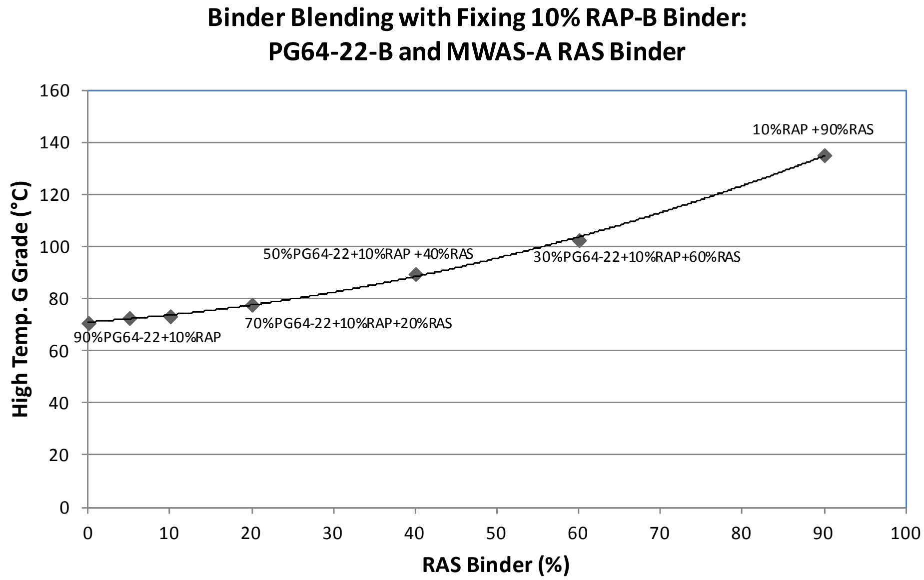


Figure 16. Binder Blending with Fixing 5 Percent MWAS-A Binder and Varying PG64-22-B and RAP-B Binder.



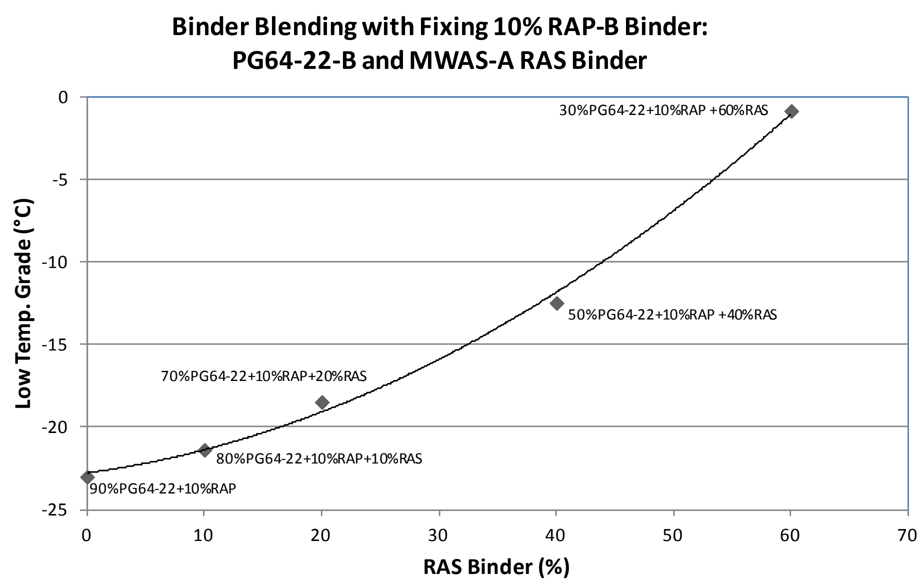


Figure 17. Binder Blending with Fixing 10 Percent RAP-B Binder and Varying PG64-22-B and MWAS-A Binder.

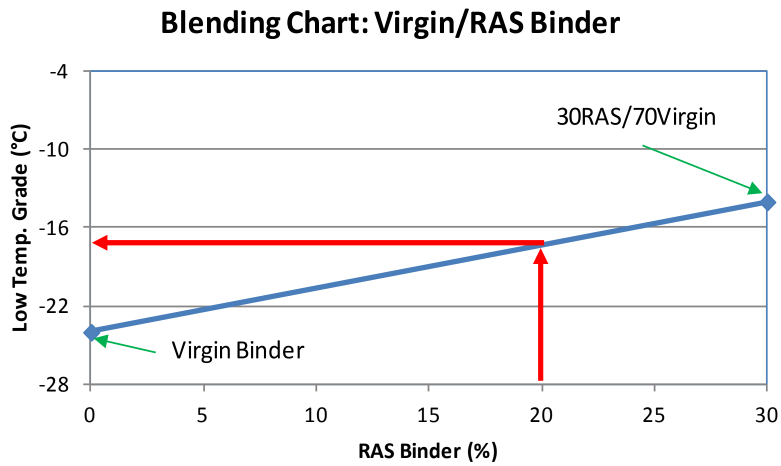
DISCUSSION ON MAXIMUM ALLOWABLE ASPHALT BINDER REPLACEMENT

The DSR and BBR test results presented above clearly indicated that RAS binders have significant influence on both high and low PG temperatures of the blended binder; positive effect on high temperature property (or rutting resistance) and negative effect on low temperature property (or cracking resistance). Thus the maximum allowable RAS binder replacement is controlled by the influence of RAS binder on the low temperature property of the blended binder. The virgin/RAS binders blending charts shown in Figures 5 and 6, clearly indicate that the maximum allowable binder replacement for MWAS should be different from that for TOAS. It seems OK to use a maximum of 20 percent MWAS binder replacement, but for TOAS binders, the binder replacement should be significantly reduced, depending on the combination of virgin and TOAS binders.

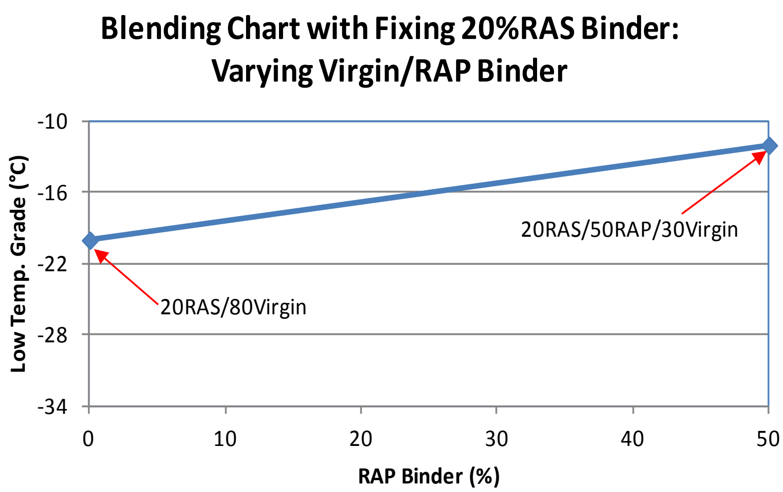
When both RAP and RAS are used, the maximum allowable recycled binder (RAP binder plus RAS binder) replacement is influenced by many factors (such as virgin binder, RAP binder, RAS binder, pavement layers [surface or base layer], climate, traffic, etc.). It will be safe to directly evaluate the blending chart for virgin, RAP, and RAS binders. Reviewing the impact of RAS binder on low temperature property of the blended binders shown in Figures 10, 11, 12, 13, 15, and 17, RAS binders, for practical applications, should be limited within 30 percent of the total binder. If this is the case, the blending chart for virgin/RAP/RAS can be significantly simplified:

- Linear blending chart is practically applicable to estimate the high and low PG temperatures of the blended virgin/RAS binders or virgin/RAP/RAS binders, which significantly reduces the DSR/BBR testing workload, because only the properties of blended binders at two ends are required, and anything in between can be linearly interpolated.

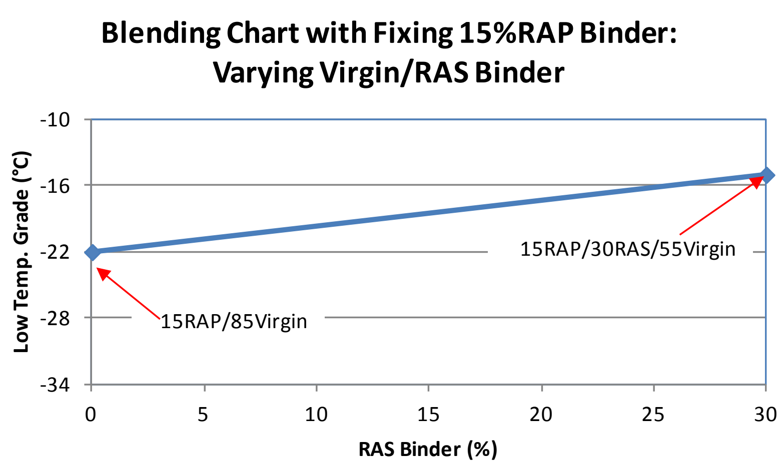
  For virgin/RAS binders blending (see Figure 18a), one only needs to determine the PG temperatures of virgin binder and the 30 percent RAS/70 percent virgin binders, respectively. Then one can determine the continuous PG temperatures of any blending through linear interpolation. For virgin/RAP/RAS binders blending (see Figures 18b and 18c), similar approach can be used for 1) fixing RAS binder replacement (say 20 percent) and varying virgin/RAP binders and 2) fixing RAP binder replacement (15 percent) and varying virgin/RAS binders. Note that RAS/RAP binder replacements shown in Figure 18b/c are just for demonstration only and can be replaced with real numbers.
- Additionally, the use of the linear blending chart and practical amount of RAP/RAS binders makes it possible to employ regular DSR and BBR test equipment to evaluate the properties of the blended virgin/RAP/RAS binders.



(a)



(b)



(c)

Figure 18. Illustration of Linear Blending Charts for Virgin/RAP/RAS Binders.

SUMMARY AND FINDINGS

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

- Increasing RAS binder will improve the high temperature grade of virgin binder, and also warm up its low temperature grade, which is good for rutting resistance but causes concerns on cracking resistance of the blended binder. Adding 20 percent RAS binder can make a PGxx-22 binder become a PGxx-16 (or even a PGxx-10 in Figure 10) binder after blending. Additionally, the necessity of using PGxx-28 virgin binder can also be seen in order to get a PGxx-22 combined binder when 20 percent RAS binder is added (Figure 11). Note that 20 percent RAS binder is corresponding to 5 percent RAS in weight of the total mix with an assumption that the optimum asphalt content of a RAS mix is 5 percent and RAS contains 20 percent asphalt binder in it.
- Impact of MWAS binders on the high and low PG temperatures of virgin binders is different from that of TOAS binders. Compared to the TOAS binders (Figures 10 and 11), the MWAS binders (Figures 13 and 14) have less impact on PG temperatures of virgin binders, which makes sense since TOAS binders are much stiffer than those MWAS binders (see Figure 7). Therefore, it is necessary to consider differentiating the MWAS from the TOAS when designing HMA containing RAS.
- Different from virgin/RAP binders blending, the virgin/RAS binder blending, in general, is non-linear. However, for practical application, the linear blending chart can still be used for estimating continuous grade (high and low temperatures) of both virgin/RAS blended binders and virgin/RAP/RAS blended binders, if the RAS binder is limited within 30 percent of the total binder. In such way, the DSR/BBR testing is significantly reduced. Furthermore, within 30 percent RAS binder, not only is the linear blending chart applicable, but the regular DSR and BBR can also be used to evaluate the high and low PG temperatures of the blended binders.

