Evaluating the Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios (2020)

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 927

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP RESEARCH REPORT 927

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FOREWORD

By Edward Harrigan
Staff Officer
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NCHRP Research Report 927 presents an evaluation of how commercially available recycling agents affect the performance of asphalt mixtures incorporating reclaimed asphalt pavement (RAP) and recycled asphalt shingle (RAS) at high recycled binder ratios. The report will be of immediate interest to materials engineers in state highway agencies and the construction industry with responsibility for design and production of asphalt paving mixtures.

Economics, energy conservation, emission reduction, and conservation of natural resources have stimulated the expanding use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in asphalt paving mixtures. RAS and RAP binders are very stiff and can create construction and performance issues. The use of relatively high percentages of stiff binders from RAP and RAS in an asphalt mixture can cause premature pavement distress in the form of fatigue cracking, reflection cracking, low temperature cracking, accelerated aging, and raveling. In addition, workability problems during placement can occur in cool weather conditions when asphalt mixtures with higher RAS and RAP contents are used. Uncertainty also exists about the ability of RAS and RAP binders to adequately blend with virgin asphalt binder at both hot and warm mix asphalt production temperatures.

Asphalt paving mixtures with high RAP and RAS contents sometimes use virgin asphalt binders that are “softer” than the binder typically selected for the project’s climate and traffic. Alternatively, high RAP and RAS content mixtures may use recycling agents to “soften” or “rejuvenate” the stiff, oxidized RAP and RAS binders. These recycling agents include aromatic extracts of crude oil, tall oils, vegetable oils, and reacted bio-based oils; all are commercial, proprietary products. While the use of such recycling agents reduces the stiffness of the resulting asphalt paving mixtures, the influence of these agents on specific aspects of asphalt mixture performance is not well understood.

The objective of NCHRP Project 09–58 was to evaluate the effectiveness of recycling agents in asphalt mixtures with high RAS, RAP, or combined RAS/RAP binder ratios through a coordinated program of laboratory and field experiments. The research was performed by the Texas A&M Transportation Institute, Texas A&M University, College Station, Texas, in association with the University of Nevada, Reno, Nevada; the University of New Hampshire, Durham, New Hampshire; and Dr. Gayle King, Consultant, Houston, Texas.

The research involved an extensive program of laboratory experiments drawing on binders, mortars, and mixtures from field construction projects in Texas, Nevada, Indiana, Wisconsin, and Delaware. These materials were tested to develop and validate the following: material selection guidelines for base binders, recycled materials, and recycling agents; a recycling agent dose selection method; material proportioning strategies; RAP binder availability factors; and binder blend and mixture evaluation tools including aging protocols, recycling agent blending methods, and laboratory performance tests and proposed thresholds to control cracking and rutting resistance of asphalt mixtures with high recycled binder ratios. The results of these experiments were analyzed to develop a proposed AASHTO Standard Practice for the informed use of recycled agents, especially in asphalt mixtures with recycled binder ratios in the range of from 0.3 to 0.5.

The key outcome of this research is the proposed AASHTO Standard Practice (Appendix I) for the use of recycling agents in asphalt mixtures incorporating RAP and RAS for consideration and possible adoption by the AASHTO Committee on Materials and Pavements. The practice provides tools based on standard test methods for selecting and proportioning recycling agents and evaluating the performance characteristics of the rejuvenated binder and mixtures.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Evaluating the Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios

More than 90% of highways and roads in the United States are built using hot-mix asphalt (HMA) or warm-mix asphalt (WMA) mixtures, and these mixtures now recycle more than 99% of some 76.2 million tons of reclaimed asphalt pavement (RAP) and about 1 million tons of recycled asphalt shingles (RAS). According to the National Asphalt Pavement Association (NAPA), cost savings in 2017 totaled approximately $2.2 billion with these recycled materials replacing virgin materials.

The use of RAP in HMA dates back to the early 1900s, with renewed focus on research and implementation in the 1970s and 1980s and again in 2008 with significant increases in the cost of petroleum products including asphalt binders. Thus, highway agencies and the paving industry have developed a renewed interest in using larger quantities of recycled materials (RAP and RAS) to maximize economic and environmental benefits that include conservation of natural resources (aggregate, binder, fuel, etc.), reduction in energy consumption, and reduction in emissions (including greenhouse gases). In spite of these symbiotic benefits, state departments of transportation (DOTs) limit the use of RAP and RAS in asphalt mixtures for reasons that include variability of the recycled materials and concerns about long-term mixture performance. In addition, mix design is more complicated and more time consuming, particularly with large quantities of recycled materials identified by high recycled binder ratios (RBRs) between 0.3 and 0.5. The potential for compactability issues during construction and decreased mixture cracking resistance is also increased as RBRs increase and corresponding mixtures become stiffer and more brittle. Thus, the environmental and economic benefits must be compared to the potential increased risks associated with construction and performance to ensure engineering benefits can also be realized. Mitigation of these construction and performance issues can be addressed through mix design with the use of higher binder contents, material selection with the use of softer binders that may be polymer modified, or additives such as recycling agents, as long as there are not compatibility concerns and mixture resistance to rutting and moisture damage is maintained.

National Cooperative Highway Research Program (NCHRP) Project 9–58, “The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios,” focused on using recycling agents to facilitate increasing RBR and met the following study objectives:

- Assess the effectiveness of recycling agents at a selected dose to partially restore binder blend rheology and improve mixture cracking performance without adversely affecting rutting resistance,
- Evaluate the evolution of recycling agent effectiveness with aging, and
- Recommend evaluation tools for assessing the effectiveness of recycling agents initially and with aging for mixtures with high RBRs in specific climatic regions.

Many materials combinations were used; these included 10 base binders, 6 RAP sources, 5 RAS sources, 5 aggregate types, and 10 recycling agents. Laboratory testing results and field performance at five field projects in Texas, Indiana, Nevada, Wisconsin, and Delaware facilitated engineering rejuvenated binder blends and corresponding mixtures and the development of evaluation tools for assessing the effectiveness of recycling agents initially and with aging for binders and mixtures with high RBRs.

The comprehensive results generated and documented in this report and in multiple publications and presentations indicated that the following factors are not distinct but instead contribute concurrently to determine the performance of mixtures with high RBRs and recycling agents initially and with aging:

- Base binder performance grade (PG) and quality (ΔT_c);
- Binder modification by polymers or WMA or other additives;
- Proportions of recycled materials (RAP binder ratio [RAPBR] and RAS binder ratio [RASBR]);
- Recycling agent type;
- Recycling agent dose; and
- Recycled binder availability, which is a function of its aging state and production temperature.

These overlapping factors and their interplay necessitated the development of the following tools that are included in the draft American Association of State Highway and Transportation Officials (AASHTO) standard practice as an appendix to facilitate the evaluation of the effectiveness of recycling agents in high RBR binder blends and corresponding mixtures initially and with aging:

- Component materials selection guidelines,
- Recycling agent dose selection method and materials proportioning,
- Binder blend rheological evaluation tools,
- Mixture performance evaluation tools, and
- Recycled binder availability factor.

The evaluation tools for binder blends and mixtures include aging protocols, recycling-agent blending methods, and laboratory tests and corresponding thresholds for adequate performance. Additional investigations of chemical compatibility of recycling agents with base and recycled binders and representative binder blending were also completed, and laboratory aging and climate effects were explored for both binder blends and mixtures.

The majority of the field projects in this study utilized significantly lower recycling agent doses than those determined by the method developed and included in the draft AASHTO standard practice. Thus a field demonstration project with a higher recycling agent dose selected by the proposed method is needed for validation of the evaluation tools also developed in this study. Additional implementation activities to apply these tools include the following:

- A review of state specifications for limiting RAP and RAS and proposed revisions as needed and
- Continued performance monitoring of the field projects established in this study to provide additional data to adjust binder blend and mixture performance thresholds.

