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16. Abstract
Recycled materials including reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS) have been widely used in asphalt mixes in Texas with at least three benefits: reducing construction cost, conserving raw materials and environment, and improving rutting resistance. However, there are two major concerns over the use of RAP and RAS: variability and premature cracking. This project addressed these two concerns.
This project developed and disseminated the best practices of processing RAP and RAS through teaching four regional workshops. Additionally, researchers evaluated many bio-rejuvenators to improve cracking resistance through a series of laboratory testing and the construction of 17 field test sections. The bio-rejuvenators performed differently in the laboratory and field test sections, and some are more effective than others. Both laboratory and field test results indicated the total fatty acid content is a performance indicator for bio-rejuvenators, and the larger fatty acid content, the more effective the bio-rejuvenator. To perform well, bio-rejuvenators should contain more than 97 percent fatty acid content and less than 50 percent saturate fatty acid. Meanwhile, it is preferred to have the mass loss of less than 5 percent after the rolling thin film oven test. This project also recommended and demonstrated a four-step balanced mix design process for designing mixes containing RAP/RAS and rejuvenators: 1) selection of rejuvenator type, 2) determination of the range of the rejuvenator amounts required to meet both the binder specification and aging characteristics, 3) determination of the range of the rejuvenator amounts required to meet mixture rutting and cracking requirements, and 4) selection of final rejuvenator amount based on engineer judgement. Additionally, it is feasible to use the dynamic shear rheometer with 50 mm parallel plates to measure dynamic viscosity of bio-rejuvenators.

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REJUVENATOR LABORATORY CHARACTERIZATION AND FIELD PERFORMANCE

by

Fujie Zhou
Senior Research Engineer
Texas A&M Transportation Institute

Pravat Karki
Associate Transportation Researcher
Texas A&M Transportation Institute

and

Sheng Hu
Associate Research Engineer
Texas A&M Transportation Institute

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College Station, Texas 77843-3135

DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purpose. The engineer in charge of the project was Dr. Fujie Zhou, P.E. (Texas # 95969).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1: INTRODUCTION

BACKGROUND

In the last 10 years, recycled materials including reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS) have been widely used in asphalt mixes in Texas. The use of RAP and RAS in asphalt mixes has at least three benefits: reducing construction cost, conserving raw materials and environment, and improving rutting resistance. However, there are two major two concerns over the use of RAS: variability and stiff binder from RAS. To address these two concerns, researchers developed best practices for the use of RAS in asphalt mixes, including instructor guidebook (Appendix A), student manual (Appendix B), and workshop materials (Appendix C).

Generally, RAS binder is severely aged and substantially stiffer than regular virgin binders, which often leads to a stiffer mix with relatively lower resistance to cracking. Consequently, the premature cracking problem has been one of the major concerns over the use of RAP/RAS in asphalt mixes. There are many different approaches for addressing the premature cracking problem. One of them is to use rejuvenators (or recycling agents). This research report documents rejuvenator laboratory characterization and field performance.

REPORT ORGANIZATION

This report is organized in five chapters. Chapter 1 provides a brief introduction. Chapter 2 describes rejuvenator characterization and the impact of rejuvenators on binder performance. Furthermore, this chapter identifies a preliminary performance indicator for the rejuvenators. Chapter 3 presents rejuvenator field performance observed on 17 test sections around Texas. Chapter 4 discusses balanced mix design for mixes containing RAP/RAS and rejuvenators. Finally, Chapter 5 offers the conclusions drawn from the laboratory and field data.

CHAPTER 2: REJUVENATOR CHARACTERIZATION AND LABORATORY PERFORMANCE

INTRODUCTION

In the last several years, the use of RAP and RAS in asphalt mixes has become a new norm. However, recycled binders from either RAP or RAS are often severely aged and substantially stiffer than regular virgin binders, as shown in Figure 1. Consequently, premature cracking problem becomes one of the major concerns with the use of RAP and RAS in asphalt mixes. One of the approaches addressing the premature cracking is to use rejuvenators (or recycling agents). This chapter presents background information about rejuvenators first and then describes laboratory characterization of representative rejuvenators in the market. Following that, this chapter discusses the effectiveness of rejuvenators in improving recycled binder properties. Furthermore, this chapter identifies a preliminary performance indicator for bio-rejuvenators. At the end of this chapter, a summary and conclusions are drawn based on the data presented.

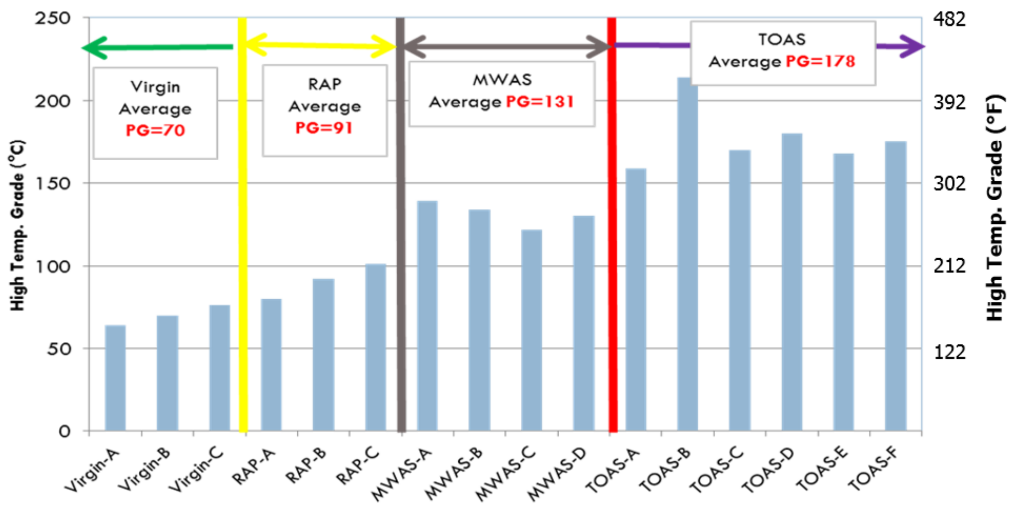


Figure 1. Comparison of Binder High Temperature Performance Grade: Virgin vs. RAP vs. RAS.

BACKGROUND

The structure of asphalt binder is often treated as a complex colloid in which insoluble asphaltenes are dispersed in the soluble maltenes. With sufficient maltene components, the asphaltene micelles under applied stress can move smoothly within asphalt. As asphalt ages, the maltenes are transformed to asphaltenes through oxidation, which results in unbalanced ratio of maltenes to asphaltenes, and consequently a hardened asphalt mix and brittle pavement (Boyer 2000, Karlsson 2002). The purpose of using rejuvenator is to 1) restore the aged asphalt characteristics to a consistency level appropriate for construction purposes and for the end use of the mixture; 2) restore the aged asphalt to its optimal chemical characteristics for durability, and 3) provide sufficient additional binder to coat new aggregate and to satisfy mix design requirements (Epps et al. 1980). According to Carpenter and Wolosick (1980), the working mechanism (or diffusion process) of a rejuvenator consists of the following four steps:

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

Rejuvenators have been developed and evolved in last several decades (Davidson et al. 1977, Dunning and Mendenhall 1978, Escobar and Davidson 1979, Kari et al. 1980, Tran et al. 2016, Yin et al. 2017, and Epps-Martin et al. 2019). In late 1970s and early 1980s, most rejuvenators were either softer asphalt binders (such as AC 1.5) or some extracts from petroleum (such as aromatic oils, paraffinic oils, and naphthenic oils). To better classify available materials as different groups, the Pacific Coast User-Producer Group evaluated various rejuvenators in late 1970s and early 1980s (Kari et al. 1980), and its research results led to ASTM D4552: Standard Practice for Classifying Hot-Mix Recycling Agent. The rejuvenators are classified into six grades (or groups) mainly through viscosity measured at 60°C (140°F), as shown in Table 1. In general, the smaller the viscosity, the more effective is the rejuvenator.

Table 1. Physical Properties of Hot-Mix Recycling Agents (ASTM D4552-10).

Test	ASTM test method	RA1	RA5	RA25	RA75	RA250	RA500
Viscosity, 60ºC, mm^2/s (cSt)	D2170 or D2171	50–175	176–900	901–4500	4501–12500	12501–37500	37501–60000
Flash point, COC, ºC [ºF]	D92	219 [425]	219 [425]	219 [425]	219 [425]	219 [425]	219 [425]
Saturates, wt, %	D2007	Max. 30	Max. 30	Max. 30	Max. 30	Max. 30	Max. 30
Tests on residue from RTFO or TFO oven 163 ºC [325 ºF]: 1) Viscosity ratio*	D2872 or D1754	Max. 3	Max. 3	Max. 3	Max. 3	Max. 3	Max. 3
2) Wt change, %		Max. 4	Max. 4	Max. 3	Max. 3	Max. 3	Max. 3
Specific gravity	D70 or D1298	Report	Report	Report	Report	Report	Report

Note: *Viscosity ratio=viscosity of residue from RTFO or TFO Oven Test/Original Viscosity.

There was no significant development in 1990s, but rejuvenators became a hot research topic in late 2000s. Since then, many new rejuvenators have been developed and commercialized. Different from the traditional petroleum-based rejuvenators, these new rejuvenators (such as Hydrogreen, Evoflex, Sylvaroad, SonneWarmix, Delta-S, Revive, Anova, or recycled vegetable oils) are derived mainly from bio-products. Characterization of these bio-rejuvenators is very limited. One of the concerns is suitability of using ASTM D4552 to classify bio-rejuvenators. To address the concern and to identify a performance indicator for the new bio-rejuvenators, this study selected typical bio-rejuvenators and preformed a series of laboratory testing, which is described in the following sections.

BIO-REJUVENATORS SELECTION AND LABORATORY CHARACTERIZATION

Bio-Rejuvenator Selection

Oxidation makes asphalt binders stiffer during production and construction, and in the following service years through aging. During the oxidative aging process, an irreversible chemical reaction with oxygen changes the molecular structure of the binder, which also leads to changes in rheological properties of asphalt binders (such as a much lower phase angle). Correspondingly, asphalt binder is stiffened and its ability to flow is reduced. To restore the flow ability and the phase angle of aged asphalt binder, various bio-rejuvenators have been developed in recent years. Different from traditional petroleum-based rejuvenators, the bio-rejuvenators have a common component: fatty acid (or lipid). A fatty acid is a carboxylic acid with an aliphatic chain with aliphatic tails of 13 to 21 carbons. Fatty acids without carbon-carbon double bonds are known as saturated; those with double bonds called as unsaturated. Unsaturated fatty acids are further categorized as monounsaturated (having one double bonds) and polyunsaturated (having more than one double bonds). As shown later, the amount of fatty acid directly impacts the performance of the bio-rejuvenators.

This study selected a total of seven typical bio-rejuvenators commercially available on the market and a recycled vegetable oil. These seven bio-rejuvenators and the recycled vegetable oil are labeled in a *random* order as BR1, BR2, BR3, BR4, BR5, BR6, BR7, and BR8.

Laboratory Tests

Three major tests were conducted on these eight bio-rejuvenators: gas chromatograph/mass spectrometry (GCMS) tests for analyzing fatty acid, viscosity tests with dynamic shear rheometer (DSR), and short term rolling thin film oven (RTFO) aging tests. Detailed test methods are described below.

GCMS for Fatty Acid

The fatty acid component was analyzed by GCMS. Researchers incubated 1 mL of sample with 20 mL of 100 percent methanol in a water bath at 65°C for 30 min. Researchers then added 1 mL of 10N KOH and mixed vigorously for about 1 min. After 2 hours incubation at 65°C, the sample was removed from water bath to cool down to room temperature with tap water. Researchers carefully added 1 mL H_2SO_4 to each sample, and the sample was incubated at 65°C in a water bath for another 2 hours. The sample was removed from the water bath, cooled down with tap water, and doped with 8 mL hexane. The mix was stirred for 5 minutes and then separated into layers using a centrifuge at 3000 rpm for 5 min. The top layer (i.e., hexane) was transferred into a new tube. The hexane extraction step was then repeated one more time. The hexane was evaporated under nitrogen gas and then 1 mL of hexane was added to re-dissolve the fatty acid methyl ester. The fatty acid composition was then analyzed by GCMS (Shimadzu Scientific Instruments, Inc.) with a Shimadzu SH-Rxi-5Sil column (30 m × 250 µm × 0.25 µm). The temperature of the injection port was set at 280°C, and the temperature of the MS transfer line was set at 100°C. The gas chromatograph oven temperature was programmed as follows: initial temperature 40°C for 0.5 min, 40–110°C at 5°C/min, and 110–300 °C at 20°C/min, requiring a total run time of 24 min. The raw chromatography and mass spectrum data were processed and analyzed using the program's chemical database.

DSR for Dynamic Viscosity

Most bio-rejuvenators are liquid in nature. Thus viscosity is a very important property of bio-rejuvenators to quantify their flow characteristic. The higher is the viscosity, the more resistant the bio-rejuvenator is to flow. During field plant production of asphalt mixes, a high-power pump is needed for bio-rejuvenators with high viscosity. Traditionally, viscosity is measured following either ASTM D2170*: Standard Test Method for Kinematic Viscosity of Asphalts (Bitumens)* or D2171: *Standard Test Method for Viscosity of Asphalts by Vacuum Capillary Viscometer*. Since the implementation of asphalt binder performance grade (PG) specification, DSR has become the most widely used instrument for characterizing asphalt binders. Thus, the authors explored the use of DSR with a 50 mm diameter parallel plate (see Figure 2) to measure the dynamic viscosity of the eight bio-rejuvenators. The gap between the parallel plates was set at 0.5 mm. For each bio-rejuvenator, the dynamic viscosity at steady state was measured at three testing temperatures: 10, 25, and 60°C. Also, each bio-rejuvenator was tested before and after the short-term oven aging.

Figure 2. Dynamic Viscosity Measurement with 50 mm Plate.

RTFO for Short Term Aging

The RTFO test was conducted following AASHTO T240*: Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)*. The mass loss of each bio-rejuvenator was determined after the RTFO test. Although long-term aging resistance is very important for pavement materials, it is more meaningful to evaluate the long-term aging properties of the blends of bio-rejuvenators and asphalt binders rather than bio-rejuvenator itself, since they are blended together during the plant production of asphalt mixes.

Laboratory Test Results and Analyses

GCMS Test Results

Figure 3 shows compositions of each bio-rejuvenators in terms of fatty acids (saturated, monounsaturated, and polyunsaturated) and non-fatty acids. The dominant saturated, monounsaturated, and polyunsaturated fatty acids in the eight bio-rejuvenators are palmitic acid, oleic acid, and linoleic acid, respectively. These rejuvenators have different compositions. However, some of them have a similar amount of components and can be further categorized as four groups with different characteristics including:

- BR1 and BR5: The characteristics of this group include 1) more than 40 percent monounsaturated and polyunsaturated fatty acids, 2) both fatty acid contents being similar or equal, 3) less than 10 percent saturated fatty acid, and 4) very low non-fatty acid (less than 3 percent).
- BR2, BR3, and BR4: The characteristics of this group are 1) more than 45 percent polyunsaturated fatty acid, 2) 30–35 percent monounsaturated fatty acid, 3) 14–22 percent saturated fatty acid, and 4) very low non-fatty acid (less than 2 percent).
- BR6 and BR8: These two bio-rejuvenators are very similar in terms of saturated, monounsaturated, and polyunsaturated fatty acid and non-fatty acid contents. Compared to Groups A and B, this group has higher saturated fatty acid and non-fatty acid contents.
- BR7: This bio-rejuvenator is very different from all others and has the highest (26 percent) non-fatty acid, the lowest (23 percent) monounsaturated fatty acid, the lowest (27 percent) polyunsaturated fatty acid, and the highest (24 percent) saturated fatty acid.

As shown later, the effectiveness of these bio-rejuvenators in changing asphalt binder PG is highly related to the GCMS test results: saturated, monounsaturated, polyunsaturated fatty acid, and non-fatty acid contents.

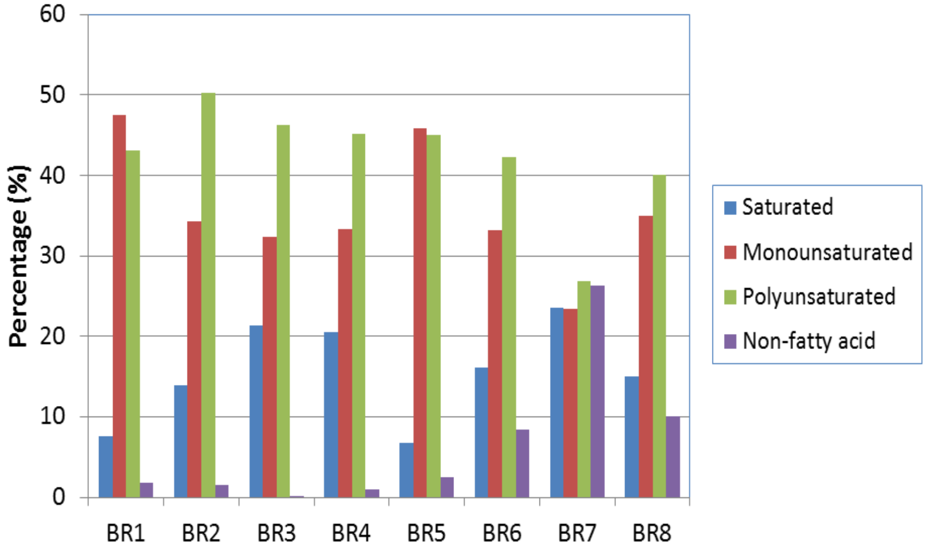


Figure 3. Fatty Acid and Non-Fatty Acid Contents.

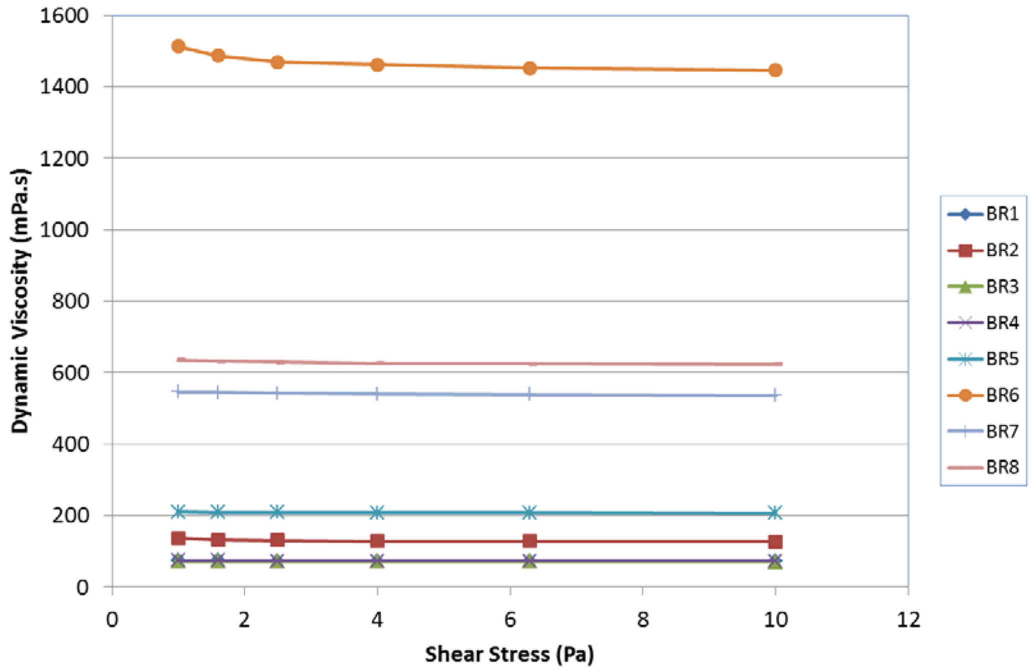
Dynamic Viscosity Test Results

Dynamic (shear) viscosity of a fluid describes its resistance to shear flow, which can be measured using DSR. The authors first evaluated whether these eight bio-rejuvenators behave like Newtonian fluid. Dynamic viscosities of each bio-rejuvenator under different shear stresses at three temperatures (10, 25, and 60°C) were measured. Figure 4 shows the test results at both 10 and 60°C. Overall, the eight bio-rejuvenators can be described as Newtonian fluid at the temperature above 10°C. Figure 5 depicts the dynamic viscosity of each bio-rejuvenator under the shear stress of 10 Pa at all three temperatures. Figure 4 and Figure 5 clearly indicate that these bio-rejuvenators have different dynamic viscosities. BR6 has the highest dynamic viscosity; BR1 and BR3 have the smallest dynamic viscosity. Based on dynamic viscosity, they can be ranked (or categorized) from the highest to the lowest as following:

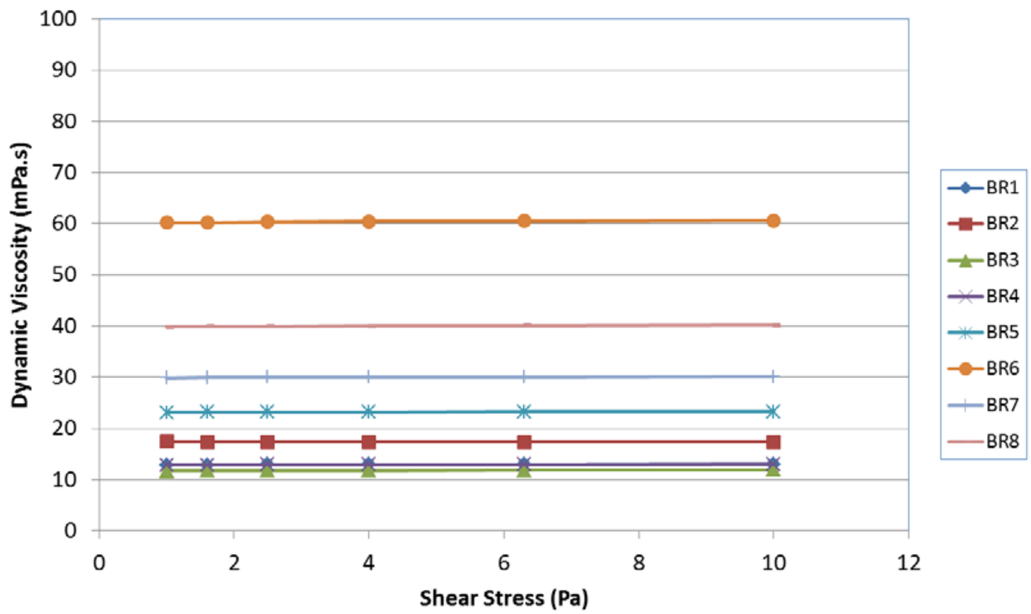
$$\mathrm{BR6} > (\mathrm{BR8} \approx \mathrm{BR7}) > (\mathrm{BR5} = \mathrm{BR4}) > \mathrm{BR2} > (\mathrm{BR1} = \mathrm{BR3})$$

It is apparent that the dynamic viscosity based ranking (or categorizing) is different from those based on the fatty acid content.

An alternative way for characterizing viscosity of a fluid is kinematic viscosity that can be measured following ASTM D2170. Actually, ASTM D4552-10 recycling agent classification (see Table 1) is based mainly on the kinematic viscosity measured at 60°C. Note that the kinematic viscosity is the ratio of the dynamic viscosity to the density of the bio-rejuvenator. The density of most bio-rejuvenators ranges from 0.91 to 0.95. Thus, the kinematic viscosity of each bio-rejuvenator can be estimated. All eight bio-rejuvenators, except BR6, have their kinematic viscosities less than 50 mm^2/s. Therefore, they cannot be classified based on current viscosity-based specification (see Table 1). Thus, the development of a new specification is necessary.



(a) 10°C



(b) 60°C

Figure 4. Dynamic Viscosities of Each Bio-Rejuvenator under Different Shear Stress: (a) at 10°C and (b) at 60°C.

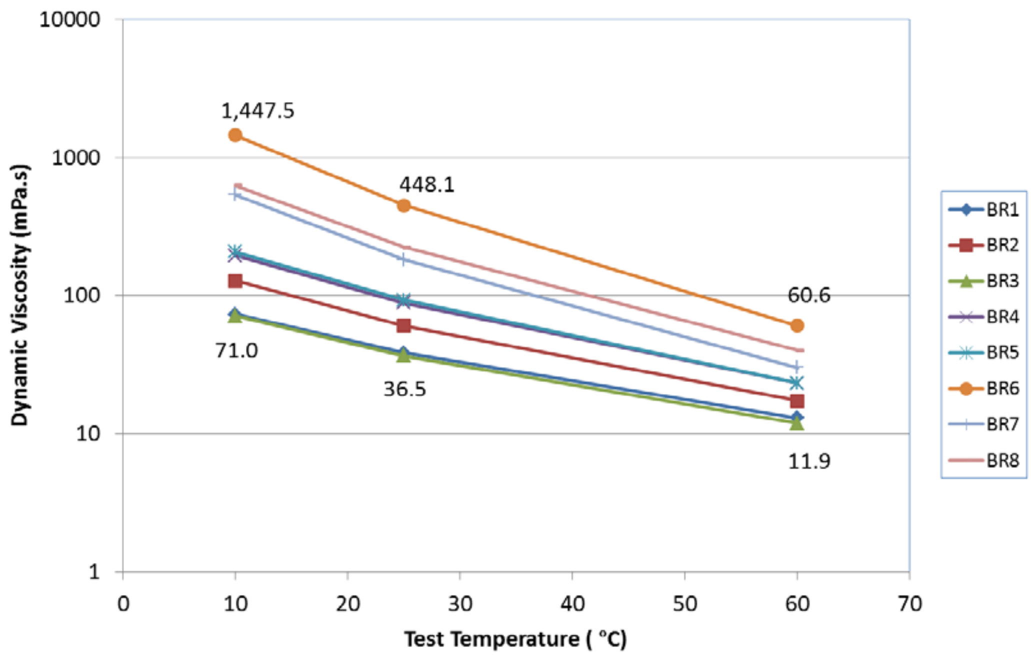


Figure 5. Dynamic Viscosities of Bio-Rejuvenators at 10 Pa and 10, 25, and 60°C.

RTFO Aging Test Results and Its Impact on Dynamic Viscosity

One of the concerns with bio-rejuvenators is how they change during the plant production. Thus, the dynamic viscosities of the RTFO aged bio-rejuvenators were measured, and the results are presented in Figure 6. Comparing with Figure 5, the ratios of dynamic viscosity of RTFO aged bio-rejuvenators to those of the original ones are all less than 2. The maximum allowed viscosity ratio is 3 in the ASTM D4552 specification. Thus, the bio-rejuvenators are better than the traditional petroleum-based rejuvenators in terms of viscosity change.

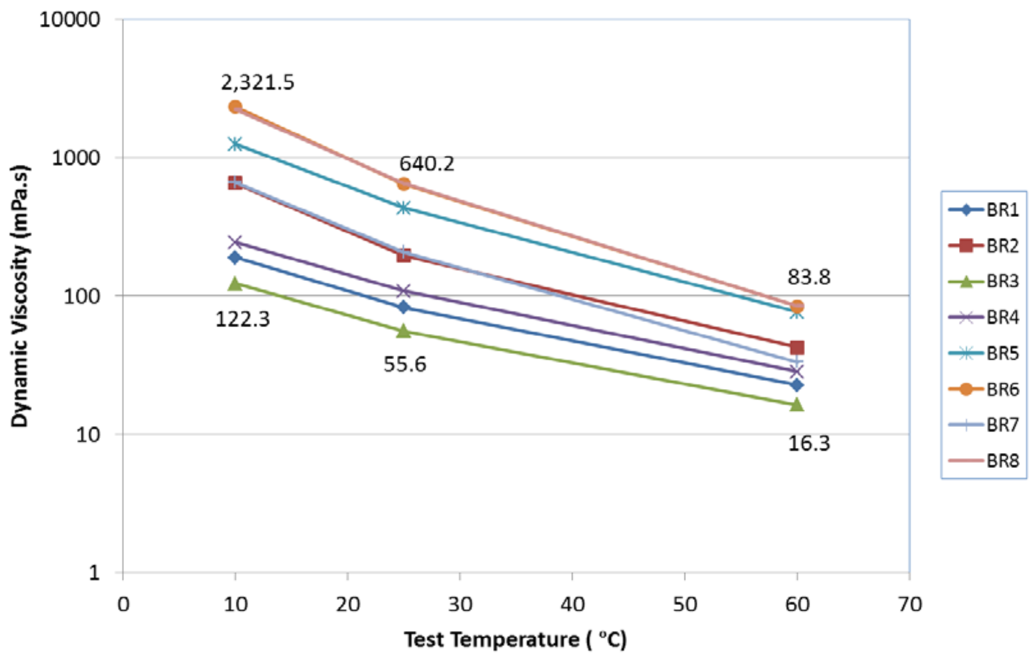


Figure 6. Dynamic Viscosity of the Bio-Rejuvenators after RTFO at 10 Pa.

Another parameter from the RTFO test is the mass loss, which shows the loss of volatiles (or smaller molecules) from the bio-rejuvenators. The smaller the mass loss is, the more thermal stable the bio-rejuvenator is. The standard RTFO test method (AASHTO T240) for asphalt binders was followed to simulate the short-term aging of bio-rejuvenators. However, using the recommended amount of liquid bio-rejuvenator during the process of setting up and rotation caused spillage from the RTFO bottle, and consequently, affected the calculated mass. After several trials, the authors chose 20 grams of bio-rejuvenators for RTFO test. The mass loss for each bio-rejuvenator was calculated, and the results are listed in Table 2. Some bio-rejuvenators (BR3, BR6, and BR8) have high volatile components. This is a potential problem during field plant production. Also, for the liquid type of rejuvenators, the authors recommended using 20 grams of liquid for RTFO test.

Table 2. Mass Loss of RTFO Test.

Name	**BR1**	**BR2**	**BR3**	**BR4**	**BR5**	**BR6**	**BR7**	**BR8**
Mass loss (%)	0.2	1.5	7.6	4.8	2.7	10.1	1.2	6.9

In summary, this section described the chemical and rheological properties of the eight bio-rejuvenators and their aging characteristics. All described acceptable short-term aging properties in dynamic viscosity change before and after the RTFO testing. Five had acceptable mass loss. Moreover, the bio-rejuvenators can be categorized based either on their chemical fatty acid contents or dynamic viscosity. How these bio-rejuvenators impact on binder blends and mixes properties is discussed next.

Impact of Bio-Rejuvenators on Binder Blends Properties

A virgin PG64-22 binder was blended with the eight bio-rejuvenators at different dosage rates, and then all the blends were graded following the Superpave PG system. The effectiveness of each bio-rejuvenator in changing PG grade is discussed below.

Materials and Sample Preparation

A PG64-22 binder was blended with the eight bio-rejuvenators (referred to as BR1 to BR8). For each bio-rejuvenator, three different dosages (2, 5, and 10 percent) were used. Altogether, 25 samples including 1 base binder and 24 binder/bio-rejuvenator blends were used for this study (i.e., 8 bio-rejuvenators × 3 dosages/bio-rejuvenator = 24 blends). The blends were prepared by heating the virgin binder at its mixing temperature of 149°C and then doping it with each bio-rejuvenator at different dosage rates. The resultant blends were thoroughly stirred for at least five minutes and then reheated. This process was repeated for three times for homogeneity. The blended samples were subjected to short-term aging in a RTFO at 163°C for 85 minutes. The short-term aged samples were then subjected to long-term aging in a pressure aging vessel (PAV) at 100°C and 2.2 kPa for 20 hours.

Laboratory PG Tests

Researchers conducted low and high temperature PG tests on all 25 blends. The high temperature PG of each blend was established by conducting DSR on the unaged and the short-term aged samples following the AASHTO T315-12 and AASHTO M320-10 standards. Similarly, researchers determined the critical low temperature PG of each of these blends by conducting the bending beam rheometer (BBR) tests on 20 hr. PAV-aged binder samples following the AASHTO T313-12 and AASHTO M320-10 standards.

Laboratory PG Test Results

Figure 7 displays the high temperature PG grade of each blend. The low temperature PG for each blend after 20 hr. PAV aging using both stiffness- (S=300 MPa) and m- (m=0.3) based criteria were calculated and the results are presented in Figure 8 and Figure 9, respectively. Both low temperature grades were analyzed because the low temperature PG grades of asphalt binder could be controlled by either stiffness (*S*) or relaxation (*m*) value. In the case of *S*-controlled binders, the rheological parameter like dynamic viscosity may be a good performance indicator for rejuvenators.

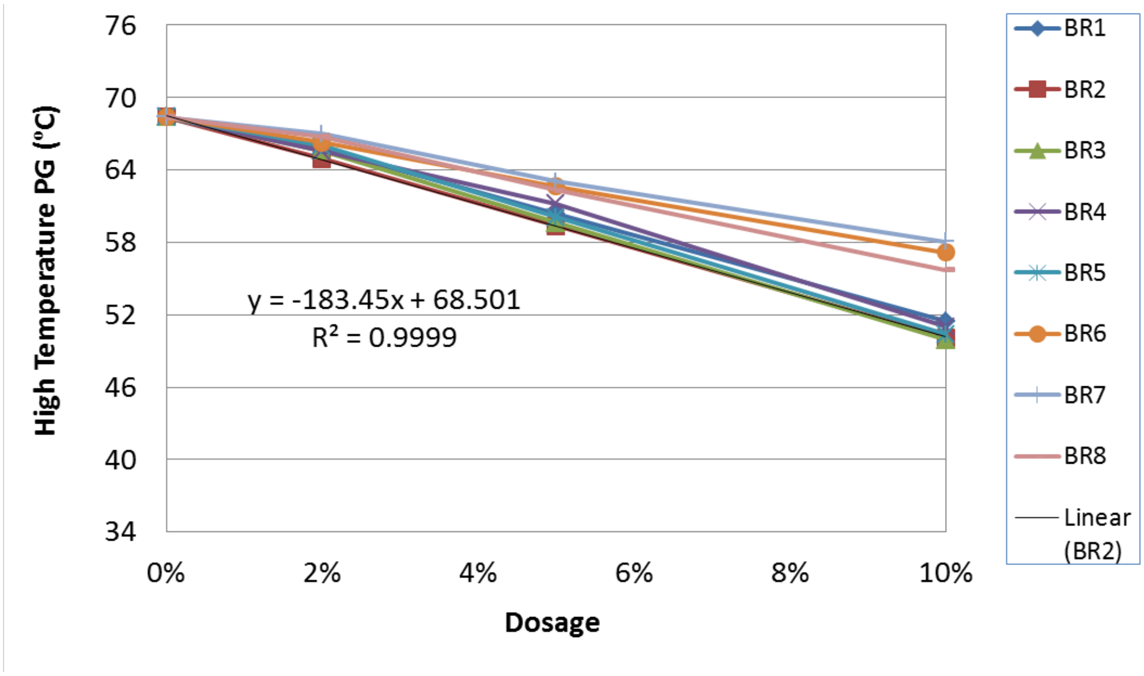


Figure 7. High Temperature PG for Each Virgin Binder/Bio-Rejuvenator Blend.

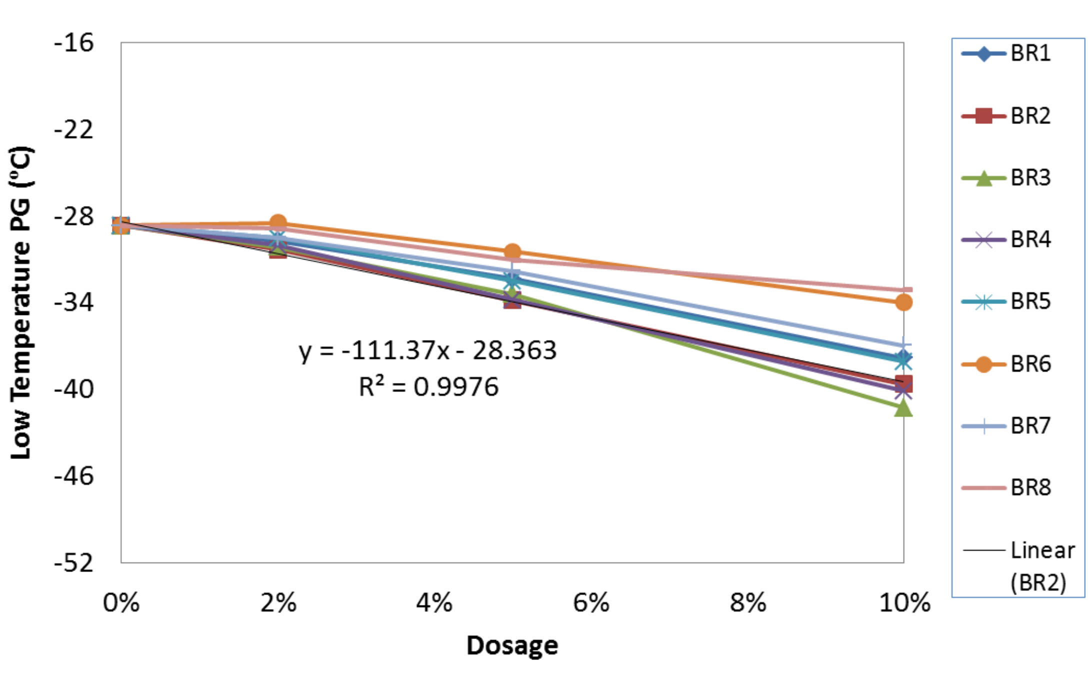


Figure 8. S-based Low Temperature PG for Each Binder/Bio-Rejuvenator Blend.

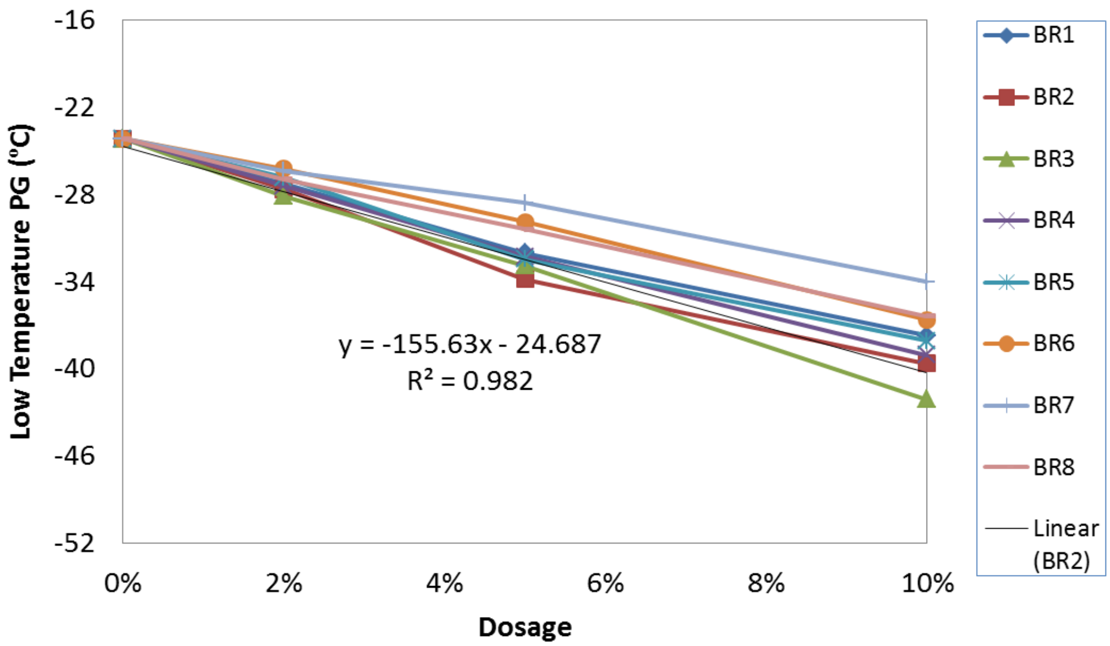


Figure 9. m-based Low Temperature PG for Each Binder/Bio-Rejuvenator Blend.

Discussion: Effectiveness of Bio-Rejuvenators on Changing Binder Properties

As shown in Figure 7 to Figure 9, the addition of bio-rejuvenators reduces the high and the low temperature PGs. Different bio-rejuvenators perform differently, and some (such as BR2, BR3) are more effective than others (such as BR6, BR7, and BR8). In order to quantify effectiveness of each bio-rejuvenator, the temperature drop for adding 1 percent bio-rejuvenator was determined using functions that represent corresponding correlations for each bio-rejuvenator in terms high temperature PG, and S-based and m-based low temperature PGs. For example, correlations were determined for the BR2 dosage with these three measures as shown in Figure 7 to Figure 9, respectively. Specifically for adding every 1 percent BR2, the corresponding temperature drop for high, S-based and m-based low PG temperature is −1.83, −1.11, and −1.56, respectively. Similarly, the temperature drops for all other bio-rejuvenators were calculated. Table 3 lists all the temperature drops per dosage rate of each bio-rejuvenator. The more negative the temperature drop per dosage rate, the more effective the bio-rejuvenator.

Table 3. Temperature Drop per Dosage Rate of Each Bio-Rejuvenator.

Name	BR1	BR2	BR3	BR4	BR5	BR6	BR7	BR8
High PG grade	−1.72	−1.83	−1.88	−1.75	−1.84	−1.13	−1.06	−1.30
S-based low PG grade	−0.94	−1.11	−1.28	−1.18	−0.97	−0.57	−0.85	−0.47
m-based low PG grade	−1.36	−1.56	-1.78	−1.49	−1.41	−1.26	−0.97	−1.21

Identification of a Preliminary Performance Indicator for Bio-Rejuvenators

There is lack of a performance indicator for bio-rejuvenators in the literature. This study used the temperature drop per dosage rate listed in Table 3 to identify a preliminary performance indicator. Two potential performance indicators are evaluated below.