Apparently, the work presented in this chapter needs to be further verified and expanded to include more virgin, RAP, and RAS binders for blending. The blending discussed in this chapter was done in the lab between virgin binders and extracted/recovered RAS (RAP) binders so that the blending is 100 percent. However, this may not be the case in the plant as explained in Chapter 2 (see Figure 9). Therefore, it is critical to evaluate the engineering properties of full mixes with RAS, which is presented in next chapter.

CHAPTER 4
LABORATORY EVALUATION OF RAS MIX ENGINEERING PROPERTIES

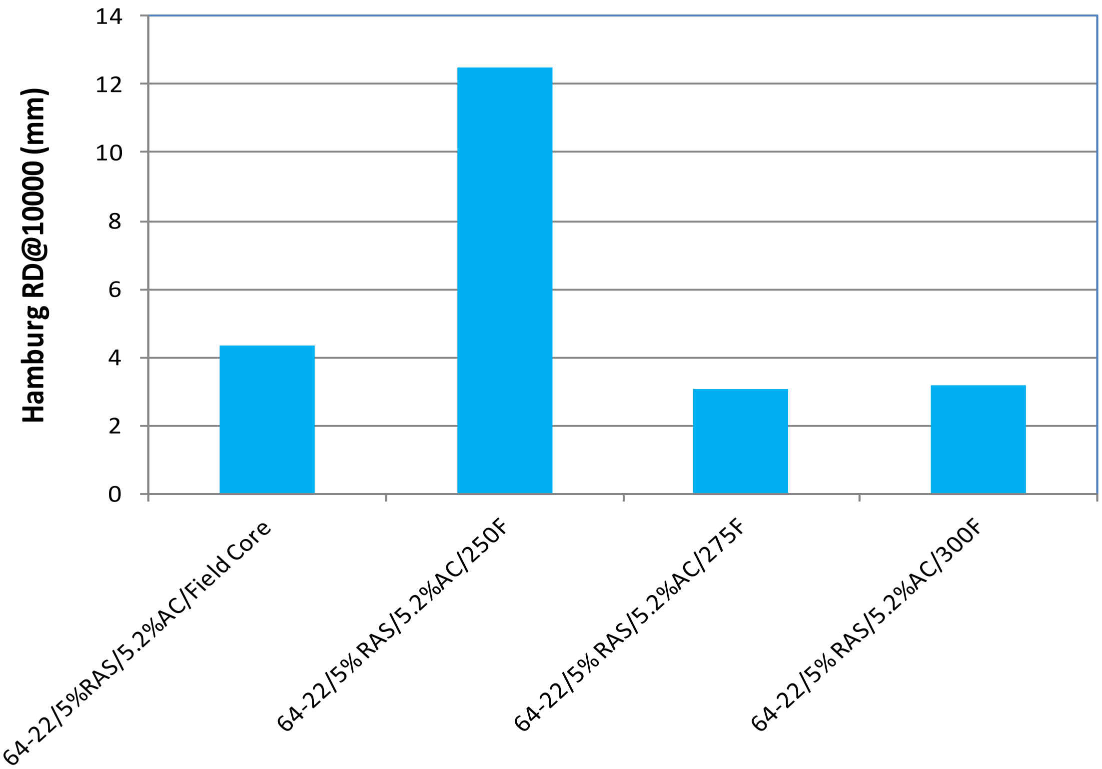
The discussions in last two chapters focused on the extracted and recovered RAS binder properties and the blending with virgin binders. Binders are just part of the whole mix and the mix engineering properties rather than binder itself have more impact on field performance. Thus, this chapter will investigate RAS mix engineering properties. Specifically three subjects will be discussed: 1) mixing and compaction temperatures for RAS mixes, 2) impact of RAS on engineering properties of HMA, and 3) actual blending between virgin and RAS binder. Each of the subjects will be described below.

PRELIMINARY INVESTIGATION OF LAB COMPACTION TEMPERATURE FOR RAS MIXES

For all virgin mixes, TxDOT has established clearly the mixing and compaction temperatures corresponding to virgin binders. For example, the mixing and compaction temperatures for a virgin mix with a PG70-22 binder are 149°C (300°F) and 135°C (275°F). However, this is not the case for mixes with RAS (or RAP). The mixing temperature and especially the compaction temperature and curing time have influence on the optimum asphalt content (OAC), rutting/moisture, and cracking resistance of the mix. Therefore, it is important to investigate this issue and establish some preliminary guidelines.

Currently, the curing time for all HMA mixes in Texas is 2 hours. This study kept the same 2 hour curing time as the current practice, but the emphasis was on the compaction temperature. One of the ways to defining the compaction temperature is to make the lab-mixed and compacted specimens have similar engineering properties to those of field cores. Based on this principle, the researchers evaluated a mix with 5 percent RAS used in one of the field test sections on FM973 in Austin District (more information on FM973 is presented in Chapter 6). It is a dense-graded Type C mix with a PG64-22 virgin binder and 5 percent TOAS-E. The high temperature PG of the extracted/recovered binder from the TOAS-E is PG166. The OAC of this RAS mix is 5.2 percent. Three most often used compaction temperatures in Texas were evaluated: 121°C (250°F), 135°C (275°F), and 149°C (300°F). Both Hamburg wheel tracking test and Overlay Test (OT) were performed on both lab-mixed and compacted specimens and field cores, following TxDOT test procedures (Tex-242-F and Tex-248-F).

Figure 19 shows the test results. It is very clear that the compaction temperature of 121°C (250°F) is too low, since Hamburg rut depth at such temperature is significantly higher than that of field cores. When comparing the OT cycles, the compaction temperature of 149°C (300°F) seems too high, because the OT cycles are only a little bit of over half of the field cores. When considering both Hamburg and OT results, it seems that 135°C (275°F) is a right choice for compaction temperature of mixes with RAS. These results are preliminary and more investigation is still needed in this area.



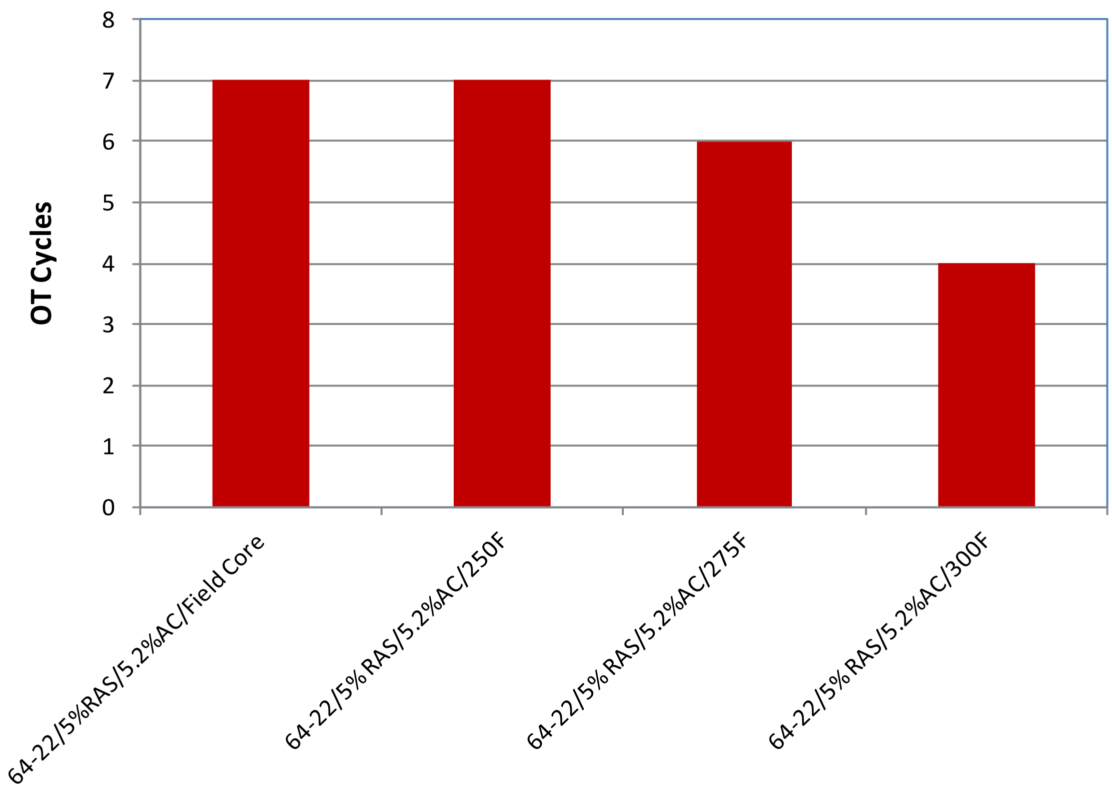


Figure 19. Hamburg and OT Testing Results: Field Core vs. Lab-Mixed and Compacted Specimens at 3 Compaction Temperatures.

IMPACT OF RAS ON MIX PROPERTIES

The inclusion of RAS materials into asphalt mixes often stiffens the mixes with higher dynamic modulus, and improves the resistance to rutting, but it may greatly jeopardize the resistance to cracking. Additionally, TOAS and MWAS may have different impact on mix performance since TOAS has significantly different high temperature grade from MWAS, as clearly shown in Figure 7. Therefore, it is necessary to thoroughly investigate the impact of RAS content and types (TOAS/MWAS) on mix 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 percent, 3 percent, and 5 percent) were considered. Note that TOAS-E is very similar to MWAS-C in terms of RAS aggregate gradation and RAS binder content, and the only difference between them is RAS binder high PG temperature: TOAS-E=166°C vs. MWAS-C=122°C. A total of six mixes with the same raw aggregates and similar gradations, as listed in Table 1, were evaluated under the dynamic modulus test, Hamburg wheel tracking test (HWTT), and OT. The 0 percent RAS/PG64-22 mix was the control mix. The 0 percent RAS/PG70-22 mix was added to compare with the mixes with 5 percent RAS/PG64-22, since many DOTs allow virgin binder one grade "dump" when 5 percent RAS is used.

Table 1. Six RAS Mixes Investigated under This Study.

<table>
<tr><th rowspan="2">RAS Type</th><th colspan="4">RAS Percentage[1] and Virgin Binder</th></tr>
<tr><th>0% RAS/PG70-22</th><th>0% RAS/PG64-22</th><th>3% RAS/PG64-22</th><th>5% RAS/PG64-22</th></tr>
<tr><td>TOAS-E</td><td rowspan="2">X</td><td rowspan="2">X</td><td>X</td><td>X</td></tr>
<tr><td>MWAS-C</td><td>X</td><td>X</td></tr>
</table>

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

The following steps were followed to investigate the impact of RAS contents and type on OAC and engineering properties of asphalt mixes:

- Step 1: Fix the RAS content (i.e., 5 percent) and adjust virgin aggregates percentage to make the total aggregates gradation for each RAS mix as close to each other as possible (Figure 20).