Additional research is also proposed on the following topics:

- Evaluation of climate effects to refine mixture performance thresholds based on climate,
- Exploration of the effects of long-term aging on mixtures with high RBRs and recycling agents and how to capture these effects in the laboratory,

- Assessment of the effects of moisture susceptibility for mixtures with high RBRs and recycling agents and possible addition of another performance threshold,
- Rheological evaluation of modified binders to determine how to capture their benefits when used in mixtures with high RBRs and recycling agents, and
- Chemical assessment of recycling agents to revise specifications for these component materials.

CHAPTER 1

Introduction

More than 90% of highways and roads in the United States are built using HMA or WMA mixtures. In the early 1990s, the Federal Highway Administration (FHWA) estimated that more than 90 million tons of asphalt pavements are milled off roads each year during resurfacing projects, and over 80% of RAP is recycled in new mixtures (FHWA 1993). Subsequent studies and surveys showed that this trend is increasing, with more recent estimates of more than 99% of some 76.2 million tons of RAP reused, making it the most recycled product in the United States. In addition, about 1 million tons of RAS are now used in paving applications (Copeland 2011; NAPA 2018).

The use of RAP in HMA dates back to the early 1900s, with renewed focus on research and implementation in the 1970s and 1980s due to dramatic increases in the cost of oil, and thus asphalt binders and fuel, needed to produce asphalt pavements. Newcomb and Epps (1981) reviewed the technologies developed during this early period of recycling, which included drum mix plants, cold milling machines, vibratory compaction rollers, cold and hot in-place recycling techniques, and mix design methods, to increase RAP contents to maximize economic and environmental benefits. These symbiotic benefits are substantial and include conservation of natural resources (aggregate, binder, fuel, etc.), reduction in energy consumption, and reduction in emissions (including greenhouse gases). For example, in a relatively high 25% RAP content HMA mixture, Robinett and Epps (2010) indicated 10% energy savings, 10% emissions reductions, and 20%–25% conservation of natural resources that translated into reduced production and construction costs. In 2017, cost savings totaled approximately $2.2 billion with recycled materials replacing virgin materials (NAPA 2018).

Interest in recycling waned during the 1990s and recycling was not considered in the Strategic Highway Research Program (SHRP). Thus recycling technologies remained largely unchanged until 2008, when the cost of petroleum products significantly increased again. So highway agencies and the paving industry have developed a renewed interest in achieving higher RBRs in asphalt mixtures through the use of larger percentages of RAP and/or the addition of RAS from either manufacturer waste asphalt shingles (MWAS) or tear-off asphalt shingles (TOAS) for the same economic and environmental benefits. To provide an overall indication of the possible binder contribution from these recycled materials, RBR is defined according to Equation 1.

$$RBR = \frac{(Pb_{RAP} \times P_{RAP}) + (Pb_{RAS} \times P_{RAS})}{100 \times Pb_{total}} \qquad \text{[Equation 1]}$$

where

Pb_{RAP} = binder content of the RAP,
P_{RAP} = percentage of RAP by weight of mixture,
Pb_{RAS} = binder content of the RAS,

P_{RAS} = percentage of RAS by weight of mixture, and
Pb_{total} = binder content of the combined mixture.

In spite of the symbiotic benefits, state DOTs limit the use of RAP and/or RAS in asphalt mixtures for reasons that include variability of the recycled materials and concerns about long-term mixture performance. In addition, mix design is more complicated and more time consuming, particularly with high RBRs between 0.3 and 0.5. The potential for the following construction and performance issues is also increased as RBRs increase and corresponding mixtures become stiffer and more brittle:

- Compactibility/workability in cool weather,
- Low-temperature cracking with accumulation of thermally induced stresses,
- Fatigue cracking and microdamage accumulation leading to crack initiation and propagation with repeated loading,
- Reflection cracking with repeated loading and daily/seasonal thermal stresses, and
- Raveling with subsequent aging or moisture damage.

Thus, the environmental and economic benefits must be compared to the potential increased risks associated with construction and performance to ensure that engineering benefits can also be realized. Mitigation of these construction and performance issues can be addressed through mix design with the use of higher binder contents, material selection with the use of softer binders that may be polymer modified, or additives such as recycling agents, as long as there are not compatibility concerns and mixture resistance to rutting and moisture damage is maintained. Mitigation through the use of recycling agents includes the following (Tran et al. 2012; Mogawer et al. 2013; Im and Zhou 2014):

- Partial restoration of stiffness and reversal of embrittlement caused by the addition of recycled materials at high RBRs,
- Improvement in cracking resistance of mixtures with high RBRs without adversely affecting rutting resistance, and
- Improvement in compactibility/workability (in some cases).

Using lower production temperatures through the use of WMA technologies will also affect these construction and performance issues and possibly offset benefits of reduced aging with decreased blending of base and recycled binders and/or generate possible compatibility concerns with WMA additives, recycling agents, and base and recycled binders.

Recycling agents were used in HMA in the early period of widespread recycling in the 1970s and 1980s for the purpose of realizing all three types of benefits—environmental, economic, and engineering. As RBRs continue to increase in the current period of widespread recycling, the use of recycling agents holds promise once again with proper understanding of their effectiveness in partially restoring rheology, its evolution with aging in HMA and WMA mixtures in both the laboratory and the field, and stiffness and cracking resistance of these binder blends and corresponding mixtures. Mix design procedures, including component material characterization to ensure that binder blends are restored as much as possible rheologically, specimen fabrication protocols to simulate field conditions, and production and construction best practices (including handling of recycled materials—fractionation and drying, for example), are needed to ensure adequate performance when using recycling agents.

1.1 Project Overview and Objectives

This final report completes NCHRP Project 09–58, "The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios." Figure 1 illustrates how Phase 1, the two parts of Phase 2 (A and B), and Phase 3 contributed to the overall study that included five