Dynamic Viscosity vs. Temperature Drops per Dosage Rate

As presented in Figure 5 and Figure 6, the dynamic viscosity is a function of temperature. The higher the temperature, the lower the dynamic viscosity. However, there is no cross over among the dynamic viscosity vs. temperature lines. Thus, it is reasonable to choose the dynamic viscosity at only one temperature for the analysis. This study chose the temperature of 60°C, because the temperature of 60°C is used in ASTM D4552 to classify recycling agents. Figure 10 to Figure 12 show the correlations of the dynamic viscosity at 60°C with the temperature drops of high, *S*-based low, and *m*-based low PG grade of all eight rejuvenators, separately. The dynamic viscosity has a fair to good correlation with both high PG temperature drop/dosage rate and the *S*-based low PG temperature drop/dosage rate, but it correlates very poorly with the *m*-based low PG temperature drop/dosage rate. This is reasonable, since the dynamic viscosity itself is a type of stiffness parameter, and both the high PG temperature drop/dosage rate and the *S*-based low PG temperature drop/dosage rate are controlled primarily by stiffness. But the *m*-based low PG temperature drop/dosage rate is controlled by the relaxation property rather than stiffness. Considering the fact that the low PG grades of most recycled asphalt binders are controlled by the relaxation property (*m* value), the dynamic viscosity is not a good performance parameter for bio-rejuvenators, since it has very poor correlation with the *m*-based low PG temperature drop/dosage rate.

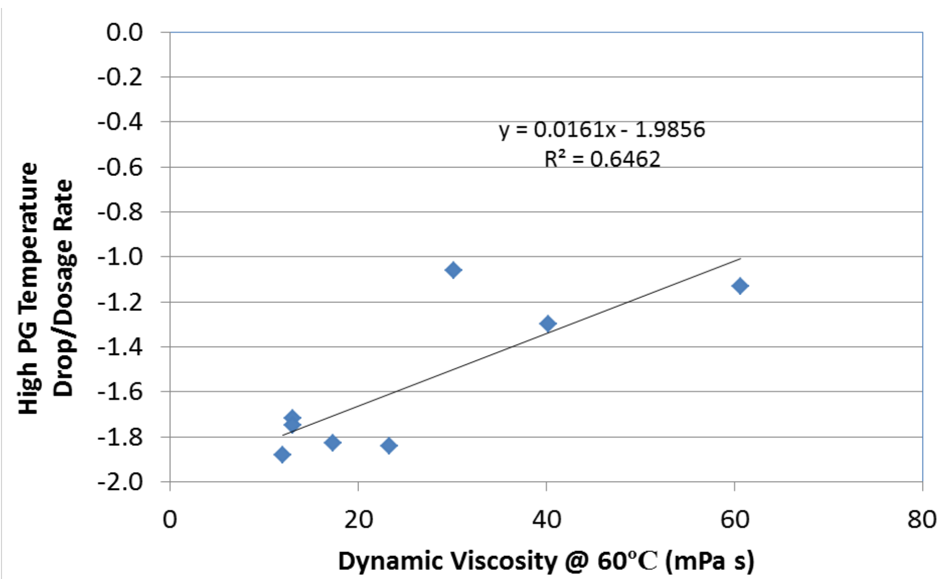


Figure 10. Correlation of Dynamic Viscosity to High PG Temperature Drop.

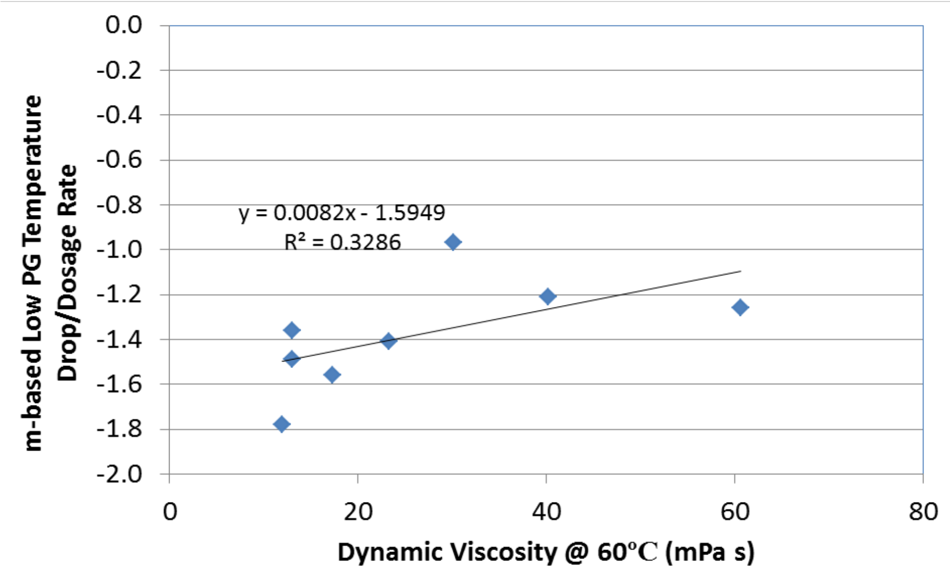


Figure 11. Correlation of Dynamic Viscosity to *m*-based Low PG Temperature Drop.

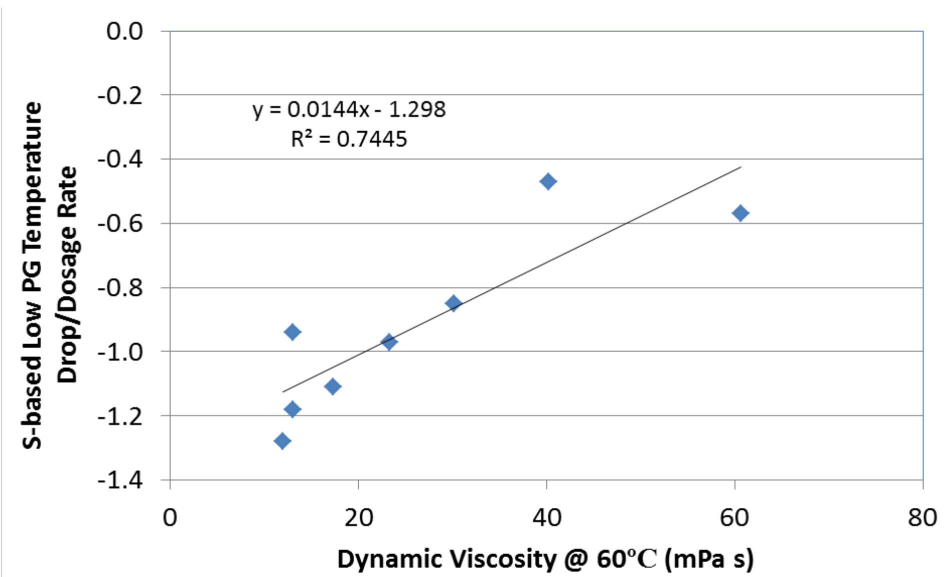


Figure 12. Correlation of Dynamic Viscosity to *S*-based Low PG Temperature Drop.

Fatty Acid vs. Temperature Drops per Dosage Rate

Researchers examined the correlation of temperature drop/dosage rate to single fatty acid content (saturated, monounsaturated, and polyunsaturated). No strong correlations were found. The potential correlations between the temperature drop/dosage rate to the combined fatty acid contents (such as saturated + monounsaturated, saturated + polyunsaturated, monounsaturated+ polyunsaturated, saturated + monounsaturated + polyunsaturated) were also analyzed. Figure 13 to Figure 15 present these results. The total fatty acid content (*saturated + monounsaturated + polyunsaturated*) had the best correlations with both high PG temperature drop and the *m*-based low PG temperature drop, but it had a very poor correlation with the *S*-based low PG temperature drops. The poor correlation with the *S*-based low PG temperature drops was caused by one bio-rejuvenator: BR7. This difference in behavior can be either just an outlier or due to some phenomenon that needs to be investigated further in future studies.

Comparing with the dynamic viscosity results shown in Figure 10 to Figure 12, the total fatty acid content was not a perfect performance indicator, because its correlation with the *S*-based low PG grade drops significantly (although it is caused by BR7 only). However, the total fatty acid content is a preferred performance indicator, because the low PG grades of recycled binders are controlled by the relaxation property (*m* value), which is what bio-rejuvenators try to improve. Therefore, the total fatty acid content measured by GCMS was chosen as the performance indicator for bio-rejuvenators. In the next section, the authors further verify the total fatty acid content as a good performance indicator for bio-rejuvenators by mixing the fatty acid compounds with the same virgin binder used and blending the bio-rejuvenators (BR2, BR5, and BR8) with a recycled binder.

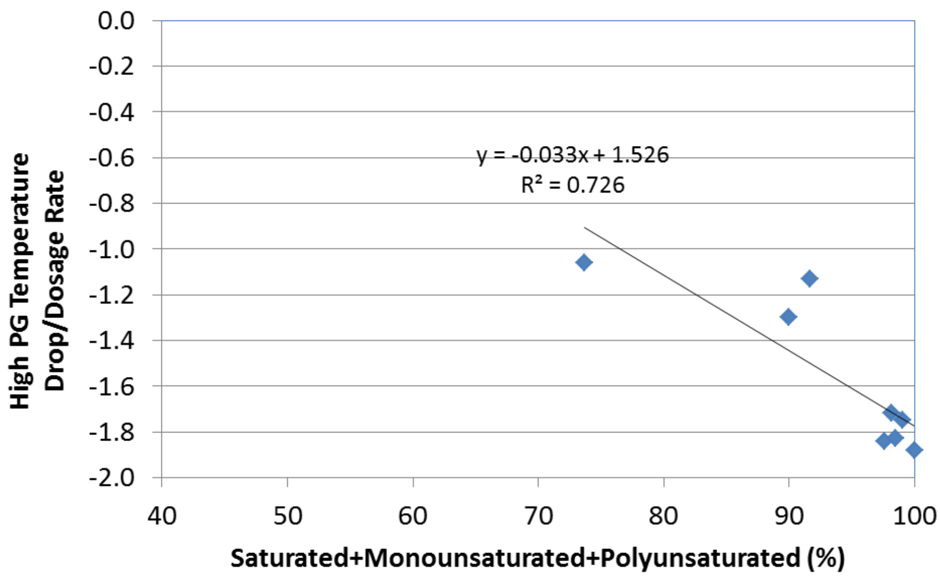


Figure 13. Correlation between Total Fatty Acid Content (Saturated + Monounsaturated + Polyunsaturated) and High PG Temperature Drop.

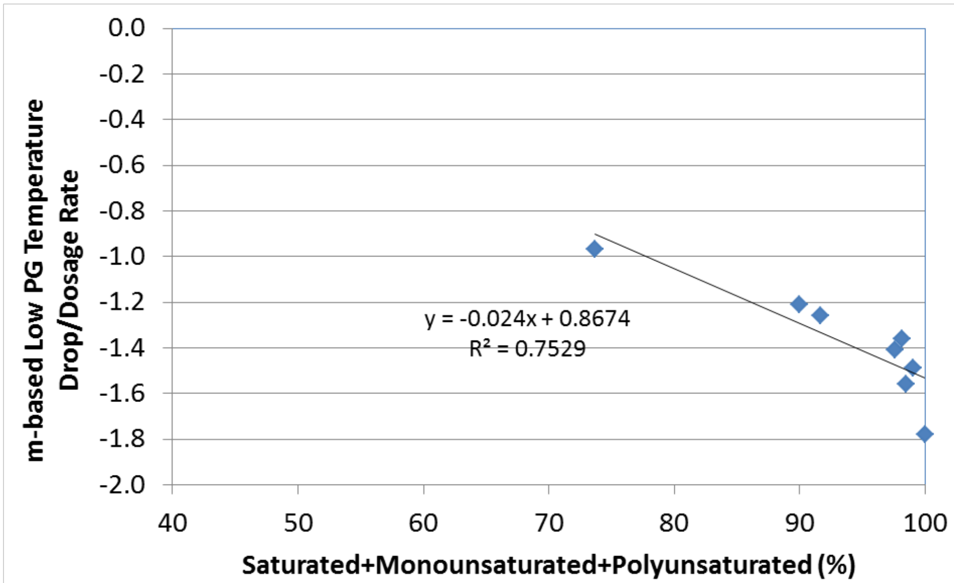


Figure 14. Correlation between Total Fatty Acid Content (Saturated + Monounsaturated + Polyunsaturated) and m-based Low PG Temperature Drop.

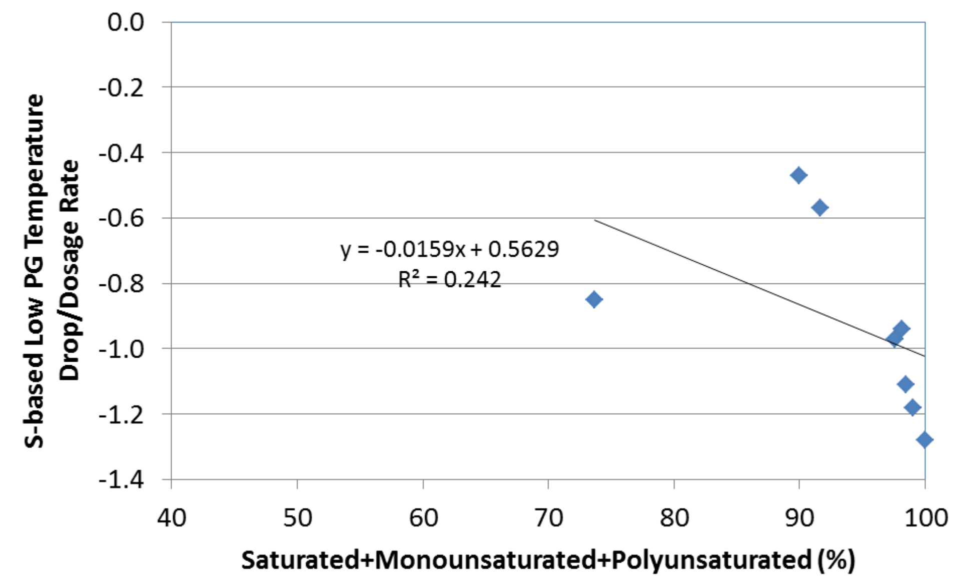


Figure 15. Correlation between Total Fatty Acid Content (Saturated + Monounsaturated + Polyunsaturated) and *S*-based Low PG Temperature Drop.

LABORATORY VERIFICATION OF THE TOTAL FATTY ACID CONTENT AS A PERFORMANCE INDICATOR

As mentioned previously, the dominant saturated, monounsaturated, and polyunsaturated fatty acids in the eight bio-rejuvenators are palmitic acid, oleic acid, and linoleic acid, respectively. To verify the identified performance indicator (the total fatty acid content rather than single fatty acid), researchers blended the pure fatty acid compounds with the same virgin PG64-22 binder.

For blending, the authors followed the procedure described previously; the only difference was the use of fatty acids or their compounds instead of the bio-rejuvenators. Additionally, three bio-rejuvenators (BR2, BR5, and BR8) were mixed with the same virgin PG64-22 binder and recycled asphalt binders extracted from RAP and RAS for further verification.

Verification Using Blends of Virgin Binders and Fatty Acid Compounds

Three fatty acids—palmitic acid (PA), oleic acid (OA), and linoleic acid (LA)—were purchased for this study; all three acids contained 99 percent pure compounds. To begin, these compounds were mixed to form the combined fatty acid compounds following the proportion ratios listed in Table 4. Note that QA and LA were liquid while PA was crystalline in state at room temperature. Therefore, PA was preheated at its melting point (i.e., 62.9°C) for a few minutes before blending. The four combined fatty acid compounds are 100 percent fatty acids, but each had different compositions. The four combined compounds were further mixed with the same PG64-22 binder used previously. For each combined fatty acid compound, three dosage rates (0, 5, and 10 percent) were used. The same sample preparation process including RTFO and PAV aging described previously was also used. The original and RTFO aged blends and the 20 hr. PAV aged blends were tested using DSR and BBR to determine both the high and low temperature PG grades, respectively. The DSR and BBR test results are displayed in Figure 16 and Figure 17, respectively.

If the identified total fatty acid content is the right performance indicator, all blends with the four combined compounds should have the same (or very similar) high and low PG grades. Figure 16 shows that the high temperature PG grades of all four combined fatty acid compounds are very similar (if not the same). In terms of the low temperature PG grades (Figure 17), they are exactly the same except for FA1 at a 10 percent dosage rate. This finding is not unexpected, because saturated fatty acid is a type of wax. Lower amount of wax in asphalt binder are not harmful to binder low temperature property. In the case of FA1, adding more than 5 percent saturated fatty acid (or wax) into the binder did not improve its low temperature property due to wax crystallization at lower temperatures. For FA2 at the 10 percent dosage rate or the total of saturated fatty acid was 3.64 percent. Therefore, researchers concluded that as long as the saturated fatty acid content is less than 5 percent in the asphalt binder, the use of total fatty acid content as a good performance indicator is valid. This limit may depend on binder source and grade though. Future studies are needed to confirm if this is the case. Meanwhile, a preliminary upper limit for the saturated fatty acid in the asphalt binder is 5 percent.

Table 4. Fatty Acid Compound Mixing Table.

Name	PA (%)	OA (%)	LA (%)	Total Fatty Acid (%)
FA1	100	0	0	100
FA2	36.4	63.6	0	100
FA3	17.6	36.2	46.2	100
FA4	7.2	46.4	46.4	100

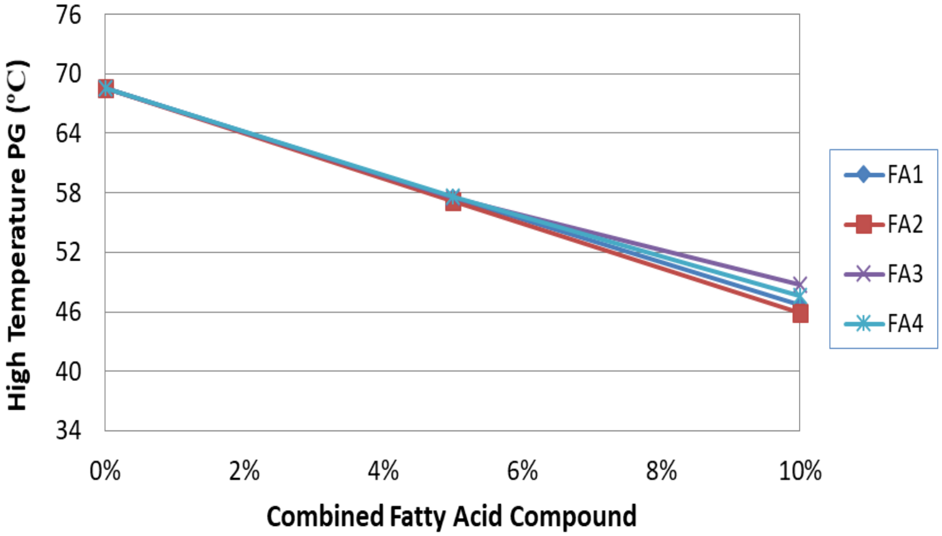


Figure 16. Impact of Combined Fatty Acid Compound on High Temperature PG.

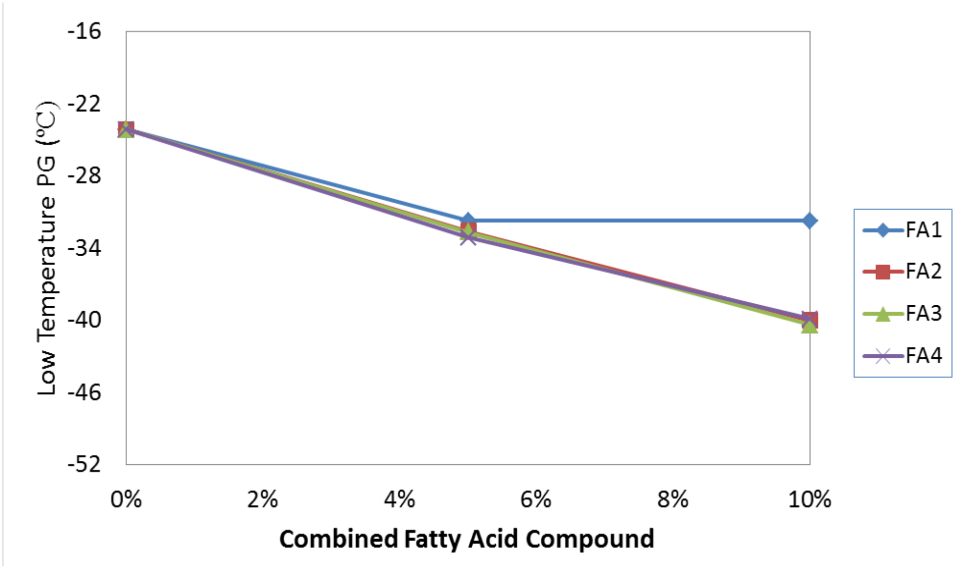


Figure 17. Impact of Combined Fatty Acid Compound on Low Temperature PG.

Verification Using Blends of Virgin Binders, Recycled Binders and Bio-rejuvenators

A recycled binder extracted from a RAP and RAS blend was used for this verification. The true high temperature grade of the recycled binder was PG98.7. This recycled binder was then mixed with the same virgin PG64-22 binder used previously in a ratio of 30 percent to 70 percent by the total weight of the blend. The measured true grade for the 30 percent recycled binder/70 percent virgin binder blend was PG76.8-21.1. This recycled/virgin binder blend was then mixed with three bio-rejuvenators (BR2, BR5, and BR8) in three dosage levels: 0, 5, and 10 percent, resulting in BRR2, BRR5, and BRR8 blends. As shown in Figure 3, BR2 and BR5 have the same amount of total fatty acid but with different amounts of compositions. Compared to BR2 and BR5, the total fatty acid content in BR8 is less. Thus, it is anticipated that BR2 and BR5 have the same (or very similar) effect on rejuvenating the recycled binder blend, and they both are better than BR8.

The same sample preparation process including RTFO and PAV aging described previously was used here. Furthermore, to verify whether or not the total amount of fatty acid is valid for the low temperature PG after long-long term aging, each blend was aged in PAV for 40 hrs. The DSR and BBR tests were conducted to determine the high and low temperature PG grade of each sample. Figure 18 displays the DSR test results, while Figure 19 and Figure 20 display the BBR data after 20 hr. and 40 hr. PAV aging, respectively. The expected results are observed in Figure 18 to Figure 20. Thus, the total fatty acid content as a performance indicator is verified again, even after 40 hr. PAV aging. The total amount of saturated fatty acid in each binder blend was less than 5 percent even though 10 percent bio-rejuvenators were mixed with the recycled/virgin binder blend.

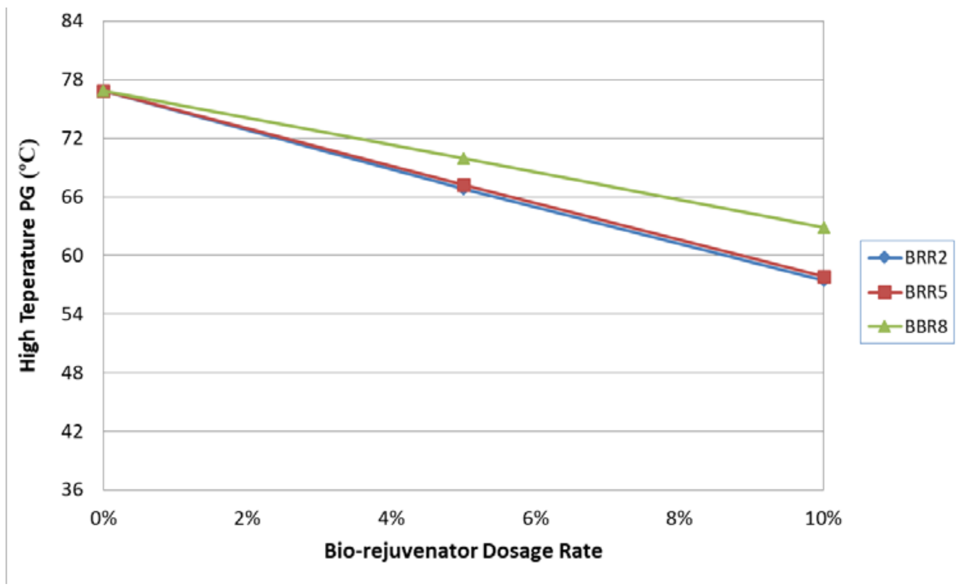


Figure 18. Impact of Bio-Rejuvenators on High Temperature PG Grade.

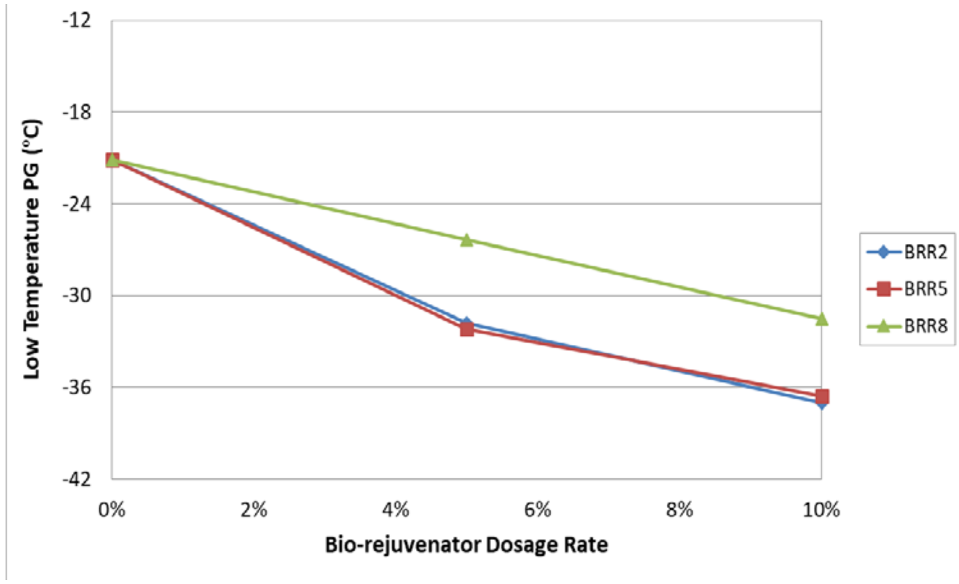


Figure 19. Impact of Bio-Rejuvenators on Low Temperature PG Grade after 20 hr. PAV.

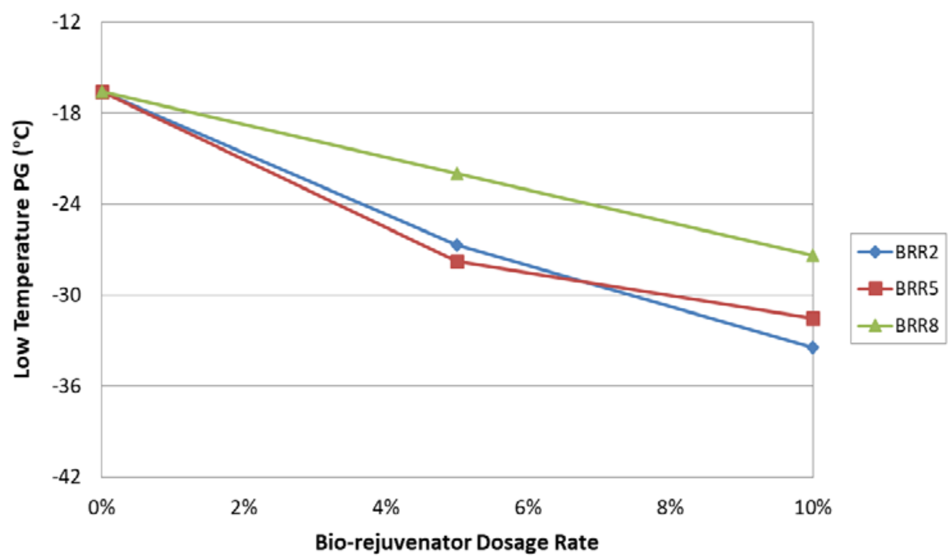


Figure 20. Impact of Bio-Rejuvenators on Low Temperature PG Grade after 40 hr. PAV.

In summary, this section verified the total amount of fatty acids as a performance indicator for bio-rejuvenator through mixing and testing the blends of virgin binder/different fatty acid compounds and the blends of recycled binder/virgin binder/bio-rejuvenators.

SUMMARY AND CONCLUSIONS

This chapter characterized bio-rejuvenators in terms of their rheological, chemical, and aging characteristics, and discussed the effectiveness of the bio-rejuvenators in modifying asphalt binders. Based on the laboratory test results, the researchers identified and preliminarily verified a performance indicator, the total fatty acid content, for bio-rejuvenators. Based on the research results presented in this chapter, the following conclusions and recommendations are made:

- The bio-rejuvenators evaluated in this study effectively modified asphalt binder properties. But different bio-rejuvenators performed differently, and some (such as BR2, BR3) are more effective than others (such as BR6, BR7, and BR8).
- The total fatty acid content measured by GCMS is the preferred performance indicator for bio-rejuvenators because 1) the low temperature PG grade of recycled asphalt binders is controlled primarily by its relaxation property (or *m* value); and 2) the total fatty acid content has much better correlation with the *m*-based low temperature PG than the dynamic viscosity.
- The total fatty acid content as a performance indicator is verified by mixing pure fatty acid compounds (PA, OA, and LA) with a virgin PG64-22 binder. Additionally, a recycled asphalt binder was mixed with the virgin PG64-22 binder and three different bio-rejuvenators (BR2, BR5, and BR8). The DSR and BBR test results further confirmed the total fatty acid content as a performance indicator for bio-rejuvenators. Furthermore, the saturated fatty acid (or wax) content is better within 50 percent, although the higher total fatty acid content is preferred.
- It is feasible to use the DSR with 50 mm parallel plates to measure dynamic viscosity of bio-rejuvenators. Since DSR has been the main instrument to characterize asphalt binders in the last two decades, the authors recommend that the dynamic viscosity be measured with DSR.

To further validate the field performance of bio-rejuvenators, several field test projects were constructed around Texas, which is described in more details in the next chapter.

CHAPTER 3: BIO-REJUVENATORS: FIELD PERFORMANCE AND DRAFT CLASSIFICATION SYSTEM

INTRODUCTION

The laboratory test results presented in Chapter 2 clearly indicated that all the bio-rejuvenators could change and modify asphalt binder and recycled binder blends, specifically improving cracking resistance. Similar findings have been reported by other researchers as well (Tran et al. 2016, Yin et al. 2017, Epps-Martin et al. 2019). However, very limited field performance data are available to confirm those laboratory test results. This chapter presents the field performance of four field projects constructed with bio-rejuvenators and then recommends a bio-rejuvenator classification system based on the observed field performance of different bio-rejuvenators.

REJUVENATOR FIELD PERFORMANCE

Since 2014, four test projects with a total of 17 field test sections have been constructed in Texas to evaluate field performance of the above six bio-rejuvenators. Detailed information on each test project and observed field performance are described below.

SH31 Test Project: Test Sections, Plant Mix Properties, and Field Performance

The first rejuvenator test project was constructed on SH31 near Tyler, Texas, in June 2014. SH31 is a two-way divided highway with annual average daily traffic (AADT) of 9800 and 10 percent truck traffic; the estimated 20-year traffic load in 18 kips is 3.5 million equivalent single axle loads (ESALs). It was an asphalt overlay project that included a 1-inch crack attenuating mix and a 2-inch Texas dense-graded Type C surface mix. The Type C surface mix was modified to include two bio-rejuvenators: BR6 and BR8. A total of five test sections were constructed on the outside eastbound lane of SH31. The asphalt mixes used are described below; note that all these five test sections had very similar gradations:

- Control (mix) section: The original dense-graded Type C mix with PG64-22 virgin binder, 10 percent RAP, and 5 percent manufacturer waste recycled shingles (MWAS) was used as control mix. The total asphalt binder content was 4.6 percent with an asphalt binder replacement of 29.2 percent (10.8 percent from RAP and 18.4 percent from MWAS).
- Virgin mix section: The RAP and RAS were removed from the control mix to have a virgin mix and the PG64-22 binder was replaced with a PG70-22 virgin binder. The total asphalt binder content for the virgin mix section was 4.5 percent.
- BR6 section: The control mix was modified with bio-rejuvenator: BR6 (2.6 percent weight of the total asphalt binder content). The total asphalt content (virgin binder and recycled binders from RAP and MWAS, and BR6) was kept the same as 4.6 percent.
- BR8 section: The control mix was modified with bio-rejuvenator-BR8 (3.7 percent weight of total asphalt binder). The total asphalt content (virgin binder and recycled binders from RAP and MWAS, and BR8) was kept the same as 4.6 percent.

- Emulsion-based R1 section: This test section evaluated an emulsion-based rejuvenator R1. Different from bio-rejuvenator sections, rejuvenator R1 (1.3 percent weight of the total asphalt binder) was added as an extra to the control mix to improve cracking resistance of the control mix. Thus, the total asphalt binder content (virgin binder, recycled binder, and rejuvenator R1) was 4.7 percent.

Plant mixes were collected during the construction, and later reheated and conditioned in an oven at 135°C (275°F) for 2 hours and 4 hours before compacting Hamburg wheel tracking test (HWTT) and Overlay Test (OT) samples, respectively. The HWTT and OT were conducted following Tex-242-F: *Hamburg Wheel-tracking Test* and Tex-248-F: *Overlay Test*, respectively. Table 5 shows both test results. The laboratory OT results show no improvement with the use of either bio-rejuvenators or rejuvenator R1. Note that the OT cycles to failure, during the mix design stage, for control, virgin, BR6, BR8, and R1 test sections are 12, 51, 94, 96, and 42, respectively. This significant difference may be caused by different loose mix conditioning time before compacting OT samples: 2 hours at 135°C (275°F) for mix design vs. 4 hours at 135°C (275°F) for plant mix. It seems that the two more hours conditioning for loose plant mixes resulted in a significant reduction in OT cycles for these limestone mixes with rejuvenators.

Each test section was around 2000 ft long. Since opening to traffic in June 2014, several surveys have been performed on these test sections. No measurable rutting was observed on any test section. However, reflective cracking occurred on every test section after the first winter, and Figure 21 shows reflective cracking development in the first 2 years. Neither BR6 nor BR8 nor R1 was effective in rejuvenating the SH31 mix with 10 percent RAP and 5 percent MWAS. Both BR6 and BR8 performed worse than the control section.

Table 5. SH31 Plant Mixes: HWTT (at 50°C) and OT (at 25°C) Results.

Test Section	**Rut Depth after 15000 passes (mm)**	**No. of cycles to failure**
SH31-Control	3.1	7
SH31-Virgin	9.1	39
SH31-BR6	2.5	5
SH31-BR8	2.9	7
SH31-R1	4.9	4

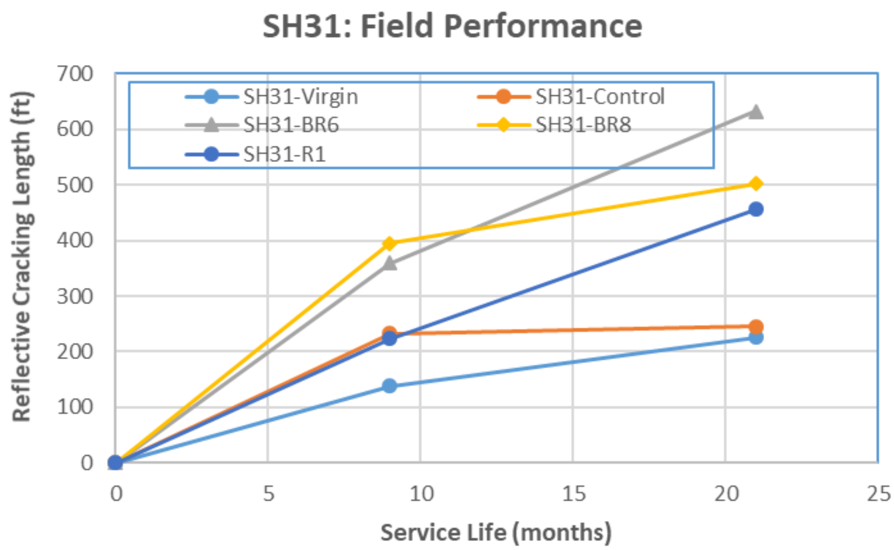


Figure 21. SH31 Field Performance: Cracking Evolution with Time.

FM468 Test Project: Test Sections, Plant Mix Properties, and Field Performance

The second rejuvenator test project was constructed on the eastbound lane of FM468 near Cotulla, Texas, in September 2015. Although FM468 is a farm to market road, it carries heavy loading with oil-gas truck traffic. The estimated 20-year traffic load in 18 kips is 11.5 million ESALs. Different from SH31 overlay project, FM468 is a major rehabilitation project. The pavement structure has a 4-inch asphalt surface layer, a 10-inch granular flexible base, a 6-inch stabilized subgrade, and a sandy subgrade. The 4-inch asphalt surface layer was modified for the field test sections. The original design called for a 4-inch dense-graded Superpave Type C surface mix with 17 percent RAP. For the test sections related to bio-rejuvenators, the RAP binder content was increased to 30 percent. A total of five test sections were constructed on FM468, but later the test section with the bio-rejuvenator BR6 was accidently removed. Therefore, only four test sections are described. Note that all these five test sections had very similar gradations:

- Virgin mix section: A virgin Superpave Type C mix with PG70-22 was designed for comparison purpose. The total asphalt binder content was 6.1 percent.
- Control (mix) section: Superpave Type C mix with PG64-22 virgin binder and 30 percent RAP (binder). The total asphalt binder content was 6.3 percent, and 30 percent the total binder was from RAP.
- BR5 section: The same control mix was modified with bio-rejuvenator: BR5 (3.0 percent weight of the total asphalt binder content). During production and quality assurance testing, the addition of bio-rejuvenator made the mix very rich and shining. To avoid future rutting problem, the total binder content (virgin binder, RAP binder, and BR5) was

reduced to 6.1 percent through cutting down the PG64-22 virgin binder content. Note that 3.0 percent BR5 amount was kept the same.
- BR3 section: The same control mix was modified with bio-rejuvenator: BR3 (2.2 percent weight of total asphalt binder). The total asphalt content (virgin binder, recycled binders from RAP, and BR3) were kept as 6.1 percent.

Plant mixes were collected during the construction, and later reheated and conditioned in an oven at 135°C (275°F) for 2 hours and 4 hours before compacting HWTT and OT samples, respectively. The HWTT and OT were conducted following Tex-242-F: *Hamburg Wheel-tracking Test* and Tex-248-F: *Overlay Test*, respectively. Table 6 lists both test results.

Each test section was around 1500 ft long. Since opening to traffic in September 2015, several surveys have been performed on these test sections. No cracking has been observed till July 2019. However, some measurable rutting was observed in the test sections. Figure 22 shows the rutting evolution with time for each test section on FM468. Both rejuvenator test sections have more rutting in the field, when compared to the control section and virgin test section. Thus, cautions on potential rutting should be exercised when selecting bio-rejuvenator dosage in the mix design stage.

Table 6. FM468 Plant Mixes: HWTT (at 50°C) and OT (at 25°C) Results.

Test Section	Rut Depth after 15000 passes (mm)	No. of cycles to failure
FM468-Virgin	15.9	669
FM468-Control	10.6	43
FM468-BR5	11.7	100
FM468-BR3	12.6	377

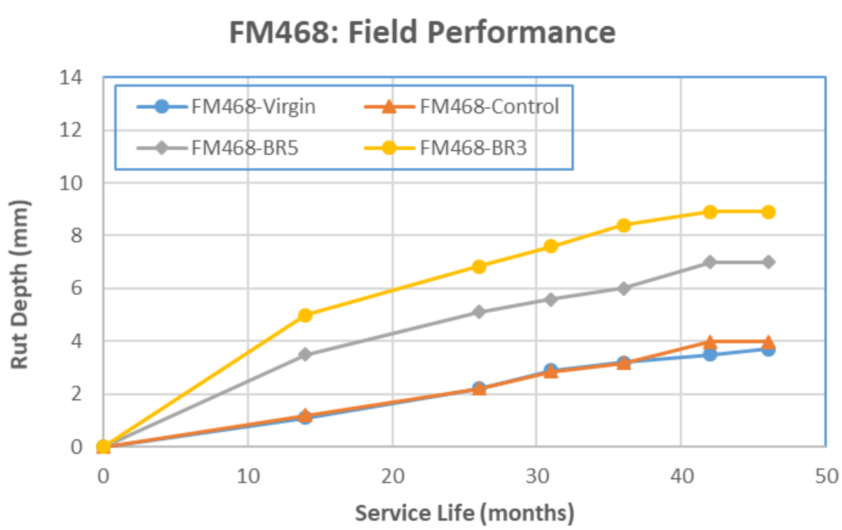


Figure 22. FM468 Field Performance: Rutting Evolution with Time.

FM1463 Test Project: Test Sections, Plant Mix Properties, and Field Performance

The third rejuvenator test project was constructed on the westbound lane of FM1463 near Katy, Texas, in September 2016. FM1463 is a two-way highway with AADT of 4129 and 10 percent truck traffic; the estimated 20-year traffic load in 18 kips is 1.83 million ESALs. FM1463 test project was a milling and inlay job. The existing asphalt layer was first milled down 1.5 inch, and then a new 1.5-inch asphalt overlay was laid. The original design for the overlay mix was a Texas dense-graded Type D mix with PG64-22 and 17 percent RAP and 3 percent tear-off RAS. This mix was then modified with three bio-rejuvenators and a total of four test sections were built on FM1463, as detailed below:

- Control (mix) section: The original dense-graded Type D mix with PG64-22 virgin binder and 17 percent RAP/3 percent RAS was used as control mix. The total asphalt binder content was 5.2 percent, and the recycled binder replacement ratio was 28.8 percent (16.3 percent from RAP and 13.5 percent from the tear-off RAS).
- BR5 section: The same control mix was modified with bio-rejuvenator: BR5 (3.5 percent weight of the total asphalt binder content). The total binder content (virgin binder, RAP binder, and BR5) was kept the same as the control mix: 5.2 percent. Note that the same BR5 used on FM468 was tested here so that the performance of BR5 could be evaluated under different environments, traffic loading, and pavement structures.
- BR7 section: The same control mix was modified with bio-rejuvenator: BR7. Different for the other two bio-rejuvenators (BR5 and BR8), BR4 was added to the control mix as an extra addition; thus, the total asphalt content for BR4 section was 5.4 percent (=5.2+5.2×0.04). The reason for the extra addition for this case was that mix cracking resistance could not be adequately improved to match those of the mixes with BR5 and BR8) if BR7 was used to replace virgin binder PG64-22.
- BR8 section: The same control mix was modified with bio-rejuvenator: BR8 (7.5 percent weight of the total asphalt binder content). The total binder content (virgin binder, RAP binder, and BR8) was kept the same as the control mix: 5.2 percent. Note that the same BR8 used on SH31 was tested here again so that the performance of BR8 could be evaluated under different climates, traffic loading, and pavement structures.