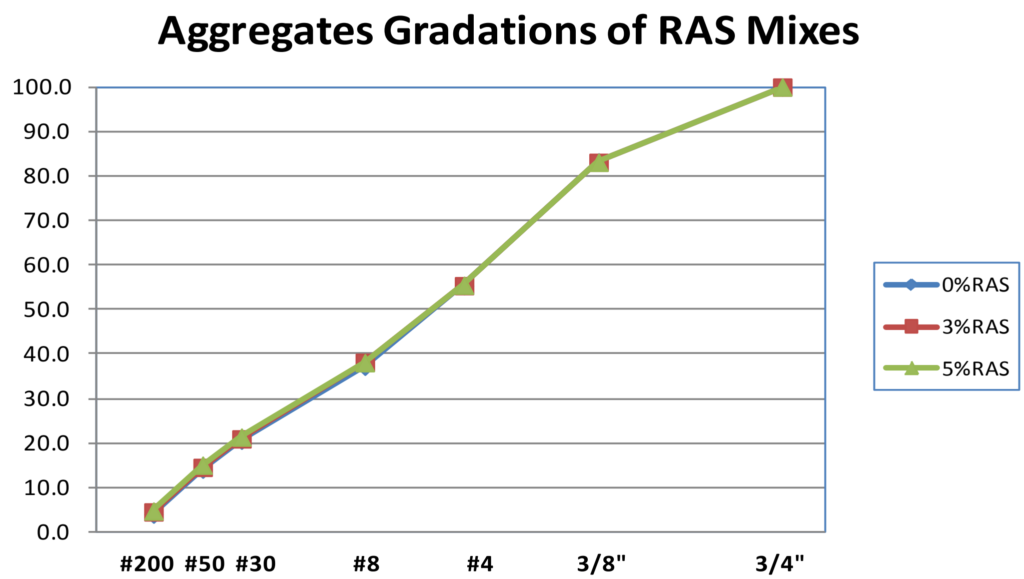


Figure 20. Gradations of HMA Mixes with Varying RAS Contents.

- Step 2: Design the RAS mixes and select an OAC following TxDOT's standard mix design procedure (Tex-204-F) for dense graded mixes, which are widely used in Texas (75 percent 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 TP79, "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 of 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 run in a displacement controlled mode with a maximum opening displacement of 0.025 inch (0.63 mm) at test temperature of 77°F (25°C). The number of cycles to failure (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 is used for comparison. The correlation between OT result and field cracking performance has been well documented (Zhou and Scullion, 2005; Zhou et al., 2007a), 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).

Impact of RAS on OAC of HMA Mixes

Three mix designs were performed for mixes with TOAS-E: 0 percent TOAS-E/PG64-22, 3 percent TOAS-E/PG64-22, and 5 percent TOAS-E/PG64-22. The OAC for each mix was determined based on 97 percent density (or 3 percent air voids) and is presented in Table 2. Also mix designs for mixes with 3 percent MWAS-C/PG64-22, and 5 percent MWAS-C/PG64-22 were conducted as well. It was found that the OACs for the mixes with 3 percent and 5 percent MWAS-C are very close to those of the mixes with 3 percent and 5 percent 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 with 0 percent RAS/PG70-22 was kept the same as that of the mix with 0 percent RAS/PG64-22, 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 2 lists the OAC of each RAS mixes evaluated under 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. 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 2. OAC of Each RAS Mix.

RAS Type	Optimum Asphalt Content (%)			
	0% RAS/PG70-22	0% RAS/PG64-22	3% RAS/PG64-22	5% RAS/PG64-22
TOAS-E	4.7	4.7	4.9	5.2
MWAS-C				

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 21 shows master curves of all six mixes. Overall, the dynamic modulus master curves of these six mixes are close, except that the 0 percent RAS/PG70-22 mix has a little bit higher moduli. Higher RAS content does not always mean higher stiffness, which depends on the OAC as well. Additionally, in terms of dynamic moduli of HMA mixes, the TOAS-E and MWAS-C have very similar impact.

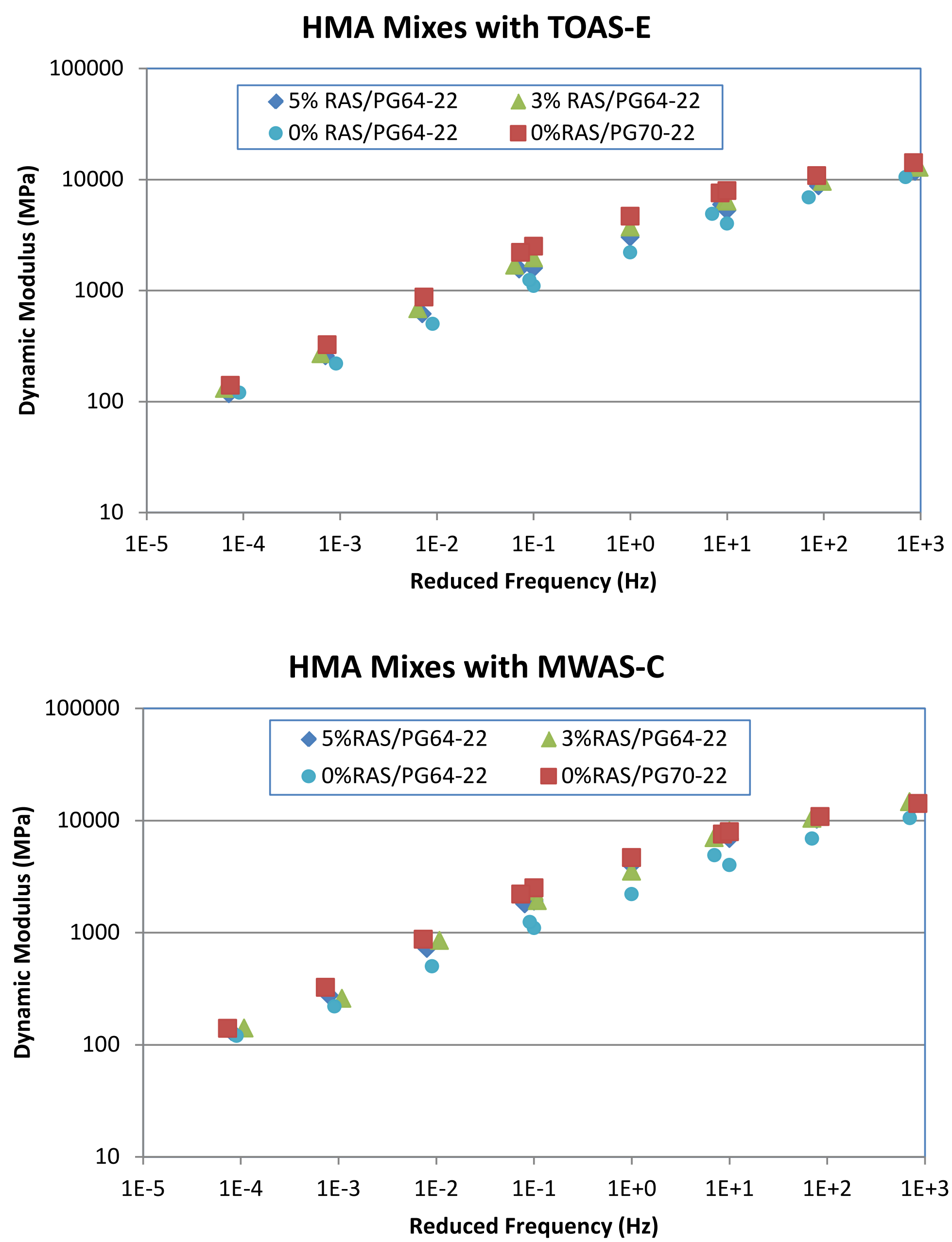


Figure 21. Impact of RAS on Dynamic Moduli of HMA Mixes.

Impact of RAS on Rutting Resistance

Figure 22 presents the HWTT test results. For those mixes with the PG64-22 binder, adding RAS improved rutting/moisture damage, regardless of TOAS-E or MWAS-C. However, such improvement is not significant enough to match the impact of the 0 percent RAS/PG70-22 binder. This observation implies that the actual blending between PG64-22 virgin binder and RAS binder in the mixing and curing process before compaction is different from the pure binders blending between PG64-22 binder and the extracted/recovered RAS binders (see Figures 2 and 4). One may take the mix with 5 percent RAS (TOAS-E)/PG64-22 as an example. If the complete (or 100 percent) blending occurs like those shown Figure 2, the blended binder is around PG80-15, which is far stiffer than PG70-22 binder, and accordingly the mix with 5 percent TOAS-E should have less rut depth. Surely there is not 100 percent blending in the mixing, curing, and then compaction processes, and this is not unexpected since the high temperature grade of the TOAS-E binder is 166°C.

Additionally, Figure 8 shows that the mixes with the TOAS-E have less rut depths than those with the MWAS-C, which is reasonable since the TOAS-E binder is stiffer than the MWAS-C binder (see Figure 7).

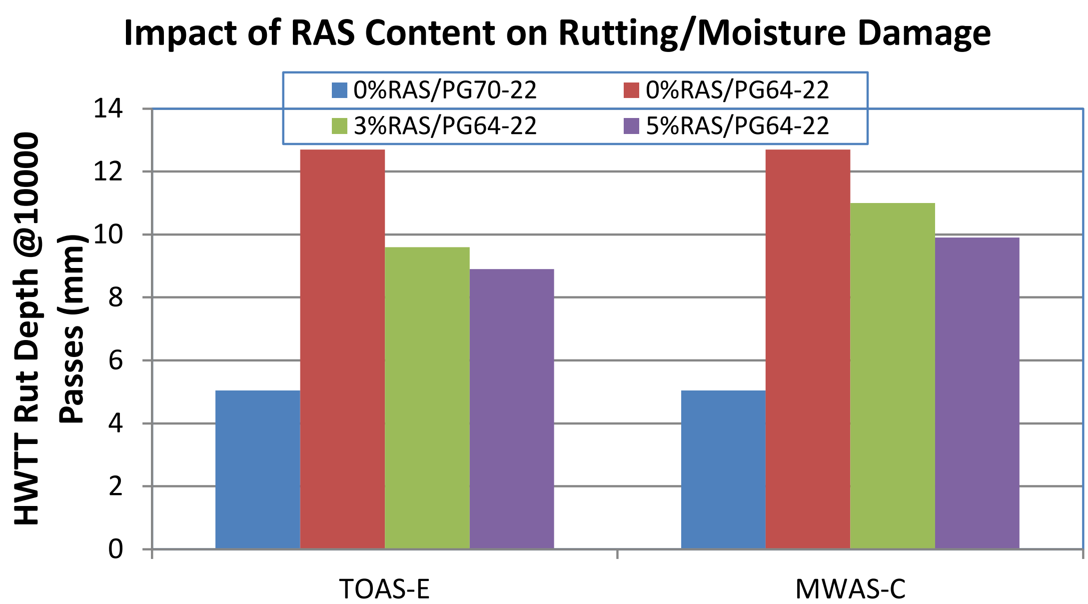


Figure 22. Impact of RAS on Rutting/Moisture Damage of HMA Mixes.

Impact of RAS on Cracking Resistance

Figure 23 shows the impact of RAS on cracking resistance of HMA mixes. For those mixes with PG64-22 binder, the use of RAS decreases cracking resistance of HMA mixes, regardless of TOAS-E or MWAS-C. The TOAS-E has worse effect than the MWAS-C, which implies that the blending between the virgin binder PG64-22 and the TOAS-E binder (or the MWAS-C binder) actually occurred. If there is no blending at all, both the mixes with the TOAS-E should have the same OT cycles as those with the MWAS-C. Although it is unknown how much the blending actually occurred, one known thing is that the mixes with the MWAS-C have much better cracking resistance than those with the 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 10 and 12).