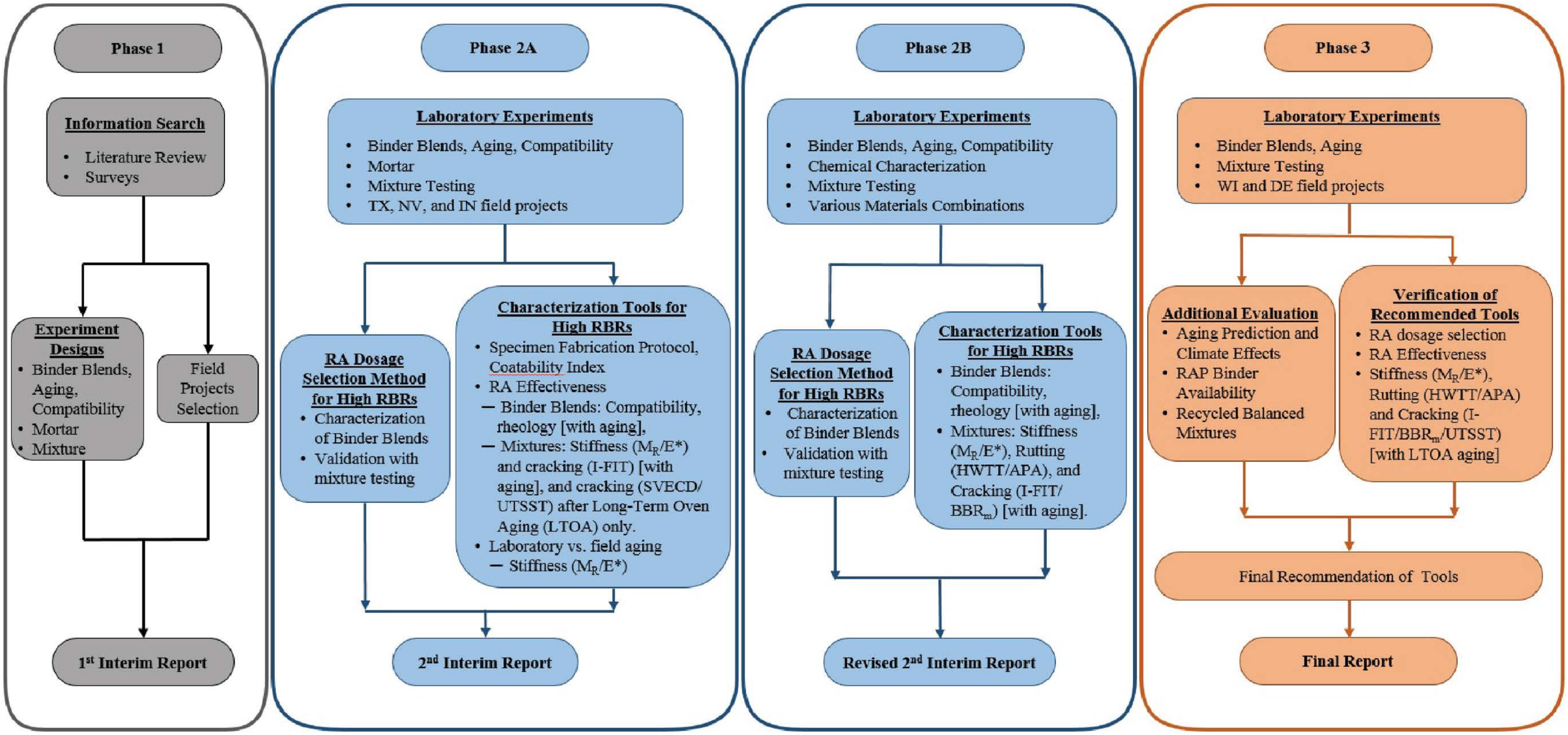


Figure 1. NCHRP 09–58 overview.

field projects in Texas (TX), Nevada (NV), Indiana (IN), Wisconsin (WI), and Delaware (DE). Phase 2B was requested based on concerns with the Phase 2A results that explored a limited set of materials combinations and indicated limited recycling-agent effectiveness with aging. Phase 2B explored some more fundamental tools and a wider range of materials combinations that included the use of an improved base binder, a softer base binder, three engineered recycling agents, and higher RBRs with TOAS. Table 1 presents the materials combinations explored throughout both parts of Phase 2 and Phase 3 that evolved based on a continuous review of results to select combinations that consider the limitations of materials, time, and budget and most efficiently meet the study objectives to

- Assess the effectiveness of recycling agents at a selected dose to partially restore binder blend rheology and improve mixture cracking performance without adversely affecting rutting resistance,
- Evaluate the evolution of recycling-agent effectiveness with aging, and
- Recommend evaluation tools for assessing the effectiveness of recycling agents initially and with aging for mixtures with high RBRs in specific climatic regions.

Many of the results for the materials combinations in Table 1 were intermediate results that are not presented in this report. During Phase 2B, coordination of field projects and procurement of materials for Phase 3 was also completed to tie the laboratory results to field performance.

Each of the materials combinations listed in Table 1 that included the following recycling agent types and binder and mixture testing results facilitated engineering rejuvenated binder blends and corresponding mixtures and the development of evaluation tools for assessing the effectiveness of recycling agents initially and with aging for binders and mixtures with high RBRs:

- Recycling agent types:
  - A1 and A2—aromatic extracts.
  - P—paraffinic oil.
  - T1 and T2—tall oils.
  - V1—vegetable oil.
  - V2 and V3—modified vegetable oils.
  - B1 and B2—reacted bio-based oils.

  These recycling agents are proprietary products labeled by generic descriptors that define their origin. Petroleum-based recycling agents in this study included aromatic extracts (A) that are traditional recycling agents refined from crude oil as a by-product of lube oil processing with dominant polar aromatic oil components and paraffinic oils (P) that are also refined as a by-product of lube oil processing, but may have similar performance as recycled engine oil bottoms (REOBs). Bio-based recycling agents are derived from plant life rather than petroleum and in this study included tall oils (T) that are by-products of paper processing from pine trees, vegetable oils (V) and simple derivatives such as esters, and other bio-based oils (B) that appear to be chemically reacted, usually to reduce impacts of oxidative aging on rheology. Based on limited data, V1 is a vegetable oil that consists of a mixture of glycerides and fatty acids, and V2 and V3 are engineered (modified) vegetable oils. B1 and B2 are reacted bio-based oils that consist of fatty amine derivatives and bio solvents.
- Binder testing results:
  - PGL—low-temperature PG.
  - PGH—high-temperature PG.
  - ΔT_c—the difference in continuous PG temperature for stiffness and relaxation properties in the bending beam rheometer (BBR); i.e., the critical temperature when S equals 300 MPa minus the critical temperature when m-value equals 0.30.
  - G-R—Glover-Rowe parameter and Black space analysis.
  - $T_{\delta = 45^\circ}$—crossover temperature.

Table 1. Materials combinations explored in NCHRP 09–58.

Materials Combinations					Binder Testing					Mortar Testing (PG)	Mixture Testing								
Base Binder	Recycled Materials			Recycling Agent Dose and Type (Dose Selection Method[c])	Rheology		Chemical Characterization	FT-IR[a]	Aging[b]		CI	M_R	|E*|	I-FIT	BBR_m (Sliver)	HWTT	APA	UTSST	S-VECD
	RBR	RAP	RAS		G-R[a]	$T_{\delta = 45°}$[a]	SAR-AD, MDSC												
TX 70-22 P (ΔT_c -4.9)	—	—	—	Base Binder	✓	—	—	—	—	✓	—	✓	✓	✓	—	—	—	✓	✓
	—	—	—	2.7% T1 (field)	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—
	0.3	0.2 TX	0.1 TX MWAS	Control (no recycling agent)	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—
				2.7% T1 (field)	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—
TX 64-22 (ΔT_c -4.6)	—	—	—	Base Binder	✓	✓	✓	✓	✓	✓	—	—	—	—	—	—	—	—	—
				2.7% T1 (field)	✓	✓	—	✓	✓	✓	—	—	—	—	—	—	—	—	—
	0.28	0.1 TX	0.18 TX MWAS	DOT Control (no recycling agent)	✓	✓	✓	✓	—	✓	—	✓	✓	✓	—	—	—	✓	✓
				2.7% T1 (field)	✓	—	—	—	✓	✓	—	✓	✓	✓	—	—	—	✓	✓
	0.28	0.1 TX	0.18 TX MWAS	4.5% T1 (PGL)	✓	—	✓	✓	—	—	—	✓	✓	✓	—	—	—	—	—
				5.5% A1 (PGL)	✓	—	✓	✓	—	—	—	✓	✓	✓	—	—	—	—	✓
				4.0% V1 (PGL)	✓	✓	—	✓	—	—	—	—	—	✓	—	—	—	—	—
				4.0% B1 (PGL)	✓	✓	—	✓	—	—	—	—	—	✓	—	—	—	—	—
				12.5% T1 (ΔT_c)	✓	✓	—	✓	—	—	—	—	—	—	—	✓	—	—	✓
				9.5% A1 (ΔT_c)	✓	✓	—	✓	—	—	—	—	—	—	—	—	—	—	—
				8.5% V1 (ΔT_c)	✓	✓	—	✓	—	—	—	—	—	—	—	—	—	—	—
				7.0% B1 (ΔT_c)	✓	✓	—	✓	—	—	—	—	—	—	—	—	—	—	—
				6.0% T1 (PGH)	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—
				6.5% A1 (PGH)	✓	—	—	—	—	—	—	—	—	—	—	✓	—	—	—
				5.5% V1 (PGH)	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—
				6.5% B1 (PGH)	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—

NOTE: Gray shading indicates TX field project material combinations; — = not applicable.