Plant mixes were collected during the construction, and later were reheated and conditioned in an oven at 135°C (275°F) for 2 hours and 4 hours before compacting HWTT and OT samples, respectively. The HWTT and OT were conducted following Tex-242-F: *Hamburg Wheel-tracking Test* and Tex-248-F: *Overlay Test*, respectively. Table 7 displays the test results.

For each test section, the monitoring length is around 1000 ft long. Since opening to traffic in September 2016, multiple surveys have been performed on these four test sections except BR7 section, because Section BR7 was removed after January 2018 due to road expansion. As of July 2019, no measurable rutting has been observed on any test section. However, some longitudinal reflective cracking was found in all test sections in last two years, as displayed in Figure 23. Similar to what was observed on SH31 test sections, all three rejuvenated test sections had more reflective cracking than the control section, although OT test results of the plant mixes indicated that the mixes with bio-rejuvenators had better cracking resistance.

Table 7. FM1463 Plant Mixes: HWTT (at 50°C) and OT (at 25°C) Results.

Test Section	Rut Depth after 15000 passes (mm)	No. of cycles to failure
FM1463-Control	4.3	29
FM1463-BR5	12.9	83
FM1463-BR7	9.4	110
FM1463-BR8	12.5	48

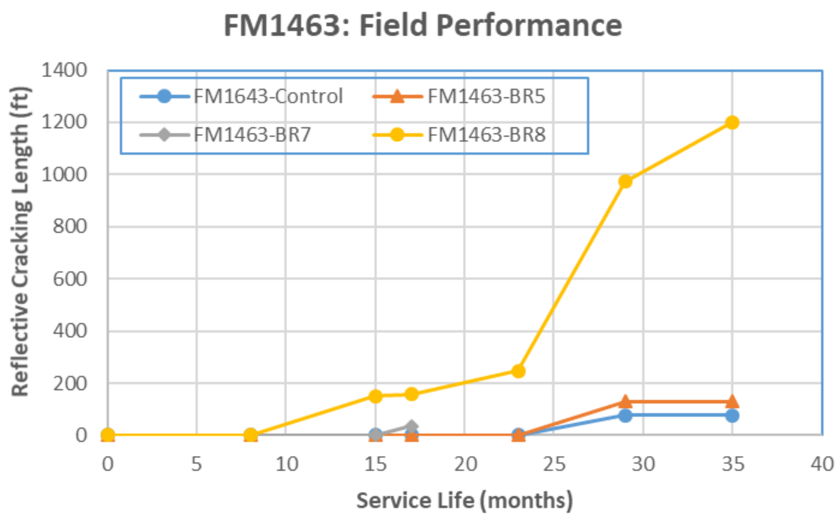


Figure 23. FM1463 Field Performance: Cracking Evolution with Time.

SH67 Test Project: Test Sections, Plant Mix Properties, and Field Performance

The SH67 test project was the last field project for evaluating performance of bio-rejuvenators. SH67 is a two-way highway with AADT of 5224 and 13.6 percent truck traffic; the estimated 20-year traffic load in 18 kips is 3.0 million ESALs. The bio-rejuvenator test sections were constructed on the westbound lane of SH67 near San Angelo, Texas, in April 2017. It was a 2-inch asphalt overlay over a cracked existing asphalt pavement. The original design for the overlay mix was a Texas dense-graded Type C mix with PG64-22 and 13 percent RAP. This mix was then modified for three test sections to evaluate field performance of two bio-rejuvenators and one R1Pro (a modified version of rejuvenator R1). Detailed information about the three test sections on SH67 is described below:

- Control (mix) section: The original dense-graded Type C mix with PG64-22 and 13 percent RAP was modified to have 30 percent RAP binder replacement through increasing RAP content. The total asphalt binder content for the control mix was 5.3 percent.
- BR3 section: The same control mix was modified with bio-rejuvenator: BR3 (3.0 percent weight of the total asphalt binder content). The total binder content (virgin binder, RAP binder, and BR3) was kept the same as the control mix: 5.3 percent. Note that the same

BR3 used on FM468 was tested here so that the performance of BR3 could be evaluated under different climates, traffic loading, and pavement structures.

- BR1 section: The same control mix was modified with bio-rejuvenator: BR1 (3.0 percent weight of the total asphalt binder content). The total binder content (virgin binder, RAP binder, and BR1) was kept the same as the control mix: 5.3 percent.
- R1Pro section: The same control mix was modified with an improved rejuvenator R1Pro: (11.0 percent weight of the total asphalt binder content). The total binder content (virgin binder, RAP binder, and R1Pro) was kept the same as the control mix: 5.3 percent.

Plant mixes were collected during the construction, and later reheated and conditioned in an oven at 135°C (275°F) for 2 hours and 4 hours before compacting HWTT and OT samples, respectively. The HWTT and OT were conducted following Tex-242-F: *Hamburg Wheel-tracking Test* and Tex-248-F: *Overlay Test*, respectively. Table 8 presents both test results.

Since opening to traffic in April 2017, multiple surveys have been performed on these three test sections. For each test section, researchers monitored a 1000 ft section. As of July 2019, neither rutting nor cracking has been observed on any test section. Thus, the effectiveness of bio-rejuvenators (BR3 and BR1) and rejuvenator R1Pro cannot be concluded on US67, although laboratory OT results indicated that both the mixes with bio-rejuvenators have better cracking resistance. Further field monitoring on these three test sections is needed.

Table 8. SH67 Plant Mixes: HWTT (at 50°C) and OT (at 25°C) Results.

Test Section	Rut Depth after 15000 passes (mm)	No. of cycles to failure
SH67-Control	5.8	51
SH67-BR5	12.7	110
SH67-BR6	12.7	72
SH67-R1Pro	12.6	149

Discussion: Rejuvenator Field Performance

Since the use of rejuvenator is mainly to address cracking problem, the impact of the bio-rejuvenators on field cracking distress is discussed here. As shown previously, cracking occurred only at two field projects: FM31 and FM1463. A total of four bio-rejuvenators: BR5, BR6, BR7, and BR8 were evaluated at these two field projects and their performance is discussed below:

- SH31 test project clearly indicated that both BR6 and BR8 performed similarly and both had more reflective cracking than the control section. Thus, neither performed well.
- BR5, BR7, and BR8 were tested at FM1463 test project. All four test sections on FM1463, except BR7, had a total asphalt binder content (virgin, recycled binder, and bio-rejuvenator) of 5.2 percent. During mix design stage, BR7 did not show enough improvement to the cracking resistance of the control mix with 17 percent RAP and 3 percent RAS. Thus, different from BR5 and BR8 test sections, BR7 was used as an extra addition to existing control mix and consequently, total asphalt binder content (virgin, recycled binder, and BR4) was 5.4 percent for the BR4 test section. As further

shown in Figure 23, BR7 test section cracked early than the control section. (Note that BR7 test section was removed after January 2018 due to road expansion.) Thus, adding extra BR7 to the control mix did not show much benefit. Thus, BR7 is considered as the worst performer among these three bio-rejuvenators (BR5, BR7, and BR8). Comparing BR5 and BR8, BR5 is better than BR8. Thus, FM1463 performance data show that BR5 is the best followed by BR8 and then BR7.

Combining the field observations on SH31 and FM1463, the four bio-rejuvenator performance can be ranked from the best to the worst as below:

$$\mathrm{BR5} > (\mathrm{BR6} \approx \mathrm{BR8}) > \mathrm{BR7}$$

VALIDATION OF THE BIO-REJUVENATOR PERFORMANCE INDICATOR

In Chapter 2, the total amount of fatty acid content was identified as a preliminary performance indicator for bio-rejuvenators. The performance data observed on the four field projects provide an opportunity to validate the preliminary performance indicator. Table 9 presents all the rankings in terms of bio-rejuvenators properties (viscosity, fatty acid content, and RTFO aging and mass loss) and field cracking performance. It is apparent that the ranking based on the fatty acid content is similar to the ranking based on field cracking distress. Thus, it is valid to use the fatty acid content of bio-rejuvenators as a preliminary performance indicator.

Furthermore, those rejuvenators having less than 97 percent fatty acid content did not perform well in the field. So, it is recommended using those bio-rejuvenators with more than 97 percent fatty acid. Note that cracking distress has not occurred on either FM468 or SH67. The data from these two field projects will be used to further validate this preliminary finding and make necessary adjustment at a later time.

Table 9. Bio-Rejuvenator Performance Ranking Comparison.

Parameter	**Ranking from the best to the worst**
Viscosity	$(\mathrm{BR5} \approx \mathrm{BR6}) > \mathrm{BR4} > \mathrm{BR3} > \mathrm{BR2} > \mathrm{BR1}$
Fatty acid content	$\mathrm{BR5} > (\mathrm{BR3} \approx \mathrm{BR6}) > (\mathrm{BR1} \approx \mathrm{BR2}) > \mathrm{BR4}$
Mass loss	$\mathrm{BR6} > \mathrm{BR4} > \mathrm{BR3} > (\mathrm{BR2} \approx \mathrm{BR5}) > \mathrm{BR1}$
Field performance	Control > BR3 > BR2 ≈ BR1> BR4

RECOMMENDATION OF BIO-REJUVENATOR CLASSIFICATION SYSTEM

Different bio-rejuvenators have been developed in recent years, and the market is flooded with various types of bio-rejuvenators. But there is no guideline for users to make a choice suitable for specific applications. Thus, development of a purchasing specification for bio-rejuvenators is critical for designing a good performance mix with recycled materials (RAP or RAS) and bio-rejuvenators. Reviewing existing rejuvenator classification specification (ASTM D4552), researchers considered the following items when developing a classification specification for bio-rejuvenator:

- Total fatty acid content for bio-rejuvenator classification.
- Saturated fatty acid content for avoiding potential negative effect of wax.
- Flashing point for safety consideration during mix plant production.
- Dynamic (or kinematic) viscosity at 60°C for providing information to pump the bio-rejuvenator to the mixing drum.
- Dynamic (or kinematic) viscosity ratio of RTFO residue to original rejuvenator for screening out the bio-rejuvenators susceptible to short term aging.
- RTFO (or TFO) mass loss for avoiding massive loss of volatiles (smaller molecules).

Based on the information presented in this chapter and the existing ASTM D4552 specification, researchers recommended a framework of the performance-related specification for bio-rejuvenators, as presented in Table 10.

In Table 10, the bio-rejuvenators are classified into three levels (Bio-R1, Bio-R2, and Bio-R3) depending on the total fatty acid content. Note that Figure 14 in Chapter 2 clearly showed that the impact of the total fatty acid content on improving relaxation property of (recycled) binders is not proportionally linear. The bio-rejuvenators are much more effective when its total fatty acid content is close to 100 percent. This is the reason for defining Bio-R1, Bio-R2, and Bio-R3 with boundaries of larger than 97 percent, 90–97 percent, and less than 90 percent, respectively. Researchers also recommended a maximum limit of 50 percent for the saturated fatty acid based on the impact of the pure palmitic acid compound (essentially, a wax) on the low temperature relaxation property of binders. The same flashing point requirement as ASTM D4552 is used in Table 10. Both dynamic viscosity at 60°C and specific gravity are considered in the specification for information only, since both are useful for plant production and purchasing. To screen out those bio-rejuvenators susceptible to short-term aging, the ratio of dynamic viscosity of RTFO (or TFO) residue to original sample is included in the proposed specification. As discussed previously (Figure 5 and Figure 6), the ratios of all eight bio-rejuvenators are less than 2. Thus, a maximum value is set as 2 in Table 10. RTFO mass loss is also important information for consideration. However, researchers recommended a temporary limit of maximum 5 percent based on the field cracking performance of four bio-rejuvenators (BR5, BR6, BR7, and BR8). More work is needed to refine and expand the framework of performance-related specification for bio-rejuvenators.

Table 10. Physical and Chemical Properties of Bio-Rejuvenators.

Parameter	Test method	Bio-R1	Bio-R2	Bio-R3
Total Fatty Acid Content (%)	GCMS	>97	90–97	<90
Saturated Fatty Acid Content (%)		Max. 50	Max. 50	Max. 50
Flash Point, COC, (ºC)	AASHTO T48 or ASTM D92	219	219	219
Dynamic Viscosity of Original Sample	DSR	Report	Report	Report
Dynamic Viscosity Ratio of RTFO (or TFO) Residue to Original Sample	DSR	Max. 2	Max. 2	Max. 2
FRTO Mass Loss (%)	AASHTO T240 or ASTM D2872	Max. 5	Max. 5	Max. 5
Specific Gravity	ASTM D1298	Report	Report	Report

SUMMARY AND CONCLUSIONS

This chapter discussed bio-rejuvenators field test sections, plant mix properties and field performance under different climates, traffic loading, and pavement structures. Based on the results presented above, the following conclusions are offered:

- Bio-rejuvenators have different rheological, chemical, and aging properties. Consequently, they performed differently in the field.
- Field performance of a total 17 test sections showed that those bio-rejuvenators containing less than 97 percent fatty acid content performed worse than the control test sections. Furthermore, rutting could become a concern for mixes with bio-rejuvenators when they are under heavy traffic loading at hot climatic conditions (like south Texas).
- Fatty acid content correlated well with field performance of bio-rejuvenators. The use of the fatty acid content as a performance indicator for bio-rejuvenators is confirmed by the observed field cracking performance.
- OT cracking test results of the field plant mixes did not match with field cracking performance of bio-rejuvenators, which implies the necessity of changing current conditioning procedure (4 hours conditioning time at 135°C) for the loose mixes with bio-rejuvenators.
- A bio-rejuvenator classification specification is recommended. A total of seven aspects of bio-rejuvenators are included: 1) total fatty acid content for bio-rejuvenator classification, 2) saturated fatty acid content for avoiding potential negative effect of wax, 3) flashing point for safety, 4) dynamic (or kinematic) viscosity for pumping the bio-rejuvenator to the mixing drum, 5) dynamic (or kinematic) viscosity ratio of RTFO residue to original rejuvenator for screening out the bio-rejuvenators susceptible to short-term aging, 6) RTFO (or TFO) mass loss for avoiding massive loss of volatiles (smaller molecules), and 7) specific gravity.

Field test data presented in this chapter are limited. The conclusions above need to be further validated with field data from the two existing field test projects (FM468 and SH67) and other field projects.

CHAPTER 4: BALANCED MIX DESIGN FOR RAP/RAS MIXES WITH REJUVENATORS

INTRODUCTION

The construction of an asphalt overlay is the most common method used to rehabilitate existing asphalt and/or concrete pavements. For an asphalt mix to perform well in the field, it must have a balance of both adequate rutting and cracking resistances. However, improving mix rutting resistance often has a negative impact on cracking resistance. The process of designing asphalt mixtures entails achieving a balance of both rutting resistance and cracking resistance. The goal of balancing asphalt mix design has been pursued for a long time by various researchers and practitioners (Monismith et al. 1985, Monismith et al. 1989, Von Quintus et al. 1991), but without much success. In the 1980s, shear failure rutting was widely observed on high volume asphalt pavements. To reduce asphalt rutting and associated safety issues, stiffer polymer modified binders, coarse aggregate gradations, lower asphalt contents, or a combination were used. As a result, the rutting problem has largely been solved or significantly minimized. However, these measures have resulted in increased early cracking (Brown 1998, Watson 2003, Brown 2004, Brown 2005, Zhou and Scullion 2005). The cracking problem became an even more serious concern for many pavement engineers in the last several years due to the wide use of RAP and RAS. In the past, the cracking problem has been considered through setting a minimum of volume of effective asphalt (VBE). This minimum VBE approach is applicable for virgin mixes, but its application to asphalt mixes containing RAP/RAS and rejuvenators is questionable, because it is unknown how much the binder from RAP/RAS is melted down and blended with rejuvenator and virgin binder. Therefore, it is imperative to have performance tests (rutting, cracking, and moisture damage) to ensure the asphalt mixes with adequate cracking resistance while meeting rutting and moisture damage requirements.

This chapter presents the development history of balanced mix design (BMD) method and then recommends a four-step BMD process for designing mixes containing RAP/RAS and rejuvenators. To demonstrate the design process, this chapter describes a case study of BMD for FM468. Finally, a summary and conclusions are presented at the end of this paper.

BMD DEVELOPMENT HISTORY

The Texas A&M Transportation Institute has been working on the BMD development since 2005. It can be divided into three stages: 1) BMD concept, 2) pilot trials and enhancement, and 3) BMD for project specific conditions.

DEVELOPMENT OF THE BMD CONCEPT

The BMD development for the Texas Department of Transportation (TxDOT) was based on the following principles and/or constrains:

- Keeping the changes to the current TxDOT design procedure as minimal as possible.
- Directly evaluating rutting and cracking resistances of the hot mix asphalt mixes.
- Balancing both rutting and cracking requirements.

The HWTT is currently being used to evaluate rutting resistance and moisture susceptibility in Texas. Based on above the principles/constrains (such as minimal changes), the HWTT is kept in the BMD procedure for evaluating rut and moisture resistance. The field validated OT was recommended for cracking evaluation. The BMD procedure proposed in 2007 is shown in Figure 24 and Figure 25 (Zhou et al. 2007):

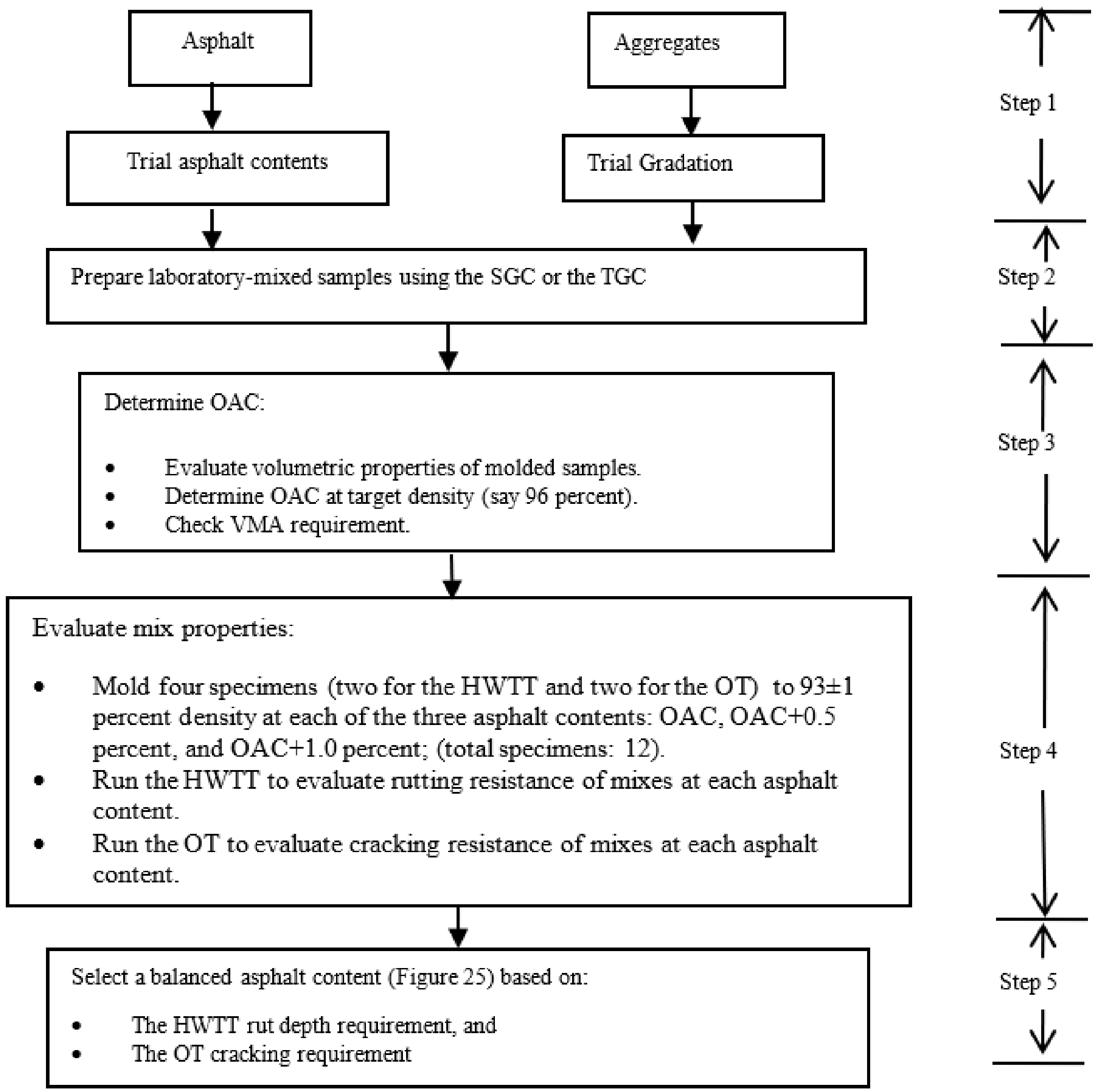


Figure 24. BMD Procedure (Zhou et al. 2007).

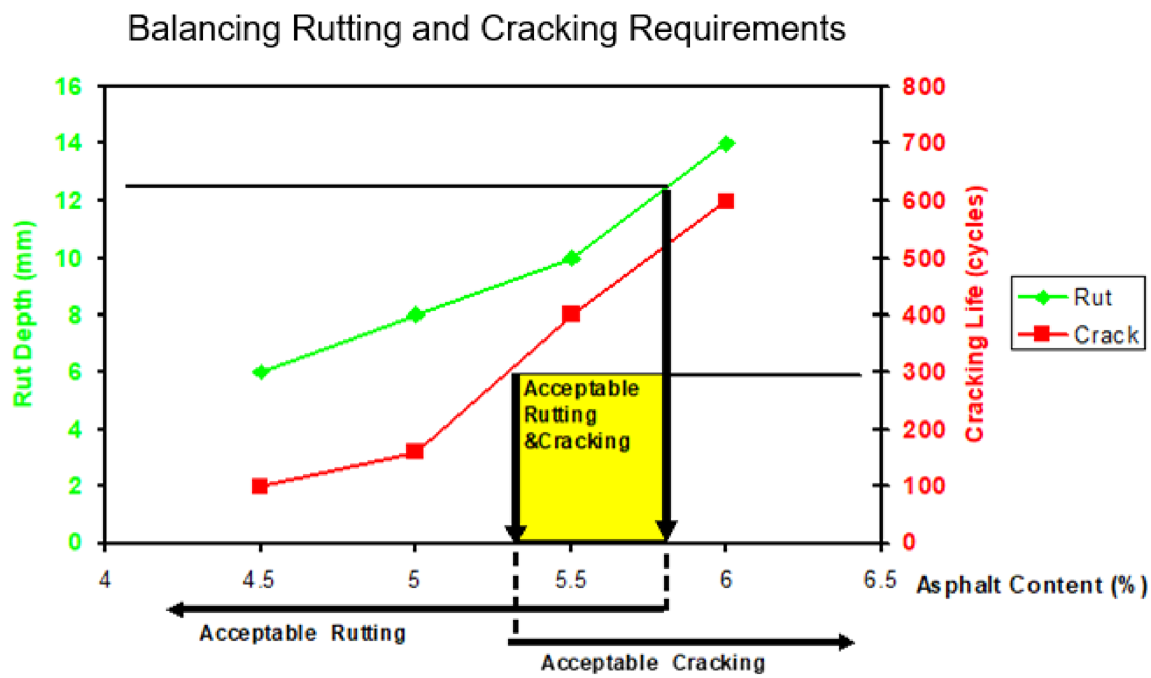


Figure 25. Concept of Selection of the Balanced Asphalt Content (Zhou et al. 2007).

BMD PILOT TRIALS AND ENHANCEMENT

Various BMD pilot trials have been constructed around Texas. Table 11 lists some of the BMD trials related to RAP and RAS mixes. Other trials with Crack Attenuating Mix and Thin Overlay Mix were constructed in Austin, Houston, and other districts. Meanwhile, substantial laboratory mixes were evaluated under Texas OT. Field performance of the pilot trials (such as those in Table 11) and laboratory OT results led to two enhancements to BMD and several observations:

- Add maximum design density requirement: 98 percent.
- Add minimum OT requirements for different types of mixes:
  - Crack Attenuating Mix: minimum OT cycles=750.
  - Thin Overlay Mix: minimum OT cycles=300.
- RAP and RAS mixes can have similar or even better field performance as long as they are designed well following proper design methods, such as BMD.
- Cracking performance is also influenced by many factors, such as traffic, climate, existing pavement conditions for asphalt overlays, and pavement structure and layer thickness. It is extremely difficult to propose a single cracking requirement for all projects. There is an urgent need to develop a RAP/RAS mix design system for project-specific conditions, including traffic, climate, existing pavement conditions, etc.

Table 11. RAP/RAS Field Test Sections and Observed Performance (Zhou et al. 2014).

Test Section			District	Weather	Traffic (mESAL/ 20 Years)	Overlay/new construction	Existing condition if overlay	OT cycles	Field performance
Highway	RAP/ RAS	Virgin binder							
IH40	20%RAP	PG64-28	Amarillo	Hot summer, cold winter	30	4 inch overlay	Severe transverse cracking	10	100% reflect. cracking after 3 year
	0%RAP	PG64-28						90	
	20%RAP	PG64-28						103	
	35%RAP	PG58-28						200	80% reflect. cracking after 3.5 year
FM1017	0%RAP	PG76-22	Pharr	Very hot summer, mild winter	0.8	New construction, 1.5 inch surface layer	N/A	28	Limited, fine cracking after 3 years
	20%RAP	PG70-22						6	
	35%RAP	PG70-22						7	
SH359	20%RAP	PG70-22	Laredo	Hot summer, mild winter	1.0	3 inch overlay	Severe transverse cracking	3	No cracking after 3 years
SH146	15%RAP/ 5%RAS	PG64-22	Houston	Hot summer, mild winter	1.5	New construction, 2 inch surface layer	N/A	3	No cracking after 2.5 years
US87	5%RAS	PG64-28 (control)	Amarillo	Hot summer, very cold winter	3.5	3 inch overlay	Severe transverse cracking	48	50% reflective cracking after 2.5 years
		PG64-28 with 0.4% more virgin binder						96	20% reflective cracking after 2.5 years

BMD FOR PROJECT SPECIFIC CONDITIONS

Currently, asphalt mix design is based on volumetric properties of asphalt mixes plus checking potential rutting and moisture damage. TxDOT already established the project specific rutting/moisture damage requirements for mixes through connecting the criteria with binder PG grades, because the selection of binder PG grade is related to climate and traffic. For example, the rut depth of a mix with PG76-22 binder should be less than 0.5 inch (12.5 mm) after 20,000 passes. However, there is no cracking requirement on dense-graded and/or Superpave mixes in the current TxDOT specification. As clearly observed in the field (Table 11), it is very difficult (if not impossible) to establish a single cracking requirement for all scenarios, because cracking performance of asphalt mixes depends on traffic, climate, pavement structure, and existing pavement conditions for asphalt overlays. Therefore, a balanced RAP/RAS mix design system for project-specific conditions, rather than a single cracking requirement, should be developed, and then implemented to ensure the mixes designed with acceptable field performance. It is envisioned that it is a two-step process: in Step 1 the site conditions will be evaluated and the performance model will be run to predict pavement performance for a range of different materials properties (different OT cycles), and the designer then selects the OT requirement to meet the design performance goal (for example less than 50 percent reflective cracking after 5 years). In Step 2, a lab mix design is run to design a mix with the required OT cycles. If this does not work, the mix will be redesigned, this time changing virgin binder type, rejuvenators, and others.

Figure 26 shows the proposed RAP/RAS mix design system for project-specific conditions (Zhou et al. 2014). This system integrates both mix design and pavement structure design, which has been pursued for long time. Basically, the proposed system is an expanded BMD procedure in which cracking performance is evaluated through a simplified asphalt overlay performance analysis system, S-TxACOL, with OT cycles as an input. Note that the same reflective cracking model as that in TxACOL (Zhou et al. 2010) is used in the S-TxACOL.

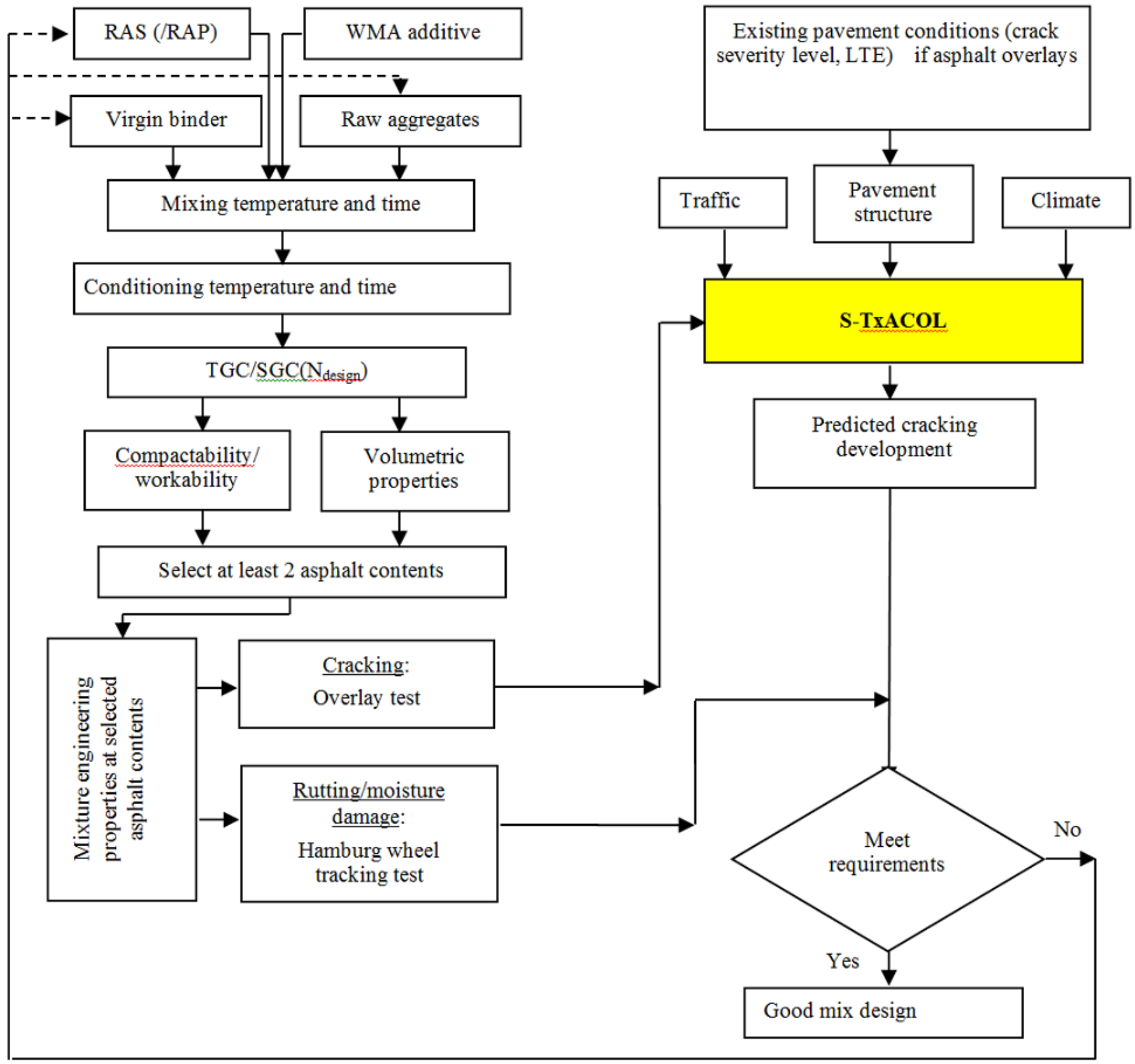


Figure 26. Balanced RAP/RAS Mix Design for Project-Specific Service Conditions (Zhou et al. 2014).

FOUR-STEP BMD PROCESS FOR DESIGNING MIXES CONTAINING RAP/RAS AND REJUVENATORS

Based on the data presented above and the previous work (Zhou et al. 2007, 2010, 2014, 2015), a four-step BMD process for designing mixes with RAP/RAS and rejuvenators is recommended:

- Selection of rejuvenator type.
- Determination of the range of the rejuvenator amounts required to meet both the binder specification and aging characteristics.
- Determination of the range of the rejuvenator amounts required to meet mixture rutting and cracking requirements.
- Selection of final rejuvenator amount based on engineer judgment.

To illustrate the whole process, researchers chose the FM468 rejuvenator mix design as an example. For the case of FM468, the original virgin mix called for a PG70-22 binder. For the rejuvenator test sections, a 30 percent RAP binder replacement was used for the test sections. The RAP binder was extracted and graded as PG94-10. Meanwhile, the original PG70-22 was substituted by a PG64-22 binder. Furthermore, the overall asphalt binder content for this 30 percent RAP mix was 6.3 percent based on Superpave volumetric design.

Selection of Rejuvenator Type

When selecting rejuvenator type, three aspects should be considered:

- Fatty acid content: Field performance of test sections with rejuvenators described in Chapter 3 clearly indicated that the rejuvenators with the fatty acid content less than 97 percent did not improve cracking performance of RAP/RAS mixes. Thus, the rejuvenators containing more than 97 percent fatty acid and less than 50 percent saturated fatty acid should be used.
- RTFO mass loss: The higher the RTFO mass loss, the higher loss potential the rejuvenator during plant production and field paving, and consequently the less effective the rejuvenator to improve cracking resistance of asphalt mixes with RAP/RAS. Thus, the rejuvenators having a mass loss larger than 5 percent are not recommended for use.
- Viscosity: The amount and hardness of the asphalt in aged asphalt mix should be considered when selecting rejuvenators. The general rule for selecting rejuvenator type is to use the rejuvenators with lower viscosity for stiff RAP and RAS binders.

Following these guidelines, bio-rejuvenator BR5 was selected as one rejuvenator for the test sections on FM468. Note that BR5 has a total fatty acid content of 97.6 percent and a mass loss of 2.8 percent after RTFO testing. Its dynamic viscosity is less than 30 mPas. After selecting the rejuvenator type, the next is to determine the rejuvenator dosage, which is described in the following three steps.

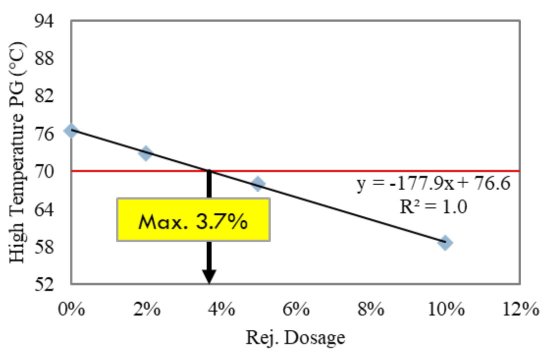
DETERMINATION OF THE RANGE OF REJUVENATOR AMOUNT TO MEET BINDER REQUIREMENTS

The intention of using rejuvenators is to make the blend of the virgin binder and the recycled binder equivalent to the original virgin binder in terms of PG level, binder quality defined by ΔTc, and aging characteristics defined by Glower-Rowe parameter. Rejuvenator/RAP/virgin binder blended samples were prepared. First, recycled binder was extracted from the RAP materials, and it was blended with a PG64-22 virgin binder targeting 30 percent ratio of recycled to total binder. Then, four different rejuvenator contents of 0, 2, 5, and 10 percent on the total binder were blended with the RAP/virgin binder. These rejuvenator/RAP/virgin binder samples were tested to find the range of rejuvenator content that can be considered for the mixture production. Details are discussed below:

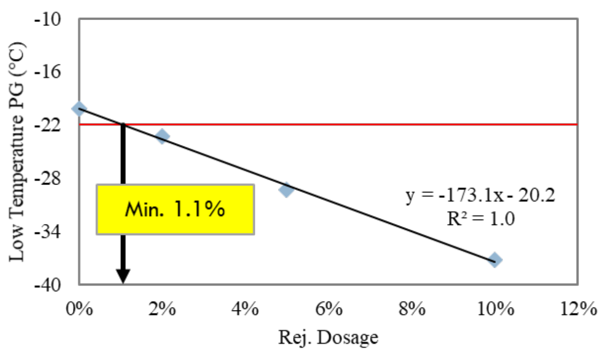
- Determine the range of rejuvenator dosage based on PG binder requirement.

  DSR tests were conducted on 25 mm diameter binder samples to determine the temperatures at which rutting parameters of original and short-term aged binder specimens $\left(\frac{G^*}{\sin\delta}\right)$ were equal to 1.0 and 2.2, respectively. Similarly, BBR tests were conducted on long-term aged asphalt binder samples to determine the temperatures at which relaxation constant (m) and flexural creep stiffness (S) at 60 seconds of loading were equal to 0.300 and 300 kPa, respectively. The test results were finally used to determine the continuous PGs of selected binder blends.

Figure 27a and b present the high and low temperature PG of rejuvenator/RAP/virgin binder samples. The figures demonstrate that addition of bio-rejuvenator BR5 decreases both high and low temperature PGs of asphalt binder blends. This observation clearly signifies the softening effect of rejuvenators. The rejuvenators have higher influence on the high temperature PG of binders than the low temperature PG. The figures also present that there is certain range of rejuvenator dosage that can change the PG of resultant blends into PG70-22. The figures also show that the high temperature PG controls the maximum allowable dosage of rejuvenator while the low temperature PG controls the minimum required dosage. Thus, for BR5, the maximum dosage is 3.7 percent to meet the high temperature PG requirement (70°C), and the minimum dosage is 1.1 percent to meet the low temperature PG requirement (−22°C).



(a) High temperature PG



(b) Low temperature PG

Figure 27. Impact of Rejuvenator BR5 on PG.

- Determine the minimum rejuvenator dosage based on ΔTc requirement.

In last several years, the difference in critical low temperature obtained from creep stiffness and creep slope (i.e., $\Delta Tc = T_{c-S} - T_{c-m}$) measured from BBR tests has been discovered to be an indicator for asphalt binder quality. Figure 28 shows the measured ΔTc values under different rejuvenator dosage. The minimum ΔTc of −6 was used for this study. The minimum rejuvenator dosage for BR5 is 1.4 percent.

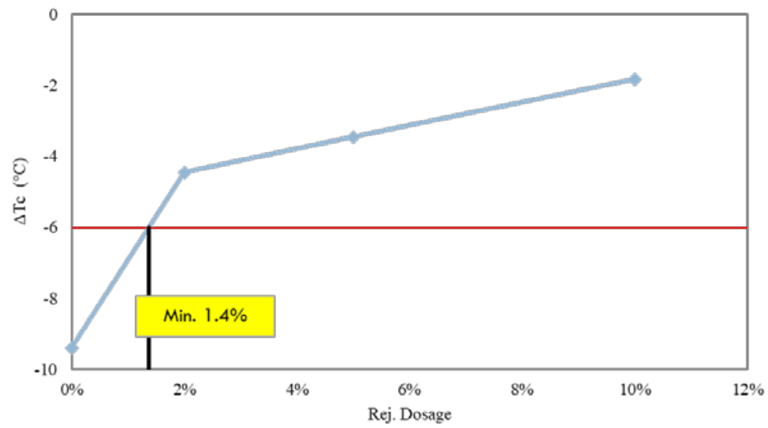


Figure 28. Impact of Rejuvenator BR5 Dosage on ΔTc.

- Determine the range of rejuvenator dosage based on aging resistance requirement.

Glover Rowe (G-R) damage parameter tests were conducted on the rejuvenator/RAP/virgin binder samples to investigate their aging characteristics—the primary reason behind premature cracking in asphalt pavement mixtures containing reclaimed materials. To this end, DSR tests were conducted on 8 mm diameter binder samples to determine their complex modulus ($G*$) $G^*$and phase angle (δ) at 0.005 rad/sec and 0.1 percent strain amplitude at 15°C . The tests were performed on rejuvenator/RAP/virgin binder samples that were subjected to 0, 20, 40 and 80 hours of PAV aging. The measured G^*andδ values were then plotted in a black space diagram containing two separate G-R damage parameter curves—one with $G^* \frac{\cos^2\delta}{\sin\delta} = 180\text{kPa}$ $G*(\cos^2\delta/\sin\delta) = 180kPa$ while the other with $G^* \frac{\cos^2\delta}{\sin\delta}$$G*(\cos^2\delta/\sin\delta) = 450kPa$. Theoretically, binders with $G*-\delta$ G^*-δvalues in the zone above the 450-kPa curve are totally damaged while those in the zone below the 180-kPa curve have not even initiated cracking.

Figure 29 presents the black space diagram of rejuvenator/RAP/virgin binder samples. The figure shows that the plots representing blends with lower dosages of rejuvenator intersect the 180 kPa- and the 450-kPa lines at lower modulus and higher phase angles than those with higher dosage of rejuvenators. The figure also shows that rejuvenated blends reach damage onset and significant cracking states at a much slower rate than the control blends. Furthermore, the figure also suggests that the blend with lower dosage of rejuvenators age and accumulate damage at a much faster rate than the blends with higher dosage of rejuvenator BR5. In order to match the aging resistance of the virgin PG70-22 binder, the minimum required dosages of BR5 for the damage onset and significant damage are 0.7 percent and 1.8 percent, respectively.