Compared with the 0 percent RAS/PG70-22 mix, those PG64-22 mixes with either 3 percent or 5 percent RAS have worse cracking resistance. This is not a surprise because if the blending between virgin PG64-22 binder and RAS binder occurs, the low temperature grade would become warmer; 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 percent RAS mixes with PG70-22 or PG64-22 binder. Regardless, the cracking resistance is a big concern for those RAS mixes.

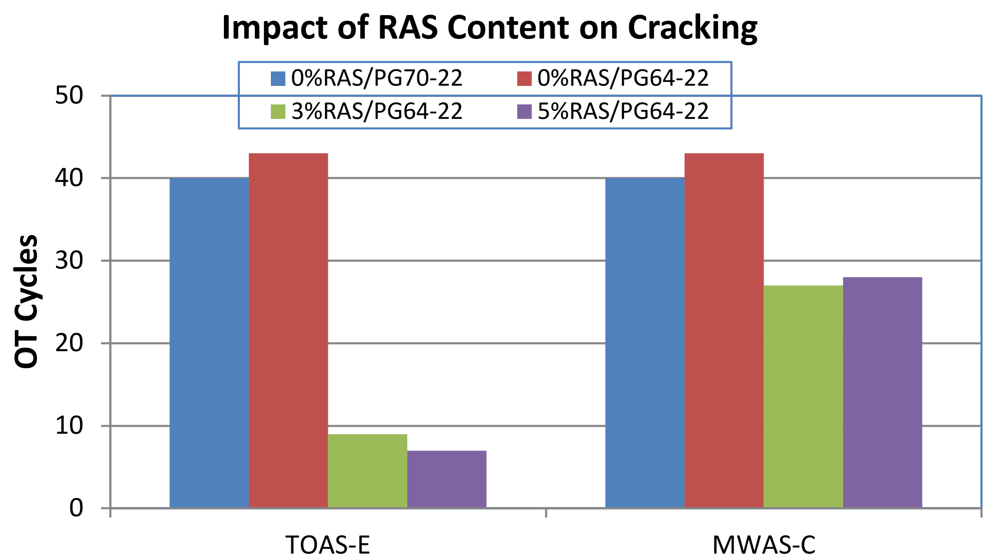


Figure 23. Impact of RAS on Cracking Resistance of HMA Mixes.

INVESTIGATION OF ACTUAL BLENDING BETWEEN VIRGIN AND RAS BINDER THROUGH MEASURING ENGINEERING PROPERTIES

The actual blending issue between virgin binder and RAS (or RAP) binder has been studied and debated for long time. There are three different opinions among different people: black rock (no blending at all or 0 percent blending), 100 percent blending, and in between. Up to now, there is no test available to accurately determine the actual blending. In last several years, there have been at least three interesting studies performed by D' Angelo et al. (2012), Bonaquist (2007), and Copeland et al. (2010) in this area. All these three studies still could not tell us how the blending actually occurs, however they provided some insights on this issue. Therefore, the researchers described these three studies first, and then present the work done in this area under this project.

Three Recent Studies on RAP Binder Blending in the Literature

- D' Angelo et al. recently conducted a simple blending study between RAP and virgin binder using size exclusion. Aggregate size exclusion means that the RAP will have a designated size in the mix and the virgin aggregates will have a different designated size. D' Angelo et al. employed HMA mixes contained only two distinct fractions (RAP and virgin aggregates) that can be easily separated by sieving through appropriate sieves after mixing with virgin binder. The separate of the individual RAP portion from the virgin after blending allows one to investigate whether or not the asphalt binder content is the same for both portions. If the RAP portion has higher binder content than the virgin aggregates portion, then the binder in the RAP did not melt and not much blending occurs between RAP binder and virgin binder. Instead, the virgin binder just coats the RAP (aggregates and binder) as a whole. The RAP itself before blending had a binder content of 3.29 percent, and after the blending, the asphalt binder content of the total mix before separation was 5.0 percent. Figure 24 shows the asphalt binder contents of RAP and virgin aggregates. RAP has much higher asphalt binder content than the virgin aggregates. As noted previously, if the RAP binder completely melts and 100 percent blending with virgin binder occurs, the RAP should have very similar binder content to the virgin aggregates and the asphalt binder content should be close to 5.0 percent. The most reasonable explanation is that the binder in the RAP did not melt and the virgin binder just coats the RAP as a whole. Therefore, it is more reasonable to treat the mixes with RAP as a composite material (see Figure 9 in Chapter 2).

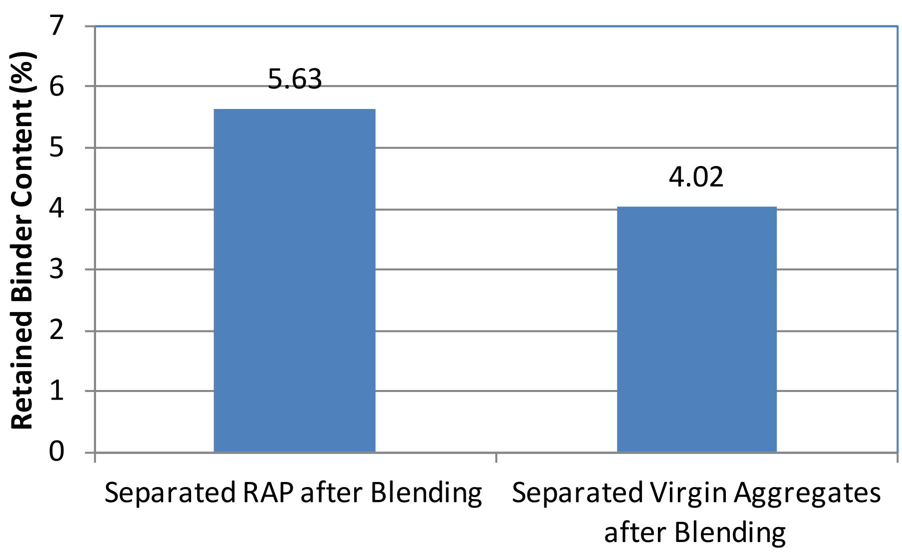


Figure 24. Retained Binder Contents for the RAP and Virgin Aggregates after Blending.

- Bonaquist developed an approach for evaluating blending of RAP and virgin binder in 2007. This approach includes five steps: 1) measure mix dynamic modulus, E*; 2) extract and recover binder (assumes 100 percent total blending); 3) measure recovered binder shear modulus using DSR test; 4) estimate E* based on measured G* using Hirsh model; and 5) compare the estimated E* to measured E*. Overlapping or similar values indicate good mixing; otherwise, it is not 100 percent blending. Since 2007, Bonaquist's approach has been advocated for determining blending issue. However, there are several facts that are worth noting about this approach:

  1. Bonaquist approach cannot tell exactly how much blending occurs if there is not 100 percent blending.
  2. Bonaquist approach requires to extract and recover asphalt binder from the E* specimen after the E* test. It is well known that the asphalt binder extraction and recovery can potentially change the binder properties and consequently, it may lead to

wrong conclusions on blending determination. Additionally, the extracted/recovered asphalt binder is 100 percent blending, and it does not represent the actual blending in the mix.

3. Dynamic modulus (E*) is an important property of asphalt mix. However, it measures the response of asphalt mix under loading. Even if there is no blending at all, the measured E* values may be close to those of mixes with partial blending, as discussed next.

- Copeland et al. (2010) recently reported that Bonaquist approach could not be used to identify the RAP and virgin binder blending. Copeland et al. conducted a side by side comparison between the normal mixing and compaction and the complete separation mixing and compaction. A 28 percent RAP mix from Maryland State Highway Agency was used in their study. Details are described below:
    - Normal mixing and compaction: virgin aggregates, RAP, and virgin binder were mixed using a normal bucket mixer in a normal way; and compacted E* samples after a 4-hour short term aging. The asphalt mixture performance test (AMPT) was used to measure E* at different temperatures.
    - Separate mixing and compaction: virgin aggregates and virgin binder were mixed using the normal way, but the RAP was left out. The RAP was mixed with the virgin materials (virgin aggregates and binder) just before the compaction. All others were performed exactly the same as those of normal mixing and compaction. Actually in this case there is no blending at all, since the RAP was separated out in the mixing process and the following 4-hour aging process.
    - The measured E* results under these two completely different mixing and compaction conditions are shown in Figure 25. There is no difference in terms of E* between the normal mixing and compaction process and the complete separation process. Therefore, the measured E* values cannot be used as an indicators for binder blending.

MD SHA 28% RAP Mix

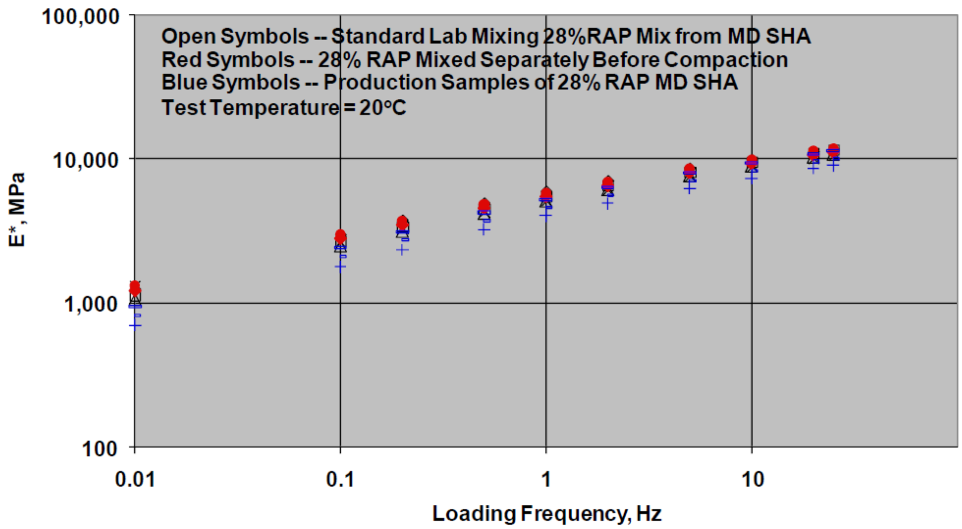


Figure 25. Measured E* Values of 28 Percent RAP Specimens Produced under Different Conditions.

In review of these three studies, at least three lessons can be learned: 1) in most cases, RAP binder does not melt and uniformly blend with virgin binder. Instead, virgin binder coats RAP as a whole and the coated virgin-RAP becomes a composite; 2) blending may not be necessary to produce properties similar to blended binder due to composite effect; and consequently; 3) Bonaquist approach may not be a valid approach for determining blending between RAP and virgin binder.

Investigation of RAS Binder Blending in Terms of E*

Similar to what Copeland et al. did on RAP binder blending in terms of E*, the researchers investigated E* difference of a RAS mix produced under normal mixing and compaction and separated mixing and then mixed just before compaction. The RAS mix contains 5 percent RAS with a PG64-22 virgin binder, and the total optimum asphalt content is 5.2 percent. Figure 26 shows the E* values at two completely different mixing and compaction processes measured from AMPT test. The observation made by Copeland et al. on RAP is true for the RAS mix: blending may not be necessary to produce properties similar to blended binder due to composite effect.