[a] At rolling thin film oven (RTFO), 20 pressure aging vessel (PAV), and 40 PAV aging.

[b] Long-term oven aging including binder master curve, G-R, $T_{\delta = 45°}$, and FT-IR.

[c] Described in Chapter 2.

Materials Combinations					Binder Testing					Mortar Testing (PG)	Mixture Testing								
Base Binder	Recycled Materials			Recycling Agent Dose and Type (Dose Selection Method[c])	Rheology		Chemical Characterization	FT-IR[a]	Aging[b]		CI	M_R	|E*|	I-FIT	BBR_m (Sliver)	HWTT	APA	UTSST	S-VECD
	RBR	RAP	RAS		G-R[a]	$T_{\delta = 45^\circ}$[a]	SAR-AD, MDSC												
TX 64-22 (ΔT_c -4.6)	0.4	0.4 TX	—	Control (no recycling agent)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
				7.5% T1 (PGL)	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—
				9.5% A1 (PGL)	✓	—	—	—	—	—	✓	—	—	—	—	—	—	—	—
	0.5	0.25 TX	0.25 TX MWAS	Control (no recycling agent)	✓	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—
				7.5% T1 (PGL)	✓	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—
				9.0% T1 (PGH)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
				Control (no recycling agent)	✓	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—
				11.5% T1 (PGL)	✓	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—
				13.5% T1 (PGH)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
NH 64-28 (ΔT_c +1.2)	—	—	—	Base Binder	✓	✓	✓	✓	✓	✓	—	—	—	—	—	—	—	—	—
				2.7% T1	✓	✓	—	✓	✓	✓	—	—	—	—	—	—	—	—	—
				6.0% A1	—	—	—	—	✓	—	—	—	—	—	—	—	—	—	—
	0.28	0.1 TX	0.18 TX MWAS	Control (no recycling agent)	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—
				2.7% T1 (field)	✓	—	—	—	—	✓	—	✓	✓	✓	—	—	—	✓	✓
				7.5% T1 (PGH)	✓	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0.4	0.4 TX	—	Control (no recycling agent)		—	—	—	—	—	—	—	—	—	—	—	—	—	—
				6% A1 (PGL)	✓	—	—	—	✓	—	—	—	—	—	—	—	—	—	—
	0.5	0.25 TX	0.25 TX TOAS	Control (no recycling agent)	✓	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—
				12.5% T1 (PGL)	✓	—	✓	✓	✓	—	✓	✓	✓	✓	—	—	—	—	✓
				15.5% T1 (PGH)	✓	✓	—	✓	—	—	—	—	—	—	—	—	—	—	—
				17.5% V1 (PGH)	✓	✓	—	✓	—	—	—	—	—	—	—	—	—	—	—

NOTE: — = not applicable.

[a] At RTFO, 20 PAV, and 40 PAV aging.

[b] Long-term oven aging including binder master curve, G-R, $T_{\delta = 45^\circ}$, and FT-IR.

[c] Described in Chapter 2.

(continued on next page)

Table 1. (Continued).

Materials Combinations					Binder Testing					Mortar Testing (PG)	Mixture Testing								
Base Binder	Recycled Materials			Recycling Agent Dose and Type (Dose Selection Method[c])	Rheology		Chemical Characterization	FT-IR[a]	Aging[b]		CI	M_R	|E*|	I-FIT	BBR_m (Sliver)	HWTT	APA	UTSST	S-VECD
	RBR	RAP	RAS		G-R[a]	$T_{\delta = 45°}$[a]	SAR-AD, MDSC												
NH 64-28 (ΔT_c +1.2)	0.5	0.4 NH	0.1 CA TOAS	9.0% T1 (PGH)[d]	✓	✓	—	✓	—	—	—	✓	—	✓	—	—	—	—	—
				9.0% V2 (PGH)[d]	✓	✓	—	✓	—	—	—	✓	—	✓	—	—	✓	—	—
		0.4 TX	0.1 TX TOAS	14.0% T1 (PGH)[d]	✓	✓	—	✓	—	—	—	✓	—	✓	—	—		—	—
				14.0% V2 (PGH)[d]	✓	✓	—	✓	—	—	—	✓	—	✓	—	—	✓	—	—
	0.7	0.7 NH	—	Control (no recycling agent)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
				8.0% B1 (PGH)[d]	✓	✓	—	✓	—	—	—	✓	—	✓	—	—	—	—	—
NV 64-28P (ΔT_c -3.6)	—	—	—	Base Binder	✓	✓	—	✓	✓	✓	—	✓	✓	✓	—	—	—	—	✓
	—	—	—	2.7% T1	✓	✓	—	✓	✓	—	—	—	—	—	—	—	—	—	—
	0.5	0.25 TX	0.25 TX TOAS	11% T1	—	—	—	—	✓	—	—	—	—	—	—	—	—	—	—
	0.33	0.3 NV	—	Control Blend	—	—	—	—	—	✓	—	✓	✓	✓	—	—	—	✓	✓
				2.0% T2 (field)	—	—	—	—	—	✓	—	✓	✓	✓	—	—	—	✓	✓
				2.0% A2 (field)	—	—	—	—	—	✓	—	✓	✓	✓	—	—	—	✓	✓
	0.33	0.3 NV	—	3.5% T2 (PGH)	—	—	—	—	—	—	—	✓	—	✓	✓	—	—	—	—
				5.5% A2 (PGH)	—	—	—	—	—	—	—	✓	—	✓	✓	—	—	—	—
IN 64-22 (ΔT_c -1.2)	0.28	0.1 TX	0.18 TX MWAS	Control (no recycling agent)	✓	✓	—	✓	—	—	—	✓	—	—	✓	—	—	—	—
				2.0% T1 (PGL/ΔT_c)	✓	✓	—	✓	—	—	—	✓	—	—	✓	—	—	—	—
				2.0% A1 (PGL/ΔT_c)	✓	✓	—	✓	—	—	—	✓	—	—	✓	—	—	—	—
				1.0% V1 (PGL/ΔT_c)	✓	✓	—	✓	—	—	—	✓	—	—	✓	—	—	—	—
				1.0% B1 (PGL/ΔT_c)	✓	✓	—	✓	—	—	—	✓	—	—	✓	—	—	—	—
				5.0% T1 (PGH)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
				6.5% A1 (PGH)	—	—	—	—	—	—	—	—	—	—	—	✓	—	—	—
				3.5% V1 (PGH)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
				4.0% B1 (PGH)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

NOTE: Gray shading indicates NV field project material combinations; — = not applicable.

[a] At RTFO, 20 PAV, and 40 PAV aging.

[b] Long-term oven aging including binder master curve, G-R, $T_{\delta = 45°}$, and FT-IR.

[c] Described in Chapter 2.

[d] Estimated recycling agent dose to match continuous PGH (from blending charts).