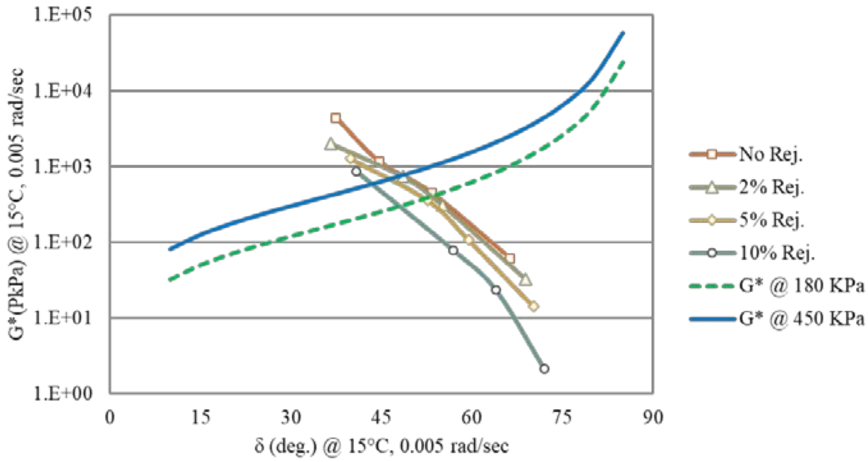


Figure 29. Impact of Rejuvenator Dosage on G-R Parameter.

In summary, Table 12 lists all the maximum and minimum dosage requirements from different perspectives. The final dosage of BR5 ranges from 1.8 percent to 3.7 percent, which will be further evaluated by mixture performance tests.

Table 12. Summary of Max. and Min. Dosages of BR5 Required to Meet Requirements of Binder Properties.

Based on PG		**Based on ΔTc**	**Based on Aging**		**Dosage Range**	
High Temp.	**Low Temp.**		**Damage Onset**	**Significant Cracking**		
Max	Min	Min.	Min	**Min**	**Min**	**Max**
3.7%	1.1%	1.4 %	0.7%	1.8%	1.8%	3.7%

Selection of Rejuvenator Dosage Range through Mixture Performance Tests

It is important to add rejuvenators so that the blended binder (substituted virgin, recycled binder, and rejuvenator) has equivalent or even better performance than the original binder (PG70-22 in this case). However, the mix properties dictate the field performance. Thus, evaluation of the mix properties at different rejuvenator dosage is critical to have a successful mix with a balanced rutting and cracking resistance. Two dosages of BR5: 2.3 percent and 3.3 percent were mixed with the virgin PG64-22 binder and then blended with aggregates and RAP to mold the HWTT and OT samples. The tests were performed following Tex-242-F: *Test Procedure for Hamburg Wheel-Tracking Test (HWTT)* and Tex-248-F: *Overlay Test*. Figure 30 shows the HWTT and OT results.

It is clear that the more the rejuvenator is used, the better the cracking resistance and worse the rutting resistance of the mix. For rutting resistance, the mix having 3.0 percent rejuvenator still meets the rutting requirement (< 12.5 mm). Also, this mix has a reasonable cracking resistance even if a 2.3 percent rejuvenator is used. The final selection of the rejuvenator amount is discussed in next step.

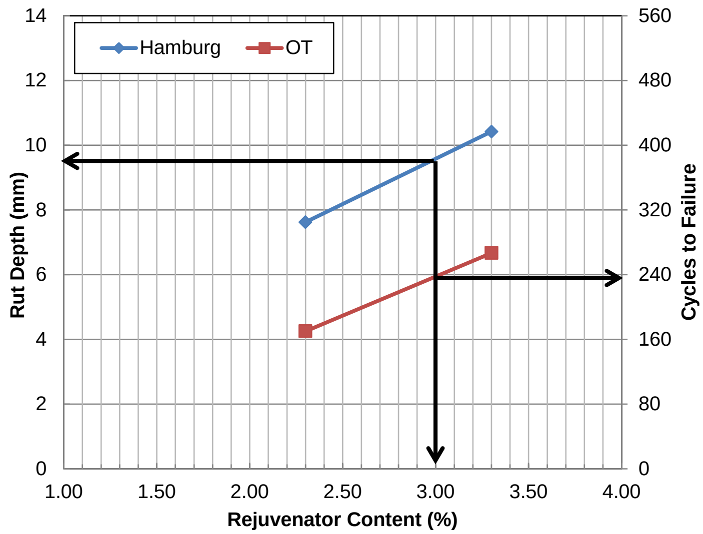


Figure 30. HWTT and OT Results.

Selection of Final Rejuvenator Dosage Using Engineer Judgment

The selection of rejuvenator dosage is a process of balancing both rutting and cracking requirements. The rutting and specifically cracking requirements depend on site specific conditions, such as traffic, climate, pavement structure and layer thickness, and existing pavement conditions particularly for asphalt overlays. In general, for those applications with high volume and heavy traffic or hot weather conditions, lower end of rejuvenator dosage may be preferred, because rutting may be the biggest concern. In contrast, for an asphalt overlay over badly cracking existing pavements and located in cold climate (such as Amarillo), cracking may be the major concern, and consequently, higher rejuvenator dosage should be used. Specifically, for the case of FM468, researchers chose 3 percent BR5 for the 30 percent RAP mix. At 3 percent dosage, the mix has a HWTT rut depth of 9.5 mm (<12.5 mm) and an OT cycles of 240 (>200). As described in Chapter 3, this rejuvenator test section has acceptable performance on FM468.

SUMMARY

This chapter discussed the BMD development in Texas. Based on the information presented, the researchers recommended and demonstrated the four-step BMD process for designing mixes containing RAP/RAS and rejuvenators: 1) selection of rejuvenator type, 2) determination of the range of the rejuvenator amounts required to meet both the binder specification and aging characteristics, 3) determination of the range of the rejuvenator amounts required to meet mixture rutting and cracking requirements, and 4) selection of final rejuvenator amount based on engineer judgement.

CHAPTER 5: SUMMARY AND CONCLUSIONS

There are two major concerns over the use of recycled materials (RAP and RAS) in asphalt mixes. They are variability and premature cracking. To address the variability of RAP and RAS, researchers developed the best practices of processing RAP and RAS and taught four regional workshops. Additionally, researchers evaluated rejuvenators to improve cracking resistance through a series of laboratory testing and the construction of 17 field test sections. Based on the data presented in this report, the following conclusions and recommendations are offered:

- The bio-rejuvenators evaluated in this study effectively modified asphalt binder properties. But different bio-rejuvenators performed differently, and some (such as BR2, BR3) are more effective than others (such as BR6, BR7, and BR8).
- The total fatty acid content is a performance indicator for bio-rejuvenators, which is verified by mixing pure fatty acid compounds (PA, OA, and LA) with a virgin PG64-22 binder. Generally, the larger fatty acid content, the more effective the bio-rejuvenator. It was independently validated by mixing a recycled asphalt binder with the virgin PG64-22 binder and three different bio-rejuvenators (BR2, BR5, and BR8). The DSR and BBR test results further confirmed the total fatty acid content as a performance indicator for bio-rejuvenators. Furthermore, it was found that the saturated fatty acid (or wax) content is better within 50 percent, although the higher total fatty acid content is preferred.
- It is feasible to use the DSR with 50 mm parallel plates to measure dynamic viscosity of bio-rejuvenators. Since DSR has been the main instrument to characterize asphalt binders in the last two decades, researchers recommended that the dynamic viscosity be measured with DSR.
- Bio-rejuvenators have different rheological, chemical, and aging properties. Consequently, they performed differently in the field. Field performance of a total 17 test sections showed that those bio-rejuvenators containing less than 97 percent fatty acid content performed worse than the control test sections. Furthermore, rutting could become a concern for mixes with bio-rejuvenators when they are under heavy traffic loading at hot climatic conditions (like south Texas).
- OT cracking test results of the field plant mixes did not match with field cracking performance of bio-rejuvenators, which implies the necessity of changing current conditioning procedure (4 hours conditioning time at 135°C) for the loose mixes with bio-rejuvenators.
- A bio-rejuvenator classification specification is recommended. A total of seven aspects of bio-rejuvenators are included: 1) total fatty acid content for bio-rejuvenator classification, 2) saturated fatty acid content for avoiding potential negative effect of wax, 3) flashing point for safety, 4) dynamic (or kinematic) viscosity for pumping the bio-rejuvenator to the mixing drum, 5) dynamic (or kinematic) viscosity ratio of RTFO residue to original rejuvenator for screening out the bio-rejuvenators susceptible to short-term aging, 6) RTFO (or TFO) mass loss for avoiding massive loss of volatiles (smaller molecules), and 7) specific gravity.
- Four-step BMD process is recommended for designing mixes containing RAP/RAS and rejuvenators: 1) selection of rejuvenator type, 2) determination of the range of the rejuvenator amounts required to meet both the binder specification and aging characteristics, 3) determination of the range of the rejuvenator amounts required to meet

mixture rutting and cracking requirements, and 4) selection of final rejuvenator amount based on engineer judgment.

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APPENDIX A. BEST PRACTICES FOR THE USE OF RAS IN HMA—INSTRUCTOR GUIDE

TTI: 5-6614-01

Best Practices for the Use of RAS in HMA: Instructor Guide

Implementation Report 5-6614-01-P1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/5-6614-01-P1.pdf

Best Practices for the Use of RAS in HMA

Instructor Guide

Fujie Zhou, Ph.D., P.E.
Research Engineer
Texas A&M Transportation Institute

Product 5-6614-01-P1
Project 5-6614-01

Project Title: Implementation of RAS Best Practices and Piloting Rejuvenators in Key Districts

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

Published: February 2019

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Introduction

The asphalt paving industry has always advocated recycling, including reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), tires, etc. The earliest recycling asphalt pavement dates back to 1915. In addition to conserving energy and protecting the environment, the use of RAP/RAS can significantly reduce the cost of hot-mix asphalt (HMA) paving. RAP has been the most extensively recycled material in the history of the asphalt paving 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 RAS in HMA has become another black gold to the asphalt paving industry since RAS contains a significant amount of asphalt binder (see Table 1). There are two basic types of roofing shingle scraps: 1) post-consumer asphalt shingles or tear-off asphalt shingles (TOAS), and 2) manufacture waste asphalt shingles (MWAS) including roofing shingle tab punch-outs and out-of-spec shingles. MWAS is called prompt roofing shingle scrap in some publications. 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 used in various pavement constructions.

Table 1. Typical Compositions of New Residential Asphalt Shingles.

Component	Organic Shingles, % by wt.	Fiberglass Shingles, % by wt.
Asphalt Cement	30–36	19–22
Reinforcing Mat	2–15	2–5
Mineral Granules/aggregate	20–38	20–38
Mineral Filler/stabilizer	8–40	8–40
Adhesives (modified asphalt based)	0.2–2	0.2–2

The main objective of this workshop is to present best practices for RAS collection, processing, screening, and stockpile management of processed shingles and RAS mix design, production, construction, and performance evaluation.

Course Organization

One or two instructors will present this half day course using the curriculum materials, which includes an instructor guide, a student handbook, and a software CD. In addition, the instructors need internet access and projector equipment.

The course is designed to run for two instructional hours, typically from 9:30 a.m. to 11:30 a.m. or from 1:30 p.m. to 3:30 p.m. The instructional time may vary plus or minus 30 minutes depending on the course sponsor.

The complete lesson plan is composed of four modules:

- Module 1: Introduction.

- Module 2: RAS processing and stockpile management.
- Module 3: RAS mix design and performance evaluation.
- Module 4: RAS mix production and construction.

Course Coordination

Usually, a Training Coordinator from the Texas Department of Transportation (TxDOT) will submit a request for the course with requested dates and training sites to the contractor's course scheduler, who in turn, will contact the course contractor. The contractor will then contact the TxDOT Training Coordinator to discuss possible dates for the course. Once a list of potential dates is compiled, the contractor will check on the availability of the instructors. The contractor will confirm the delivery date with the TxDOT Training Coordinator, Course Scheduler, and instructors. Then the course session is formally scheduled for the agreed dates and training site. This also will authorize the contractor to conduct the course. A confirmation is emailed to the instructors.

The contractor will communicate with the host DOT Coordinator to: 1) confirm times of instruction; 2) obtain directions to training facility; and 3) discuss host requirements.

Class Size

The maximum class size permitted is 40 people; however, the smaller the class size, the better, with a minimum of 5. The participant student handbook should be placed at each participant's seat by the TxDOT Training Coordinator prior to the beginning of the class. TxDOT will provide sign-in sheets, pencils, etc. The TxDOT Training Coordinator needs to notify the contractor's Course Scheduler concerning any changes to the number of students.

Host Agency Responsibilities

Host agency is responsible for visual aids for this course, which include the following:

- LCD projector compatible with a notebook computer (e.g., InFocus® or similar make).
- Cable necessary to connect projector to computer, if possible.
- Electronic remote to advance slides in PowerPoint® presentation (if available).
- Projection screen.
- Laser pointer (if available).
- Whiteboard with dry erase pens and eraser.

All equipment should be placed in the room for the instructors to check a half hour prior to the course.

Room Requirements

Instructors will arrange the classroom as they deem most appropriate given the number of participants. All participants should be able to see the screen and instructors. Participants and instructors should be able to move about the room without obstruction.

A preparation table and presentation table should be provided for the instructors. The presentation table will be for the audiovisual equipment, and the preparation table will be for the instructors' materials. The room should be in a quiet area and have a lighting system that permits convenient dimming of the lights, especially where the screen is located.

Training Site

Great care should be taken to select a room that is handicap accessible and will not be overcrowded, too hot or too cold, or subject to outside distractions. The instructors should provide any specific requirements for the training facility so that the training coordinator may:

- Reserve a training room for the duration of the course.
- Check to see if anyone else will be using the room for nighttime functions.
- Determine if books and equipment can be left in the room. Training courses, requiring special equipment or computers, must have after-hours security.

Participants and Instructors

Participants and instructors should be:

- Informed of course starting and ending times.
- Advised on training site address.
- Furnished with maps.
- Advised on parking arrangements.

Final Arrangements

Instructors will be responsible for:

- Reconfirming the training facilities.
- Discussing the seating arrangements and who will set up the room.
- Discussing what time the room is unlocked/locked.
- Checking to make sure a technician is available in case there are problems setting up the room or if something goes wrong during the course.

One day before the course:

- Set-up the Classroom.
- Organize the participant materials.
- Post directional signs.
- Test all equipment.

During the course:

- Instructors will identify whom they should contact if they need assistance.
- Instructors will provide a copy of the student handbook for all course participants.

After the course:

- Instructors will check to make sure students have the course evaluation forms.
- Students will complete evaluations.
- Clean up room and turn off lights and electronic equipment as needed.

Participant Requirements

TxDOT should provide notepads and pens, or instruct participants to bring notepads and pens with them.

Target Audience

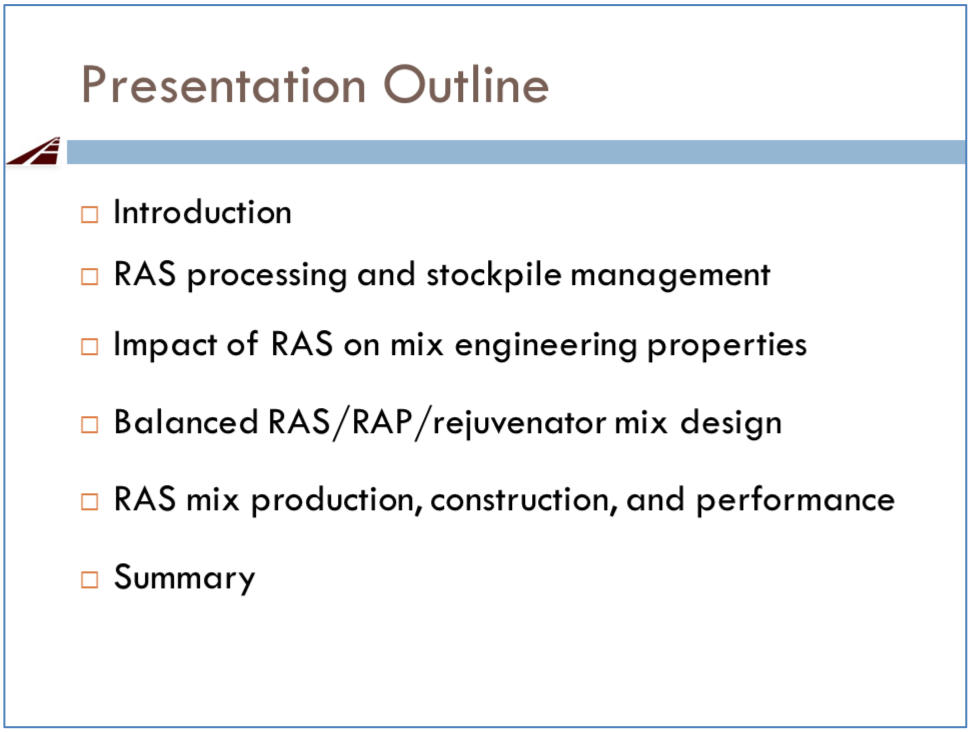
This course is designed for any individuals seeking to best use RAS/RAP in asphalt mixes.

Course Goal

The goal of this course is to present best practices for RAS collection, processing, screening, and stockpile management of processed shingles and RAS mix design, production, construction, and performance evaluation.

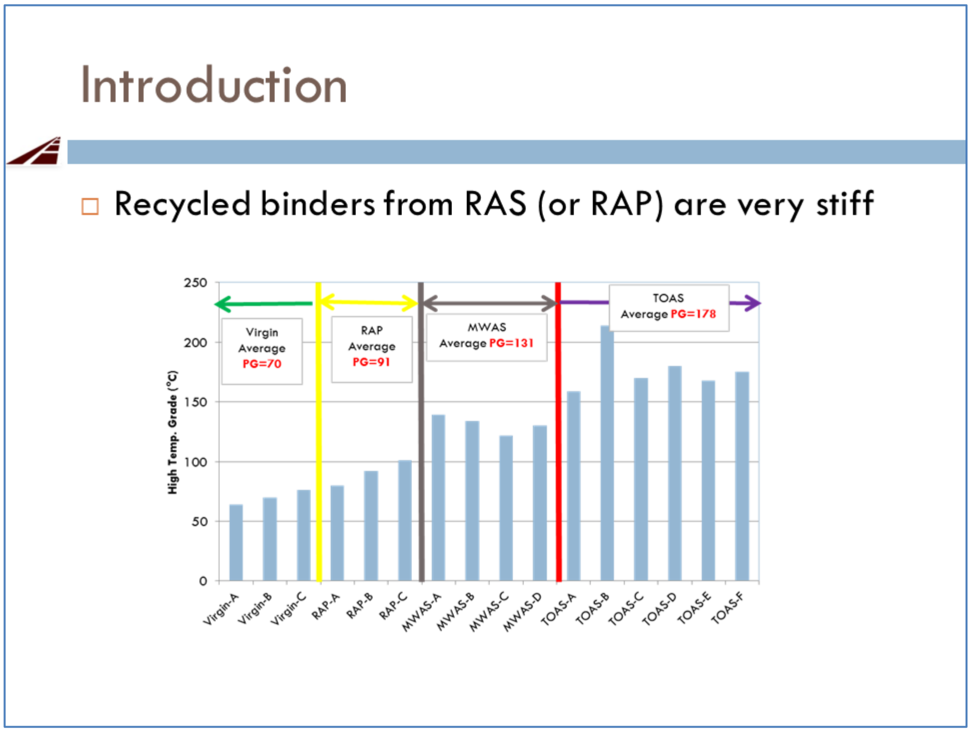
Course Modules

Key Message:	Training title
Interactivity:	**Tell:** In this lesson, we will learn the best practices for the use of RAS in HMA.
Notes:	NA

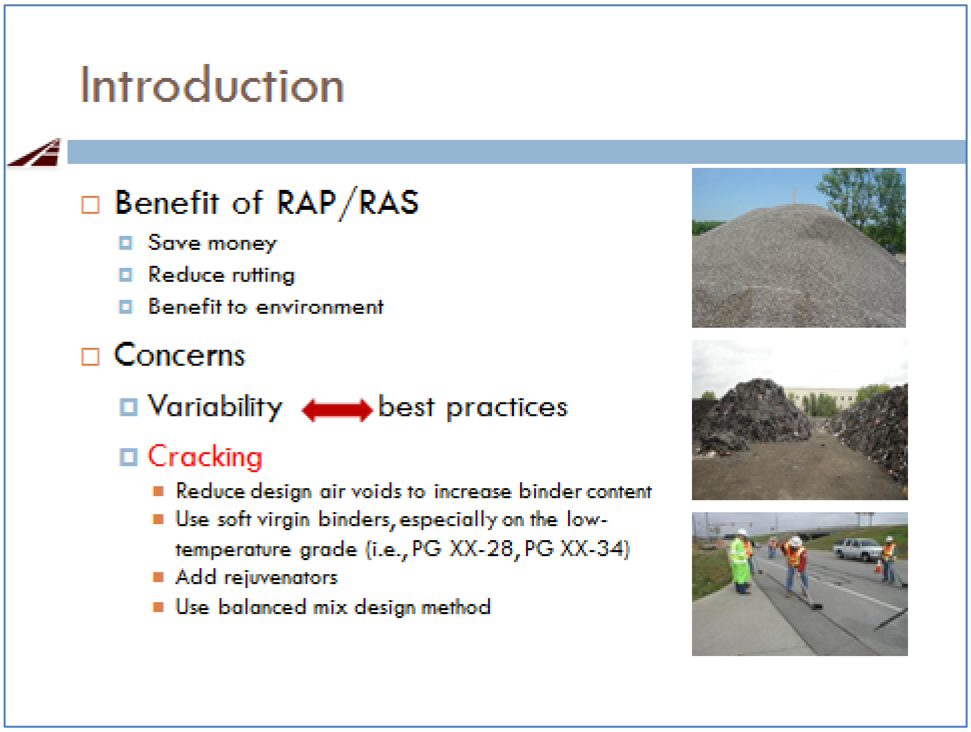


Key Message:	Outline
Interactivity:	**Tell:** This lesson will include six parts: ▪ Introduction. ▪ RAS processing and stockpile management. ▪ Impact of RAS on mix engineering properties. ▪ Balanced RAS/RAP rejuvenator mix design. ▪ RAS mix production, construction, and performance. ▪ Summary.
Notes:	NA

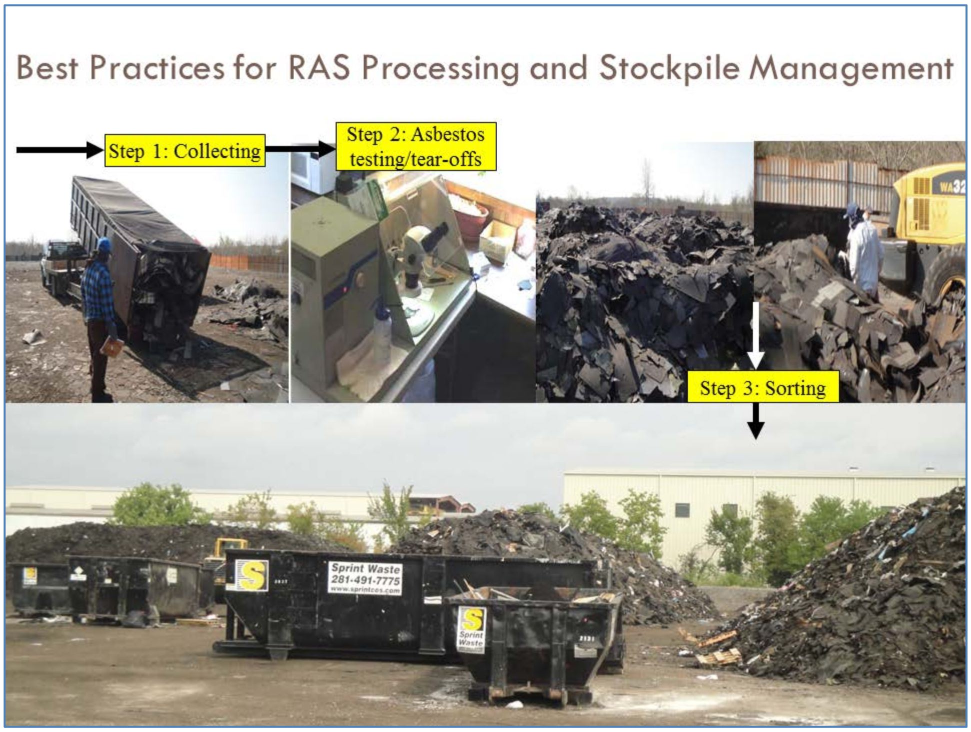
Key Message:	RAS types and characteristics
Interactivity:	**Tell:** Two types of RAS are available: ▪ Manufacture waste asphalt shingles (MWAS). ▪ Tear-off asphalt shingles (TOAS). **Tell:** RAS has very high asphalt content, 20 percent or more.
Notes:	NA



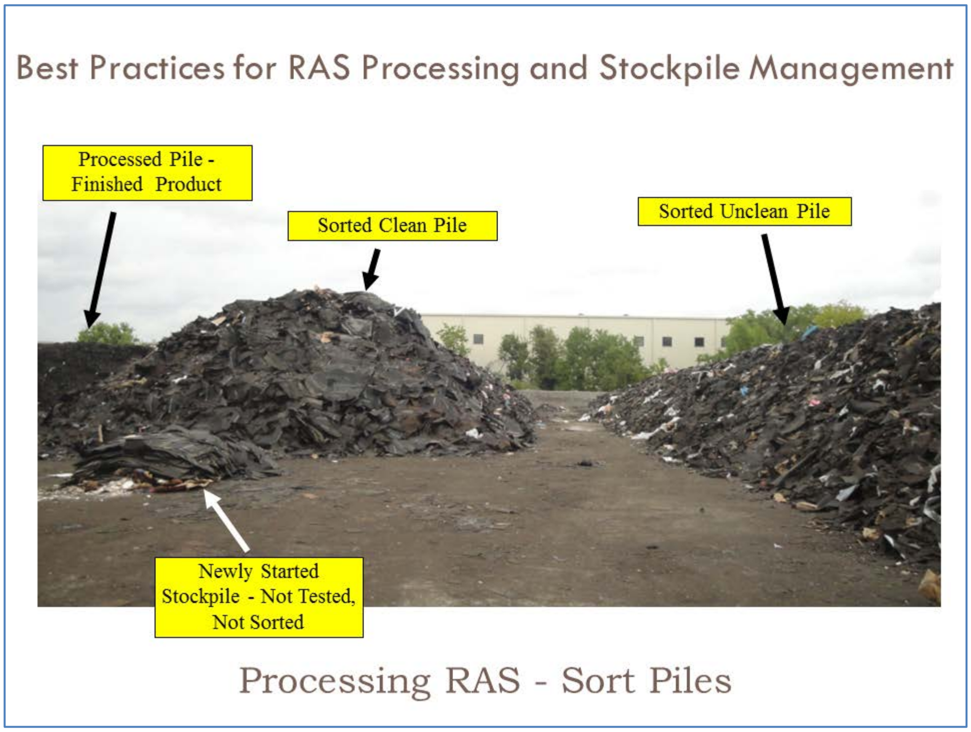
Key Message:	RAS binder characteristics
Interactivity:	**Ask:** Does anyone know how stiff the RAS binder is? **Tell:** Compare the RAS binder with most often used virgin binders in Texas and RAP binders to show that RAS binder is far stiffer than the stiffest virgin binder used in Texas.
Notes:	N/A.



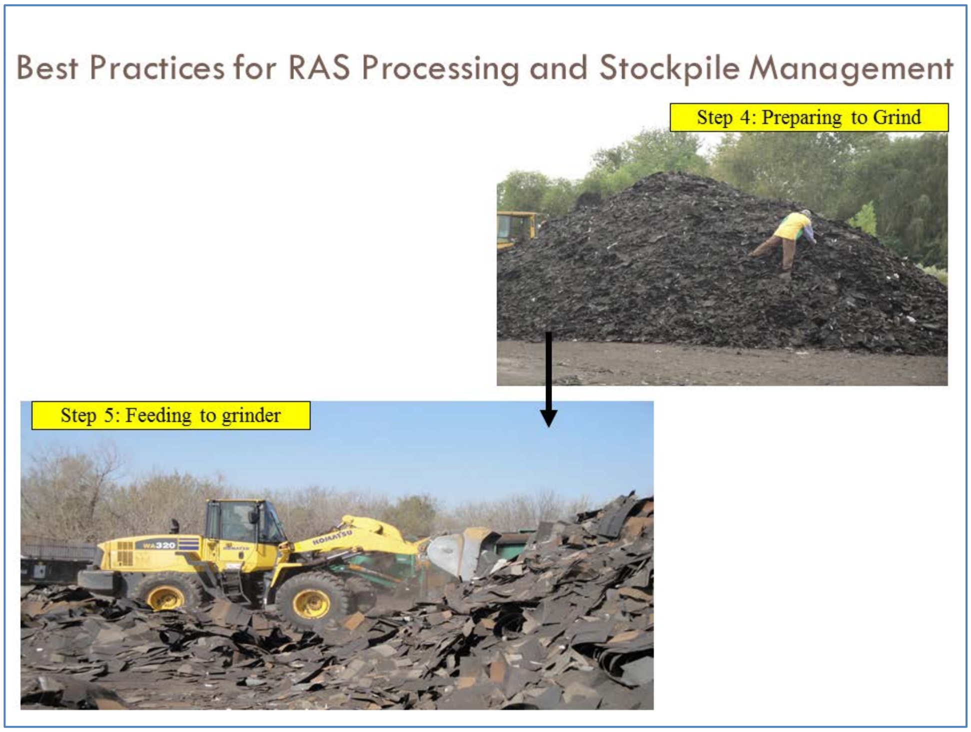
Key Message:	Three benefits and two major concerns on the use of RAS in HMA
Interactivity:	**Tell:** Why do we use RAS? Because of three benefits: 1) save money, 2) reduce rutting, and 3) good to the environment. **Tell:** there are also two major concerns: variability and premature cracking issue. Also the instructor should discuss different ways to address the premature cracking issue: ▪ Reduce design air voids to increase binder content. ▪ Use soft virgin binders, especially on the low-temperature grade (i.e., PG XX-28, PG XX-34). ▪ Add rejuvenators. ▪ Use balanced mix design method.
Notes:	You should be no more than 10 minutes into the lesson at this point.



Key Message:	Best practices for RAS processing and stockpile management
Interactivity:	**Tell:** Best practices for RAS processing and stockpile management include a total of eight steps: ▪ Step 1: RAS collection. ▪ Step 2: Asbestos testing for tear-off asphalt shingles. ▪ Step 3: RAS sorting.
Notes:	NA



Key Message:	Best practices for RAS processing and stockpile management
Interactivity:	**Tell:** The instructor further describes the RAS sorting process.
Notes:	NA



Key Message:	Best practices for RAS processing and stockpile management
Interactivity:	**Tell:** Best practices for RAS processing and stockpile management include a total of eight steps: ▪ Step 4: Preparing to grind RAS. ▪ Step 5: Feeding RAS to grinder.
Notes:	NA

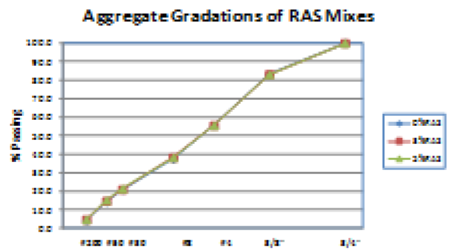
Key Message:	Best practices for RAS processing and stockpile management
Interactivity:	**Tell:** Best practices for RAS processing and stockpile management include a total of eight steps: ▪ Step 6: Grinding RAS. ▪ Step 7: Screening the grinded RAS. ▪ Step 8: Stockpiling RAS in a covered area
Notes:	NA

Impact of RAS on Mix Engineering Properties

- RAS Mixes

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

- Gradation
- Testing
  - E*
  - Hamburg
  - Overlay Test (OT)



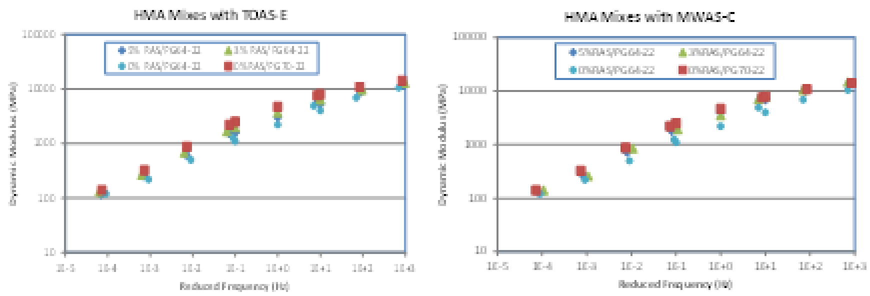
Key Message:	Impact of RAS on mix engineering properties
Interactivity:	**Tell:** On this screen, the instructor will discuss the potential impact of RAS on three mix engineering properties: ▪ Dynamic modulus (E*). ▪ Rutting resistance through Hamburg wheel tracking test. ▪ Cracking resistance through Overlay test (OT). **Tell:** A dense-graded Type C mix is used for this study and three RAS contents are considered: 0, 3, and 5 percent.
Notes:	NA

Impact of RAS on Mix Engineering Properties

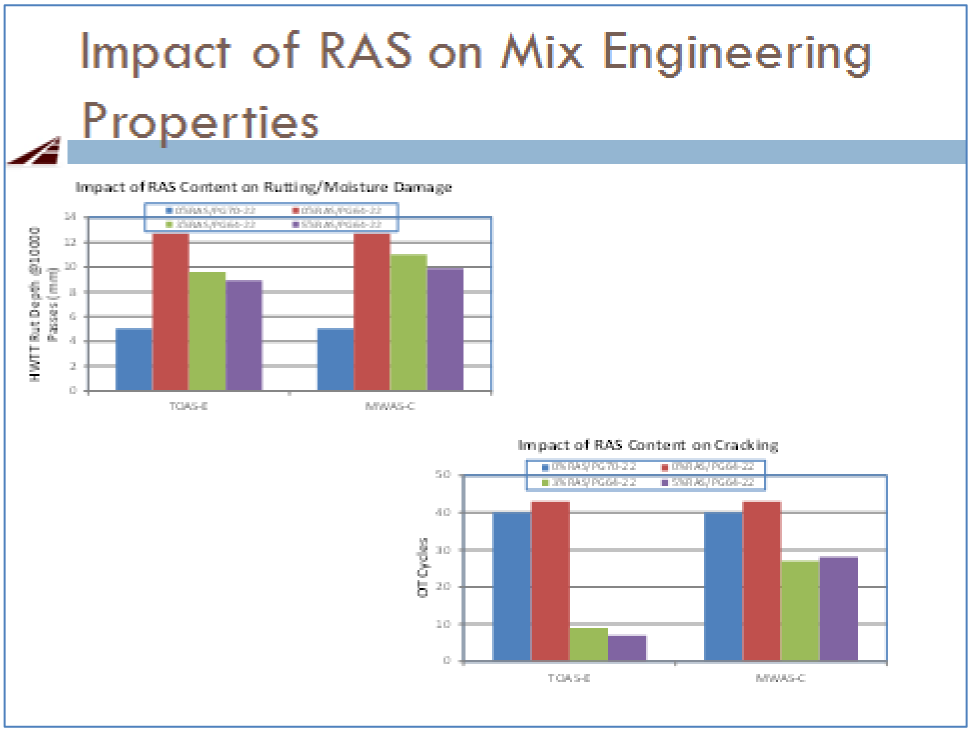
- RAS Mixes

<table>
<tr><th rowspan="2">RAS Type</th><th colspan="4">Optimum Asphalt Content (%)</th></tr>
<tr><th>0% RAS/ PG 70-22</th><th>0% RAS/ PG 64-22</th><th>3% RAS/ PG 64-22</th><th>5% RAS/ PG 64-22</th></tr>
<tr><td>TOAS-E</td><td rowspan="2">4.7</td><td rowspan="2">4.7</td><td rowspan="2">4.9</td><td rowspan="2">5.2</td></tr>
<tr><td>MWAS-C</td></tr>
</table>

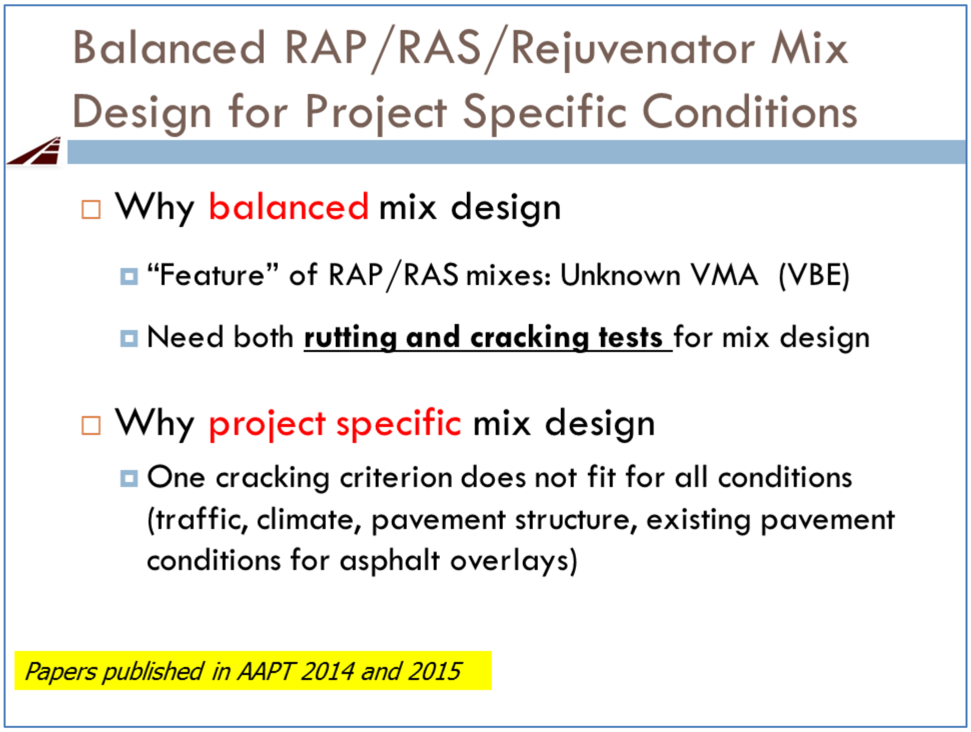
- E*



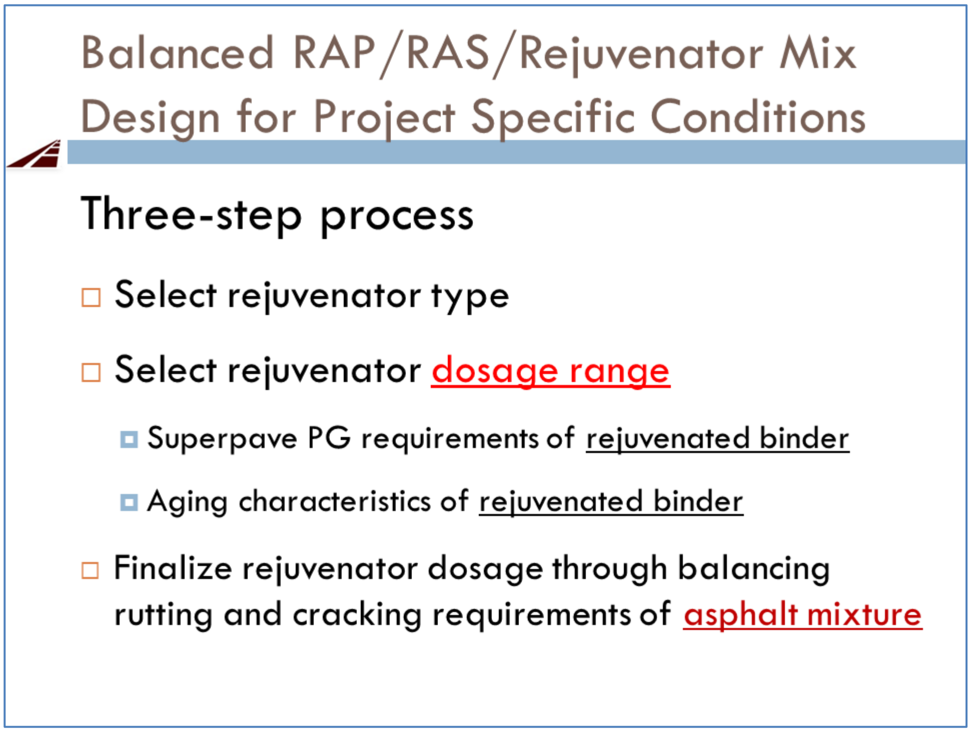
Key Message:	Impact of RAS on dynamic modulus
Interactivity:	**Tell:** The mixes with RAS have higher dynamic modulus than the virgin mix. The addition of RAS makes the mix stiffer.
Notes:	NA



Key Message:	Impact of RAS on rutting and cracking resistance
Interactivity:	**Tell:** The mixes with RAS have better rutting resistance but poorer cracking resistance.
Notes:	NA



Key Message:	Balanced RAP/RAS/Rejuvenator mix design for project specific conditions
Interactivity:	**Tell:** The slide mainly discusses two things: ▪ Why do we need balanced mix design? ▪ Why do we need to perform the mix design for project specific conditions?
Notes:	NA