The researchers further checked the Bonaquist approach for estimating blending. Figure 27 shows the shear modulus master curve of extracted/recovered asphalt binder (including both virgin and RAS binders) from the E* specimens. The comparison between the measured E* from AMPT test and the predicted E* from Hirsh model is presented in Figure 28. It seems that the predicted E* values are all larger than the measured E*. This indicates that the blending is very little, because this happens only when the RAP binder does not blend with virgin binder and the measured E* is dominated by the virgin binder. However, as discussed previously, this may be due to composite effect. Therefore, it is difficult to make conclusions on this issue. As shown in Chapter 2, the shingles binders, regardless of MWAS or TOAS, are very stiff. So the question, discussed in the next section, is: does one really want 100 percent blending?

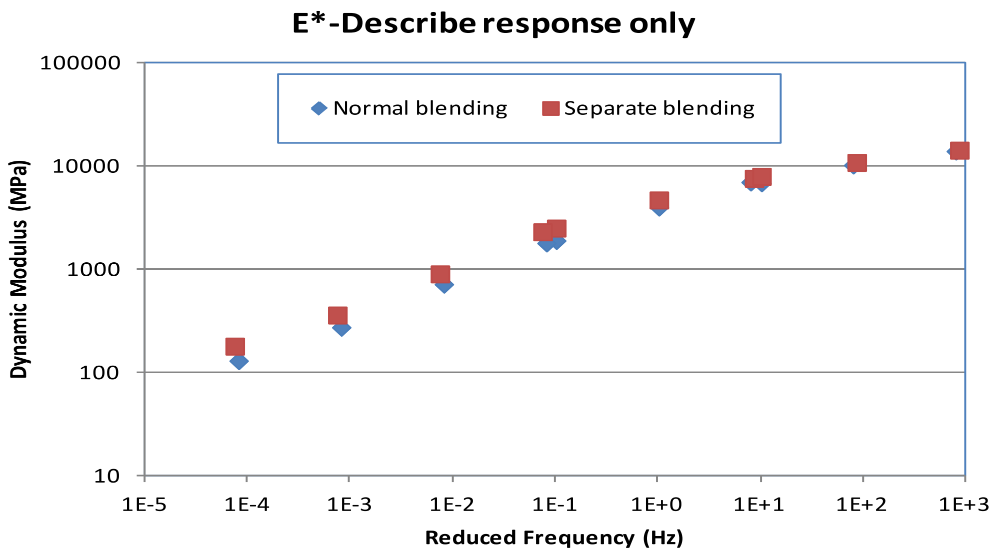


Figure 26. Measured E* Values of 5 Percent RAS Specimens Produced under Different Conditions.

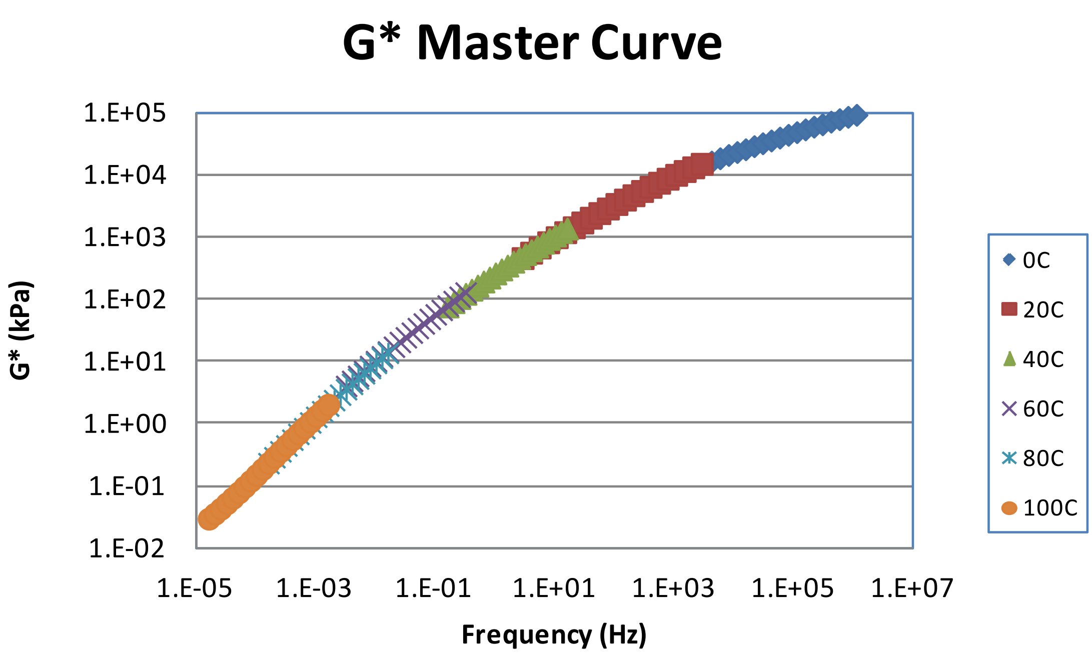


Figure 27. Master Curve of Extracted/Recovered Binder.

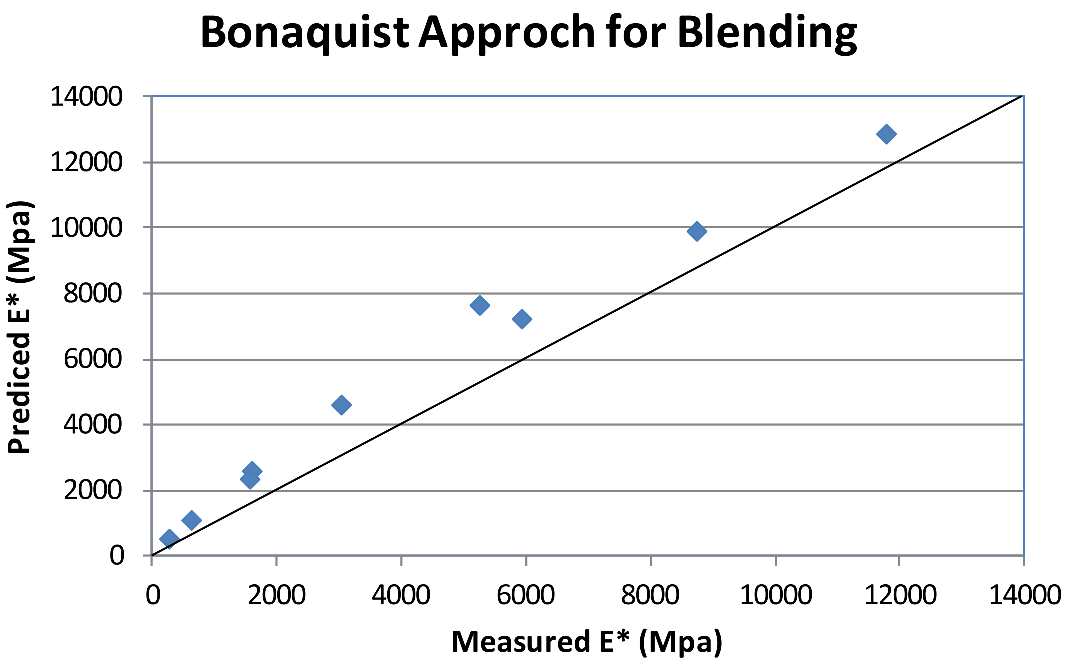


Figure 28. Measured vs. Predicted E* Values.

Does 100 Percent Blending Really Matter?

The researchers also compared the true 100 percent blending between RAS binder and virgin binder and the normal mixing and compaction in terms of Hamburg and OT testing. The 100 percent blending was achieved through extracting and recovering RAS binder in advance and then manually mixing the RAS binder with virgin binder. Figure 29 illustrates mixing and molding processes. Figure 30 presents the Hamburg and OT test results. Additionally, the same mix produced in the plant and compacted in the field was also tested under Hamburg and OT tests. The results also are shown in Figure 30. As seen in Figure 30, 100 percent blending did not improve the engineering properties of the RAS mix in terms of Hamburg and OT tests.

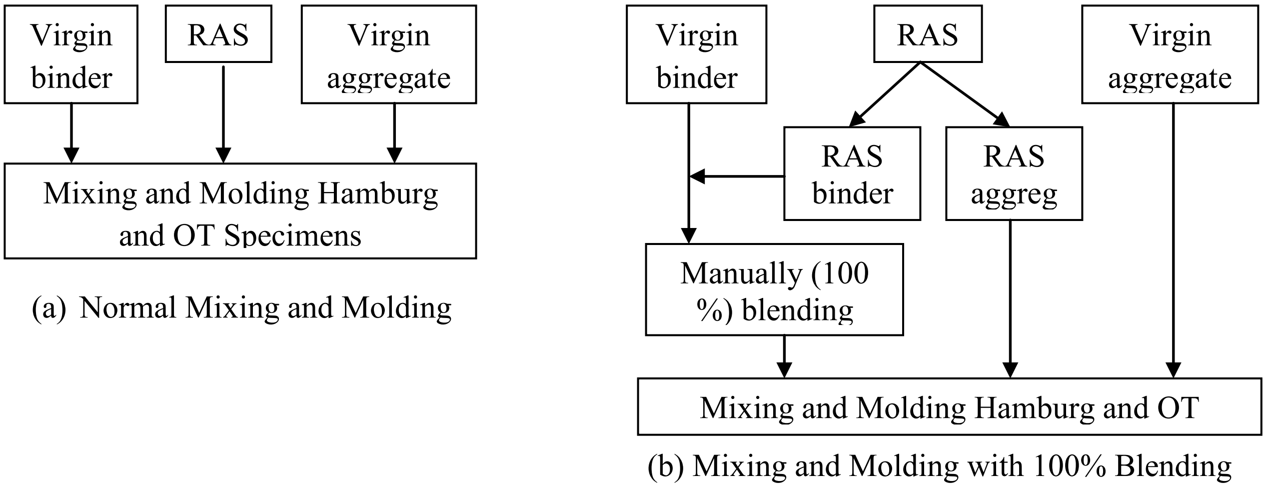


Figure 29. Illustration of Different Mixing and Molding Processes.

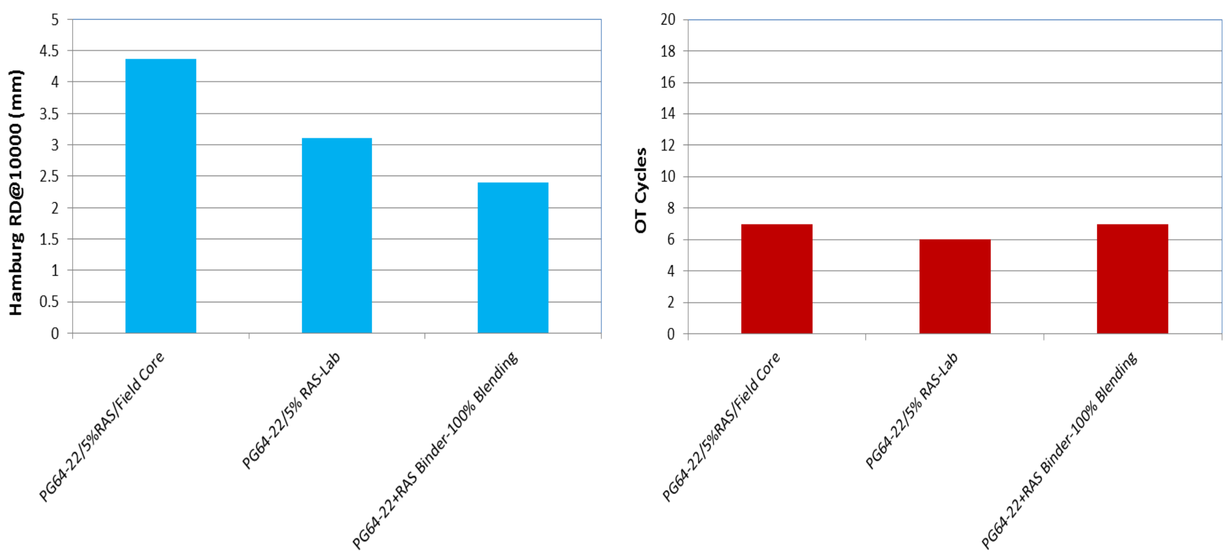


Figure 30. Field Core vs. Lab Normal Blending vs. Lab 100 Percent Blending.