Materials Combinations					Binder Testing						Mixture Testing								
Base Binder	Recycled Materials			Recycling Agent Dose and Type (Dose Selection Method[c])	Rheology		Chemical Characterization	FT-IR[a]	Aging[b]	Mortar Testing (PG)	CI	M_R	|E*|	I-FIT	BBR_m (Sliver)	HWTT	APA	UTSST	S-VECD
	RBR	RAP	RAS		G-R[a]	$T_{\delta=45°}$[a]	SAR-AD, MDSC												
IN 64-22 (ΔT_c -1.2)	—	—	—	Base Binder	✓	—	—	—	—	—	—	✓	✓	✓	—	—	—	✓	✓
IN 58-28 (ΔT_c -8)	—	—	—	Base Binder	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0.32	0.25 IN	0.07 IN MWAS	DOT Control (no recycling agent)	✓	—	—	—	—	—	—	✓	✓	✓	—	—	—	✓	✓
	0.42	0.14 IN	0.28 IN MWAS	3.0% T2 (field)	✓	—	—	—	—	—	—	✓	✓	✓	—	—	—	✓	✓
	0.42	0.14 IN	0.28 IN MWAS	6.5% T2 (ΔT_c)	✓	—	—	—	—	—	—	✓	✓	✓	—	✓	—	—	—
		0.28 IN	0.14 IN MWAS	8.0% T2 (PGH)[d]	✓	—	—	—	—	—	—	✓	✓	✓	—	—	—	—	—
	0.5	0.36 IN	0.14 IN MWAS	9.5% T2 (PGH)[d]	✓	—	—	—	—	—	—	✓	✓	✓	—	—	—	—	—
	0.7	0.7 IN	—	10.0% T2 (PGH)[d]	✓	—	—	—	—	—	—	✓	✓	✓	—	—	—	—	—
MN 58-28 (ΔT_c 0)	—	—	—	Base Binder		—	—	—	—	—	—	—	—	—	—	—	—	—	—
	0.5	0.25 TX	0.25 TX TOAS	16.5% T1 (PGH)	✓	✓	—	✓	—	—	—	—	—	—	—	—	—	—	—
				16.5% V1 (PGH)	✓	✓	—	✓	—	—	—	—	—	—	—	—	✓	—	—

NOTE: Gray shading indicates IN field project material combinations; — = not applicable.

[a] At RTFO, 20 PAV, and 40 PAV aging.

[b] Long-term oven aging including binder master curve, G-R, $T_{\delta=45°}$, and FT-IR.

[c] Described in Chapter 2.

[d] Estimated recycling agent dose to match continuous PGH (from blending charts).

(continued on next page)

Table 1. (Continued).

Materials Combinations					Binder Testing					Mortar Testing (PG)	Mixture Testing								
Base Binder	Recycled Materials			Recycling Agent Dose and Type (Dose Selection Method[c])	Rheology		Chemical Characterization	FT-IR[a]	Aging[b]		CI	M_R	|E*|	I-FIT	BBR_m (Sliver)	HWTT	APA	UTSST	S-VECD
	RBR	RAP	RAS		G-R[a]	$T_{\delta = 45°}$[a]	SAR-AD, MDSC												
WI 58-28 (ΔT_c -3.4)	—	—	—	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—	—
	0.22	0.22 WI	—	DOT Control (no recycling agent)	✓	✓	—	—	—	—	—	✓	✓	✓	✓	—	—	✓	✓
	0.31	0.31 WI	—	Recycled Control (no recycling agent)	✓	✓	—	—	—	—	—	✓	✓	✓	—	—	—	✓	✓
WI 52-34 (ΔT_c +0.4)	0.31	0.31 WI	—	Recycled Control (no recycling agent)	✓	✓	—	—	—	—	—	✓	✓	✓	✓	—	—	✓	✓
WI 58-28 (ΔT_c -3.4)	0.31	0.31 WI	—	1.2% V2 (field)	✓	✓	—	—	✓	—	—	✓	✓	✓	✓	—	—	✓	✓
	0.31	0.31 WI	—	5.5% V2 (PGH)	✓	✓	—	—	—	—	—	✓	✓	✓	✓	✓	✓	✓	—
	0.5	0.5 WI	—	9% V2 (PGH)	✓	✓	—	—	—	—	—	✓	✓	✓	✓	✓	✓	—	—
DE 64-28 (ΔT_c -0.1)	0.34	0.17 DE	0.17 MWAS	DOT Control (no recycling agent)	✓	✓	—	—	—	—	—	✓	✓	✓	✓	—	—	—	—
	0.41	0.24 DE	0.17 MWAS	0.8% T2 (field)	✓	✓	—	—	—	—	—	✓	✓	✓	✓	—	—	—	—
	0.41			Recycled Control (no recycling agent)	✓	✓	—	—	—	—	—	✓	✓	✓	—	—	—	—	—
	0.41	0.24 DE	0.17 MWAS	8.5% T2 (PGH)	✓	✓	—	—	—	—	—	✓	✓	✓	✓	✓	✓	—	—
	0.5	0.33 DE		10% T2 (PGH)	✓	✓	—	—	—	—	—	✓	✓	✓	✓	✓	✓	—	—

NOTE: Gray shading indicates WI and DE field project material combinations; — = not applicable.

[a] At RTFO, 20 PAV, and 40 PAV aging.

[b] Long-term oven aging including binder master curve, G-R, $T_{\delta = 45°}$, and FT-IR.

[c] Described in Chapter 2.

  - SAR-AD—saturates, aromatics, resins–asphaltene determinator fractions.
  - CII—colloidal instability index.
  - TPA—total pericondensed aromatics.
  - T_g—glass transition temperature by modulated differential scanning calorimeter (MDSC).
  - T_g End—high-end temperature of the glass transition by MDSC.
  - FT-IR—Fourier transform-infrared spectra.
- Mixture testing results:
  - CI—coatability index.
  - M_R—resilient modulus.
  - G-R_m—mixture Glover-Rowe parameter and Black space analysis.
  - FI and CRI—flexibility index and cracking resistance index by Illinois Flexibility Index Test (I-FIT).
  - S_m, m-value$_m$—creep stiffness and relaxation rate by BBR for mixtures (BBR$_m$) or sliver test.
  - $N_{12.5}$—number of load cycles to 12.5-mm rut depth by asphalt pavement analyzer (APA) and Hamburg wheel-tracking test (HWTT).
  - CRI_{Env}—environmental cracking resistance index by uniaxial thermal stress and strain test (UTSST).
  - D^R, N_f at $G^R = 100$—average reduction in pseudo stiffness up to failure and the number of load cycles for specific rate of damage accumulation by simplified viscoelastic continuum damage (S-VECD) fatigue test.

1.2 Key Results from Phase 1

The use of RAP/RAS in new HMA and WMA mixtures is a sustainable engineering practice that reduces production and construction costs and protects the environment by conserving natural resources and decreasing energy consumption and emissions. As the percentage of RAP/RAS increases, these benefits also increase. State DOTs and contractors alike have recognized these benefits, but to ensure engineering benefits are also realized, state DOTs and other highway agencies require recycled mixtures to meet the same mix design and performance standards as mixtures with all virgin materials by specifying maximum RAP/RAS contents and allowing the use of a softer (substitute) base binder (Epps Martin et al. 2015). This study aimed to explore the effectiveness of using recycling agents to partially restore rheology and thus allow for an increase in the allowable RAP/RAS content. This section provides a summary of the following key results identified in the literature review and surveys in Phase 1 and remaining issues that were addressed to some extent in this study:

- Separation of RAP and RAS Contributions to RBR: The Phase 2 laboratory experiment designs include specification of an overall RBR and the contribution from RAP and RAS separately as RAPBR and RASBR according to the following equations (NCAT 2014):

$$RAPBR = \frac{Pb_{RAP} \times P_{RAP}}{100 \times Pb_{total}} \qquad \text{[Equation 2]}$$

$$RASBR = \frac{Pb_{RAS} \times P_{RAS}}{100 \times Pb_{total}} \qquad \text{[Equation 3]}$$

where

Pb_{RAP} = binder content of the RAP,
P_{RAP} = percentage of RAP by weight of mix,
Pb_{RAS} = binder content of the RAS,
P_{RAS} = percentage of RAS by weight of mix, and
Pb_{total} = binder content of the combined mixture.