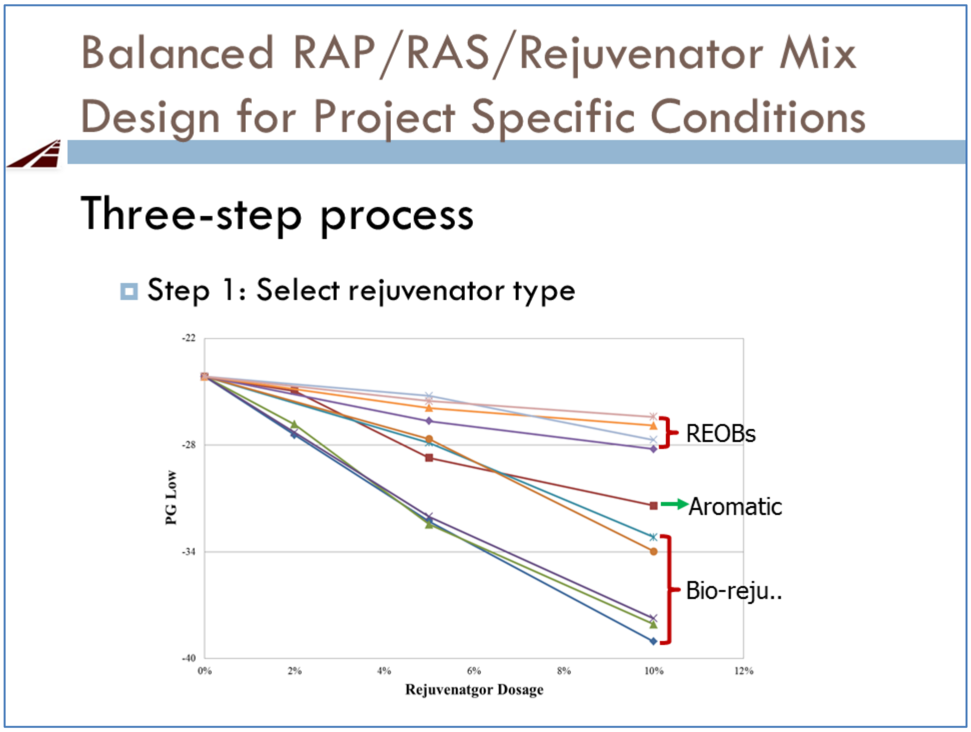


Key Message:	Balanced RAP/RAS/Rejuvenator mix design for project specific conditions
Interactivity:	**Tell:** The balanced RAP/RAS/Rejuvenator mix design for project specific conditions has three steps: ▪ Select rejuvenator type. ▪ Select rejuvenator dosage range. ▪ Finalize rejuvenator dosage through balancing rutting and cracking with a consideration of air voids.
Notes:	N/A

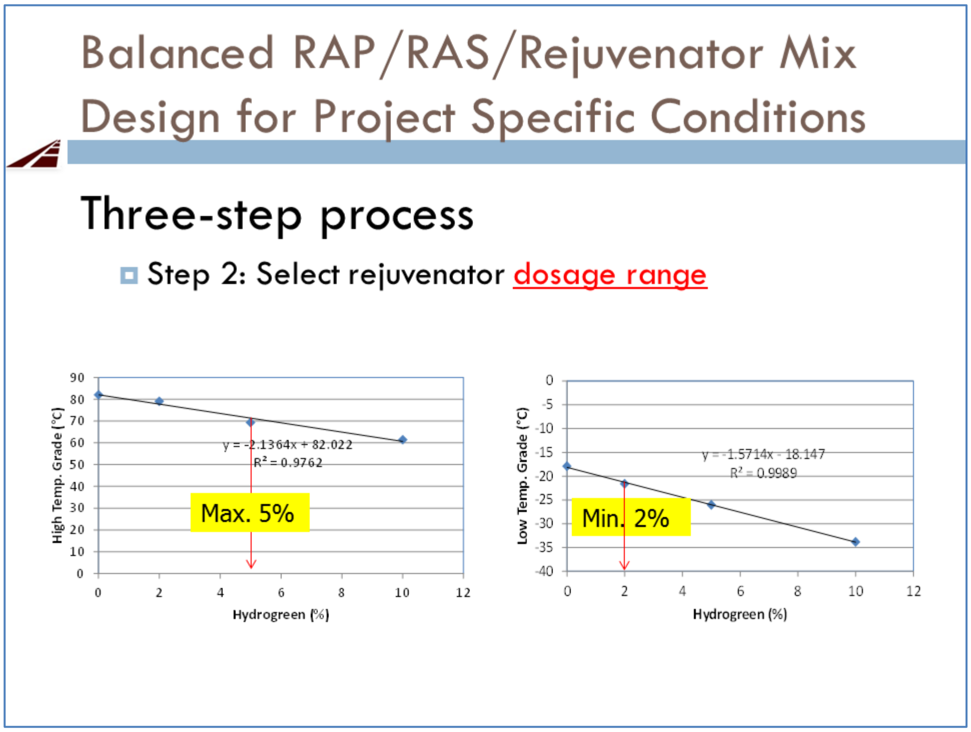
Balanced RAP/RAS/Rejuvenator Mix Design for Project Specific Conditions

- Hamburg test for rutting/moisture damage
- Overlay test for cracking
  - *OT requirement determined by Overlay program*
- Max. density-98% for controlling potential bleeding

Key Message:	Balanced RAP/RAS/Rejuvenator mix design for project specific conditions
Interactivity:	**Tell:** This slide details rutting, cracking, and density (or air voids) requirements.
Notes:	NA



Key Message:	Balanced RAP/RAS/Rejuvenator mix design for project specific conditions: Step 1: select rejuvenator type
Interactivity:	**Tell:** Three types of rejuvenators are available on the market. It seems that bio-based rejuvenators are the most effective ones. However, even within each group, rejuvenators perform differently. Specific blend may be needed for each specific case.
Notes:	NA

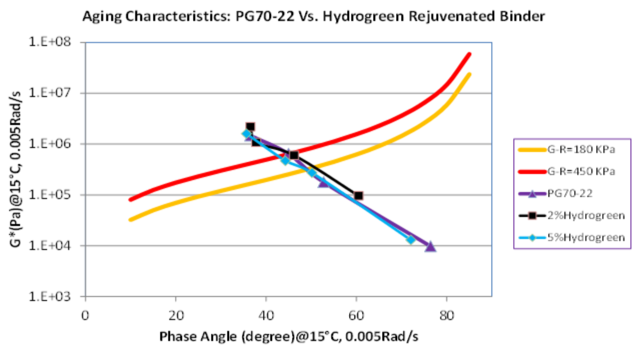


Key Message:	Balanced RAP/RAS/Rejuvenator mix design for project specific conditions: Step 2: select rejuvenator dosage range
Interactivity:	**Tell:** The high temperature PG controls the maximum dosage of rejuvenators and the low temperature PG controls the minimum dosage of rejuvenators.
Notes:	NA

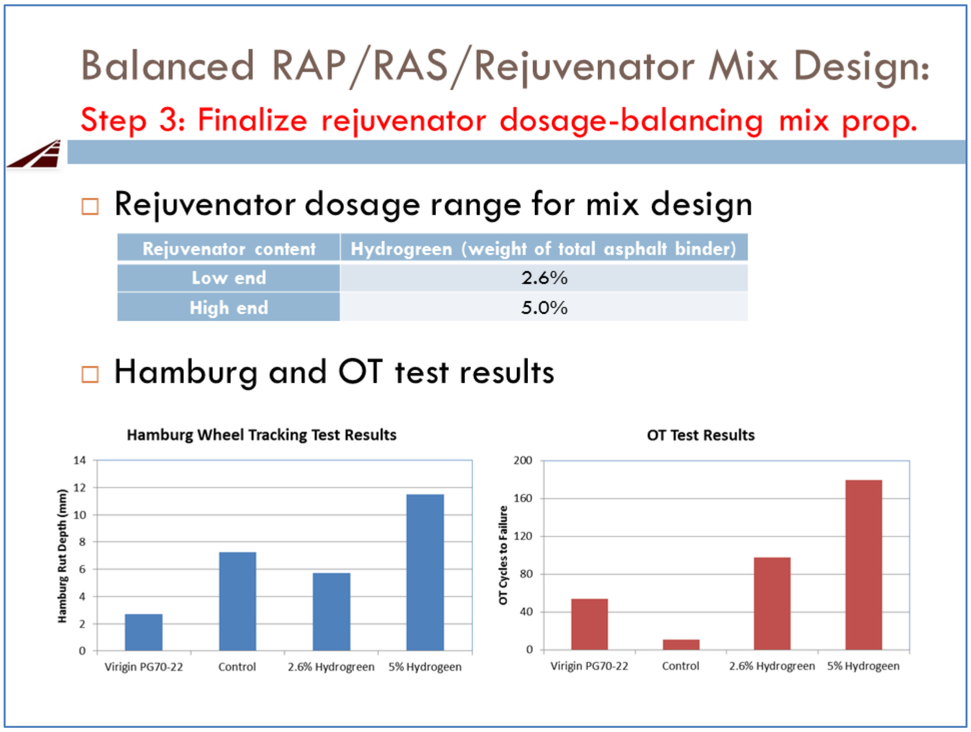
Balanced RAP/RAS/Rejuvenator Mix Design for Project Specific Conditions

Three-step process

- Step 2: Select rejuvenator dosage range



Key Message:	Balanced RAP/RAS/Rejuvenator mix design for project specific conditions: Step 2: select rejuvenator dosage range
Interactivity:	**Tell:** In addition to binder PG requirement, the aging characteristics of the blend should be evaluated through Glower-Rowe parameter. The blend should have similar or even better aging resistance than the virgin binder.
Notes:	NA



Key Message:	Balanced RAP/RAS/Rejuvenator mix design for project specific conditions: Step 3: Finalize rejuvenator dosage through balancing mix rutting and cracking requirements
Interactivity:	**Tell:** Select the final rejuvenator dosage based on rutting and cracking test results and associated requirements for specific project conditions.
Notes:	N/A

Key Message:	A typical asphalt mix production plant
Interactivity:	**Tell:** A separate RAS bin at this plant.
Notes:	N/A

Key Message:	A typical construction site with paver, loading truck, and paving crew
Interactivity:	**Tell:** A good organized on-site construction sequence is very important, especially for the mixes containing RAP/RAS.
Notes:	NA

RAS Mix Production and Construction

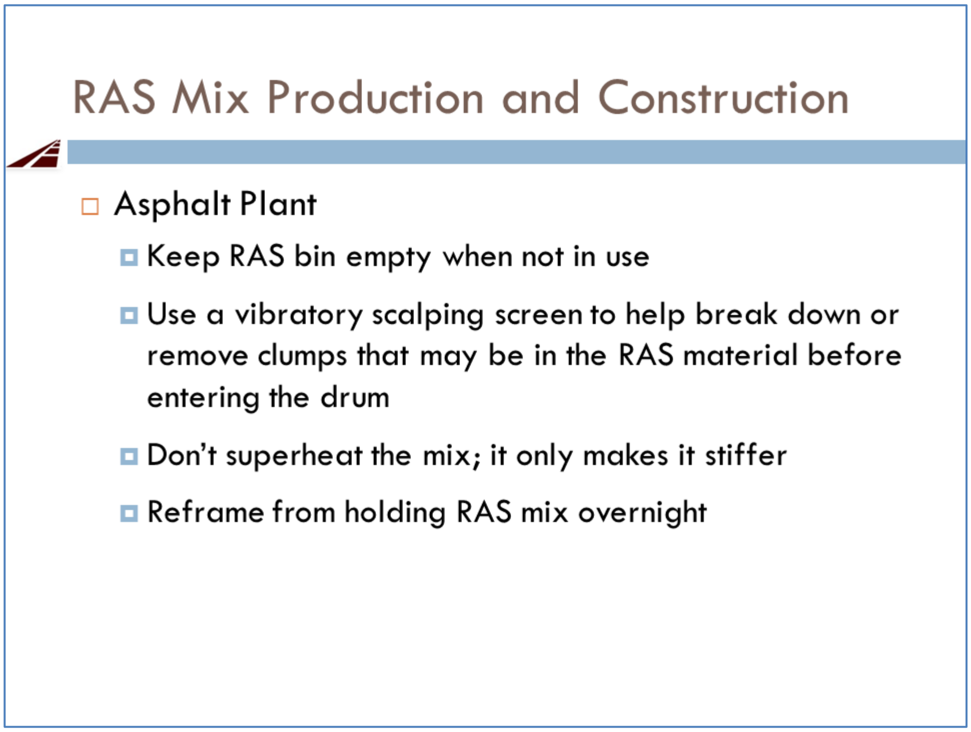
- Areas of Concern
  - Clumping after grinding
  - Crusting more severe on long hauls
  - Tendency to stiffen quicker in trucks than standard hot mix
  - More difficult to hand work
  - Mat can be more sensitive to temperature segregation

Key Message:	Potential concerns on RAS mix production and construction
Interactivity:	**Tell:** Overall concerns on RAS mix production and construction as listed in the slide.
Notes:	NA

RAS Mix Production and Construction

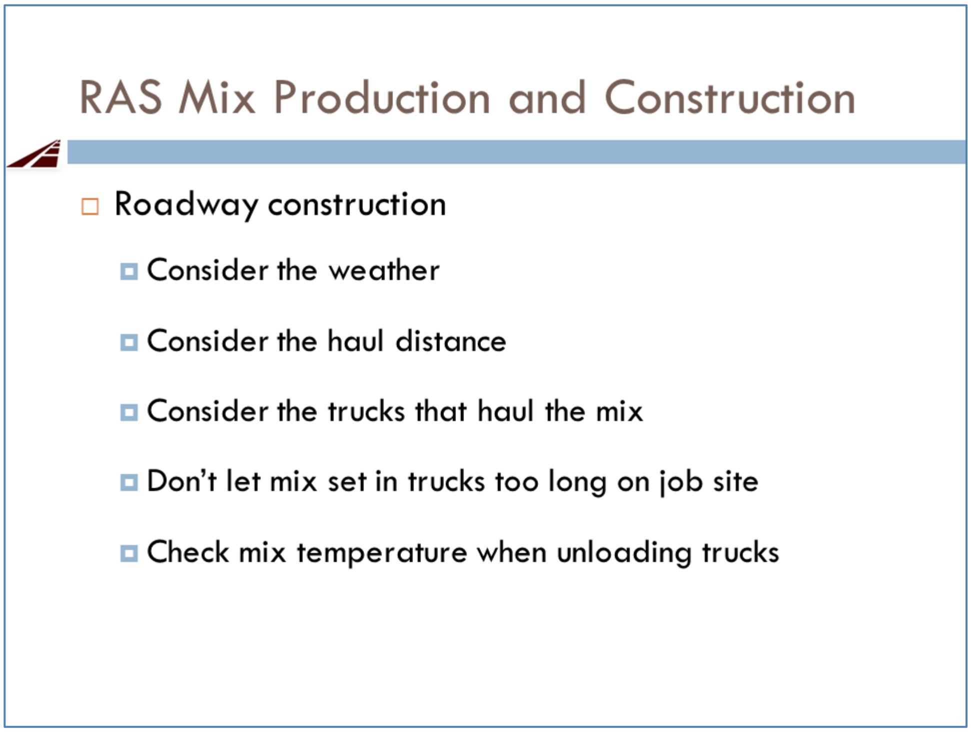
- RAS Stockpile
  - Keep loaders off RAS stockpiles
  - Keep RAS stockpiles covered
  - RAS stockpiles will retain moisture; run moisture content each day prior to running mix
  - Separate high AC RAS from low AC RAS

Key Message:	RAS mix production and construction
Interactivity:	**Tell:** The instructor discuss five specific tips for RAS stockpile.
Notes:	**N/A**

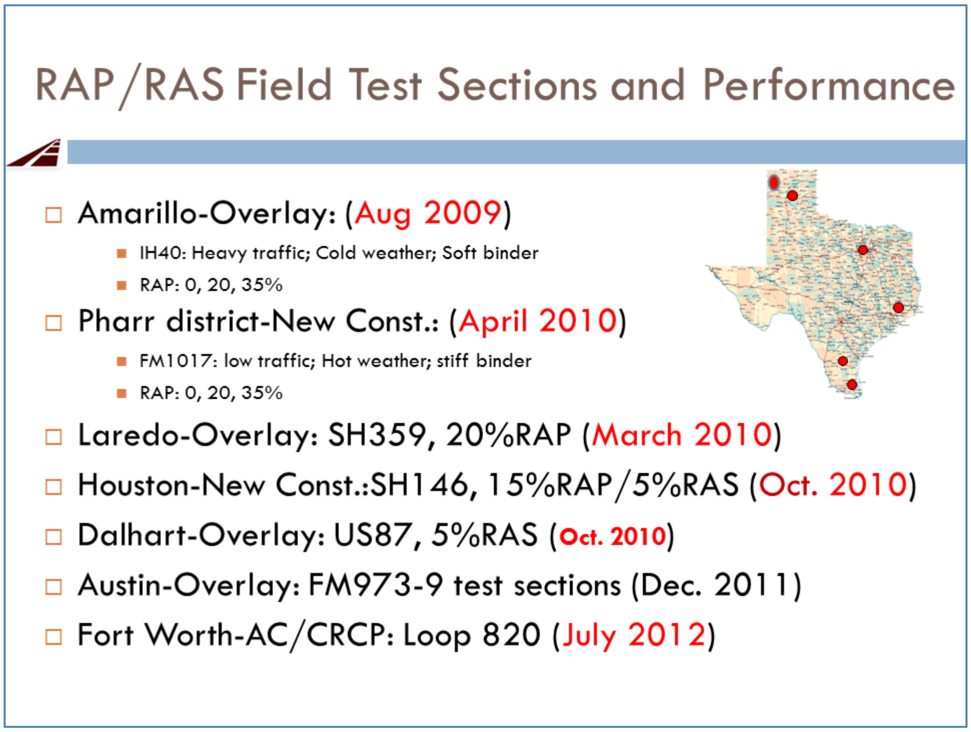


Key Message:	RAS mix production and construction
Interactivity:	**Tell:** This screen shows four specific items worth of paying attention to at the asphalt plant.
Notes:	NA

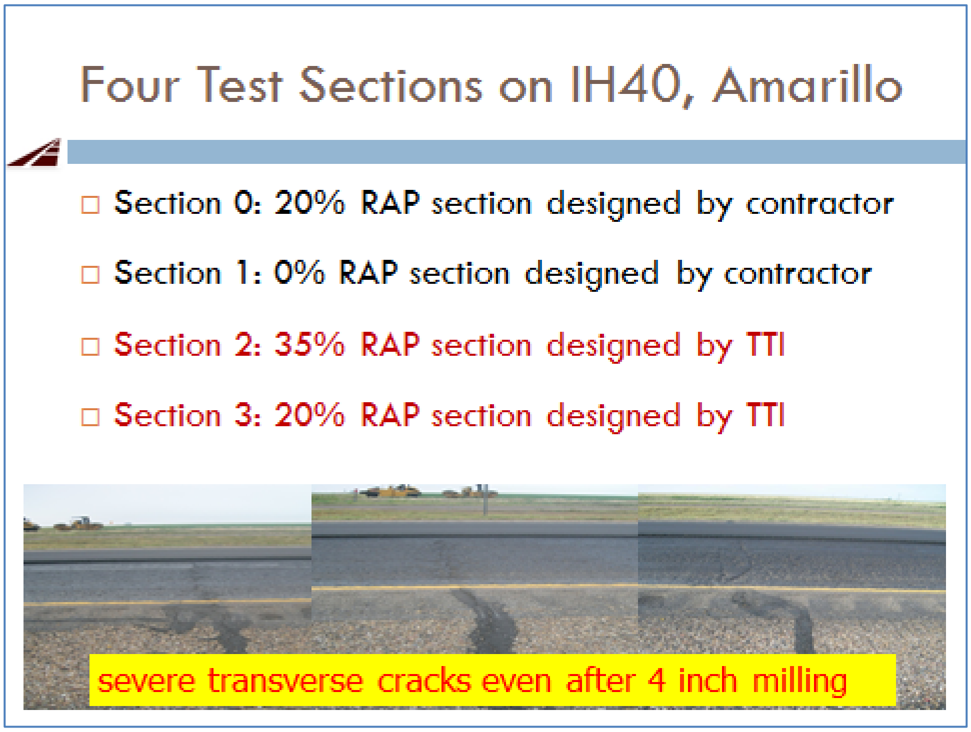
Key Message:	RAS mix production and construction
Interactivity:	**Tell:** The instructor should emphasize the importance of the vibratory scalping screen to loosen the clumped RAS.
Notes:	NA



Key Message:	RAS mix production and construction
Interactivity:	**Tell:** This screen lists five key items for roadway construction to ensure good quality construction.
Notes:	N/A



Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** This screen shows the locations of many field test sections with RAP/RAS being constructed in the past.
Notes:	NA

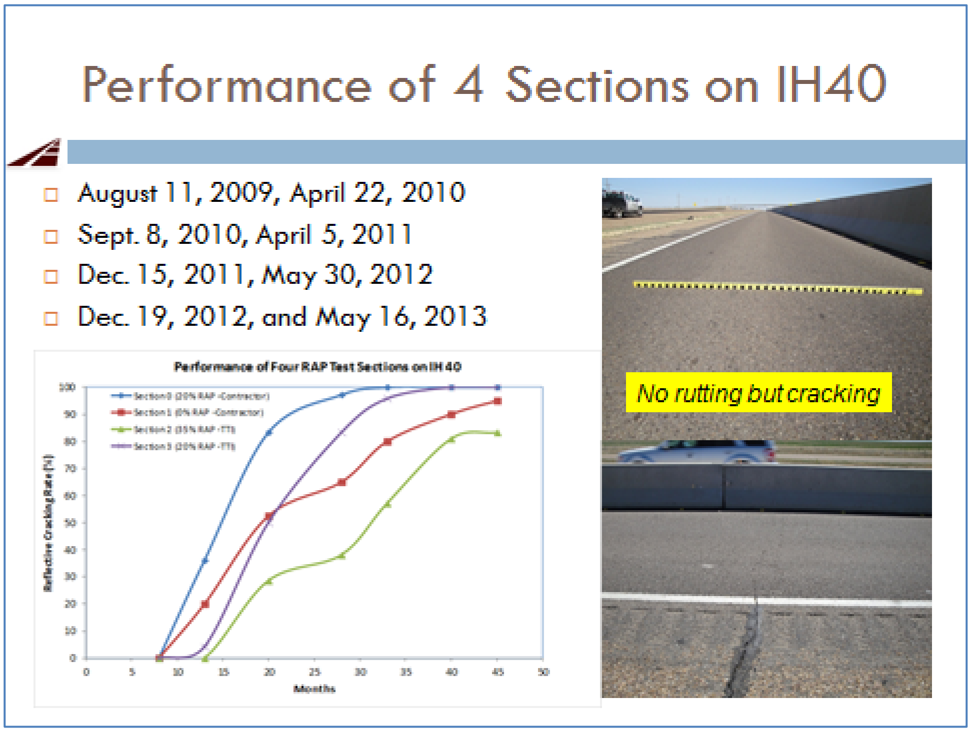


Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** This slide shows four specific test sections on IH40.
Notes:	NA

Summary: RAP Mix Design on IH40

Section	RAP (%)	Virgin binder	Mix design approach	AC (%)	Hamburg rut depth @20000	OT cycles
0	20	PG64-28	Item 340-Type C	5.0	3.7 mm	10
1	0	PG64-28	Item 340-Type C	4.8	4.4 mm	95
2	35	PG58-28	Balanced mix design	5.5	8.0 mm	200
3	20	PG64-28	Balanced mix design	5.3	7.4 mm	103

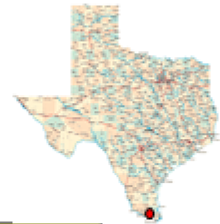
Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** The balanced mix design method was used to design the test sections on IH40. The table in this slide details mix design information of each test section including both rutting and cracking test results.
Notes:	N/A



Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** In this slide, the performance history of four test sections on IH40 is displayed. Apparently, the 30 percent RAP mixes designed with balancing rutting and cracking requirements performed the best.
Notes:	N/A

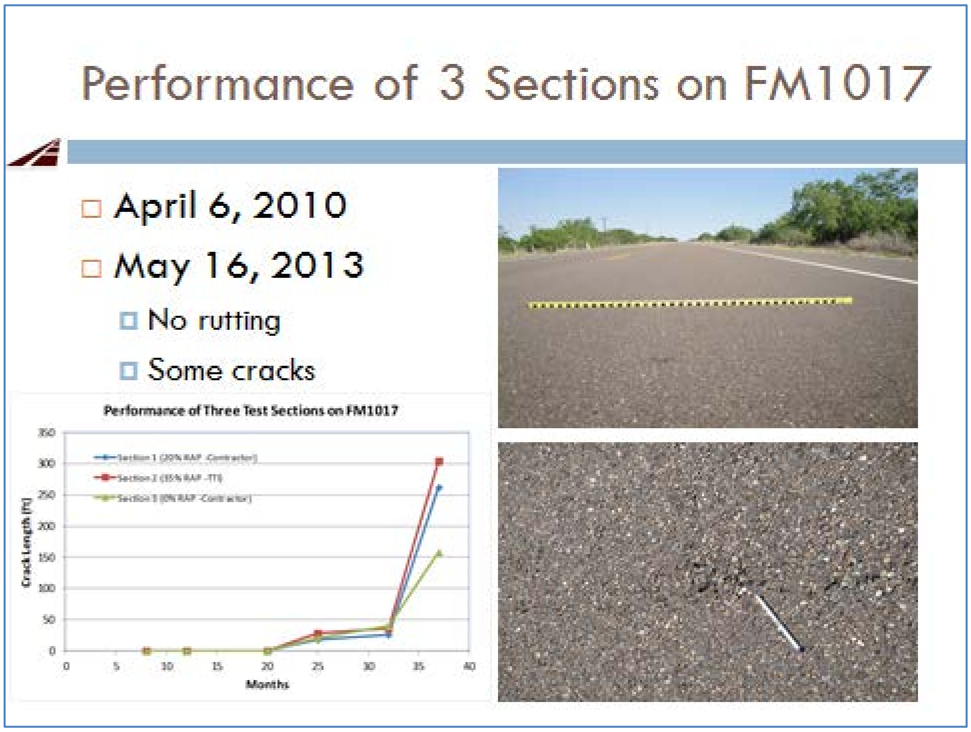
Three Test Sections on FM1017, Pharr

- New construction pavement
- 1.5 inch asphalt layer
- Hot weather
- FM road with low traffic

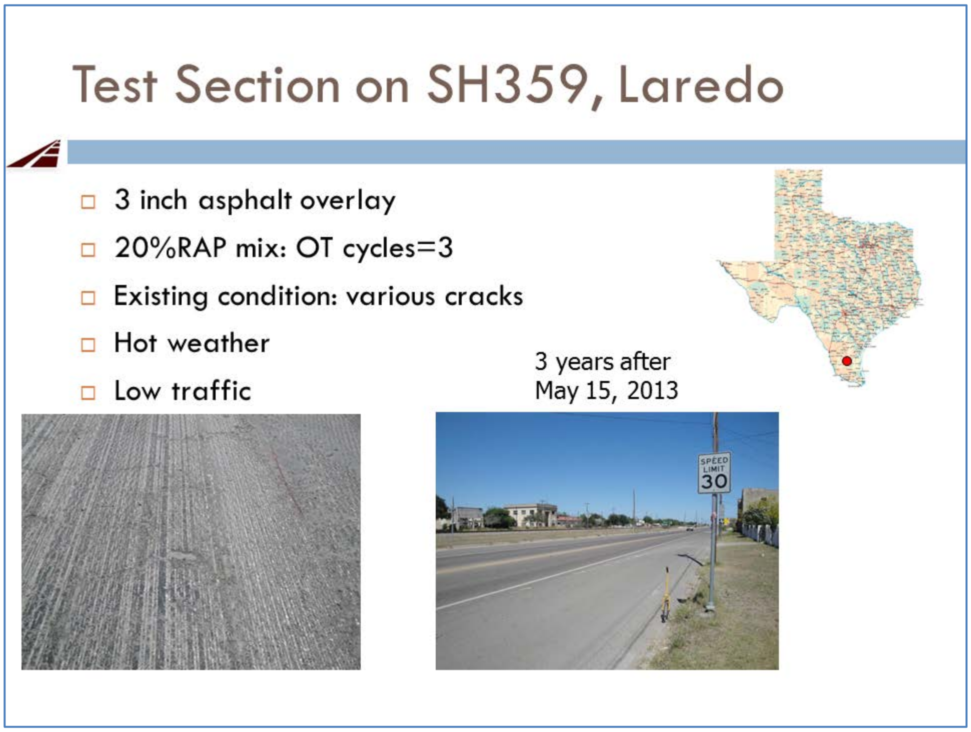


Section	RAP (%)	Virgin binder	Mix design approach	AC (%)	Hamburg rut depth @20000	OT cycles of plant mixes
1	20	PG64-22	Item 340-Type D	5.0	3.4 mm	6
2	35	PG64-22	Balanced mix design	6.4	9.3 mm	7
3	0	PG76-22	Item 340-Type D	4.9	2.2 mm	28

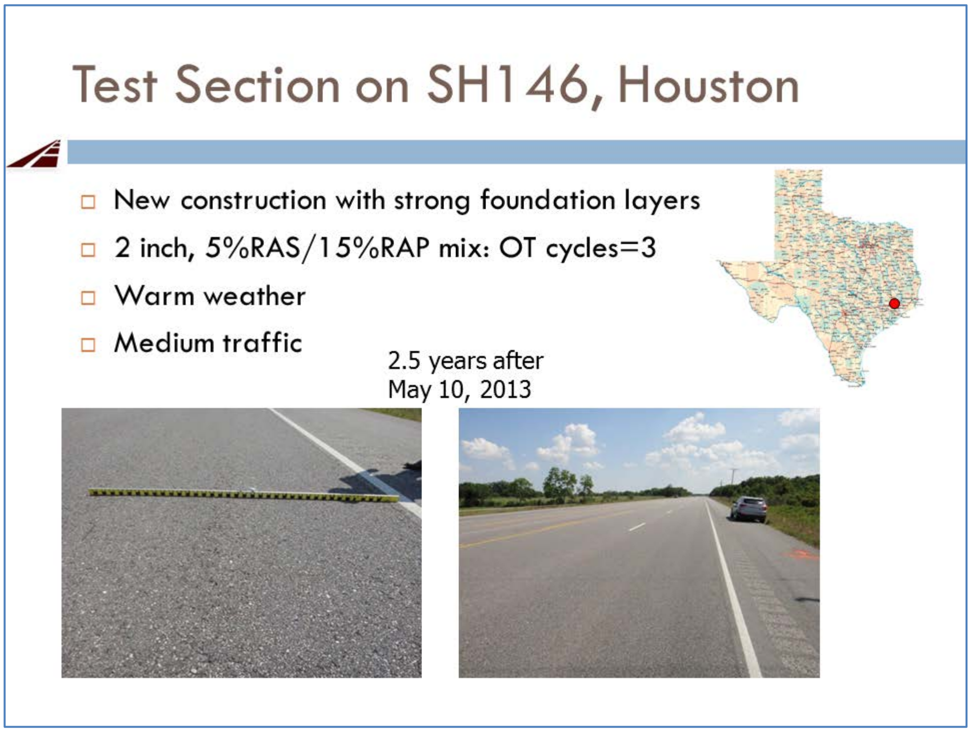
Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** On FM1017, three sections with different percentage of RAP were constructed in a hot climatic area. The five features of these test sections are listed below: ▪ New construction pavement. ▪ 1.5 inch asphalt layer. ▪ Hot climate. ▪ Low traffic. ▪ All mixes with relatively poor cracking resistance.
Notes:	N/A



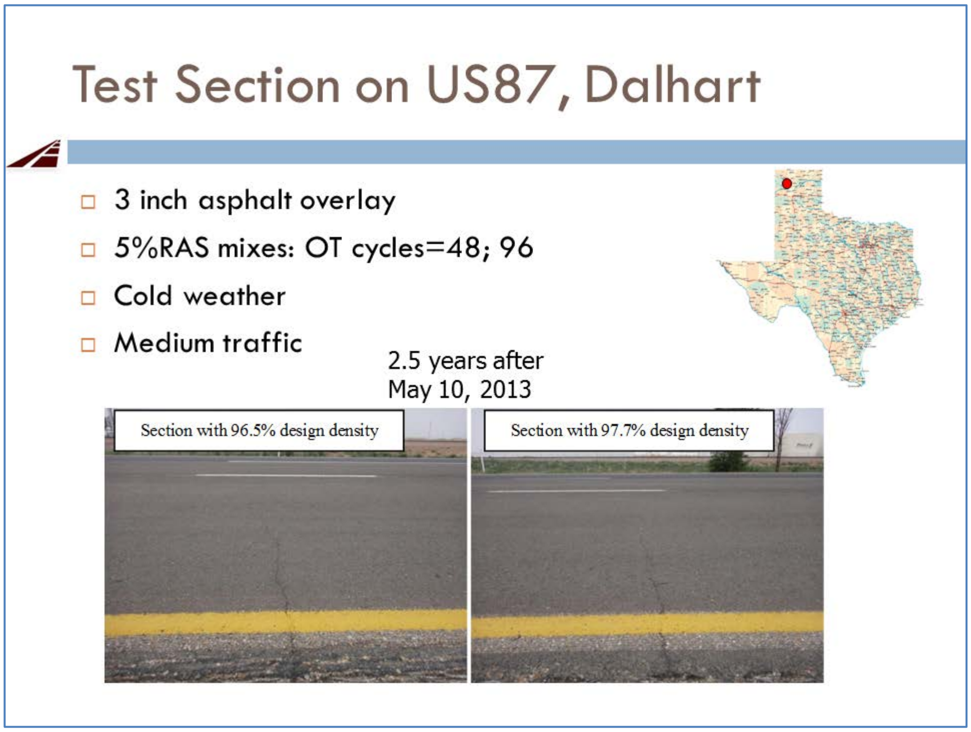
Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** This slide shows the performance history of these three test sections. It indicated that the performance of these sections is acceptable in the conditions of hot weather, low traffic, and no pre-existing cracks, although the three mixes have relatively poor cracking resistance.
Notes:	N/A



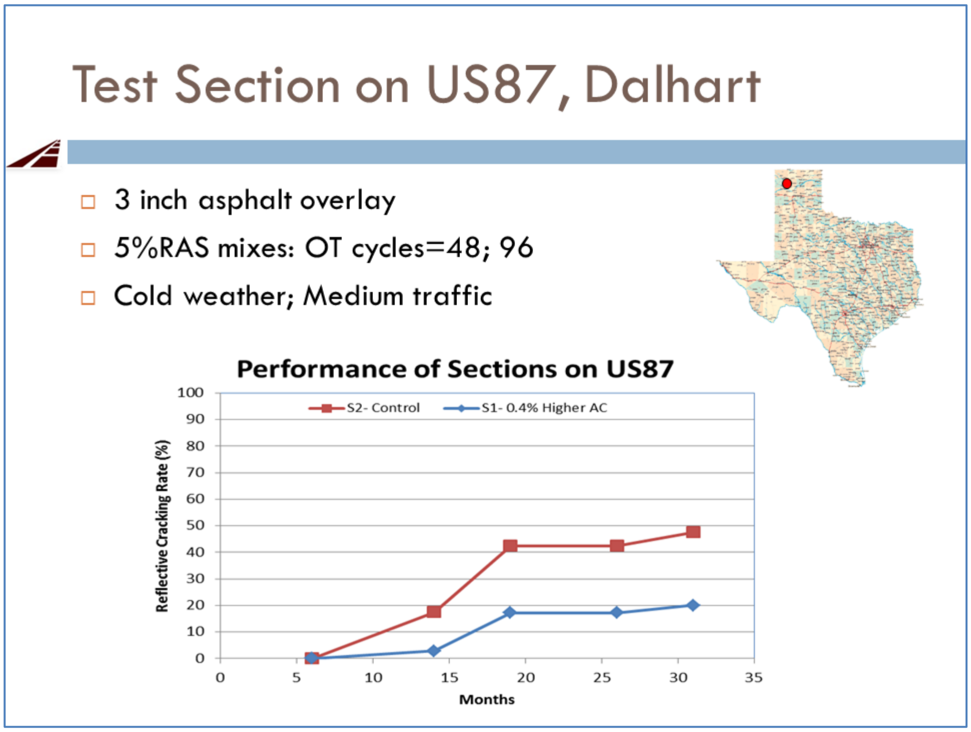
Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** Another case for RAP mix with very few OT cycles performed well in the field due to low traffic and hot weather.
Notes:	**N/A**



Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** This slide shows again that RAP/RAS mix has acceptable performance when it is applied in suitable conditions (new construction, strong foundation layers, warm weather, and medium traffic).
Notes:	N/A



Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** This case demonstrates the impact of design density and extra 0.3 percent asphalt binder on cracking resistance of RAS mix.
Notes:	N/A

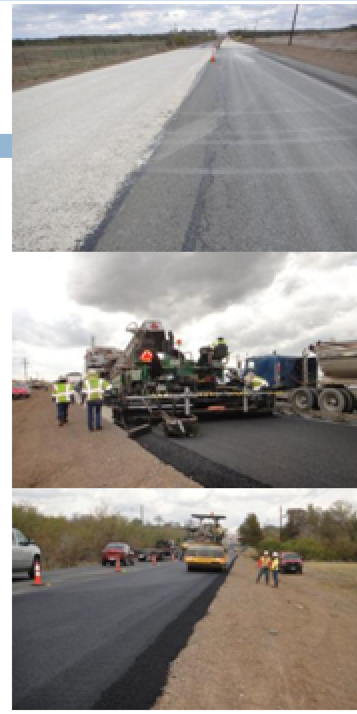


Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** This case clearly demonstrates the use of higher design density and higher asphalt content can improve cracking resistance of asphalt mixes, even in the coldest climate in Texas.
Notes:	N/A

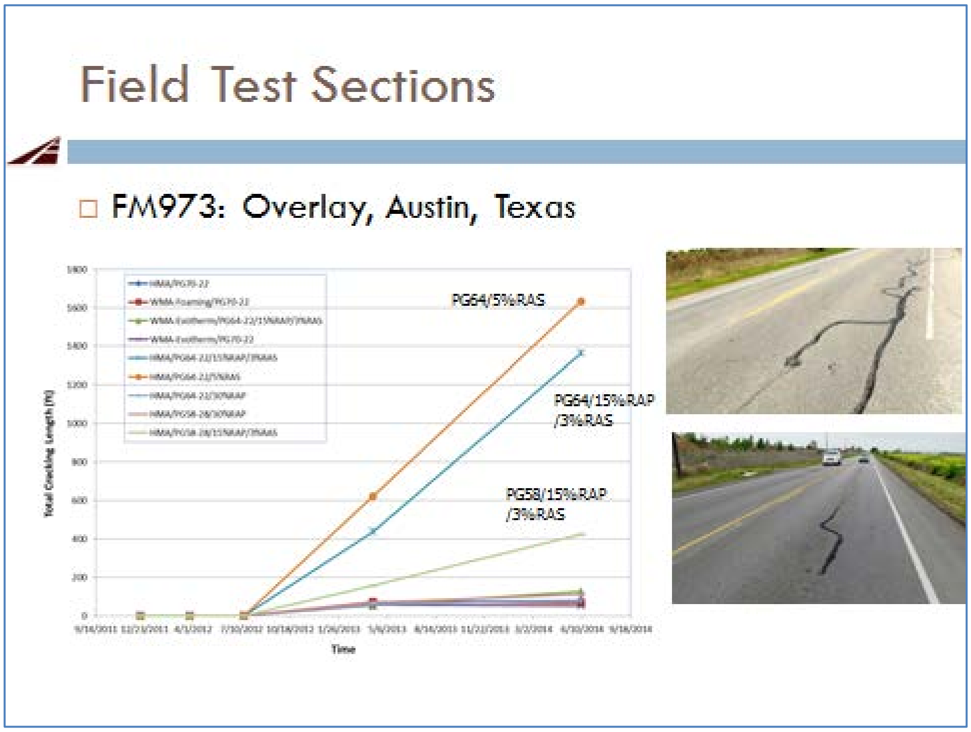
Field Test Sections

- Soft Binder
  - FM973: Overlay, Austin, Texas

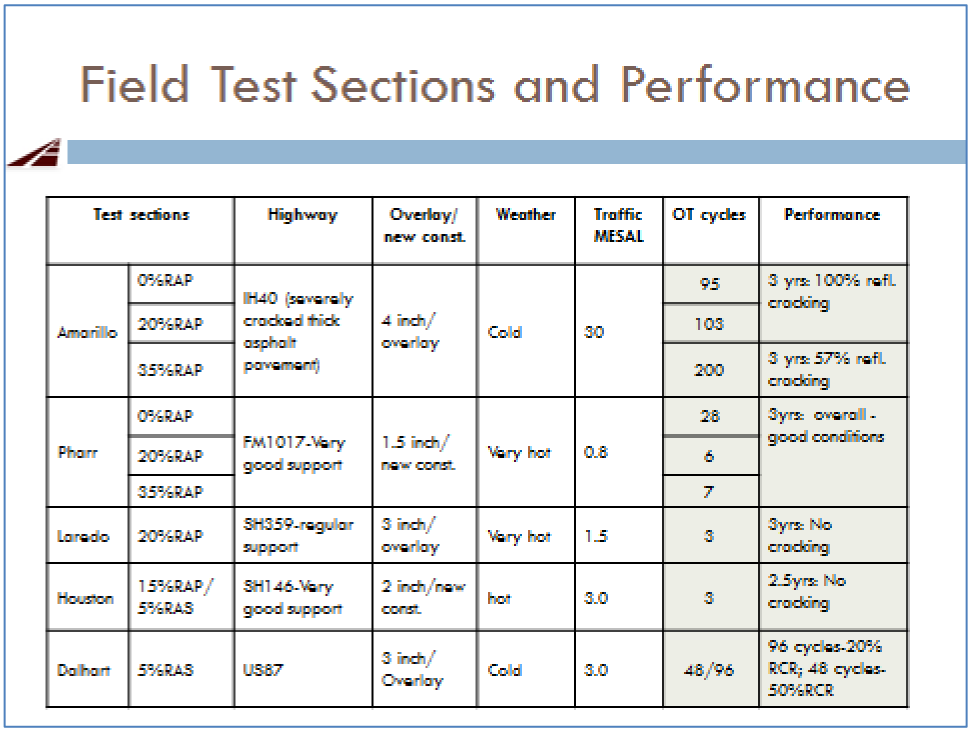
Section	Type	Binder	RAP	RAS
1	HMA	70-22	0	0
7	WMA Foaming	70-22	0	0
8	WMA Evotherm	70-22	0	0
9	WMA Evotherm	64-22	15	3
3	HMA	64-22	15	3
4	HMA	64-22	0	5
2	HMA	64-22	30	0
5	HMA	58-28	30	0
6	HMA	58-28	15	3



Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** A total of nine test sections with different RAP/RAS combinations were constructed on FM973, close to Austin, Texas. One of the purposes was to validate the effect of soft binder on improving cracking resistance of RAP/RAS mixes.
Notes:	N/A

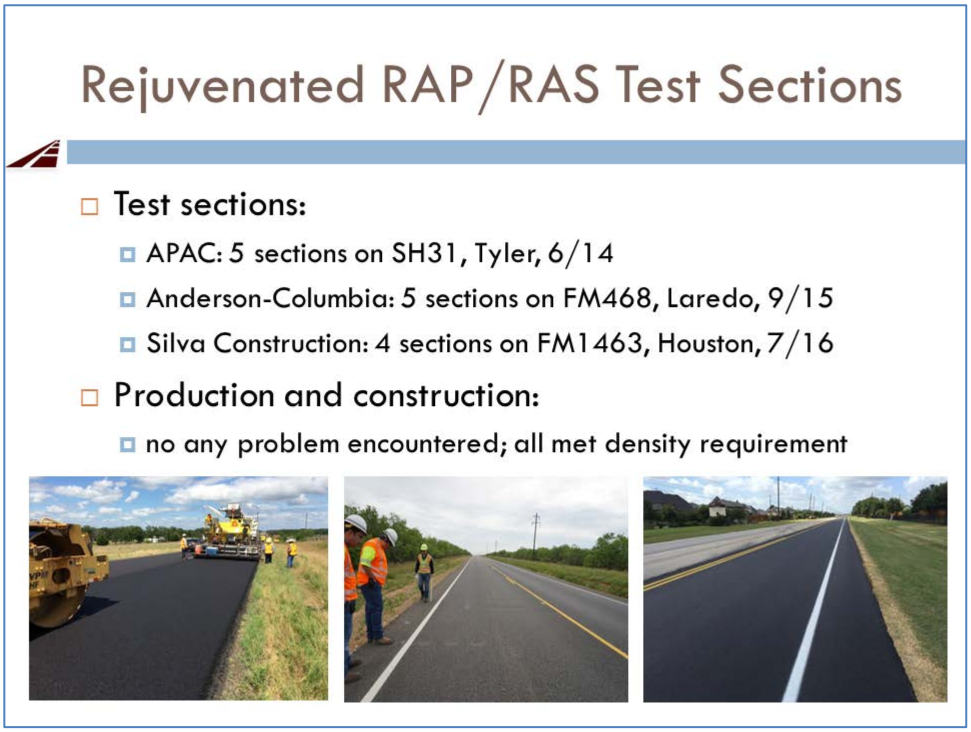


Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** The performance of the nine test sections clearly demonstrates that soft binder worked well to improve cracking resistance of RAP/RAS mixes.
Notes:	N/A



Test sections		Highway	Overlay/ new const.	Weather	Traffic MESAL	OT cycles	Performance
Amarillo	0%RAP	IH40 (severely cracked thick asphalt pavement)	4 inch/ overlay	Cold	30	95	3 yrs: 100% refl. cracking
	20%RAP					103	
	35%RAP					200	3 yrs: 57% refl. cracking
Pharr	0%RAP	FM1017-Very good support	1.5 inch/ new const.	Very hot	0.8	28	3yrs: overall - good conditions
	20%RAP					6	
	35%RAP					7	
Laredo	20%RAP	SH359-regular support	3 inch/ overlay	Very hot	1.5	3	3yrs: No cracking
Houston	15%RAP/ 5%RAS	SH146-Very good support	2 inch/new const.	hot	3.0	3	2.5yrs: No cracking
Dalhart	5%RAS	US87	3 inch/ Overlay	Cold	3.0	48/96	96 cycles-20% RCR; 48 cycles-50%RCR

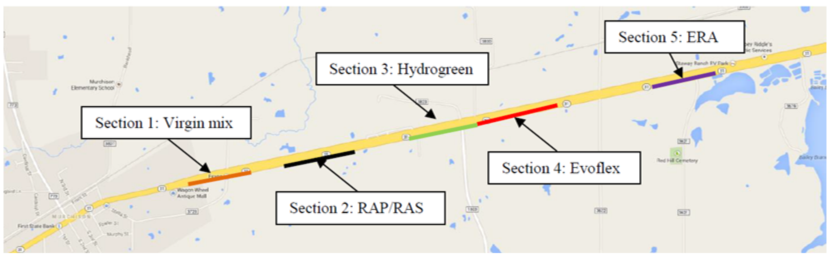
Key Message:	RAP/RAS field test sections and performance
Interactivity:	**Tell:** This slide summarizes the performance of field test sections and compared with OT cycles. It indicates that performance of RAP/RAS mixes depends on pavement structure, climate, traffic, and material engineering properties. They could have similar or even better performance than virgin mixes if designed and used in suitable conditions.
Notes:	N/A



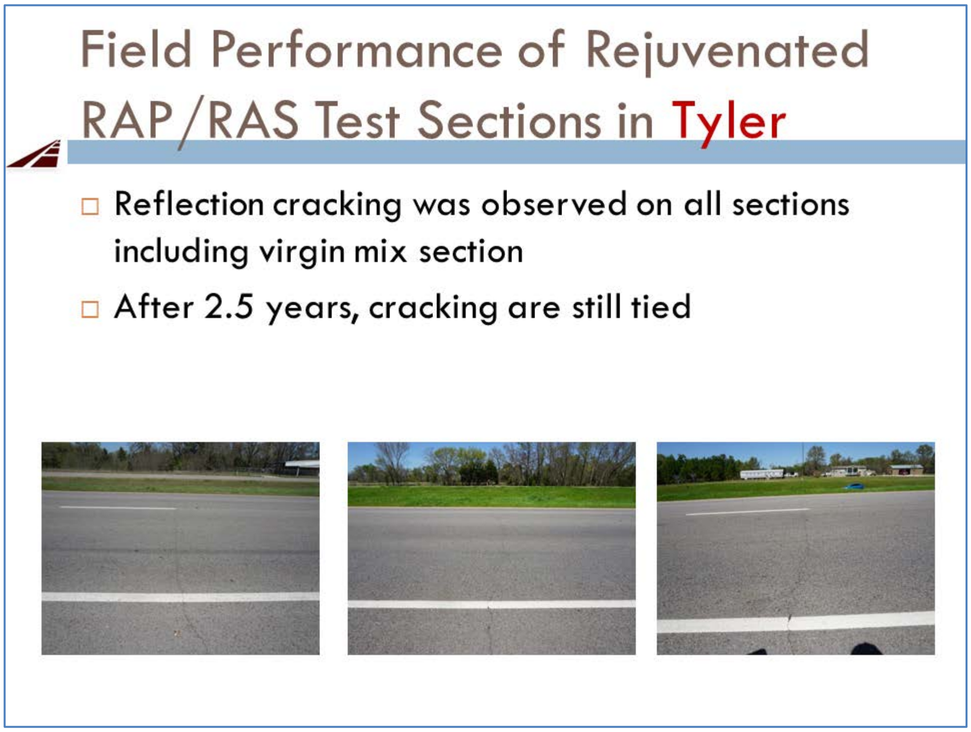
Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** This slide describes all rejuvenator test sections constructed in Teaxs.
Notes:	N/A

Field Performance of Rejuvenated RAP/RAS Test Sections in Tyler

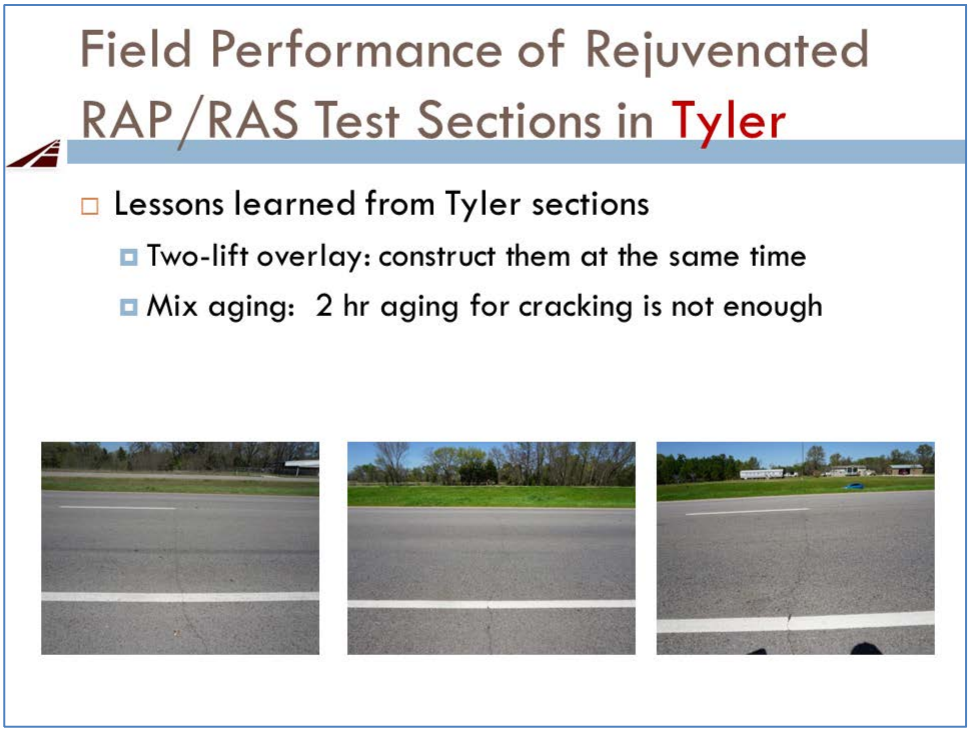
- Virgin mix with PG70-22
- RAP/RAS mix with PG64-22
- RAP/RAS mix with PG64-22 and 2.6% Hydrogreen
- RAP/RAS mix with PG64-22 and 3.7% Evoflex
- RAP/RAS mix with PG64-22 and 2.0% ERA



Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** This is the first test sections with rejuvenators in Texas. A total of five sections listed in the slide were constructed on SH31 close to Tyler.
Notes:	N/A



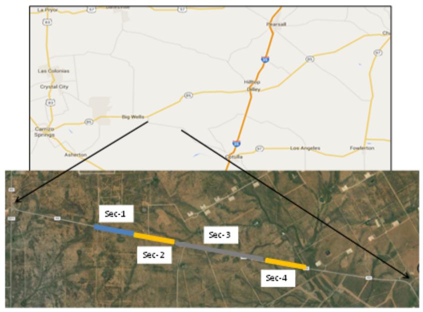
Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** The performance of the five test sections is discussed here.
Notes:	N/A



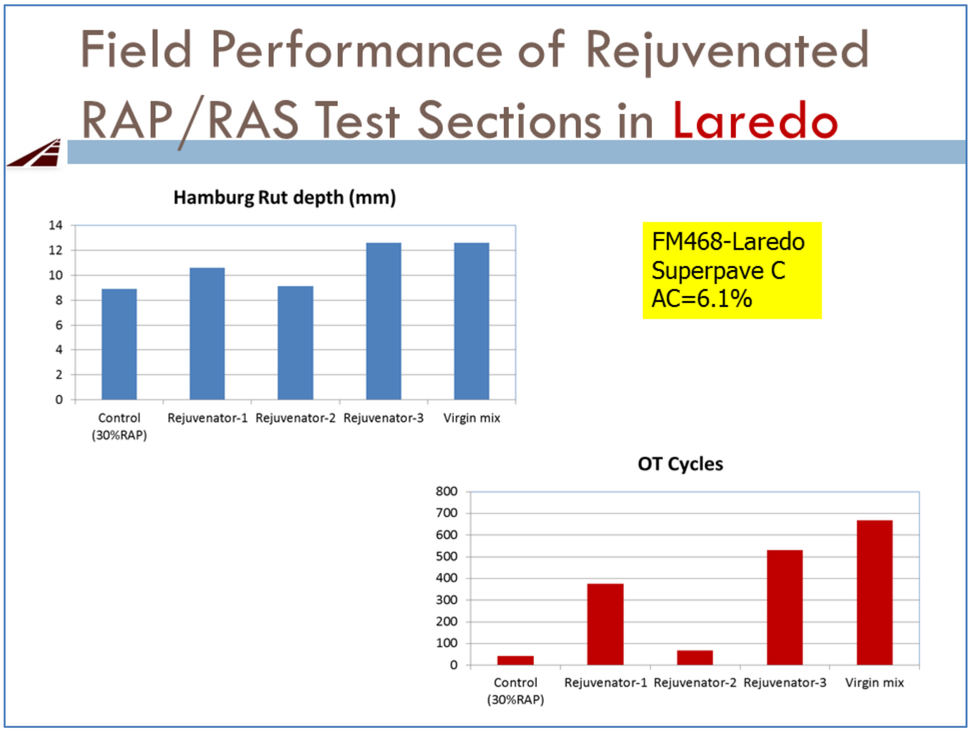
Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** This slide discusses two main lessons learned from SH31.
Notes:	N/A

Field Performance of Rejuvenated RAP/RAS Test Sections in Laredo

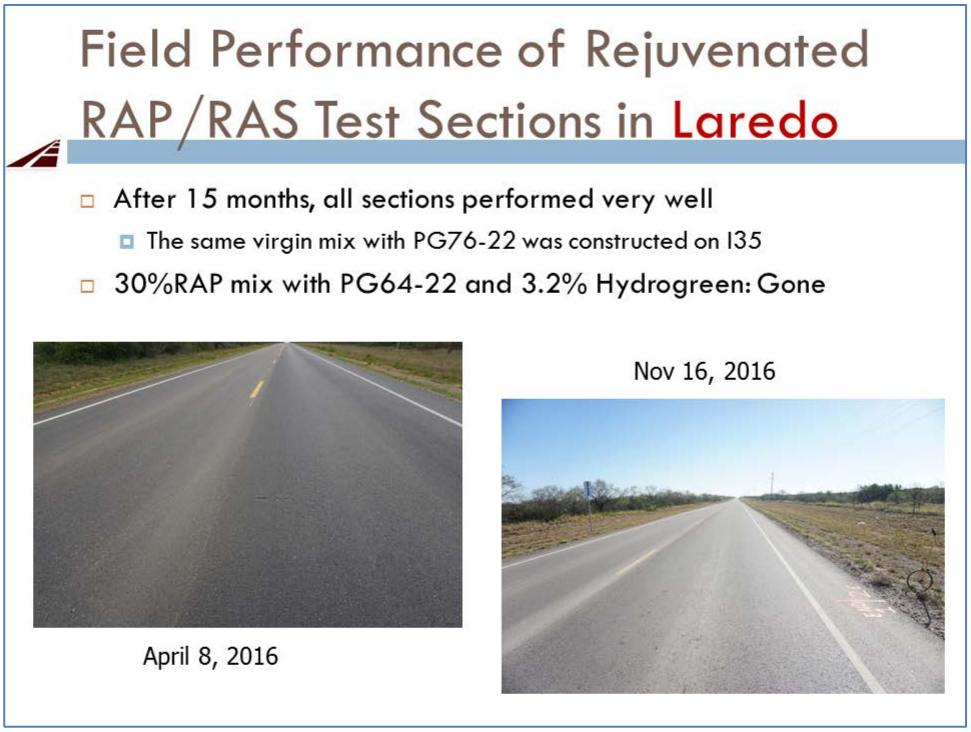
- Virgin mix with PG70-22
- 30%RAP mix with PG64-22
- 30%RAP mix with PG64-22 and 2.2% Road Science
- 30%RAP mix with PG64-22 and 3.0% Arizona Chemical
- 30%RAP mix with PG64-22 and 3.2% Hydrogreen



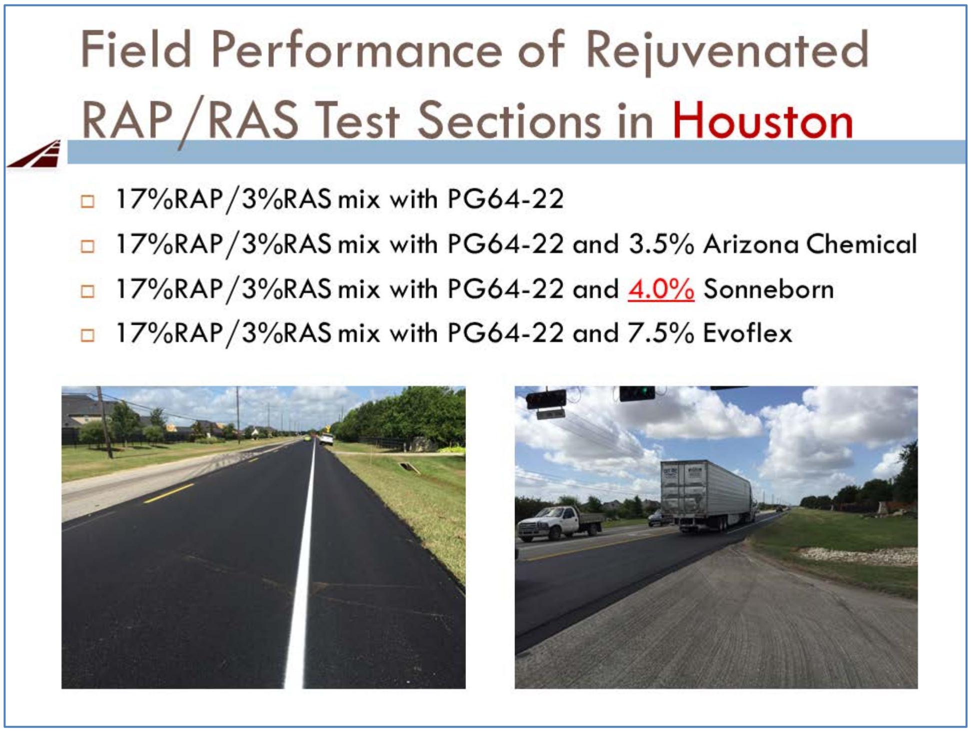
Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** Another five test sections were constructed on FM468 in Laredo District.
Notes:	N/A



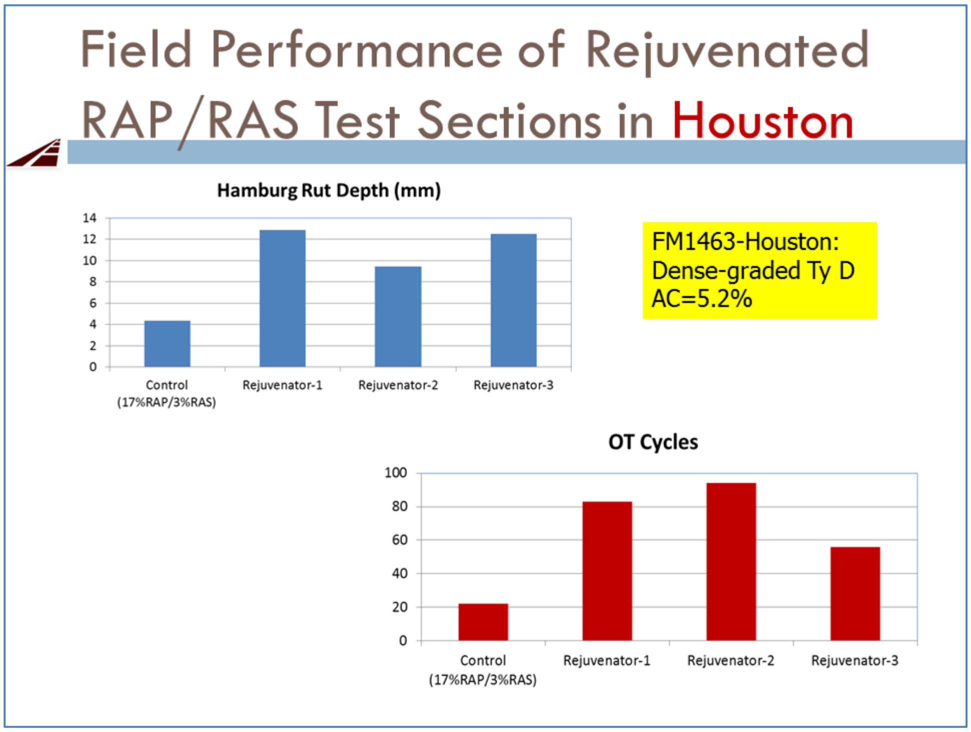
Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** Laboratory Hamburg and OT test results of five mixes used in the field are presented in this slide. One lesson learned is that the rejuvenator has better effect when it is directly mixed with virgin binder. The direct spraying rejuvenator on the RAP materials turned out to be not that effective.
Notes:	N/A



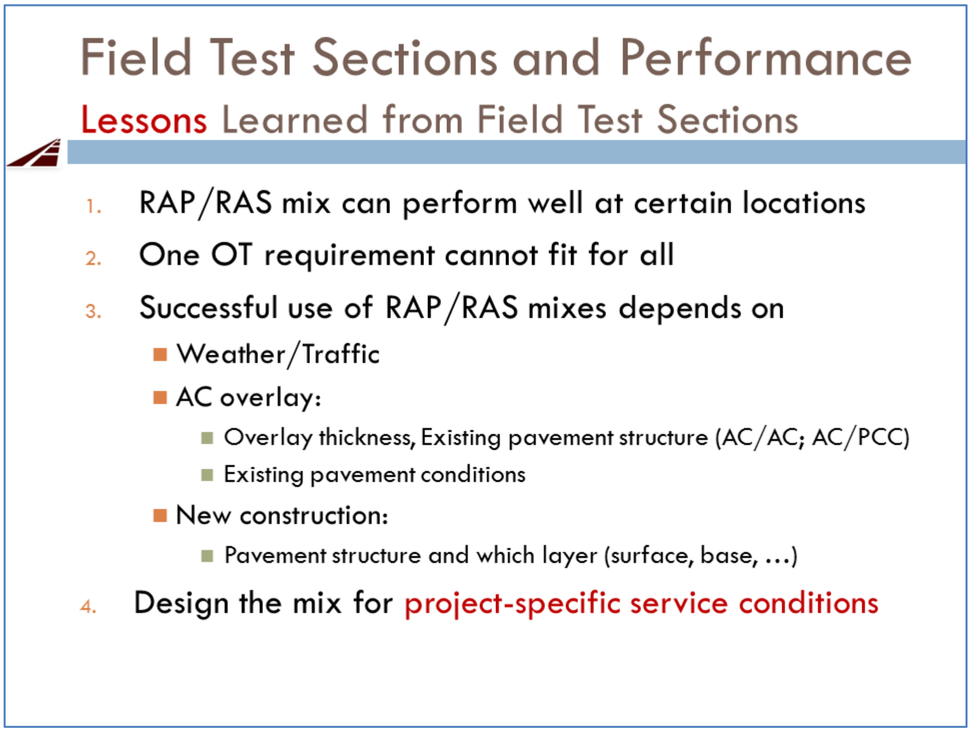
Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** This slide shows that all five test sections on FM468 performed well in the first 15 months.
Notes:	N/A



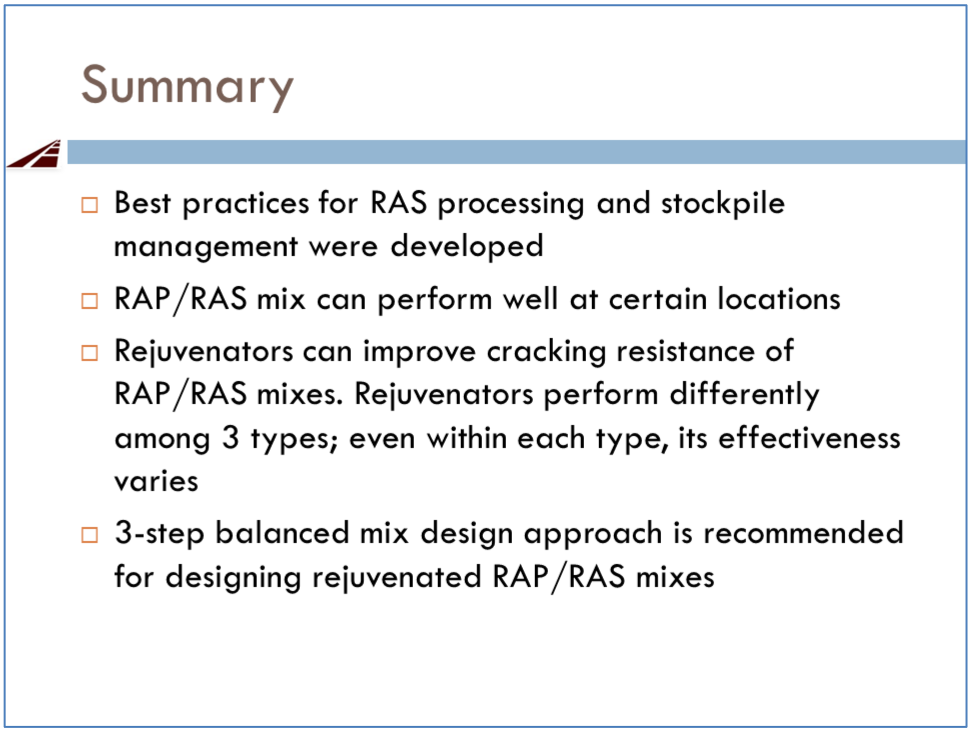
Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** Another four test sections were constructed on FM1463 in Houston District.
Notes:	N/A



Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** Laboratory test results of plant mixes from FM1463 are discussed here.
Notes:	N/A



Key Message:	RAP/RAS/rejuvenator field test sections and performance
Interactivity:	**Tell:** This slide summarizes all the lessons learned from field test sections.
Notes:	N/A



Key Message:	Summary of the workshop
Interactivity:	**Tell:** This slide simply summarizes this workshop.
Notes:	N/A

Key Message:	Q/A time
Interactivity:	**Tell:** It's Q/A time.
Notes:	N/A

Training Evaluation Form

for participants in RAS Best Practices Trainings

Date: ___________________

Title and location of training:

Trainer:

Instructions: Please indicate your level of agreement with statements listed below in #1–7.

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1. The objectives of the training were clearly defined.	0	0	0	0	0
2. The topics covered were relevant to me.	0	0	0	0	0
3. The materials distributed were helpful.	0	0	0	0	0
4. This training experience will be useful in my work.	0	0	0	0	0
5. The trainer was knowledgeable about the training topics.	0	0	0	0	0
6. The time allotted for the training was sufficient.	0	0	0	0	0
7. The meeting room and facilities were adequate and comfortable.	0	0	0	0	0

8. What did you like most about this training?

9. What aspects of the training could be improved?

10. Please share other comments here:

Thank you for your feedback!

APPENDIX B. BEST PRACTICE FOR THE USE OF RAS IN HMA—WORKSHOP STUDENT HANDBOOK

TTI: 5-6614-01

Best Practices for the Use of RAS in HMA: Workshop Student Handbook

Product 5-6614-01-P2

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/5-6614-01-P2.pdf

BEST PRACTICES FOR THE USE OF RAS IN HMA

Workshop Student Handbook

by

Fujie Zhou, Ph.D., P.E.
Research Engineer
Texas A&M Transportation Institute

Product 5-6614-01-P2
Project 5-6614-01

Project Title: Implementation of RAS Best Practices and Piloting Rejuvenators in Key Districts

Performed in cooperation with the
Texas Department of Transportation
and the
Federal Highway Administration

Published: February 2019

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DISCLAIMER

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Table 2. Potential Major Cracking Distresses for Different Applications. 13

CHAPTER 1: INTRODUCTION

The asphalt paving industry has always advocated recycling, including reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), tires, etc. The earliest recycling asphalt pavement dates back to 1915. In addition to conserving energy and protecting the environment, the use of RAP/RAS can significantly reduce the cost of hot-mix asphalt (HMA) paving. RAP has been the most extensively recycled material in the history of the asphalt paving industry. With recent increases in the price of asphalt cement and subsequent price fluctuations, the industry has further amplified its recycling efforts (Hansen, 2009). Most recently, the use of RAS in HMA has become another black gold to the asphalt paving industry since RAS contains a significant amount of asphalt binder (see Table 1). There are two basic types of roofing shingle scraps: 1) post-consumer asphalt shingles or tear-off asphalt shingles (TOAS), and 2) manufacture waste asphalt shingles (MWAS) including roofing shingle tab punch-outs and out-of-spec shingles. MWAS is called prompt roofing shingle scrap in some publications. 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 used in various pavement constructions.

Table 1. Typical Compositions of New Residential Asphalt Shingles.

(modified after Krivit, 2007)

Component	**Organic Shingles, % by wt.**	**Fiberglass Shingles, % by wt.**
Asphalt Cement	30–36	19–22
Reinforcing Mat	2–15	2–5
Mineral Granules/aggregate	20–38	20–38
Mineral Filler/stabilizer	8–40	8–40
Adhesives (modified asphalt based)	0.2–2	0.2–2

More than 30 years ago, some of the original pioneers established the first shingle recycling plants, investigated HMA mix designs incorporating 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, several additional HMA producers and departments of transportation have developed substantial in-house expertise in shingle recycling in HMA (Grzybowski, 1993; Newcomb et al., 1993; Button et al., 1996; Janisch and Turgeon, 1996; NAHB, 1999; Dykes, 2002; Lum, 2006; Brock 2007; Schroer, 2007). Within the last two or three years, a few contractors and state departments of transportation have begun using or studying the use of recycled shingles in warm mix asphalt (WMA) (Robinette and Epps, 2010; Maupin, 2010; Middleton and Forfylow, 2009).

With the recent increased use of asphalt shingles in asphalt mixtures, there is a need to further study this issue. The main objective of this workshop is to present best practices for RAS collection, processing, screening, and stockpile management of processed shingles and RAS mix design, production, construction, and performance evaluation.

This handbook is organized in four chapters. Chapter 1 provides an introduction, and Chapter 2 presents the best practices for the RAS processing and stockpile management in Texas. Chapter 3 discusses the balanced mix design for RAS/RAP/rejuvenators, and the production and field construction of RAS mixes. Finally, this report concludes with a summary described in Chapter 4.

CHAPTER 2:
BEST PRACTICES FOR RAS PROCESSING AND STOCKPILE MANAGEMENT

RAS processing is one of the critical steps for using the RAS in HMA and producing high quality RAS mixes. As noted previously, two types of RAS are available for processing: MWAS and TOAS. For use in HMA, MWAS has traditionally been preferred over TOAS, primarily because MWAS contains fewer contaminants (Hansen, 2009; Maupin, 2008), plus the asphalt in MWAS is less oxidized (Button et al., 1996). MWAS only requires grinding with little or no sorting, inspection, testing, or separation of undesirable materials. Specifically, there is no need for asbestos testing for MWAS. However, MWAS is geographically significantly more restricted than TOAS, as shingle manufacturing facilities are typically located only in densely populated areas (see Figure 1). In contrast, TOAS are more readily available to contractors and recyclers. The main concerns with TOAS are potential asbestos, deleterious materials (including metal, wood, plastic, paper, etc.), and very hard highly oxidized asphalt. Consequently, it becomes more difficult to process the TOAS, and asbestos testing is required in Texas.

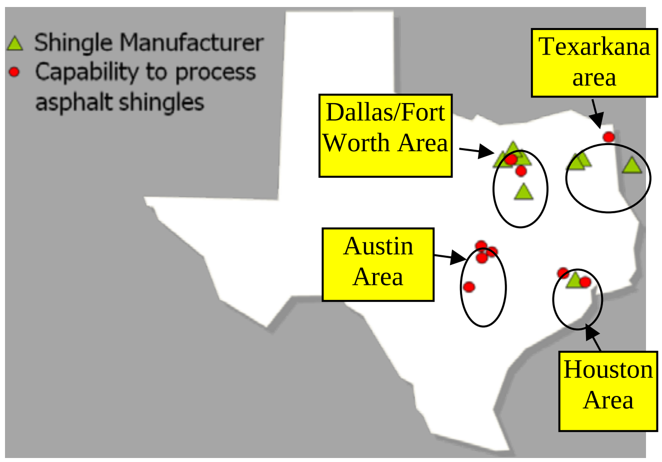

Figure 1. Shingle Manufacturers and Processors in Texas.

Processing RAS basically includes five steps: collecting, sorting, grinding, screening, and storing the processed RAS plus asbestos testing for the TOAS. The research team visited different recyclers and contractors in Texas and reviewed published literature to identify the best practices for each of the steps. Figure 2 shows the best practices identified; detailed explanations and associated guidelines follow.

Step 1: Collecting

Step 2: Asbestos testing for TOAS

Step 3: Sorting

Step 4: Grinding

Step 5: Screening

Step 6: Storing

Figure 2. Proposed RAS Processing Steps.

STEP 1. COLLECTING

Quality (cleanness) of RAS and a sustainable supply are two major issues related to collecting RAS. MWAS is relatively clean, but its supply is limited. In contrast, TOAS has relatively more supplies, but its cleanness (or contamination) is a bigger problem. According to Krivit (2007), the two basic types of strategies to develop a clean, secure supply are:

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

Under either strategy, Krivit (2007) continues, TOAS recyclers must work proactively with suppliers to ensure that no asbestos containing material (ACM) is delivered to the recycling plant. After the TOAS are tipped at the recycling plant, a second stage of quality inspection and sorting occurs. Most facilities use both manual separation (e.g., dump and pick, sorting conveyors) and mechanical equipment (e.g., screens, air classifiers). Shingle recyclers have demonstrated a wide variety of techniques to cost-effectively meet and exceed the minimum waste sampling and asbestos testing requirements. They have recently developed innovations, such as establishing in-house laboratories that use standard detection methods and certified personnel. Such internal laboratories minimize the turnaround time for test results. Together with other in-house personnel training and supplier technical assistance, TOAS recyclers are proactively managing their supplies through upstream quality control and quality assurance.

Hanson (2009) points out that as part of the quality control and acceptance program, shingle recycling operations need an inspection and testing plan for waste shingles delivered to the site, which should include:

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

A list of prohibited materials for TOAS recyclers should include (Krivit, 2007):

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

STEP 2. ASBESTOS TESTING FOR TOAS

According to Hansen (2009), the main issue that impedes recycling of TOAS is concern over potential asbestos content. In the past, asbestos was sometimes used in manufacturing asphalt shingles and other shingle installation materials. Asphalt shingle manufacturers generally acknowledged that, between 1963 and the mid-1970s, some manufacturers did use asbestos in the fiber mat in some of their shingle products, but the total asbestos content of those shingles was always less than 1 percent. Other materials used in shingles, such as some tarpapers and some types of asphalt cement, also reportedly contained asbestos. In reality, while asbestos was used in some asphalt roofing materials, asbestos was rarely used in the shingles themselves.

Since TOAS may contain asbestos, the Texas Department of State Health Service (TDSHS) regulates asbestos-containing materials including TOAS. More detailed information on asbestos program can be found at TDSHS' website: http://www.dshs.state.tx.us/asbestos/pubs.shtm. Generally, asbestos testing (Figure 3) involves sampling each layer of roofing material. Details of asbestos testing are described in *Test Method for the Determination of Asbestos in Building Materials* (Perkins and Harvey, 1993). The complete test method is available at: http://www.rti.org/pubs/Test-Method-for-Determination.pdf. Representative samples must be properly selected, labeled, recorded in a sample log book, and then sent to an accredited asbestos testing laboratory for assay of asbestos content. TOAS recyclers should contact the appropriate state environmental and/or health agency to determine specific requirements for sample collection, analytical procedures, data reporting, and records preservation.

Figure 3. Setup for Asbestos Testing (after Krivit, 2007).

Krivit (2007) advised that shingle recycling operators should attend state-sponsored training courses to become licensed asbestos inspectors. Trained personnel should inspect each load to visually detect possible ACM. This will help increase the awareness of potential asbestos containing materials and allow company personnel to help provide accurate, timely, and state-approved information and related technical assistance to material suppliers and other customers. Shingle recycling operators should contact their state representative for the National Emission Standards for Hazardous Air Pollutants to explore technical assistance resources, including a listing of organizations providing asbestos inspector training. The website www.shinglerecycling.org is an excellent source of EPA and other regulatory information on asbestos, management, and recommended best practices. Specifically, in Texas, TCEQ has several regulations that may impact asphalt shingle processors, which can be found using the following links:

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

STEP 3. SORTING

Generally, little sorting work is needed for MWAS. However, substantial sorting work is required for TOAS because various debris (e.g., nails, wood, and insulation) contaminate this type of shingle. Any debris must be removed to prevent equipment damage during size reduction and produce high-quality processed RAS. There is no standard processing equipment to accomplish this task; in most cases, the debris has to be sorted out manually (see Figure 4).

Figure 4. Sorting RAS Manually.

Note that most facilities will recover metal and cardboard (perhaps in baled form) as secondary recyclable products. Trash from such sorting consists of plastic, non-recyclable metal, and paper. Recovery rates of TOAS from mixed waste sorting systems range from 15 to over 90 percent, depending on the feedstock and the efficiency of the separation (Krivit, 2007).

STEP 4. GRINDING

The vast majority of RAS used in asphalt paving mixes is ground into pieces smaller than 1/2 in. (13 mm) in size using a shingle grinding or shredding machine consisting of a rotary shredder and/or a high-speed hammer mill. It seems logical that, as shingles are ground finer, more RAS asphalt can be mobilized into the paving mixture.

According to Krivit (2007), each grinder manufacturer uses a unique combination of material handling and size reduction designs. RAS sizing is a key specification and will determine the product's suitability for various applications. For example, the larger particle size (+ 3/4 in.) may be more suitable for aggregate supplement. In general, the grinder will include a loading hopper; a grinding chamber that includes cutting teeth, sizing screens, and exit conveyor; and a feeding drum to present the shingles into the grinding chamber. A pulley head magnet at the end of the exit conveyor is standard equipment for removing nails and other ferrous metal. The final RAS product is stacked using a stacking conveyor and/or front-end loader. During visits to recyclers and contractors, the research team noted that it is important and necessary to pick up some debris left in the sorted, clean pile before feeding to the grinder (see Figure 5).

Figure 5. Preparation for Grinding.

To prevent agglomerating during grinding, the material may be passed through the grinding equipment only once to reduce heating, or it is kept cool with water spray at the hammer mill. However, the application of water is not very desirable, since the processed material becomes quite wet and must be dried (thus incurring additional fuel cost) prior to introduction into the HMA (Chesner et al., 1997).

STEP 5. SCREENING

Ground shingles may contain oversized pieces that do not meet the specification requirement. To remove the oversized pieces, the operators ideally should screen the processed RAS using a trommel screener (Figure 6). This equipment can help customize the size of processed RAS, guaranteeing that the specifications are met. Furthermore, the oversized pieces can be reground to the ideal size. Chesner et al. (1997) contends that scrap shingle greater than 1/2 in. may not readily disperse in HMA and may function much like aggregate particles; too small particles can release short fibers, which act as a filler substitute. Hansen (2009) adds that several HMA producers have found that grinding to less than 3/8 in. improves blending. The Texas Department of Transportation (TxDOT) specifies 100 percent passing the 1/2-in. sieve with 95 percent passing the 3/8-in. sieve.

Figure 6. Screening RAS Using Trommel Screen Machine.

STEP 6. STORING

Storing the processed RAS is typically similar to that of aggregate or RAP. Because the average gradation of RAS is very small, a stockpile can absorb a large amount of water, which can cause problems during HMA mixing (inadequate coating), compaction (mat tenderness), and performance (higher stripping potential) as well as require more fuel for drying. Ideally, a RAS stockpile should be covered (Figure 7). Additionally, it is important to keep loaders off RAS stockpiles and separate high AC RAS (tear-offs) from low AC RAS (manufacture waste).

Button et al. (1996) deduced that, during static storage in a stockpile, shredded roofing shingle material can agglomerate. High temperatures and the stickier manufacturing waste shingles can magnify this issue. Significant agglomeration or consolidation of processed roofing material necessitates reprocessing and rescreening prior to introduction into the hot mix plant. To mitigate this problem, processed roofing shingle scrap may be blended with a small amount of less sticky carrier material, such as sand or RAP, to prevent the RAS particles from clumping together.

Figure 7. Covered RAS Storing Facility.

SUMMARY

This chapter discussed best practices for RAS processing and proposed guidelines for collecting, sorting, grinding, screening, and storing the processed RAS. The asbestos test is required for the TOAS.

CHAPTER 3: BALANCED RAS/RAP MIX DESIGN, PRODUCTION, AND CONSTRUCTION

INTRODUCTION

Although there is no significant difference between RAS mixes and virgin mixes in terms of production in the plant, designing RAS mixes is more complicated than that for virgin asphalt mixes. Not only must the virgin aggregate and virgin binder information be obtained, but RAS binder content and RAS aggregate gradation must be determined through the ignition oven. Asphalt binder recovery tests may be needed to grade the RAS binder in order to use the asphalt blending chart. Additionally, there are at least five more challenges when designing RAS mixes in Texas.

Cracking Resistance of HMA Mixes with RAS

Virgin HMA mixes designed using the Texas gyratory compactor (TGC) are generally dry and have good rutting resistance but relatively poor fatigue and reflection cracking resistance. Poor cracking resistance may become even worse when mixes containing stiff, hard RAS binders are placed. It is critical for HMA mix designs with RAS to have acceptable cracking resistance through increasing the density requirement for TGC designed mixes or reducing N_{design} for Superpave Gyratory Compactor (SGC) designed mixes so that enough virgin binder is included in the mix. Alternatively, a balanced mix design approach Zhou et al. (2007) proposed can be used to design mixes with RAS, whereby the optimum asphalt content (OAC) is selected based on target air voids (or density), rutting/moisture, and cracking resistances determined using the Hamburg wheel tracking test (HWTT) and the Overlay test (OT), respectively.

Virgin and RAS Binder Blending

The virgin and RAS binder blending issue has not been well investigated. The actual blending between virgin and RAS binder during production is unknown. Although some approaches (e.g., dynamic modulus-based approaches) have been proposed for RAP/virgin binder blending, how much of the RAS binder actually blends with the virgin binder is very difficult, if not impossible, to determine accurately. Apparently, more work is needed in this area.

RAS Heating

RAS needs heating to make it workable and activate RAS binder. Many methods are available for handling RAS in the lab during the mix design process, but none of them can truly simulate the plant production process.