Discussion

The data presented above indicated that no procedure is available to accurately determine the actual blending of RAP/RAS mixes, regardless of measuring E*, Hamburg rut depth, and OT cycles. Therefore, the question becomes:

- Is it really important to have a method to determine blending or
- ***Is it more important to ensure that the required engineering properties of RAS mixes (such as max. Hamburg rut depth, Min. OT cycles) are met in the mix design process?***

For the time being, the researchers believe that it is critical and practical to ensure the designed RAS mixes have acceptable rutting/moisture resistance and cracking resistance through Hamburg and OT testing.

SUMMARY AND DISCUSSION

Reviewing the results presented above, several findings and a discussion are provided below:

- Comparing with engineering properties of field cores, the laboratory compaction temperature and curing time for HMA containing RAS are 135°C (275°F) and 2 hour.
- The use of RAS has no significant influence on dynamic moduli of HMA mixes, but improves their rutting/moisture damage. Meanwhile, adding RAS generally increases OAC of HMA mixes and the higher OAC corresponding to higher RAS content. However, RAS mixes have very poor cracking resistance, compared to the 0 percent RAS mixes with PG64-22 or PG70-22, 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 resistant. Compared with the TOAS-E mixes, the MWAS-C mixes have much better cracking resistance. This finding is consistent with the results of binders blending discussed previously.
- The data presented above indicated that no procedure is available to accurately determine the actual blending of RAP/RAS mixes, regardless of measuring E*, Hamburg rut depth, and OT cycles. For the time being, the researchers believe that it is critical and practical to ensure the designed RAS mixes have acceptable rutting/moisture resistance and cracking resistance through Hamburg and OT testing.

Although the actual blending extent is still unknown, one known fact is that the use of RAS decreases cracking resistance of HMA mixes, and some remedies need to be explored, as discussed in next chapter.

CHAPTER 5
APPROACHES FOR IMPROVING CRACKING RESISTANCE OF RAS MIXES

As discussed in Chapter 4, the use of RAS can improve rutting resistance of HMA mixes, but it causes poor cracking resistance of the mix and, consequently, the poor durability of HMA mixes. Therefore, some approaches need to be taken to balance the performance of RAS mixes. In general, there are at least four approaches:

- Reducing RAS usage (i.e., from 5 percent to 3 percent).
- Rejuvenating RAS binder in the mix design process.
- Using soft virgin binders especially on the low temperature grade (i.e., PGXX-28, PGXX-34).
- Increasing design density (lowering design air voids) or reducing N_{design}.

Naturally, the first choice is to use less RAS. However, the previous results shown in Figure 23 indicated that reducing RAS usage from 5 percent to 3 percent does not have significant improvement on cracking resistance. Further reducing the RAS usage will make no sense in terms of recycling. The second choice is to rejuvenate RAS binder using some rejuvenating agents. It sounds like a good idea and potentially improves cracking resistance of RAS mixes (Tran et al., 2012), but there are lots of practical and technical issues when applied to normal asphalt plant operations. Apparently, more research is needed in the area of rejuvenating agents and practical application. Thus, this study focused on the last two approaches: using soft binder and increasing design density and evaluated the effectiveness of these two approaches in improving cracking resistance of RAS mixes.

USE OF SOFT BINDERS

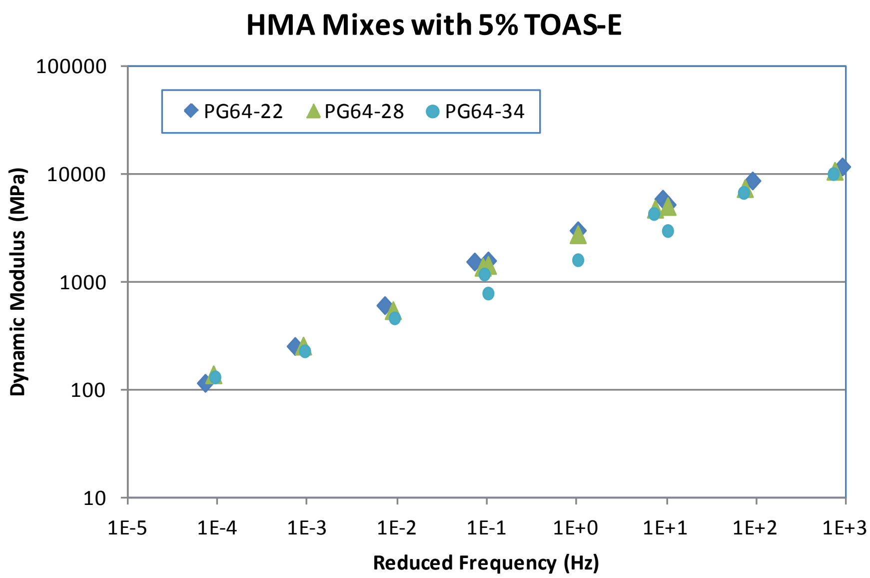
The same 5 percent RAS/PG64-22 mixes with the TOAS-E and MWAS-C previously designed were used as control mixes. Two soft binders selected in this study are PG64-28 and PG64-34. A total of six mixes (2 RAS and 3 virgin binders) listed in Table 3 were evaluated under dynamic modulus test (AASHTO TP79), 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 31, 32, and 33 show the test results.

Table 3. 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 31 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 32. 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 33 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 no much impact on dynamic moduli of RAS mixes; whereas, it can improve both rutting and cracking resistance of RAS mixes, especially on cracking resistance.



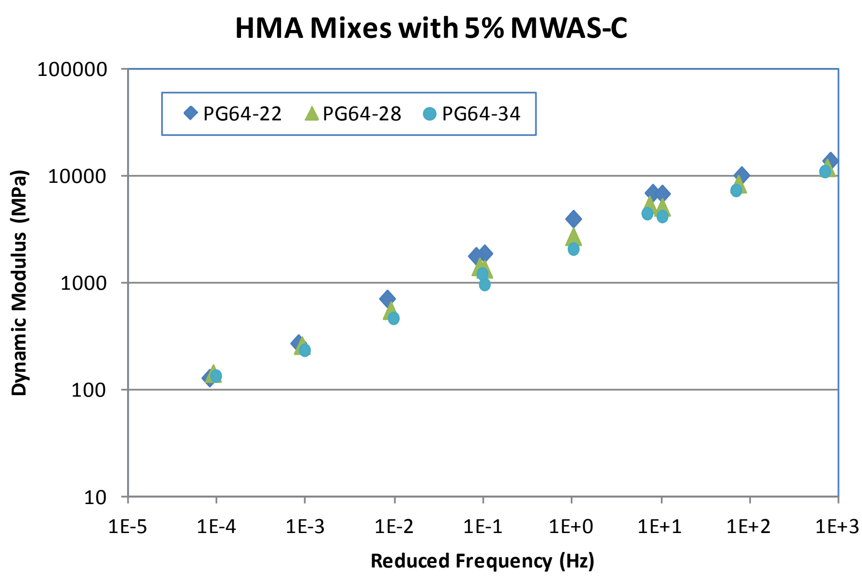


Figure 31. Impact of Soft Binders on Dynamic Modulus of 5 Percent RAS Mixes.

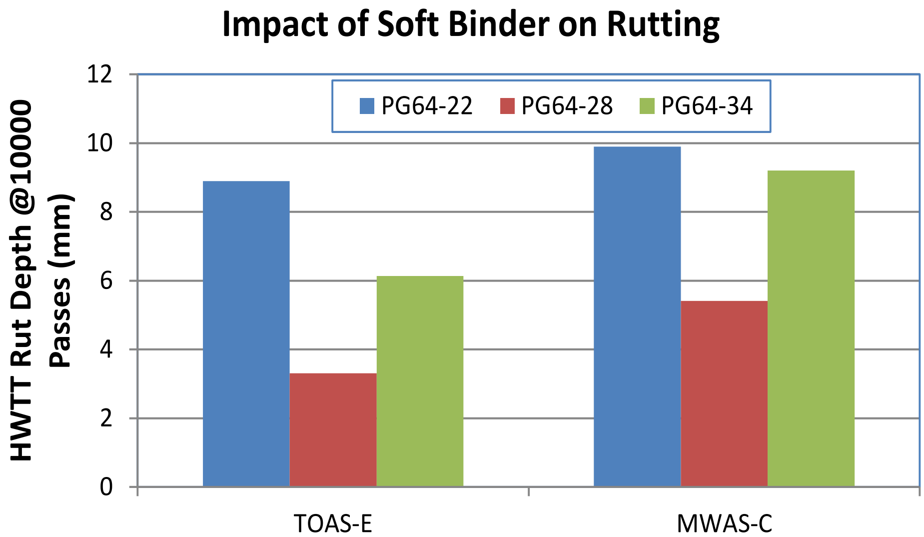


Figure 32. Impact of Soft Binders on Rutting/Moisture Damage of 5 Percent RAS Mixes.

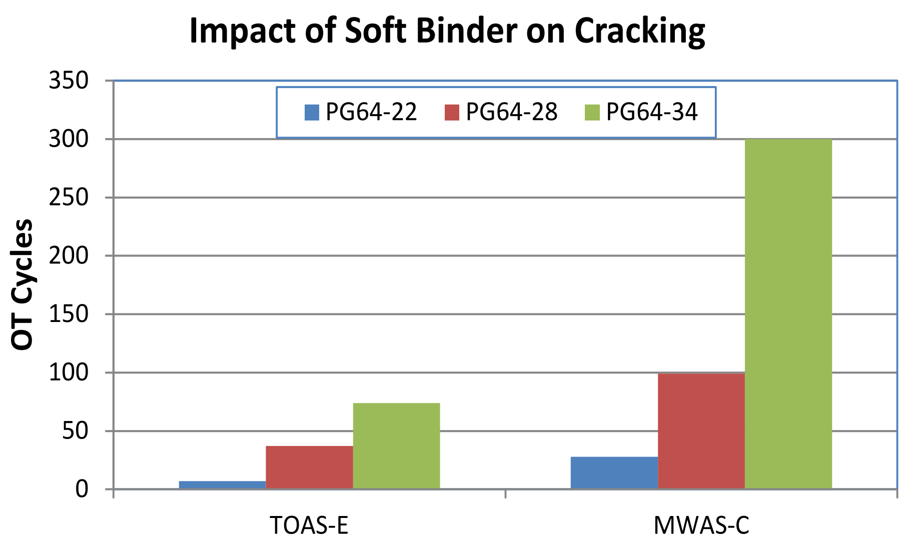


Figure 33. Impact of Soft Binder on Cracking Resistance of 5 Percent RAS Mixes.