- Predominant Use of RAP at High RBRs: Despite the widespread acceptance across state DOTs of the use of recycled materials in HMA and WMA mixtures, survey results reported in the first interim report indicated that most DOTs do not commonly use a high percentage of RAP (60% use 11%–20%, or approximately 0.1–0.2 RAPBR, and 23% use 21%–30%, or approximately 0.2–0.3 RAPBR) and do not commonly use a high percentage of RAS (65% use 0%–3%, or approximately 0–0.13 RASBR, and 29% use 4%–6%, or approximately 0.17–0.26 RASBR). Surveys also indicated that state DOTs and contractors predominantly use RAP in mixtures with high RBRs since this recycled material is more readily available compared to RAS, but concerns remain with respect to material variability.
- Increased Use of Recycling Agents at High RBRs: Recycling agents were used in HMA in the early period of widespread recycling in the 1970s and 1980s toward realizing the environmental, economic, and engineering benefits. Despite this long history of use, survey results indicated that more than 80% of state DOTs do not use or do not allow the use of recycling agents in mixtures. According to these DOTs, the main barriers to using recycling agents in recycled mixtures are the lack of experience and, most importantly, the absence of tests and criteria to determine dose and/or to assess the performance of mixtures with recycling agents. These shortcomings become more pronounced as RBRs increase and recycling agents are required to partially restore rheology. Based on the survey, state DOTs considering mixtures with high RBRs are predominantly exploring the use of tall oils as recycling agents.
- Characterization of Binder Blend Rheology: With aging, the stiffness of a binder increases and the phase angle decreases. With the addition of recycling agents that partially restore or rejuvenate aged binder rheology, and not just soften the material, the aging process is expected to be reversed, with the stiffness decreasing and phase angle increasing. Both of these processes (aging and rejuvenation) are illustrated with the G-R parameter in Black space. Other chemical and rheological parameters provide additional tools for assessing the effectiveness of recycling agents in restoring binder blend rheology initially and with aging. FT-IR spectroscopy and determination of carbonyl area (CA) can be used to track oxidative aging of the binder blend. Binder blend master curves, determined through dynamic shear rheometer (DSR) isothermal frequency sweeps tests, can also be used to determine other rheological indices, such as crossover temperature ($T_{\delta = 45°}$).
- Representative Characterization of Binder Blends: To characterize the aged, recycled binder in RAP/RAS and to quantify the effect of blending these recycled binders with a base binder, extraction and recovery are required. However, this process alters the recycled binder properties due to incomplete extraction, remaining solvent, possible binder-solvent reaction, and binder aging due to high temperatures during the process. The mortar procedure defined by the latest draft of AASHTO T XXX-12 Estimating Effect of RAP and RAS on Blended Binder Performance Grade without Binder Extraction (www.arc.unr.edu/Outreach.html) provides a more representative method for characterizing the effect of the aged, recycled binders on a base binder with or without recycling agents as compared to the binder blend with complete blending after extraction and recovery. These mortar results agree with mixture results and field performance in terms of low-temperature cracking when recovered PG binder grades do not.
- Primary Concern of Mixture Cracking Resistance: As expected, survey results indicated that rutting resistance of mixtures with high RBRs is not a concern unless higher recycling agent doses are used. Of greater concern in recycled mixtures is fatigue, reflective, and thermal cracking since cracking resistance decreases with aging, and mixtures with high RBRs are expected to have lower cracking resistance due to their aged, stiff, and brittle binders. Most existing models/tests to predict crack growth in mixtures are generally empirical or phenomenological in nature and include indirect tensile (IDT) strength, thermal stress restrained specimen test (TSRST), beam fatigue, and overlay test (OT). More recent mechanistic-based approaches and associated tests, such as the UTSST, the S-VECD approach, and the energy-based mechanistic (EBM) method, provide improved characterization tools for evaluating cracking resistance of mixtures with high RBRs. These approaches can be used along with the

semicircular bend (SCB) test recommended by NCHRP Project 9–57, "Experimental Design for Field Validation of Laboratory Tests to Access Cracking Resistance of Asphalt Mixtures" (Zhou and Newcomb 2015) after long-term oven aging (LTOA) to evaluate the effectiveness of recycling agents in improving cracking resistance for mixtures with high RBRs. In addition, differences in laboratory specimen fabrication and field production and construction of mixtures with recycling agents must be considered with respect to short-term laboratory aging protocols for use in mix design and quality-assurance testing.

- Evolution of Recycling-Agent Effectiveness: Although many studies have shown the effect of recycling agents in improving the cracking resistance of mixtures with high RBRs, the surveys indicated that state DOTs remain concerned with the evolution of recycling-agent effectiveness with aging and the resulting long-term performance of these mixtures. Binder and mortar rheology and mixture stiffness and cracking resistance results after laboratory LTOA can be subsequently tied to field project locations in terms of climate and construction date, which play a role in the blending of the binder components through diffusion. This is one approach to evaluating long-term performance of mixtures with high RBRs and recycling agents. A companion approach that predicts long-term performance uses a computational pavement oxidation model that is based on fundamentals of heat and mass transfer together with measured binder oxidation kinetics and rheological hardening properties to provide changes in binder rheology as a function of time and depth below the surface. The model is founded on local climate and weather data as well as parameters for the specific binder used in the pavement. For sufficiently oxidized binder blends, data suggest that the model also provides meaningful durability calculations for polymer-modified binders. This model provides a tool to capture the unknown effect of recycling agents on binder oxidation kinetics and resulting evolution of recycling agent effectiveness with aging.

1.3 Recent Relevant Literature

A comprehensive literature review was presented in the first interim report (Epps Martin et al. 2015), and a list of recent relevant literature organized by discussion area was provided in the revised second interim report (Epps Martin et al. 2017). Table 2, Table 3, Table 4, Table 5, and Table 6 provide a summary of the literature used throughout the study that indicates the dependency of recycling-agent effectiveness with short- and long-term aging on its type and dose and on the type of recycled materials (RAP versus RAS).

1.4 Scope of Final Report

Chapter 1 of this final report begins with a brief history of the use of recycled materials in HMA and WMA mixtures, the construction and performance challenges associated with using high percentages of these materials through high RBRs, and the use of recycling agents to overcome these challenges. An NCHRP 09–58 overview with objectives and a summary of key results from Phase 1 and recent relevant literature is also provided, followed by the scope of this final report, which includes a list of associated publications to date. Next, the field projects and associated materials and selected laboratory tests and specimen fabrication protocols are introduced.

Chapter 2 summarizes the key results completed in Phase 2, including the following:

- Development of recycling agent dose selection method,
- Chemical compatibility of binder blends,
- Rheological balance of binder blends,
- Representative binder blending,
- Mixture cracking resistance by S-VECD, and
- Comparison of specimen types.

Table 2. Previous research on the effect of recycling agents on rejuvenated binder blends.