It is important to heat RAS materials to ensure the RAS binder becomes an active part of the HMA binder. Basically, there are two issues with RAS heating in the laboratory: time and temperature. Different methods are available. Some designers preheat RAS materials at the target mixing temperature for a certain period of time before mixing with virgin aggregates. Others superheat the virgin aggregate to ensure heat transfer to the RAS, which is added at room temperature. There is no specific information on RAS heating in the literature. Based on the research team's experience with RAP mix design and limited data on RAS mix design, a two-step preheating process is recommended: (1) warm the RAS overnight (12–15 hours) at 140°F

(60°C), which is a common temperature to dry materials, and 2) preheating the RAS at the mixing target temperature for two hours, which is a common time for preheating virgin binder. This two-step preheating process needs further verification.

Mixing and Compaction Temperatures

Mixing and compaction temperatures are important and influence compaction, volumetrics (e.g., air voids, VMA), and consequently OAC. For any virgin asphalt mix, the mixing and compaction temperatures are selected based on virgin binder properties (i.e., viscosity). When RAS is added, one has to consider both virgin binder and RAS binder properties. Guidelines are needed for selecting suitable mixing and compaction temperatures, especially when designing HMA mixes with high RAS content.

Mixing and compaction temperatures for high RAS mixes have not been well addressed in the literature. For RAS mixes, there are at least three options for selecting laboratory mixing and compaction temperatures:

- Those corresponding to the virgin binder.
- Those corresponding to the blended virgin/RAS binder.
- Those corresponding to the RAS binder.

Generally RAS binder is stiffer than virgin binder. The virgin binder will be overheated and, consequently significantly aged if Option 3 (those corresponding to the RAS binder) is chosen. Increasing the mixing and compaction temperatures lowers the OAC and consequently, cracking resistance of RAS mixes, since the higher mixing and compaction temperatures lead to lower OAC. From the conservative point of view, researchers propose to use Option 1: the mixing and compaction temperatures corresponding to virgin binder. This potentially provides RAS mixes adequate OAC, so better cracking resistance.

RAS in Warm Mix Asphalt

A few researchers (Robinette and Epps, 2010; Middleton and Forfylow, 2009) recently reported that RAS had been used in WMA, but no lab testing has been done to make conclusive findings on RAS/WMA. The only one report (Maupin, 2010) was found in which testing of WMA containing RAS was performed. However, after carefully reviewing the work done by Maupin (2010), researchers found that neither additives nor a forming system was used to produce the WMA. Instead, he simply lowered the mixing temperature to 250°F from the regular HMA temperature of 300°F, so more work is definitely needed in this area.

BALANCED RAS/RAP MIX DESIGN

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

Table 2. Potential Major Cracking Distresses for Different Applications.

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

Currently, asphalt mix design in Texas is based on volumetric properties of asphalt mixes plus checking potential rutting and moisture damage. Texas and other states have already established the rutting/moisture damage requirements for mixes with different types of binders. For example in Texas, the rut depth of a mix with PG76-22 binder should be less than 1/2 in. (12.5 mm) after 20,000 passes. However, there is no cracking requirement on most Texas mixes. As clearly observed in the field, it is very difficult (if not impossible) to establish a single cracking requirement for all scenarios, because cracking performance of asphalt mixes depends on traffic, climate, pavement structure, and existing pavement conditions for asphalt overlays. A balanced RAP/RAS mix design system for project-specific conditions, rather than a single cracking requirement, should be developed and then implemented to ensure the mixes designed with acceptable field performance.

This system is a two-step process. In Step 1, the site conditions will be evaluated and the performance model will be run to predict pavement performance for a range of different materials properties (different OT cycles), and the designer then selects the OT requirement to meet the design performance goal (for example less than 50 percent reflective cracking after 5 years). In Step 2, a lab mix design is run to develop a mix with the required OT cycles. If this does not work, the mix will be redesigned, this time changing overlay thicknesses or virgin binder (or others).

In the last 10 years, TTI researchers have made significant progress toward that goal—the balanced RAP/RAS mix design system for project-specific conditions, as shown in Figure 8. This system integrates both mix design and pavement structure design, which has been pursued for long time. Basically, the proposed system is an expanded balanced mix design procedure in which cracking performance is evaluated through a simplified asphalt overlay performance analysis system, S-TxACOL, with OT cycles as an input, as shown in Figure 9. The same reflective cracking model as that in TxACOL (Zhou et al., 2010) is used in the S-TxACOL.

Three mechanisms (shearing, bending, and daily thermal movement) of reflective cracking are all modeled through fracture mechanics.

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

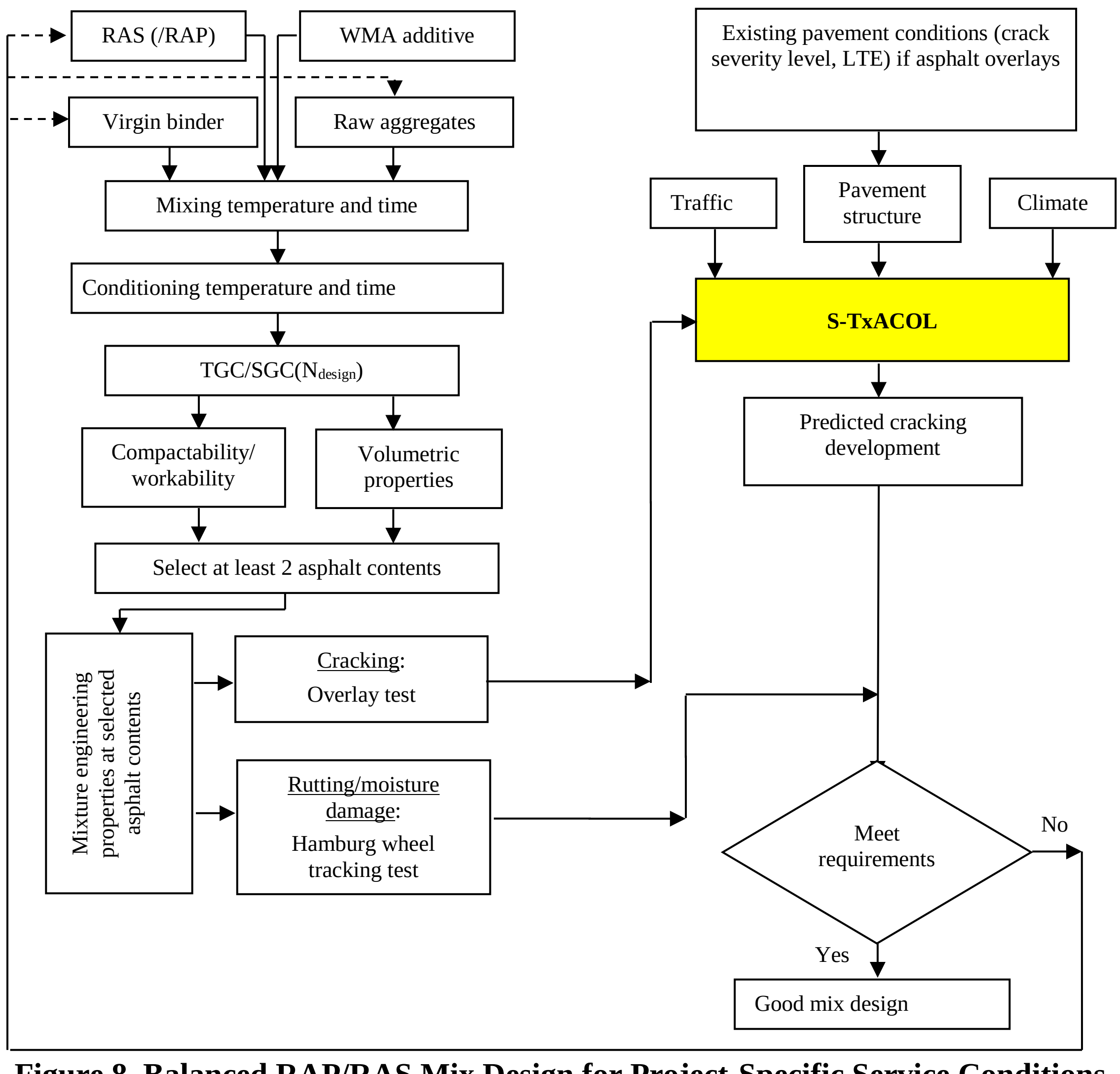

Figure 8. Balanced RAP/RAS Mix Design for Project-Specific Service Conditions.

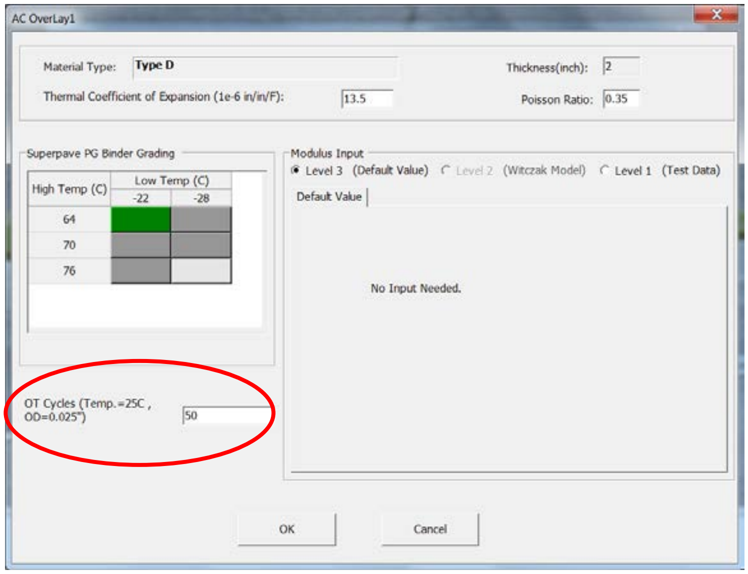

Figure 9. OT Cycles Input Interface for S-TxACOL.

DEMONSTRATION OF VARIOUS CRACKING REQUIREMENTS FOR PROJECT-SPECIFIC CONDITIONS

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

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

A 2 in. (50 mm) asphalt overlay with PG 70-22 binder is applied to the following existing pavements with different load transfer efficiency (LTE) in Bastrop County, Austin District. The traffic level is 3 million Equivalent Single Axle Load (ESAL) within 20 years. The relationship between OT cycles and cracking development for each application predicted from S-TxACOL is shown in Figures 10 and 11:

- 10 in. (250 mm) jointed portland concrete pavement (JPCP) over 6 in. (150 mm) base with LTE=70 percent.
- 3 in. (75 mm) asphalt pavement over 10 in. (250 mm) cement stabilized base (CTB) with LTE=70 percent.
- 5 in. (125 mm) asphalt layer over 12 in. (300 mm) granular base with medium severity cracking (LTE=70 percent).
- 10 in. (250 mm) continuous reinforced concrete pavement (CRCP) over 6 in. (150 mm) base with LTE=90 percent.
- 8 in. (200 mm) asphalt layer over 10 in. (250 mm) very stiff base with low severity level (LTE=50 percent).

The results shown in Figure 10 and Figure 11 clearly indicate that varying OT cycles (or cracking requirement) are necessary for different applications. In order to have the same overlay life, the mix being used for asphalt overlay over JPCP should have higher OT cycles, when compared to asphalt overlay over CRCP. Clearly, it is much safer to use RAP/RAS mixes for asphalt overlay over CRCP.

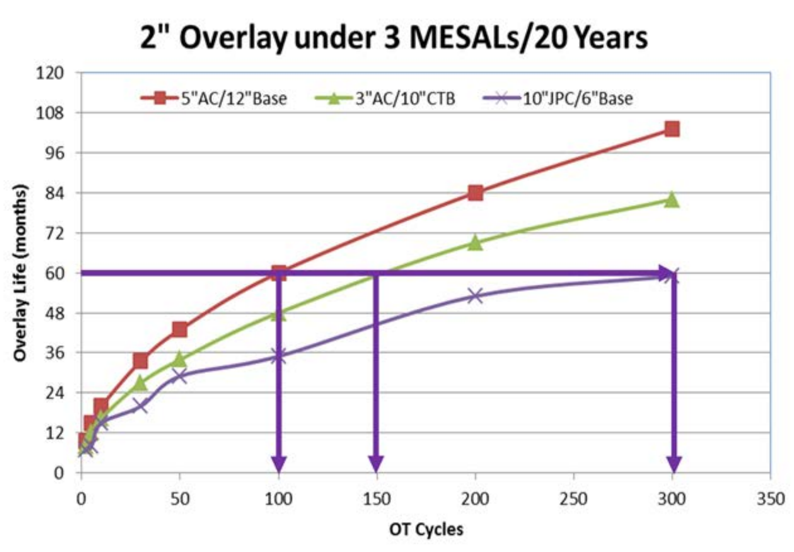

Figure 10. Relationships between OT Cycles and Cracking Development for Three Applications with Medium Cracking Severity.

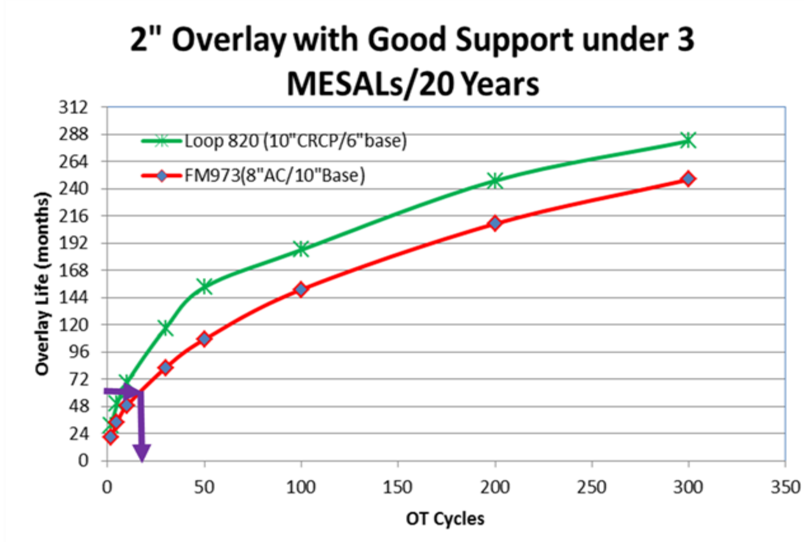

Figure 11. Relationships between OT Cycles and Cracking Development for Two Applications with Very Good LTE.

Case 2: Impact of Climate on Cracking Requirements

Again, the same 2 in. (50 mm) asphalt overlay with PG 70-22 binder is assumed to apply to the following existing pavements at three climatic zones: Amarillo, Austin, and McAllen. Amarillo has severe winter conditions with lots of freeze-thaw cycling, and McAllen has a very mild winter with no freeze-thaw cycle. The same traffic level of 3 million ESALs within 20 years is assumed. Figure 12, Figure 13, and Figure 14 show the relationship between OT cycles and cracking development for each application predicted from S-TxACOL. The overlay life is defined as time until 50 percent return of reflective cracking. It is obvious that climate has significant influence on cracking development and consequently on cracking requirement:

- 10 in. (250 mm) JPCP over 6 in. (150 mm) base with LTE=70 percent.
- 3 in. (75 mm) asphalt pavement over 10 in. (250 mm) CTB with LTE=70 percent.

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

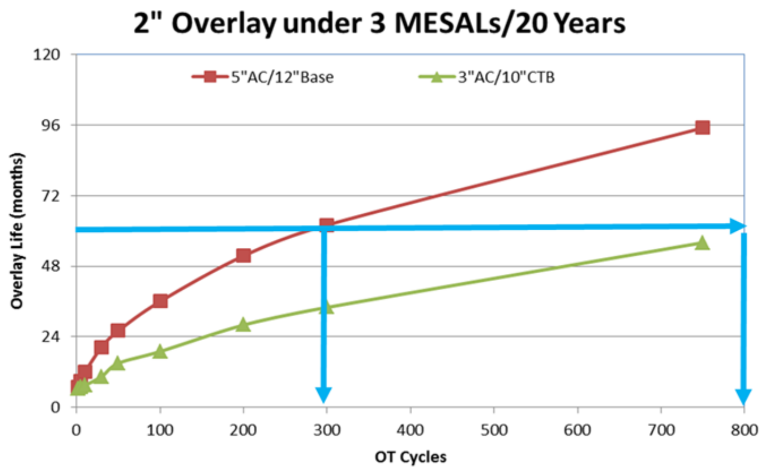

Figure 12. Amarillo: Relationships between OT Cycles and Cracking Development.

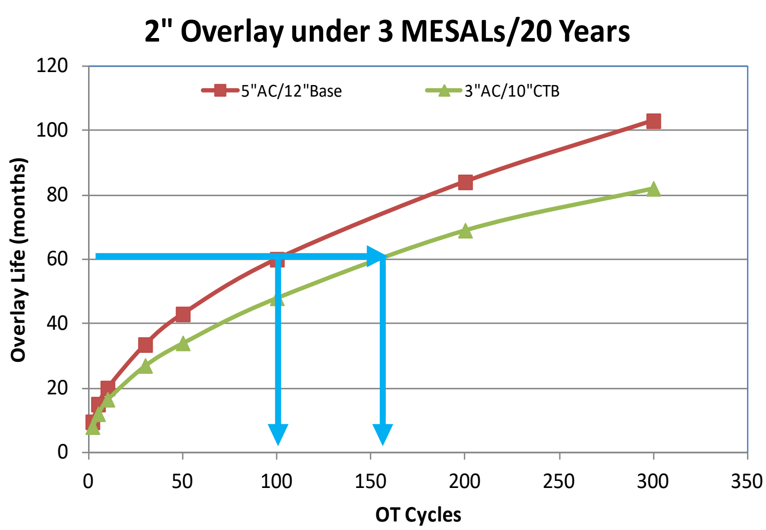

Figure 13. Austin: Relationships between OT Cycles and Cracking Development.

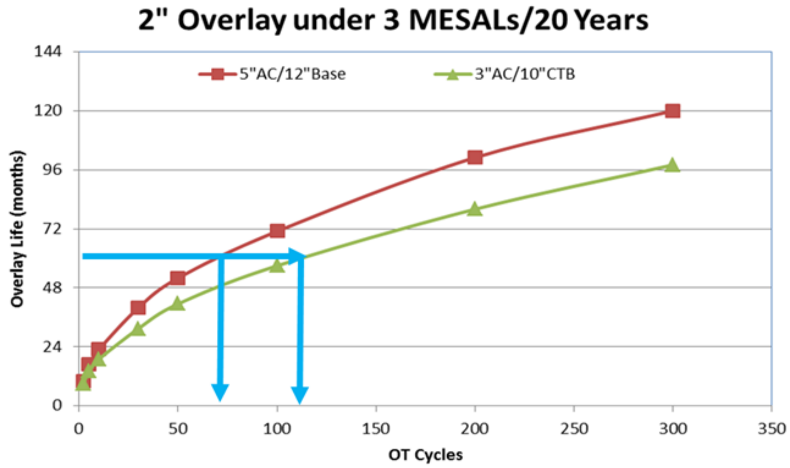

Figure 14. McAllen: Relationships between OT Cycles and Cracking Development.

RAS MIX PRODUCTION

Producing RAS mixes is similar to that for RAP mixes. Normally RAS is treated like RAP with a cold bin and is fed into the plant. As Morton (2011) noted, there are at least four specific issues that are worth watching when producing RAS mixes:

- Keep RAS bin empty when not in use.
- Use a vibratory scalping screen (Figure 15) to help break down or remove clumps that may be in the RAS material before entering the drum.

Figure 15. Vibratory Scalping Screen (after Morton, 2011).

- Do not superheat the mix; it makes the RAS mix stiffer and more difficult to work with in the field.
- Avoid holding RAS mix in silo overnight.

RAS MIX CONSTRUCTION

Construction of RAS mixtures is similar to that for RAP mixes. Again there are several specific issues to consider during RAS mix construction, as Morton (2011) pointed out:

- Consider the weather.
- Consider the haul distance.
- Consider the trucks that haul the mix.
- Do not let mix sit in trucks too long on job site.
- Check RAS mix temperature when unloading trucks.
- Stiffen quicker in trucks than standard hot mix.
- Be more difficult to hand work.
- Be more sensitive to temperature segregation.

SUMMARY

This chapter discussed issues related to balanced RAS/RAP mix design, production, and field construction.

CHAPTER 4: SUMMARY AND RECOMMENDATION

This handbook presented the best practices for using RAS in asphalt mixes in terms of RAS processing and stockpile management, balanced RAS/RAP mix design, production, and field construction. Based on the information presented, the following findings and conclusions are offered:

- A six-step RAS processing guideline is proposed in this study, which includes: collecting, sorting, grinding, screening, and storing the processed RAS plus asbestos testing for TOAS.
- RAS binders are very stiff. It is critical to investigate blending between virgin binders and RAS binders. Note that the low temperature PG of RAS binder is **above** 0°C.
- Issues related to RAS mix design, production, and construction were identified and discussed. Specifically, the balanced RAS/RAP mix design is proposed for project specific conditions.

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APPENDIX C. BEST PRACTICE FOR THE USE OF RAS IN HMA—PRESENTATION

Best Practices for The Use of RAS in HMA

Texas A&M Transportation Institute

Product 5-6614-01-P3

Presentation Outline

- Introduction
- RAS processing and stockpile management
- Impact of RAS on mix engineering properties
- Balanced RAS/RAP/rejuvenator mix design
- RAS mix production, construction, and performance
- Summary

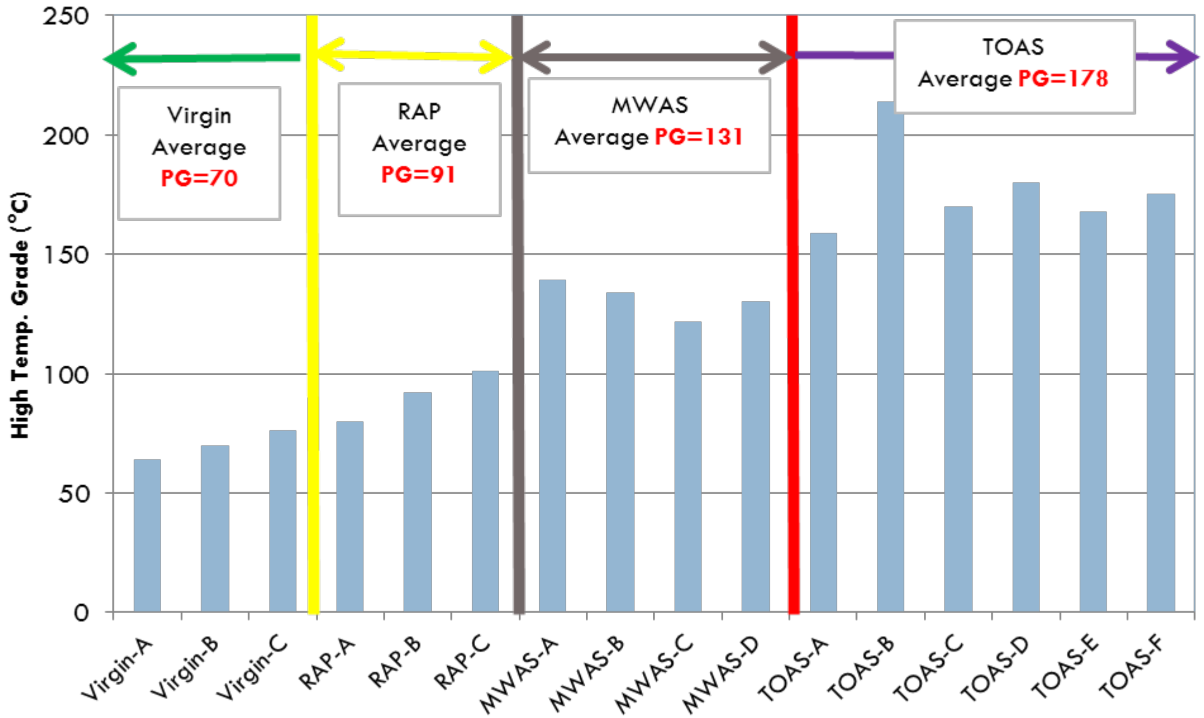
Introduction

- Recycled asphalt shingle (RAS)
  - Two types: Manufacture waste and Tear-offs

  - RAS has high binder content: 20% or more
    - 5% RAS sometimes is equivalent to 20% RAP

Introduction

- Recycled binders from RAS (or RAP) are very stiff



Introduction

- Benefit of RAP/RAS
  - Save money
  - Reduce rutting
  - Benefit to environment
- Concerns
  - Variability ⟷ best practices
  - Cracking
    - Reduce design air voids to increase binder content
    - Use soft virgin binders, especially on the low-temperature grade (i.e., PG XX-28, PG XX-34)
    - Add rejuvenators
    - Use balanced mix design method

Best Practices for RAS Processing and Stockpile Management

Best Practices for RAS Processing and Stockpile Management

Processing RAS - Sort Piles

Best Practices for RAS Processing and Stockpile Management

Step 4: Preparing to Grind

Step 5: Feeding to grinder

Best Practices for RAS Processing and Stockpile Management

Step 6: Grinding

Step 7: Screening

Step 8: Stockpiling

Impact of RAS on Mix Engineering Properties

- RAS Mixes

<table>
<tr><th rowspan="2">RAS Type</th><th colspan="4">RAS Percentage and Virgin Binder</th></tr>
<tr><th>0% RAS/
PG 70-22</th><th>0% RAS/
PG 64-22</th><th>3% RAS/
PG 64-22</th><th>5% RAS/
PG 64-22</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>
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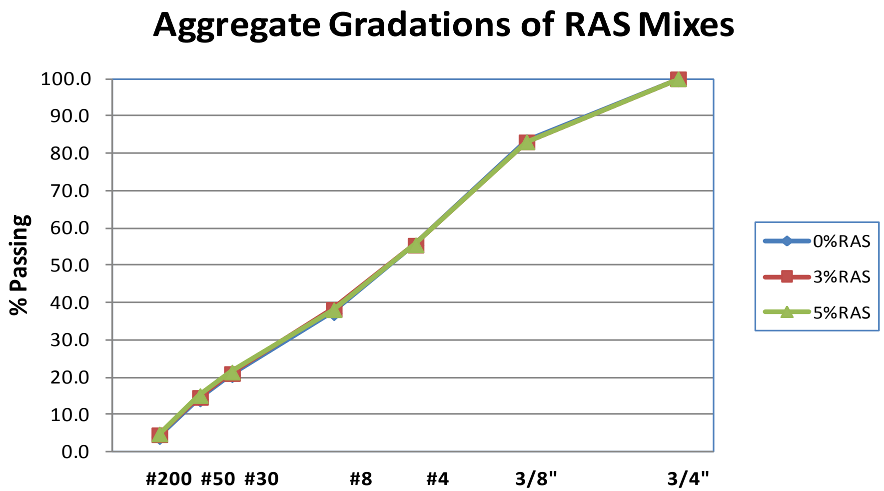
- Gradation
- Testing
  - E*
  - Hamburg
  - Overlay Test (OT)

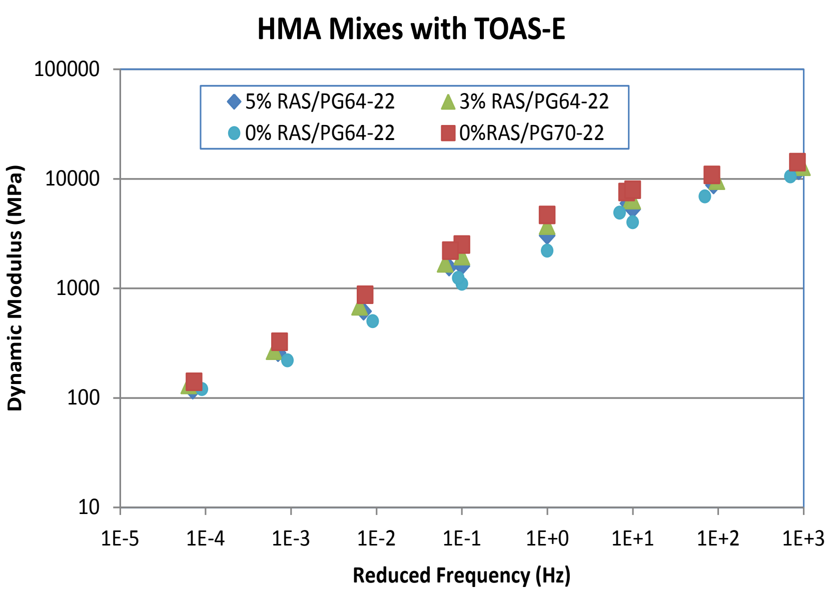


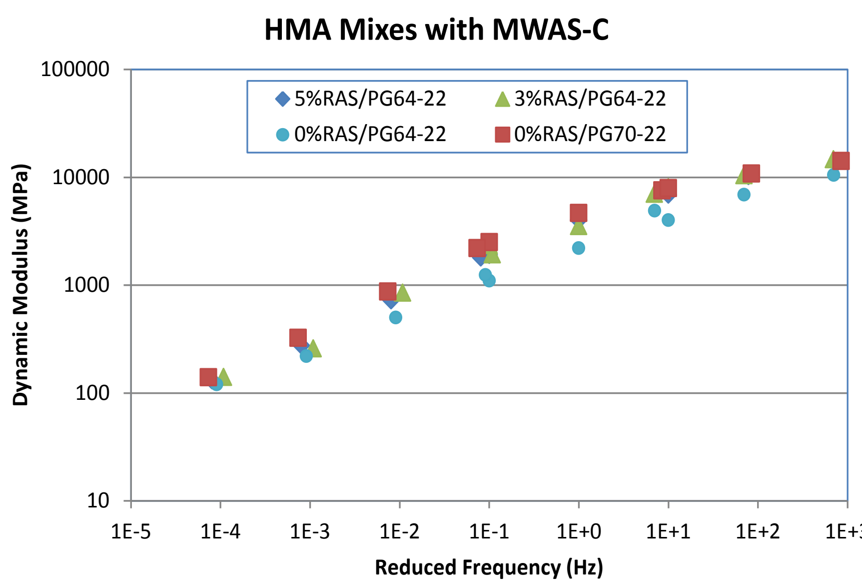
Impact of RAS on Mix Engineering Properties

- RAS Mixes

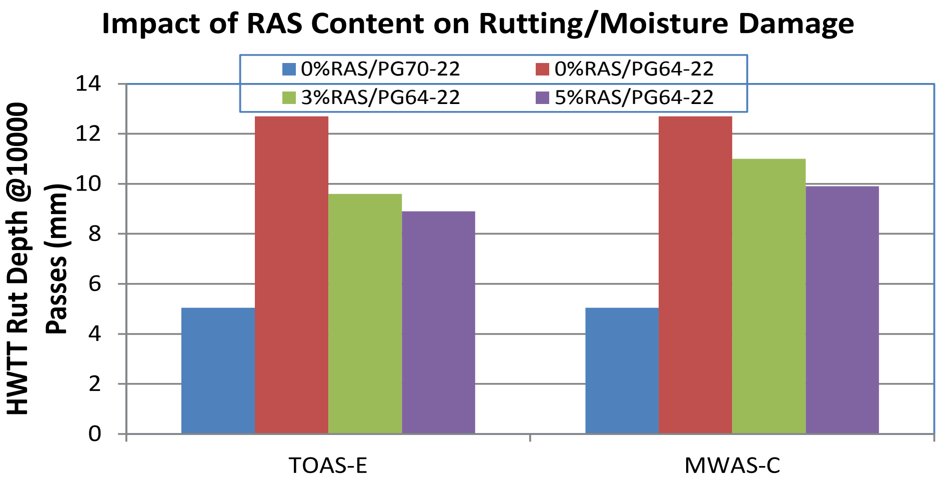
RAS Type	Optimum Asphalt Content (%)			
	0% RAS/ PG 70-22	0% RAS/ PG 64-22	3% RAS/ PG 64-22	5% RAS/ PG 64-22
TOAS-E	4.7	4.7	4.9	5.2
MWAS-C				

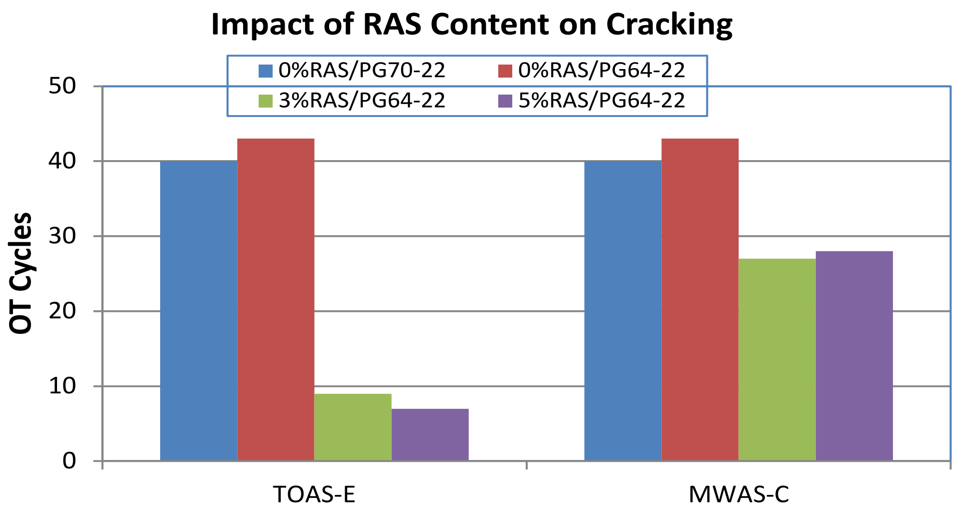
- E*





Impact of RAS on Mix Engineering Properties





Balanced RAP/RAS/Rejuvenator Mix Design for Project Specific Conditions

- Why balanced mix design
  - "Feature" of RAP/RAS mixes: Unknown VMA (VBE)
  - Need both **rutting and cracking tests** for mix design
- Why project specific mix design
  - One cracking criterion does not fit for all conditions (traffic, climate, pavement structure, existing pavement conditions for asphalt overlays)

Papers published in AAPT 2014 and 2015

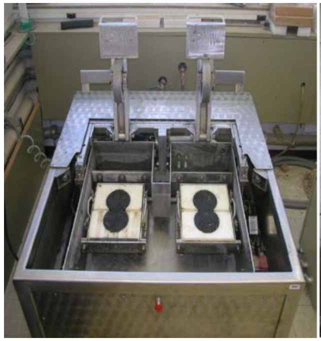
Balanced RAP/RAS/Rejuvenator Mix Design for Project Specific Conditions

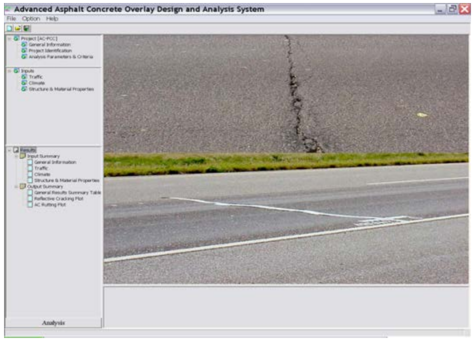
Three-step process

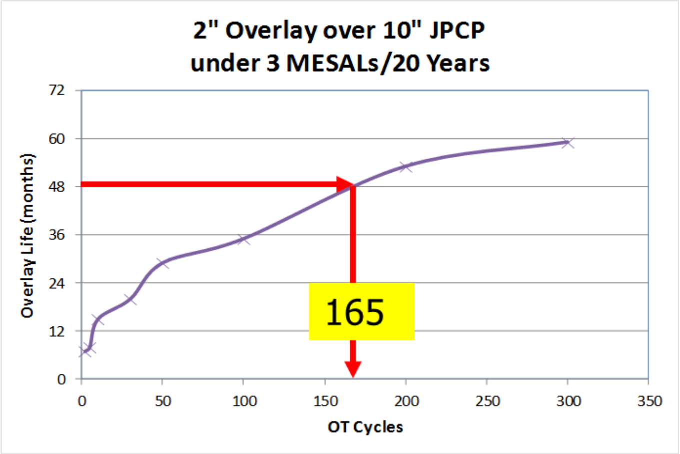
- Select rejuvenator type
- Select rejuvenator dosage range
  - Superpave PG requirements of rejuvenated binder
  - Aging characteristics of rejuvenated binder
- Finalize rejuvenator dosage through balancing rutting and cracking requirements of asphalt mixture

Balanced RAP/RAS/Rejuvenator Mix Design for Project Specific Conditions

- Hamburg test for rutting/moisture damage
- Overlay test for cracking
  - OT requirement determined by Overlay program
- Max. density-98% for controlling potential bleeding



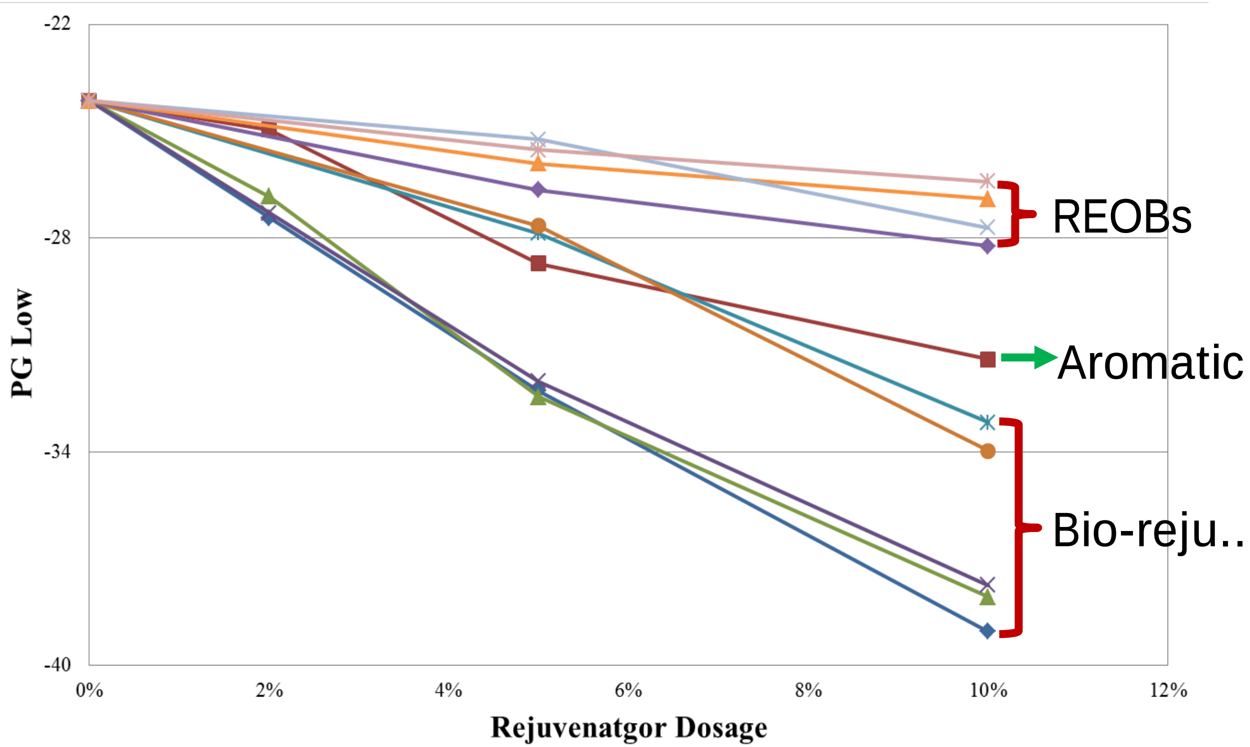




Balanced RAP/RAS/Rejuvenator Mix Design for Project Specific Conditions

Three-step process

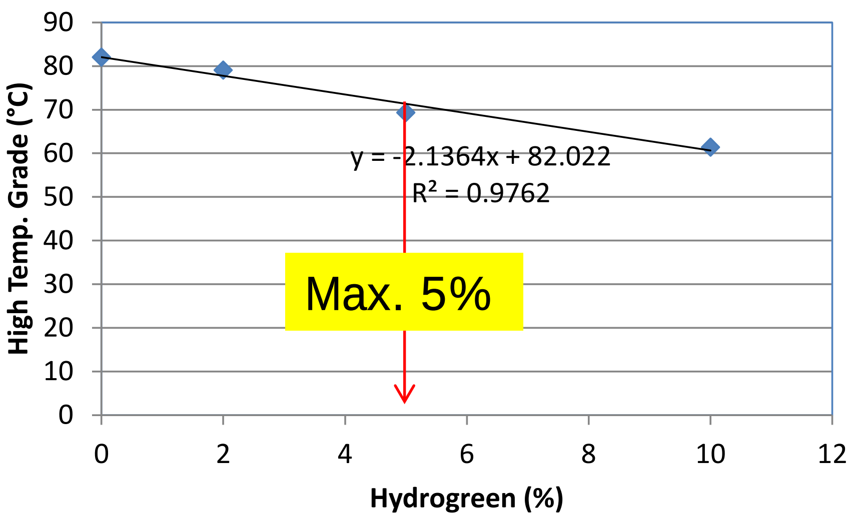
- Step 1: Select rejuvenator type

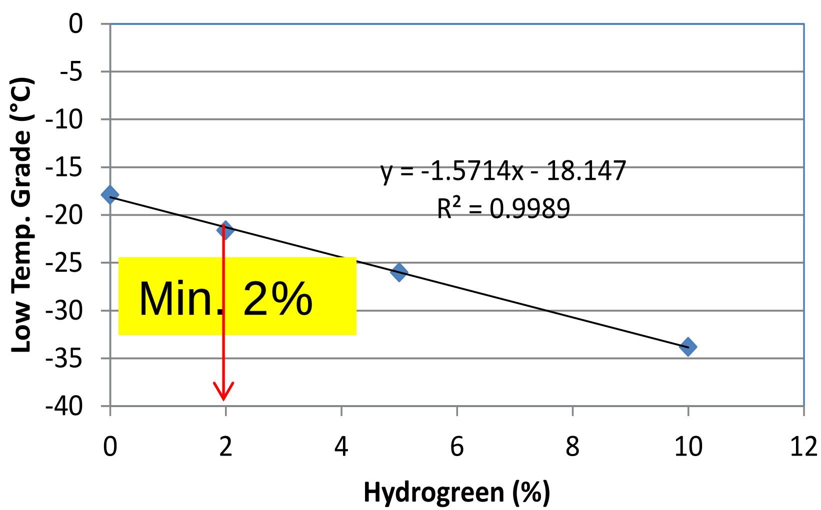


Balanced RAP/RAS/Rejuvenator Mix Design for Project Specific Conditions

Three-step process

- Step 2: Select rejuvenator dosage range

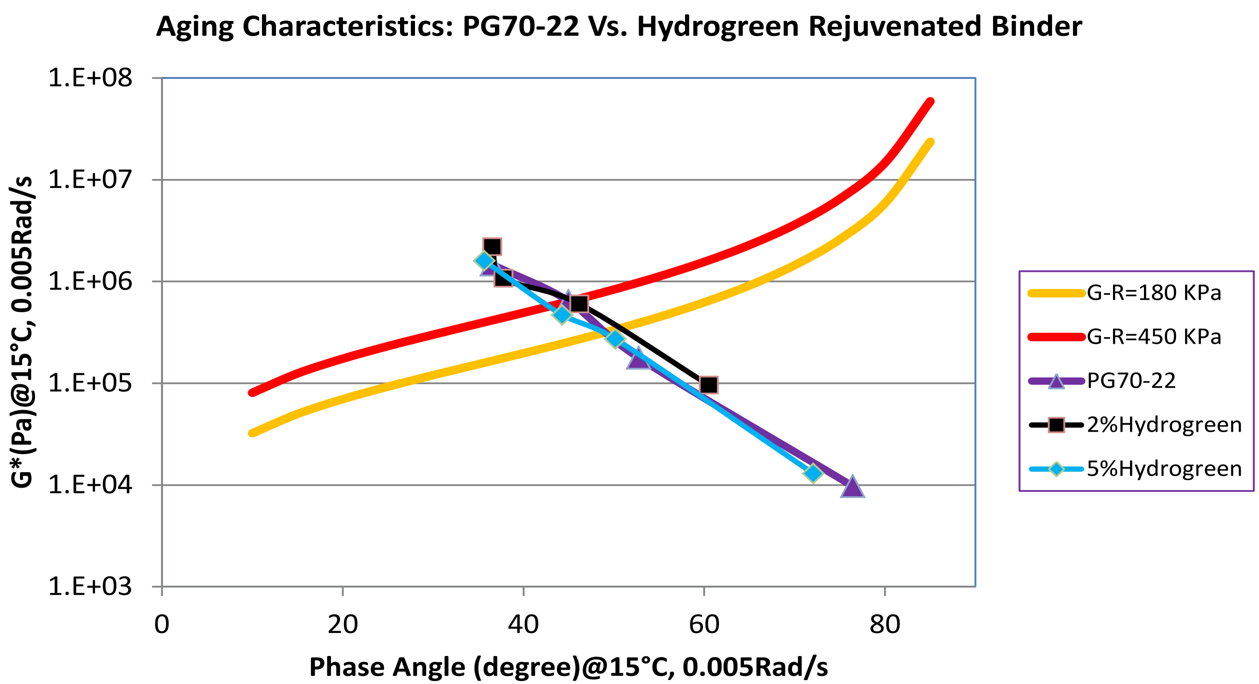




Balanced RAP/RAS/Rejuvenator Mix Design for Project Specific Conditions

Three-step process

- Step 2: Select rejuvenator dosage range



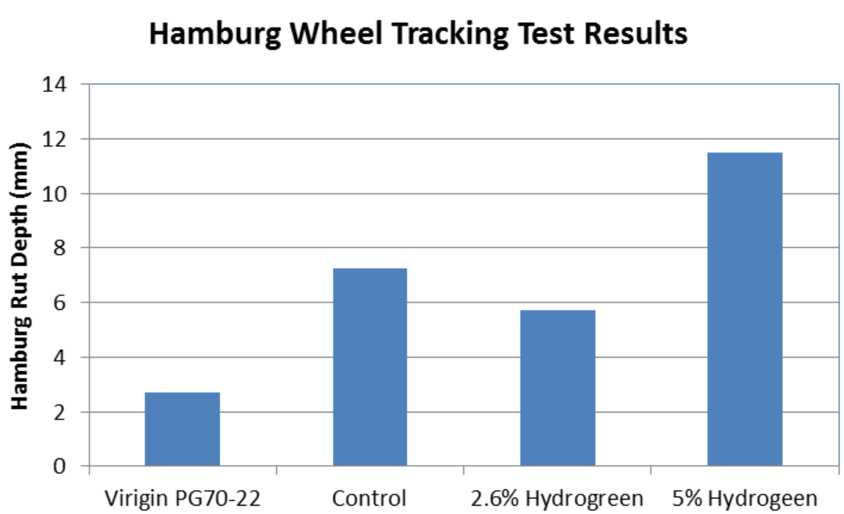
Balanced RAP/RAS/Rejuvenator Mix Design:

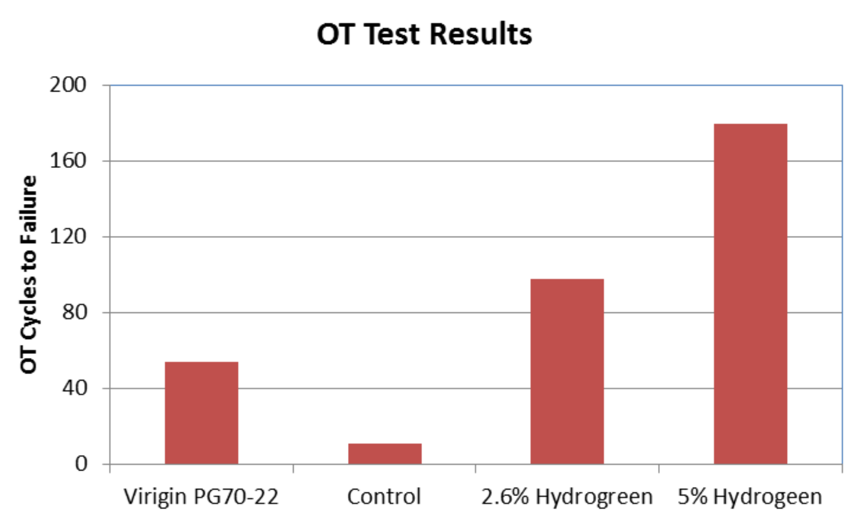
Step 3: Finalize rejuvenator dosage-balancing mix prop.