INCREASING DESIGN DENSITY

Another simple way to improve cracking resistance of RAS mixes is to add more virgin binder into the mixes through increasing design density (or lowering the design air voids) when selecting OAC. (Alternatively, one can reduce N_{design}.) Currently the design density for selecting OAC of RAP/RAS mixes is 97 percent. To avoid bleeding problem, the maximum design density should be less than 98 percent. Again, the same 5 percent RAS/PG64-22 mixes with the TOAS-E and MWAS-C previously designed were used here. Two design densities: 97 percent and 97.7 percent were used, and accordingly the corresponding OACs are 5.2 percent and 5.7 percent, respectively. Only the HWTT (Tex-242-F), and OT (Tex-248-F) testing was performed, and the dynamic modulus test was omitted since the previous results did not show much difference among different RAS mixes. Figure 34 shows the test results.

Figure 34 shows that the higher OAC corresponding to increase design density significantly improves cracking resistance, which is desirable. Meanwhile the higher OAC makes the RAS mixes more susceptible to potential rutting/moisture damage. Therefore, one must exercise cautions when improving cracking resistance of RAS mixes through increasing design density.

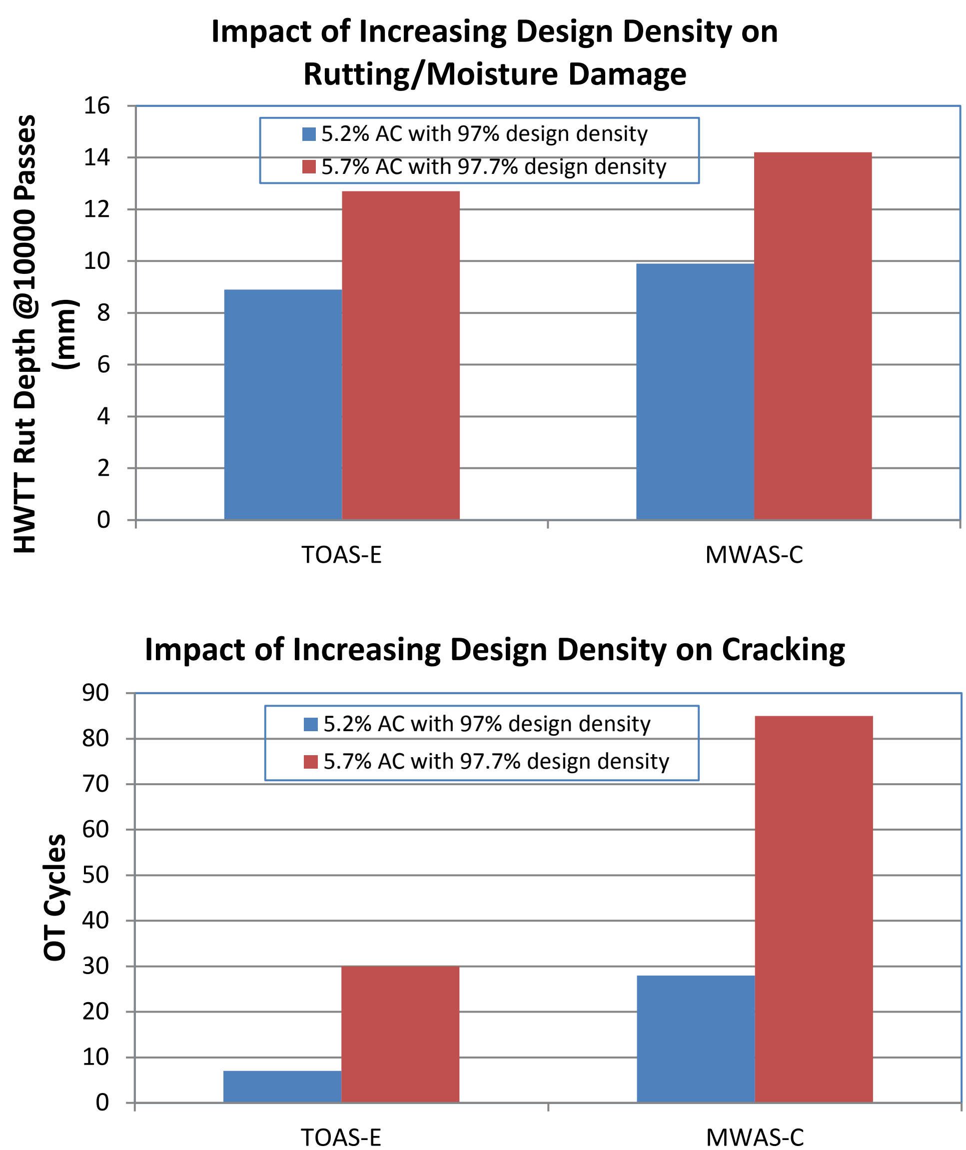


Figure 34. Impact of Increasing Design Density on Rutting/Moisture Damage and Cracking Resistance of RAS Mixes.

SUMMARY

The OT results presented above clearly indicated that both using soft binder and increasing design density can improve cracking resistance of RAS mixes. When considering rutting/moisture damage of RAS mixes, using soft binder is superior to increasing design density (see Figures 32 and 34). In order to validate these laboratory test results and these two approaches, field test sections were constructed in Texas, which is discussed in next section.

CHAPTER 6
PERFORMANCE OF FIELD TEST SECTIONS WITH RAS MIXES

This chapter documents all field test sections constructed with a purpose of recording field performance of RAS mixes and validating the approaches for improving cracking performance of RAS mixes: using soft binder and increasing design density. Another purpose of field test sections is to identify the locations RAP/RAS mixes can be used with low risk. A variety of field test sections were built under this study around Texas. Detailed information about these test sections and field performance observed so far are presented below.

RAS TEST SECTIONS ON US87, AMARILLO AND OBSERVED FIELD PERFORMANCE

Two 3-inch asphalt overlay test sections were constructed side by side on the same lane and traveling direction on US87, Amarillo, Texas, in late October 2010. The main objective of these two test sections was to validate the effectiveness of increasing design density on improving cracking resistance of RAS mixes. The RAS mixes used on the two test sections are exactly the same (aggregates, gradation, virgin binder, and RAS) except the OAC; the OAC for control section was 4.6 percent corresponding to 96.5 percent design density and the other one being 5.0 percent corresponding to 97.3 percent design density. 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. The US87 in Amarillo, Texas, has medium traffic with around 5 million ESALs in 20 years. The existing asphalt pavement had severe transverse cracking before asphalt overlay. The cold weather and severe existing pavement cracking plus traffic make these two sections a good case study to rapidly validate the effectiveness of increasing design density on improving cracking resistance of RAS mixes.

After the completion of the construction of these two RAS test sections, three field surveys have been conducted on Apr. 5, 2011, Dec. 15, 2011, and May 30, 2012, respectively. So far, no rutting has been observed, but reflective cracking occurred on both test sections (Figure 35). The development history of the observed reflective cracking is shown in Figure 36. Note that prior to placing the overlay the number of pre-existing cracks in each section was documented and mapped. The reflective cracking rate is therefore defined as the ratio of the number of reflective cracks to the original number of cracks before the 3-inch overlay. Apparently, increasing design density significantly improved reflective cracking performance of the RAS mix on US87, which is clearly shown in Figure 36.

Figure 35. Observed Reflective Cracking of RAS Test Sections on US87, Amarillo, Texas.

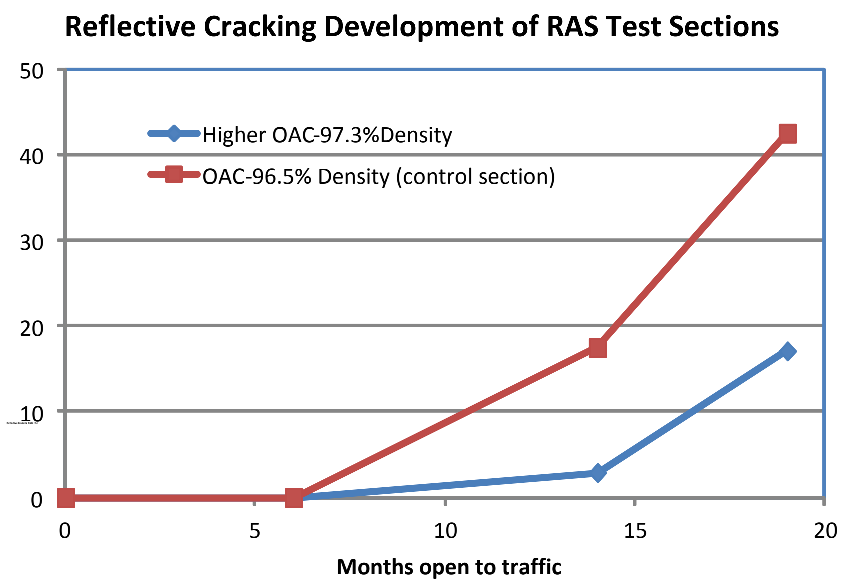


Figure 36. Reflective Cracking Development History of RAS Test Sections on US87, Amarillo, Texas.

FIELD TEST SECTION ON SH146, HOUSTON AND OBSERVED PERFORMANCE

In contrast to the extreme cold weather in Amarillo, a field test section was constructed on SH146 in Houston area where the weather is warm. Furthermore, the test section on SH146, different from the asphalt overlay on US87, is a new construction and the 15 percent RAP/5 percent RAS mix was used as the top 2-inch surface layer. The main features of this section are 1) new construction and 2) 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 37. The researchers will continue to monitor this test section.

Figure 37. Perfect Condition of RAP/RAS Test Section on SH146, Houston.

FIELD TEST SECTIONS ON FM973, AUSTIN, TEXAS, AND ASSOCIATED 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 Dec. 2011 and Jan. 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 4 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 performance of HMA mixes with WMA mixes side by side.

Prior to the 2-inch asphalt overlay, the overall pavement condition was not bad, and some areas had low severity level of longitudinal cracking along the wheel passes. The overall deflection measured using falling weight deflectometer is around 0.28 mm (11 mils). So the 2-inch 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 38 shows the conditions of Sections 3 and 6 in July 2012. Apparently, more time is needed for these test sections to show 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 4. Nine Test Sections on FM973, Austin, Texas.

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 38. Pavement Conditions of RAP/RAS Test Sections 3 and 6 on FM973, Austin, Texas, in July 2012.

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

Most recently, four more field test sections were constructed on Loop 820, Fort Worth side by side. Table 5 presents detailed information on these four test sections. The main features of these four test sections are 1) RAP/RAS/WMA with Advera additive, 2) soft virgin binder without changing the OAC, 3) extra virgin binder without changing virgin binder grade, and 4) pre-blending WMA additive with processed RAS. Additionally, these four test sections are a 2-inch asphalt overlay over cracked continuously reinforced concrete pavement (CRCP), as shown in Figure 39. Apparently, these test sections provided opportunity to check the impact of soft binder and extra virgin binder on rutting and cracking performance of RAP/RAS mixes.

The test sections were built on July 19, 2012. So far no distress has been observed yet. The researchers will continue to monitor these four test sections.

Table 5. Four Field Test Section on Loop 820.