Author(s) and Year	Laboratory Test(s)	Main Findings
Shen and Ohne (2002)	PG and penetration	Nonlinear reduction in PGH with increased recycling-agent dose, but linear reduction in PGL.
Shen et al. (2007)	PG	Linear reduction in PGH and PGL of RAP binder with increased recycling-agent dose.
Tao et al. (2010)	PG and penetration	Linear reduction in PGH and PGL, and linear increase in penetration, with increased recycling-agent dose. Linear increase in ductility with increased recycling-agent dose, up to 10% dose. Beyond 10%, a slower increase in ductility with recycling-agent dose. A specific type of recycling agent is required to rejuvenate aged polymer-modified binders to ensure long-term durability.
Tran et al. (2012)	PG	Linear reduction in PGH and PGL of RAP/RAS binders with increased recycling-agent dose.
Oliveira et al. (2013)	DSR frequency sweep and penetration	Linear reduction in penetration at 25°C of RAP binder with increased recycling-agent dose. Recycling-agent addition decreased $\lvert G^*\rvert$ and increased δ in DSR test.
Zaumanis et al. (2014)	PG and penetration	Linear reduction in PGH and PGL of RAP binder with increased recycling-agent dose, but nonlinear reduction in intermediate-temperature PG (PGI). Organic products (waste vegetable oil and distilled tall oil) require much lower doses compared to petroleum products (aromatic extract and waste engine oil) to deliver the same effect on PG.
Yu et al. (2014)	DSR frequency sweep and PG	Recycling-agent addition decreased $\lvert G^*\rvert$ and increased δ in DSR and decreased S and increased m-value in BBR, depending on aged binder source and recycling-agent type. Waste vegetable oil is much more effective than aromatic extract.
Ali (2015)	PG and rotational viscometer	Linear reduction in PGH and viscosity with increased recycling-agent dose. Bio-based oil and petroleum distillate products require lower doses compared to other products to deliver the same effect on PGH and viscosity.
Zhou et al. (2015)	PG	Linear reduction in PGH and PGL of RAP/RAS binders with increased recycling-agent dose, only when the dose is 20% or less. Beyond 20%, a nonlinear decrease in PGH with recycling-agent dose.
Mohammadafzali et al. (2015)	PG	Petroleum-based and bio-based recycling agents accelerated aging in the blends, while a paraffinic-based recycling agent slowed down aging. Bio-based oils increased aging the most.
Alavi and He et al. (2015)	dynamic shear modulus	The addition of a petroleum-based recycling agent decreased the stiffness of binder blends with 25% and 40% RAP and 15% RAS for five different base binders.
Pradyumna and Jain (2016)	Marshall stability, tensile strength ratio, and resilient modulus	Rejuvenated mixtures that contain recycling agents with higher colloidal instability index (CII) had better moisture susceptibility and load spreading properties than those containing recycling agents with lower CII.
Nayak and Sahoo (2016)	DSR frequency sweep	The plant-based oil performed better in terms of fatigue resistance then the naphthenic aromatic recycling agent, while this was reversed for rutting performance.
Karki and Zhou (2016)	DSR frequency sweep and PG	Linear reduction in PGH and PGL of RAP/RAS binders with increased recycling agent dose. Higher dose is required to restore PGH than PGL. Recycling-agent addition decreased $\lvert G^*\rvert$ and increased δ depending on the dose.
Osmari et al. (2017)	rotational viscometer and DSR frequency sweep	Petroleum-based recycling agents require higher doses than waste cooking oil and castor oil to deliver the same effect on viscosity. Waste cooking oil and castor oil had more impact in reducing $\lvert G^*\rvert$ than petroleum-based recycling agent.
Tabatabaee and Kurth (2017)	SARA Fractionation	Blends with vegetable oils have a lower CII than blends with aromatic extracts.

Table 3. Previous research on the effect of recycling agents on stiffness of recycled asphalt mixtures.

Author(s) and Year	Laboratory Test(s)	Main Findings
Mallick et al. (2010)	dynamic modulus	Recycling-agent addition dropped the stiffness of 100% RAP mixture at high loading frequencies (5 Hz and 10 Hz) but increased the stiffness at lower loading frequencies (1 Hz and 0.1 Hz) at the highest testing temperature (54.4°C).
Uzarowski et al. (2010)	dynamic modulus	Recycling-agent addition significantly dropped the stiffness of rejuvenated mixtures.
O'Sullivan (2011)	dynamic modulus	Recycling-agent addition decreased the stiffness of 80%, 90%, and 100% RAP mixtures to below the stiffness of the virgin mixture.
Tran et al. (2012)	dynamic modulus	After short-term aging, recycling-agent addition dropped the stiffness of the rejuvenated RAP/RAS mixtures closer to that of the virgin mixture. After long-term aging, rejuvenated mixtures with recycling agent appeared to age faster than the RAP/RAS mixtures without recycling agent.
Mogawer et al. (2013)	dynamic modulus	Recycling agent addition dropped the stiffness of rejuvenated mixtures closer to that of the virgin mixture. Rejuvenated mixtures with RAS and RAP/RAS showed less significant reduction in stiffness after incorporating the recycling agent, as compared to RAP-only rejuvenated mixtures.
Im et al. (2014)	dynamic modulus	Recycling-agent addition dropped the stiffness of the rejuvenated mixtures at high testing temperature (40°C) and low frequency ranges but did not affect the stiffness at lower temperatures (4°C and 20°C).
Alavi and He et al. (2015)	dynamic shear modulus	The addition of a petroleum-based recycling agent decreased the stiffness of fine aggregate mixtures with 25% and 40% RAP and 15% RAS for five different base binders.
Haghshenas et al. (2016)	dynamic modulus	The petroleum-based recycling agent had a greater impact in reducing |E*| than soybean oil and tall oil.

Table 4. Previous research on the effect of recycling agents on intermediate-temperature cracking resistance of recycled asphalt mixtures.

Author(s) and Year	Laboratory Test(s)	Main Findings
Lin et al. (2011)	IDT	Recycling-agent addition improved cracking resistance, depending on recycling-agent type.
Tran et al. (2012)	energy ratio test	Recycling-agent addition improved fracture properties of rejuvenated mixtures.
	Texas OT	Recycling-agent addition increased the average number of cycles to failure.
Mogawer et al. (2013)	OT	Recycling-agent addition improved the cracking performance of rejuvenated RAP/RAS mixtures, depending on recycling-agent type.
Yan et al. (2014)	four-point bending	Recycling-agent addition highly improved the fatigue cracking resistance of rejuvenated 30%, 40%, and 50% RAP mixtures, depending on recycling-agent type. Rejuvenated mixtures containing recycling agents with higher CII had better fatigue cracking resistance.
Im et al. (2014)	OT	Recycling-agent addition increased the average OT number of cycles to failure, from approximately 110% to 300%, depending on recycling-agent type.
Cooper et al. (2015)	SCB	Mixtures rejuvenated with napthenic oil exhibited better fracture resistance at intermediate temperature than those rejuvenated with vegetable oil.
Ali (2015)	OT	Recycling-agent addition increased the average OT number of cycles to failure as compared to the virgin and 100% RAP mixture.
Nabizadeh et al. (2017)	I-FIT	Recycling-agent addition increased the FI. Aromatic extract was more effective than tall oil and soybean oil.
Espinoza-Luque et al. (2018)	I-FIT	Recycling-agent addition increased the FI, depending on recycling-agent dose.
Cooper et al. (2015)	SCB	Recycling agent adversely affected the fracture resistance of the rejuvenated mixtures with RAS.

Table 5. Previous research on the effect of recycling agents on low-temperature cracking resistance of recycled asphalt mixtures.

Author(s) and Year	Laboratory Test(s)	Main Findings
Shen et al. (2004)	TSRST	Recycling-agent addition significantly improved low-temperature fracture properties, depending on recycling-agent type.
Tran et al. (2012)	IDT	Recycling-agent addition reduced the critical failure temperature of rejuvenated RAP/RAS mixtures.
Mogawer et al. (2013)	TSRST	Recycling-agent addition considerably improved the low-temperature cracking resistance of rejuvenated RAP/RAS mixtures.
Zaumanis et al. (2013)	IDT creep compliance	Recycling-agent addition increased the low-temperature creep compliance (and thus reduced low-temperature cracking potential) of rejuvenated 100% RAP mixture.
	IDT	Recycling-agent addition increased indirect tensile strength and fracture energy, depending on recycling-agent type.
Hajj and Souliman et al. (2013)	TSRST	Recycling-agent addition improved the low-temperature cracking resistance with a decrease in the fracture stress and microcracking.
Yan et al. (2014)	three-point bending	Recycling-agent addition improved the low-temperature cracking resistance, depending on recycling-agent type.
Cooper et al. (2015)	TSRST	Recycling agent adversely affected the low-temperature performance of the rejuvenated mixtures with RAS.