- Rejuvenator dosage range for mix design

Rejuvenator content	Hydrogreen (weight of total asphalt binder)
Low end	2.6%
High end	5.0%

- Hamburg and OT test results





RAS Mix Production and Construction

RAS Mix Production and Construction

RAS Mix Production and Construction

- Areas of Concern
  - Clumping after grinding
  - Crusting more severe on long hauls
  - Tendency to stiffen quicker in trucks than standard hot mix
  - More difficult to hand work
  - Mat can be more sensitive to temperature segregation

RAS Mix Production and Construction

- RAS Stockpile
  - Keep loaders off RAS stockpiles
  - Keep RAS stockpiles covered
  - RAS stockpiles will retain moisture; run moisture content each day prior to running mix
  - Separate high AC RAS from low AC RAS

RAS Mix Production and Construction

- Asphalt Plant
  - Keep RAS bin empty when not in use
  - Use a vibratory scalping screen to help break down or remove clumps that may be in the RAS material before entering the drum
  - Don’t superheat the mix; it only makes it stiffer
  - Reframe from holding RAS mix overnight

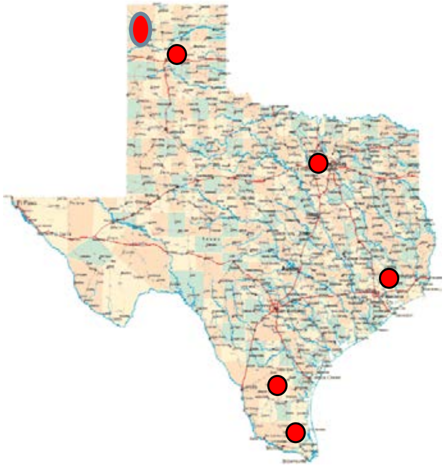
RAS Mix Production and Construction

- Vibratory scalping screen

RAS Mix Production and Construction

- Roadway construction
  - Consider the weather
  - Consider the haul distance
  - Consider the trucks that haul the mix
  - Don’t let mix set in trucks too long on job site
  - Check mix temperature when unloading trucks

RAP/RAS Field Test Sections and Performance



- Amarillo-Overlay: (Aug 2009)
  - IH40: Heavy traffic; Cold weather; Soft binder
  - RAP: 0, 20, 35%
- Pharr district-New Const.: (April 2010)
  - FM1017: low traffic; Hot weather; stiff binder
  - RAP: 0, 20, 35%
- Laredo-Overlay: SH359, 20%RAP (March 2010)
- Houston-New Const.:SH146, 15%RAP/5%RAS (Oct. 2010)
- Dalhart-Overlay: US87, 5%RAS (Oct. 2010)
- Austin-Overlay: FM973-9 test sections (Dec. 2011)
- Fort Worth-AC/CRCP: Loop 820 (July 2012)

Four Test Sections on IH40, Amarillo

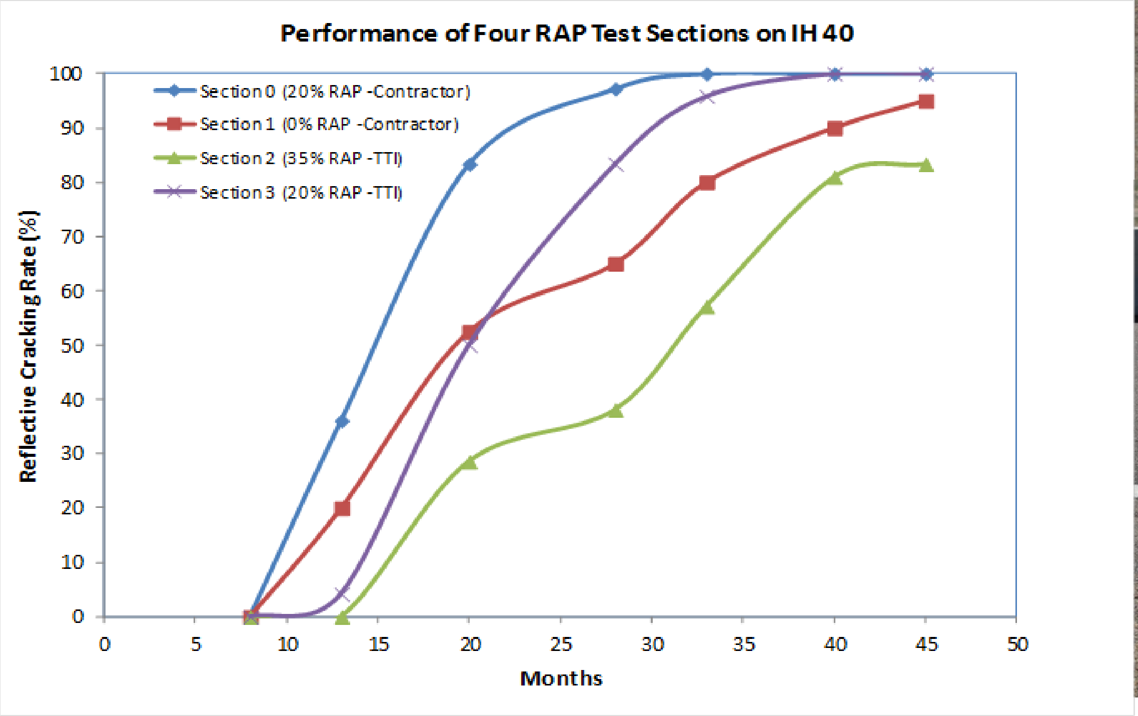
- Section 0: 20% RAP section designed by contractor
- Section 1: 0% RAP section designed by contractor
- Section 2: 35% RAP section designed by TTI
- Section 3: 20% RAP section designed by TTI

Summary: RAP Mix Design on IH40

Section	RAP (%)	Virgin binder	Mix design approach	AC (%)	Hamburg rut depth @20000	OT cycles
0	20	PG64-28	Item 340-Type C	5.0	3.7 mm	10
1	0	PG64-28	Item 340-Type C	4.8	4.4 mm	95
2	35	PG58-28	Balanced mix design	5.5	8.0 mm	200
3	20	PG64-28	Balanced mix design	5.3	7.4 mm	103

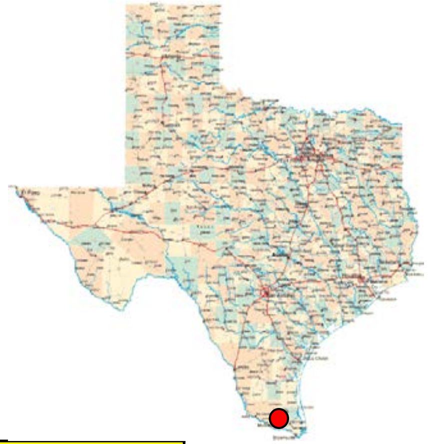
Performance of 4 Sections on IH40

- August 11, 2009, April 22, 2010
- Sept. 8, 2010, April 5, 2011
- Dec. 15, 2011, May 30, 2012
- Dec. 19, 2012, and May 16, 2013



Three Test Sections on FM1017, Pharr

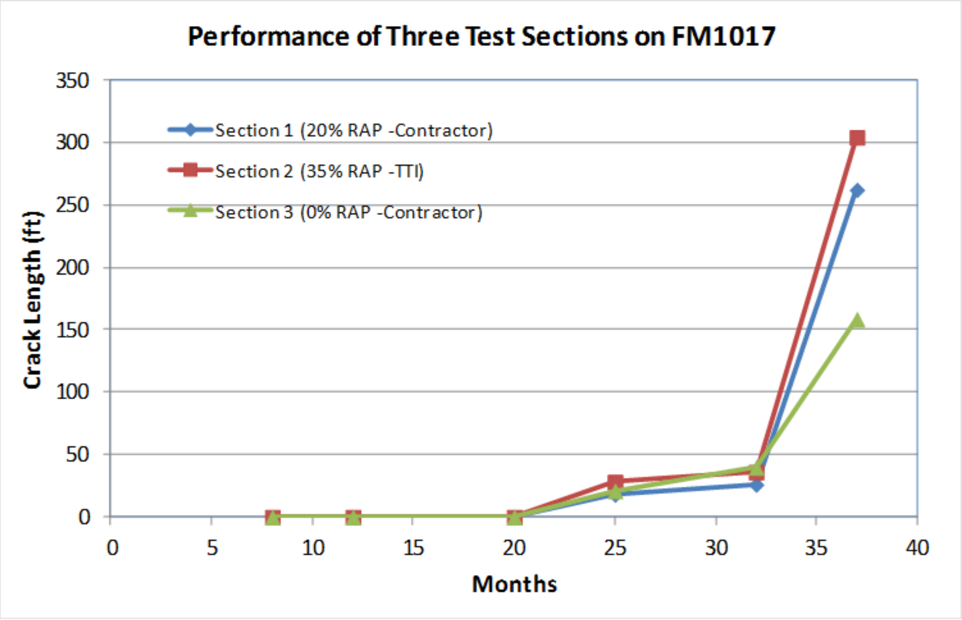
- New construction pavement
- 1.5 inch asphalt layer
- Hot weather
- FM road with low traffic



Section	RAP (%)	Virgin binder	Mix design approach	AC (%)	Hamburg rut depth @20000	OT cycles of plant mixes
1	20	PG64-22	Item 340-Type D	5.0	3.4 mm	6
2	35	PG64-22	Balanced mix design	6.4	9.3 mm	7
3	0	PG76-22	Item 340-Type D	4.9	2.2 mm	28

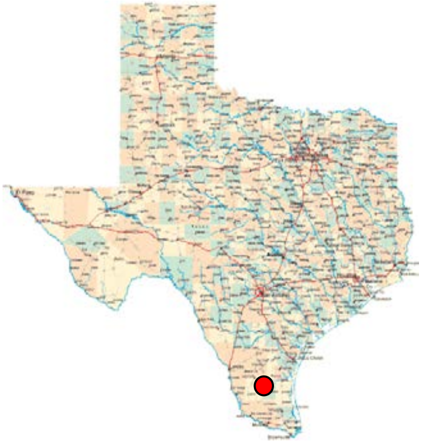
Performance of 3 Sections on FM1017

- April 6, 2010
- May 16, 2013
  - No rutting
  - Some cracks



Test Section on SH359, Laredo

- 3 inch asphalt overlay
- 20%RAP mix: OT cycles=3
- Existing condition: various cracks
- Hot weather
- Low traffic



3 years after
May 15, 2013

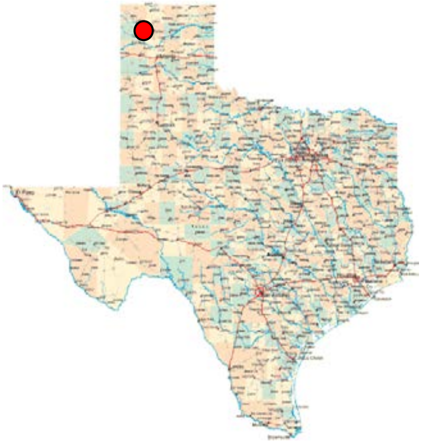
Test Section on SH146, Houston

- New construction with strong foundation layers
- 2 inch, 5%RAS/15%RAP mix: OT cycles=3
- Warm weather
- Medium traffic

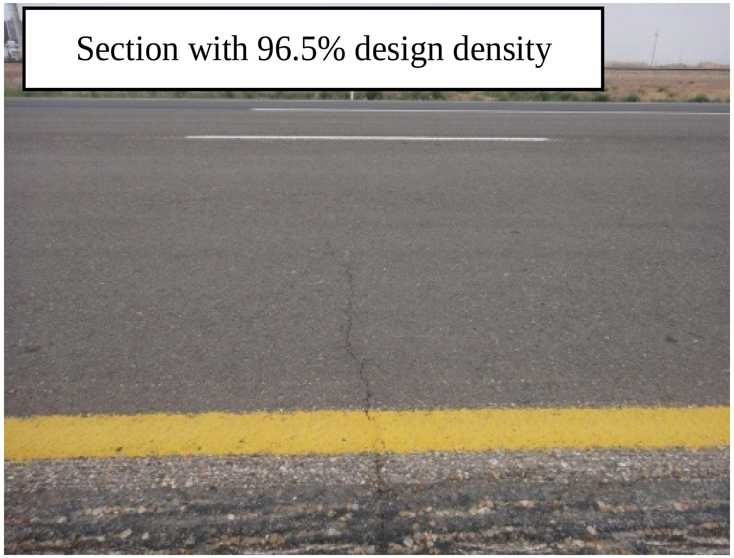
2.5 years after
May 10, 2013

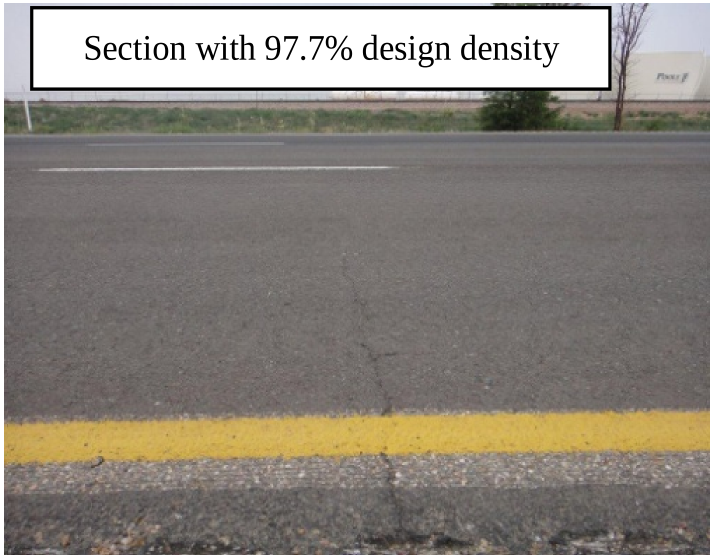
Test Section on US87, Dalhart

- 3 inch asphalt overlay
- 5%RAS mixes: OT cycles=48; 96
- Cold weather
- Medium traffic



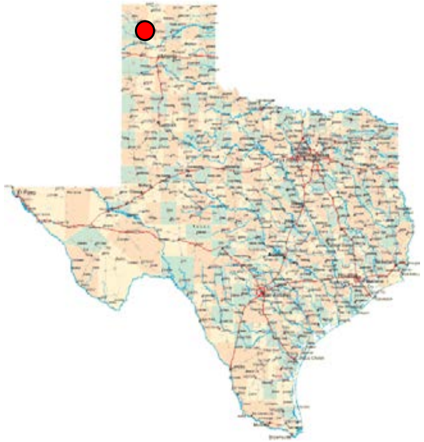
2.5 years after
May 10, 2013

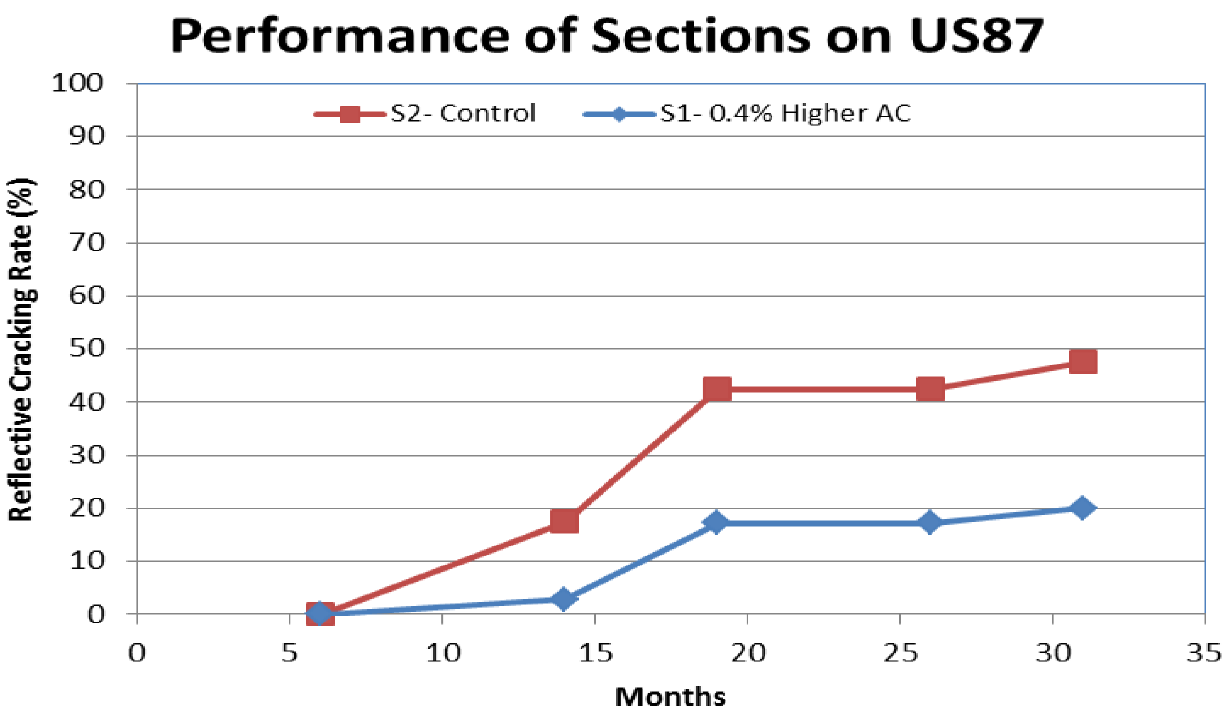




Test Section on US87, Dalhart

- 3 inch asphalt overlay
- 5%RAS mixes: OT cycles=48; 96
- Cold weather; Medium traffic





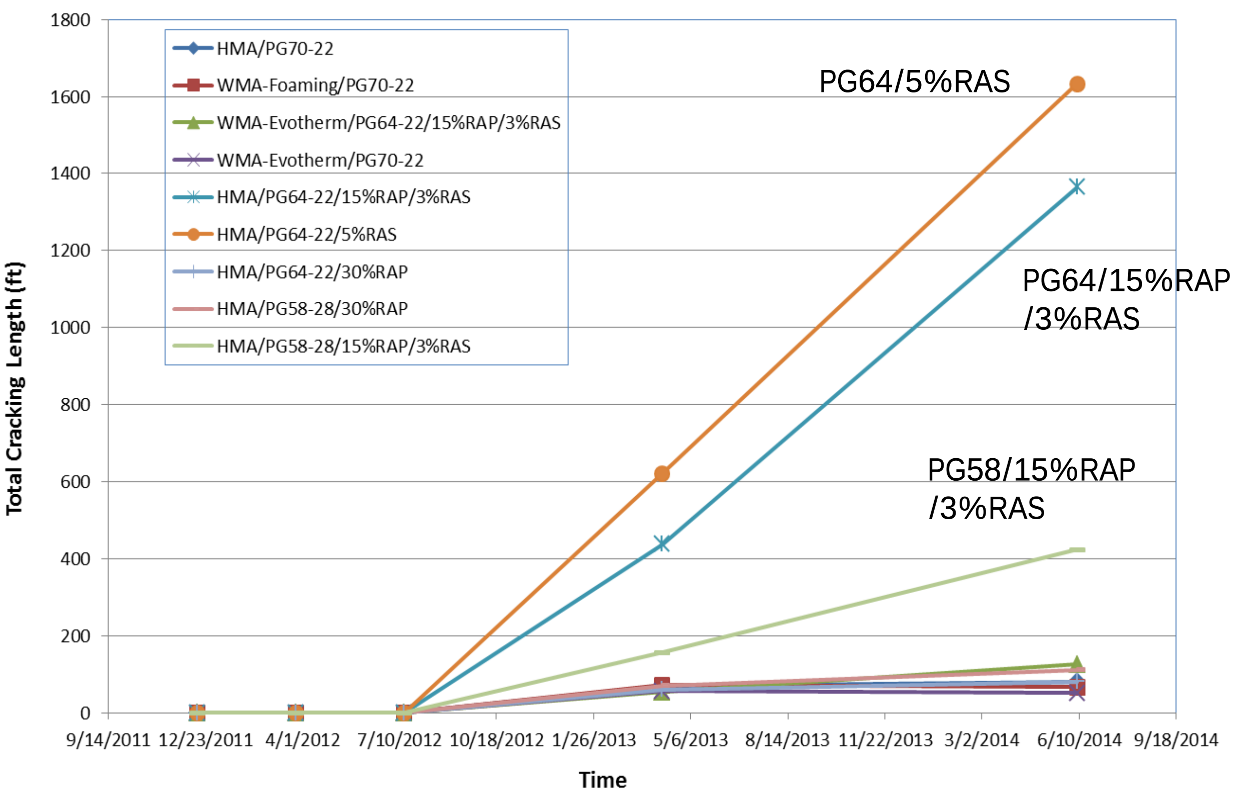
Field Test Sections

- Soft Binder
  - FM973: Overlay, Austin, Texas

Section	Type	Binder	RAP	RAS
1	HMA	70-22	0	0
7	WMA Foaming	70-22	0	0
8	WMA Evotherm	70-22	0	0
9	WMA Evotherm	64-22	15	3
3	HMA	64-22	15	3
4	HMA	64-22	0	5
2	HMA	64-22	30	0
5	HMA	58-28	30	0
6	HMA	58-28	15	3

Field Test Sections

- FM973: Overlay, Austin, Texas



Field Test Sections and Performance

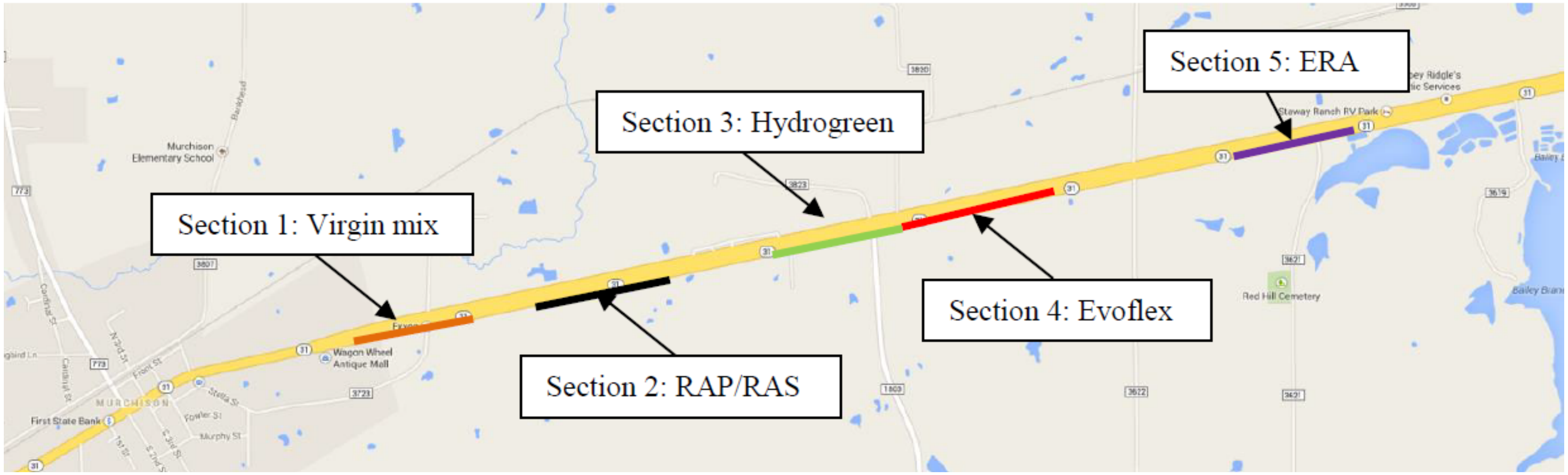
Test sections		Highway	Overlay/ new const.	Weather	Traffic MESAL	OT cycles	Performance
Amarillo	0%RAP	IH40 (severely cracked thick asphalt pavement)	4 inch/ overlay	Cold	30	95	3 yrs: 100% refl. cracking
	20%RAP					103	
	35%RAP					200	3 yrs: 57% refl. cracking
Pharr	0%RAP	FM1017-Very good support	1.5 inch/ new const.	Very hot	0.8	28	3yrs: overall - good conditions
	20%RAP					6	
	35%RAP					7	
Laredo	20%RAP	SH359-regular support	3 inch/ overlay	Very hot	1.5	3	3yrs: No cracking
Houston	15%RAP/ 5%RAS	SH146-Very good support	2 inch/new const.	hot	3.0	3	2.5yrs: No cracking
Dalhart	5%RAS	US87	3 inch/ Overlay	Cold	3.0	48/96	96 cycles-20% RCR; 48 cycles-50%RCR

Rejuvenated RAP/RAS Test Sections

- Test sections:
  - APAC: 5 sections on SH31, Tyler, 6/14
  - Anderson-Columbia: 5 sections on FM468, Laredo, 9/15
  - Silva Construction: 4 sections on FM1463, Houston, 7/16
- Production and construction:
  - no any problem encountered; all met density requirement

Field Performance of Rejuvenated RAP/RAS Test Sections in Tyler

- Virgin mix with PG70-22
- RAP/RAS mix with PG64-22
- RAP/RAS mix with PG64-22 and 2.6% Hydrogreen
- RAP/RAS mix with PG64-22 and 3.7% Evoflex
- RAP/RAS mix with PG64-22 and 2.0% ERA



Field Performance of Rejuvenated RAP/RAS Test Sections in Tyler

- Reflection cracking was observed on all sections including virgin mix section
- After 2.5 years, cracking are still tied

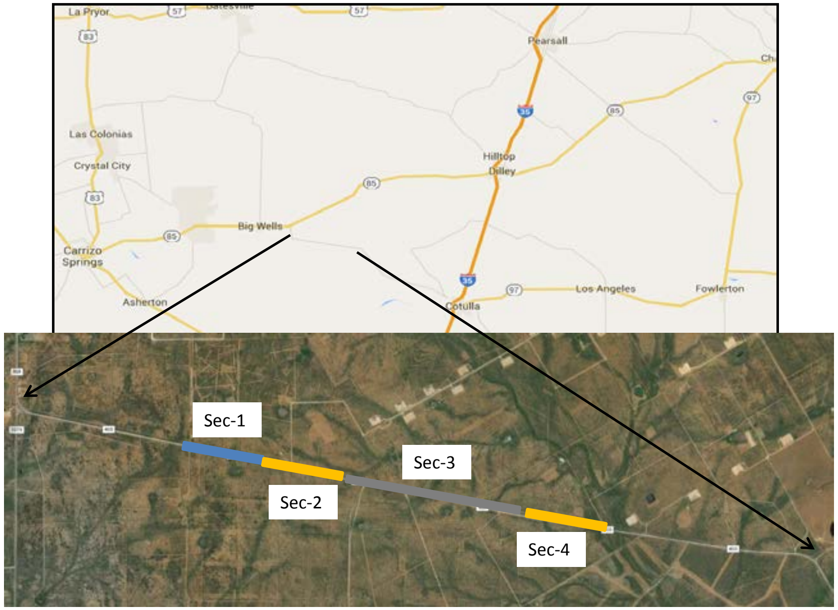
Field Performance of Rejuvenated RAP/RAS Test Sections in Tyler

- Lessons learned from Tyler sections
  - Two-lift overlay: construct them at the same time
  - Mix aging: 2 hr aging for cracking is not enough

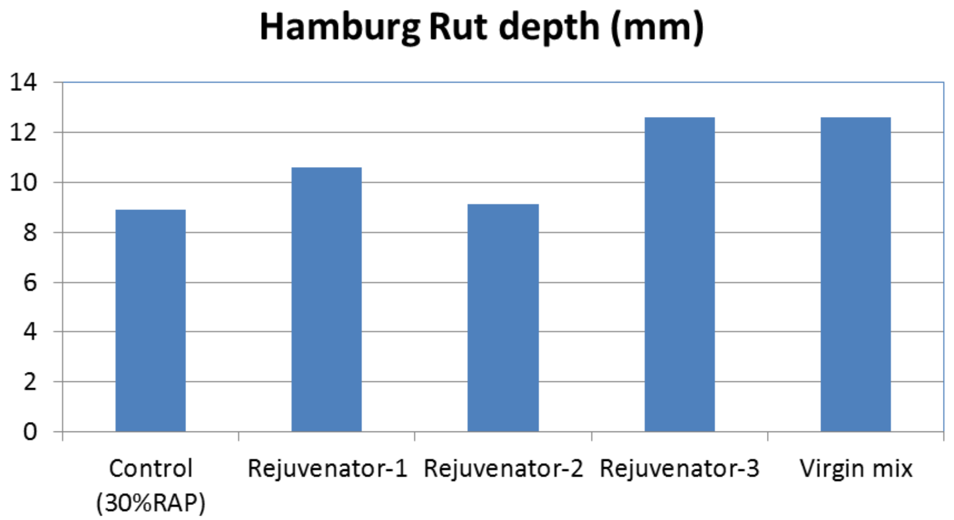


Field Performance of Rejuvenated RAP/RAS Test Sections in Laredo

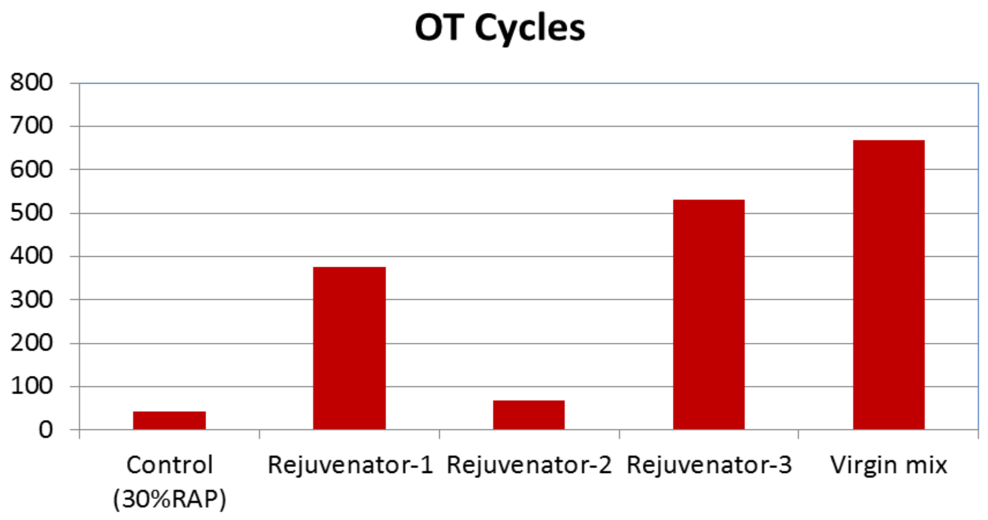
- Virgin mix with PG70-22
- 30%RAP mix with PG64-22
- 30%RAP mix with PG64-22 and 2.2% Road Science
- 30%RAP mix with PG64-22 and 3.0% Arizona Chemical
- 30%RAP mix with PG64-22 and 3.2% Hydrogreen



Field Performance of Rejuvenated RAP/RAS Test Sections in Laredo



FM468-Laredo
Superpave C
AC=6.1%



Field Performance of Rejuvenated RAP/RAS Test Sections in Laredo

- After 15 months, all sections performed very well
  - The same virgin mix with PG76-22 was constructed on I35
- 30%RAP mix with PG64-22 and 3.2% Hydrogreen: Gone

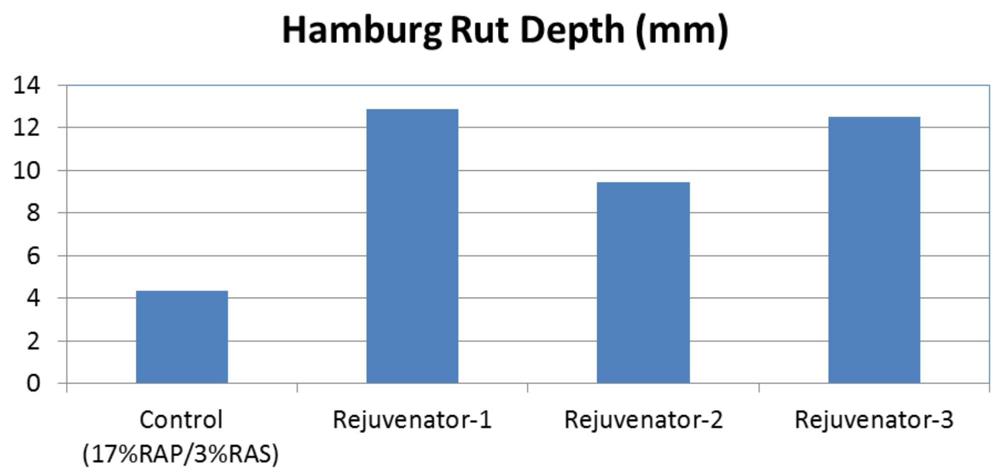
April 8, 2016

Nov 16, 2016

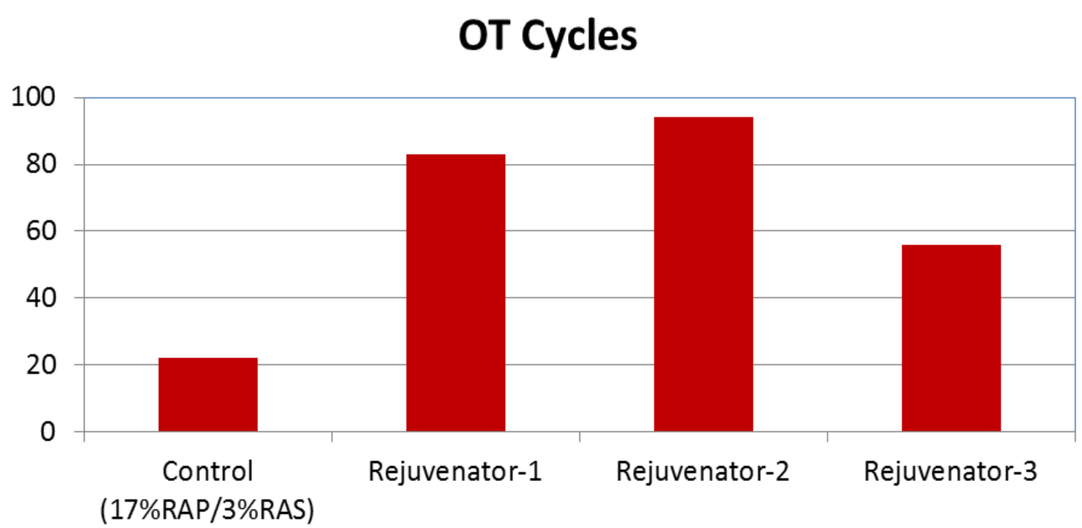
Field Performance of Rejuvenated RAP/RAS Test Sections in Houston

- 17%RAP/3%RAS mix with PG64-22
- 17%RAP/3%RAS mix with PG64-22 and 3.5% Arizona Chemical
- 17%RAP/3%RAS mix with PG64-22 and 4.0% Sonneborn
- 17%RAP/3%RAS mix with PG64-22 and 7.5% Evoflex

Field Performance of Rejuvenated RAP/RAS Test Sections in Houston



FM1463-Houston:
Dense-graded Ty D
AC=5.2%



Field Test Sections and Performance

Lessons Learned from Field Test Sections

1. RAP/RAS mix can perform well at certain locations
2. One OT requirement cannot fit for all
3. Successful use of RAP/RAS mixes depends on
   - Weather/Traffic
   - AC overlay:
     - Overlay thickness, Existing pavement structure (AC/AC; AC/PCC)
     - Existing pavement conditions
   - New construction:
     - Pavement structure and which layer (surface, base, …)
4. Design the mix for project-specific service conditions

Summary

- Best practices for RAS processing and stockpile management were developed
- RAP/RAS mix can perform well at certain locations
- Rejuvenators can improve cracking resistance of RAP/RAS mixes. Rejuvenators perform differently among 3 types; even within each type, its effectiveness varies
- 3-step balanced mix design approach is recommended for designing rejuvenated RAP/RAS mixes

Thank You All!