Test section	Virgin binder	OAC (%)	WMA additive: Advera
Section 0	PG64-22	5.1	Advera as external additive
Section 1	PG64-22	5.1	Advera pre-blended with processed RAS
Section 2	PG64-28	5.1	Advera as external additive
Section 3	PG64-22	5.5	Advera as external additive

Figure 39. Existing CRCP Condition and Construction of RAP/RAS Test Sections on Loop 820, Fort Worth.

SUMMARY

A variety of RAP/RAS test sections have been constructed with different features around Texas. The two main objectives of field test sections are to 1) identify where the RAP/RAS mixes works with low risk and 2) validate the approaches for improving cracking resistance of RAP/RAS mixes. Based on the performance of test sections observed so far, two preliminary findings are made:

- RAP/RAS mixes can be used as surface layer with strong foundation for new constructions without much risk, such as SH146.
- Use of extra virgin binder (or increasing design density) can improve cracking resistance of RAP/RAS mixes as shown on US87.

Apparently, these two findings are very preliminary and continuously monitoring all these test sections is necessary and critical for making final conclusions.

CHAPTER 7
ENVIRONMENTAL AND COST IMPACTS OF RAS ON ASPHALT MIXTURES

INTRODUCTION

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

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

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

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

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

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

ENVIRONMENTAL ISSUES

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

Asbestos

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

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

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

Asbestos was once used in asphalt shingles to act as reinforcement (i.e., a fibrous mat) for the shingle and also acted as a fireproofing/insulating material. Asbestos was also used in certain other roofing products. Townsend et al. (2007) presented a summary of information published in the Federal Register along with data they collected by from other sources showing how asbestos was used in shingles and other roofing products (Table 6).

Table 6. Asbestos-Containing Asphalt Roofing Products (after Townsend et al., 2007).

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

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

Polycyclic Aromatic Hydrocarbons

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

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

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

Greenhouse Gas Emissions

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

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

Other Air Emissions

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

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

Energy Savings

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

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

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

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

Life-Cycle Environmental Impacts

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

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

- Energy consumption.
- CO_2 emissions.
- NO_x emissions.
- PM_{10} emissions.
- SO_2 emissions.

- CO emissions.
- Leachate information.

Waste Reduction Model

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

ECONOMIC FACTORS

According to Krivit (2007), the economics of TOAS recycling are currently driven by three main factors: (1) prevailing landfill tipping fees; (2) price of virgin AC; and (3) cost of RAS production. The virgin AC price, as a world commodity, will generally follow national/international trends. The future of AC costs is expected to continue to increase over the long term. An illustration of the price trend for AC is depicted in Figure 40 (Peterson, 2011). Note that the prices in Figure 40 are rack prices; to estimate typical bid prices for asphalt, one should add about $100 or a little more to these values. The point here is that, as the price of asphalt increases, so does the value of asphalt shingles.

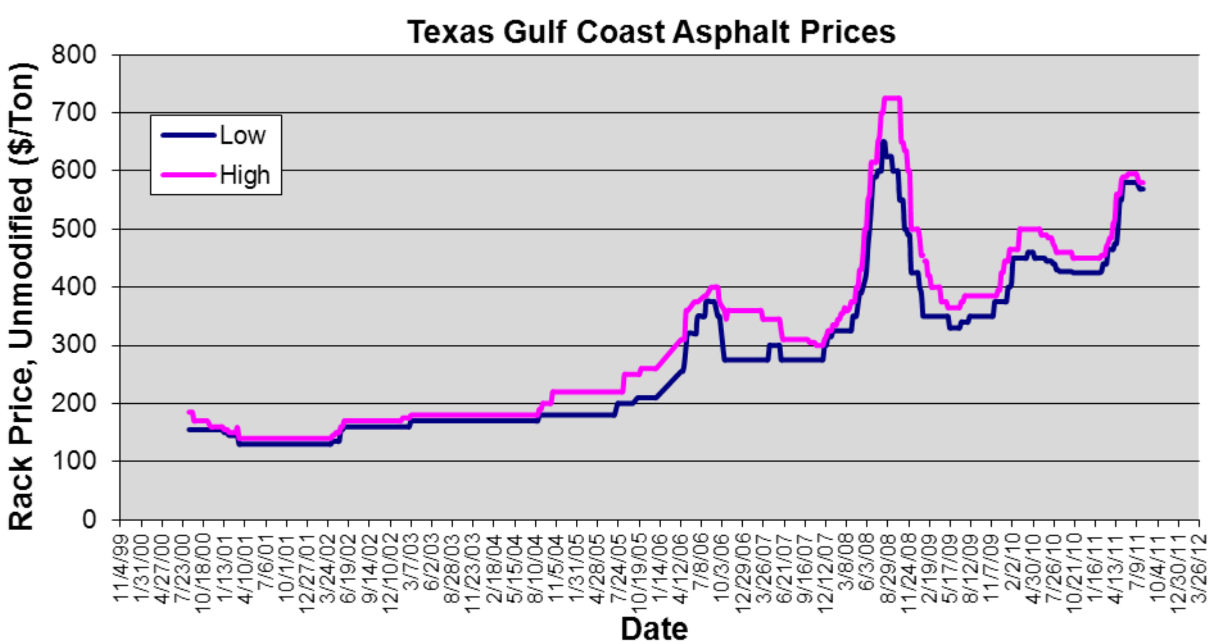


Figure 40. Price Trends for Liquid Asphalt from 1999 to 2011 (after Peterson, 2011).

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

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

Brock (2007), of Astec Industries, used the values for composition of three different types of shingles, shown in Table 7, and prepared a simplified economic analysis of RAS in HMA when the cost of liquid AC was $400 per ton (Table 8). Therefore, in 2011, with the cost of AC now around $600/ton, the cost savings would be significantly greater. Although the value of RAS has surely increased with the price of AC, the price of RAS has probably not escalated to the same degree as virgin AC.

Table 7. Typical Shingle Composition (modified after Brock, 2007).

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

Table 8. Typical HMA Plant Economic Savings When Using RAS (after Brock, 2007).

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

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

Hot Mix Savings Using Roofing Shingles

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

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

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

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

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

Hughes (1997) originally presented a very simplified economic analysis or worksheet for recycling RAS into HMA based on a generic cost-benefit model (Table 9). Krivit (2007) added Item G, in Table 3, to account for capital costs, as he contended that any specific net savings calculations must include calculations for the budgeted capital (e.g., land, buildings, and equipment) and operations/maintenance costs. He included additional items in Item H, stating that cost estimates should include labor, sales, and other marketing costs as well as utilities (including water) and transportation. Krivit (2007) further commented that all QA/QC costs related to RAS must be included, along with any laboratory costs for asbestos testing and final product engineering tests. A notable economic benefit to using MWAS over TOAS is that asbestos testing is not required.

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

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

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

Table 9. Method for Calculating the Value of RAS in Asphalt Mixtures (modified after Hughes, 1997; Hansen, 2009; Krivit, 2007).

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

Rand (2011) deduced that proper use of unmodified binders (e.g., PG 64-22 instead of PG 70-22 or PG 76-22) along with RAP and RAS can reduce the cost of asphalt pavement material by more than $15/ton. The assumptions shown in Table 10 were used to determine the HMA cost estimates in Table 11 and Figure 41. Note that the cost estimates in Table 11 and Figure 41 represent material costs only. These do not reflect the total as-constructed cost of HMA and are based on 2011 cost data in Texas. Costs can vary significantly with circumstances.

Table 10. Assumptions Used for Asphalt Pavement Cost Estimates.

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

*Source: Louisiana Asphalt Pavement Association

Table 11. Asphalt Pavement Cost Estimates.

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

*Includes 15% RAP and 5% RAS

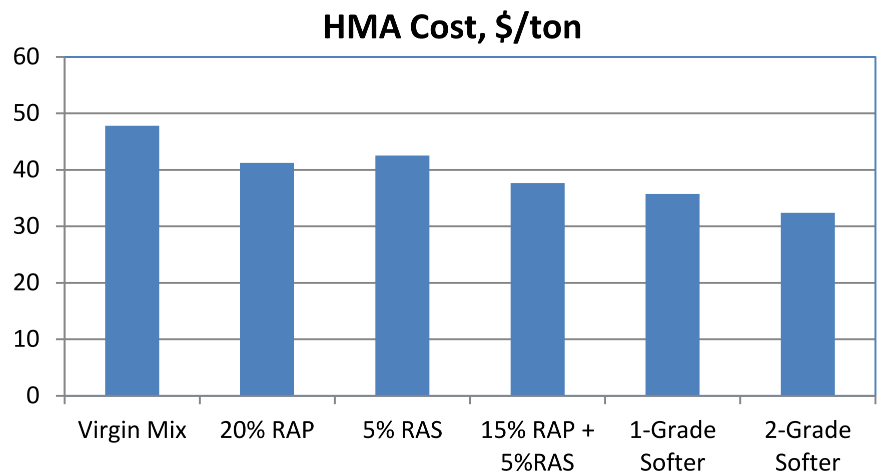


Figure 41. HMA Cost in Dollars per Ton for Type D (1/2-inch NMAS) Mix Containing PG 76-22.

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

PERTINENT ACTIVITIES TO ENCOURAGE RECYCLING

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

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

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

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

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

SUMMARY AND CONCLUSIONS

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

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

CHAPTER 8
SUMMARY AND CONCLUSIONS

This report presents a comprehensive study on HMA mixes containing RAS, including 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. Furthermore, a variety of RAS field test sections were constructed to validate the approaches for improving cracking resistance of RAS mixes. Additionally, this report discusses the environmental and economic benefit of using RAS in HMA. Based on the research presented in this report, the following conclusions are offered:

- RAS binders are very stiff. TOAS binders with an average of high temperature grade of 175°C are much stiffer than MWAS binders, which have an average of high temperature grade of 131°C. The MWAS has smaller variation in the high temperatures grade, compared to the TOAS varying from 159°C to 214°C.
- Generally, the virgin and RAS binders blending is non-linear. For practical application, the linear blending chart can still be used if the RAS binder percentage is not beyond 30 percent. Within 30 percent RAS binder, not only is the linear blending chart applicable, but the regular DSR and BBR can also be used to evaluate the high and low ends of the PG grade of the blended binder.
- Impact of MWAS binder on the high and low PG temperatures of virgin binder is different from that of TOAS binders. 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 those TOAS binders. Thus it is important to consider differentiating MWAS from TOAS when used in asphalt mixes.
- The use of RAS has no significant influence on dynamic moduli of HMA mixes, but improves their rutting/moisture damage. Meanwhile, adding RAS generally increases OAC of HMA mixes and the higher OAC corresponding to higher RAS content. However, RAS mixes have very poor cracking resistance, compared with the 0 percent RAS mixes with PG64-22 or PG70-22, even though the RAS mixes have higher OAC. Therefore, cracking resistance is a big concern for the RAS mixes.
- Two approaches for improving cracking resistance of RAS mixes were explored in the laboratory. The test results clearly indicated that both using soft binder and increasing design density can improve cracking resistance of RAS mixes. When considering rutting/moisture damage of RAS mixes, using soft binder is superior to increasing design density.
- Performance of field test sections observed so far indicated that RAS mixes can be successfully used as surface layer of new construction with strong foundation. It also has been observed that the use of extra virgin asphalt binder (or increasing design density) can effectively improve cracking performance of RAS mixes.

The findings from this study still need to be further validated with field performance data from different test sections under various scenarios. More work is also needed to investigate the performance of RAS/RAP mixes produced at the warm mix temperatures.

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