Table 6. Previous research on the effect of recycling agents on rutting resistance and moisture susceptibility of recycled asphalt mixtures.

Author(s) and Year	Laboratory Test(s)	Main Findings
Shen et al. (2004)	dynamic stability test (wheel-tracking rut test)	Recycling-agent addition significantly decreased the dynamic stability by a range of 20% to 50% depending on recycling-agent dose (2% to 7.4%).
Shen et al. (2007)	APA	Recycling-agent addition and the use of a softer binder decreased the rut depth, but the rut depths of rejuvenated mixtures with recycling agent were smaller than those using a softer base binder.
	tensile strength ratio (TSR)	Recycling-agent addition and softer binder usage did not affect moisture susceptibility compared to the virgin mixture.
Uzarowski et al. (2010)	APA	Recycling-agent addition significantly dropped the rutting resistance of rejuvenated mixtures.
Lin et al. (2011)	Marshall stability	With increasing recycling agent dose from 10% to 40%, the reduction in rejuvenated mixture stability ranged from 25% to 55% depending on recycling-agent type.
Tran et al. (2012)	APA	Recycling-agent addition increased mixture susceptibility to rutting, but with rut depths less than 5.5 mm to withstand at least 10 million equivalent single axle loads.
	TSR	Recycling-agent addition did not negatively affect the TSR value.
Mogawer et al. (2013)	Hamburg wheel-tracking device (HWTD)	Recycling-agent addition increased mixture susceptibility to rutting and moisture damage in rejuvenated RAP/RAS mixtures.
Yan et al. (2014)	Marshall stability, wheel-tracking rut test	Rejuvenated mixtures containing recycling agents with higher CII had better rutting resistance.
Im et al. (2014)	HWTD	Rutting and moisture susceptibility of rejuvenated mixtures with RAP/RAS and recycling agents depend on the type and dose of recycling agent.
Espinoza-Luque et al. (2018)	HWTD	Recycling-agent addition increased mixture susceptibility to rutting, depending on recycling-agent dose.
Cooper et al. (2015)	HWTD	Recycling-agent addition did not negatively affect the rutting or moisture susceptibility of the rejuvenated mixtures with RAS.

Chapter 3 presents a summary of field performance of high RBR mixtures in the field projects and a comparison of field and corresponding laboratory performance toward development of thresholds for cracking resistance.

Chapter 4 provides more detailed laboratory performance results of high RBR binder blends and associated mixtures in terms of the following challenges associated with the evaluation of the effectiveness of recycling agents in high RBR binder blends initially and with aging:

- Binder blend rheology with aging,
- Binder blend aging prediction,
- Recycling-agent characterization,
- Mixture performance, and
- Recycled binder availability.

Chapter 5 describes the following practical tools developed in this study and incorporated into a draft AASHTO standard practice to facilitate the evaluation of the effectiveness of recycling agents in high RBR binder blends and corresponding mixtures initially and with aging:

- Component materials selection guidelines,
- Recycling-agent dose selection method and materials proportioning,
- Binder blend rheological evaluation tools,
- Mixture performance evaluation tools, and
- Recycled binder availability factor.

A discussion of laboratory aging and climate effects is also provided.

Chapter 6 provides conclusions and suggested research and implementation activities for other considerations outside the scope of this study to conclude this final report.

Construction reports for the five field projects are presented as Appendices A through E, and Appendices F through I provide additional data on binder blend aging prediction, recycling-agent characterization, an economic analysis of the use of RAP in asphalt mixtures, and a draft AASHTO standard practice to increase RBR in asphalt mixtures by using recycling agents.

During this study, the following papers were published and provide additional details on specific topics presented in this final report and other collaborative efforts:

- Kaseer, F., E. Arámbula-Mercado, L. Garcia Cucalon, and A. Epps Martin (2018a) "Performance of Asphalt Mixtures with High Recycled Materials Content and Recycling Agents." *International Journal of Pavement Engineering.*
- Garcia Cucalon, L., F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, N. Morian, S. Pournoman, and E. Y. Hajj (2018) "The Crossover Temperature: Significance and Application towards Engineering Balanced Recycled Binder Blends." *Road Materials and Pavement Design*, https://doi.org/10.1080/14680629.2018.1447504.
- Oshone, M., J. Sias Daniel, E. Dave, R. Rastegar, F. Kaseer, and A. Epps Martin (2018) "Exploring Master-Curve Based Parameters to Distinguish between Mix Variables," *Proceedings of the International Society for Asphalt Pavements (ISAP) 13th Conference on Asphalt Pavements*, Fortaleza, Brazil, June 19–21.
- Arámbula-Mercado, E., A. Epps Martin, and F. Kaseer (2018a) "Case Study on Balancing Mixtures with High Recycled Materials Contents," *Proceedings of the International Conference on Advances in Materials and Pavement Performance Prediction (AM3P)*, Doha, Qatar, April 16–18.

- Kaseer, F., L. Garcia Cucalon, E. Arámbula-Mercado, A. Epps Martin, and J. Epps (2018b) "Practical Tools for Optimizing Recycled Materials Content and Recycling Agent Dosage for Improved Short- and Long-Term Performance of Rejuvenated Binder Blends and Mixtures," *Journal of the Association of Asphalt Paving Technologists* 87.
- Morian, N., E. Y. Hajj, S. Pournoman, J. Habbouche, and D. Batioja-Alvarez (2018) "Low Temperature Behavior of Asphalt Binders, Mortars, and Mixtures with High Recycled Materials Content," *Journal of the Association of Asphalt Paving Technologists* 87.
- Pournoman, S., E. Y. Hajj, N. Morian, and A. Epps Martin (2018) "Impact of Recycled Materials and Recycling Agents on Asphalt Binder Oxidative Aging Predictions," *Transportation Research Record*.
- Menapace, I., L. Garcia Cucalon, F. Kaseer, E. Masad, and A. Epps Martin (2018a) "Application of Low Field Nuclear Magnetic Resonance to Evaluate Asphalt Binder Viscosity in Recycled Mixes," *Construction and Building Materials* 170, 725–736, https://doi.org/10.1016/j.conbuildmat.2018.03.114.
- Kaseer, F., F. Yin, E. Arámbula-Mercado, A. Epps Martin, J. Daniel, and S. Salari (2018c) "Development of an Index to Evaluate the Cracking Potential of Asphalt Mixtures Using the Semi-Circular Bending Test Construction & Building Materials," *Construction and Building Materials* 167, 286–298, https://doi.org/10.1016/j.conbuildmat.2018.02.014.
- Arámbula-Mercado, E., F. Kaseer, A. Epps Martin, F. Yin, and L. Garcia Cucalon (2018b) "Evaluation of Recycling Agent Dosage Selection and Incorporation Methods for Asphalt Mixtures with High RAP and RAS Contents," *Construction and Building Materials* 158, 432–442, https://doi.org/10.1016/j.conbuildmat.2017.10.024.
- Menapace, I., L. Garcia Cucalon, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, E. Masad, and G. King (2018b) "Effect of Recycling Agents in Recycled Asphalt Binders Observed with Microstructural and Rheological Tests," *Construction and Building Materials* 158, 61–74, https://doi.org/10.1016/j.conbuildmat.2017.10.017.
- Garcia Cucalon, L., G. King, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, T. F. Turner, and C. J. Glover (2017) "Compatibility of Recycled Binder Blends with Recycling Agents: Rheological and Physicochemical Evaluation of Rejuvenation and Aging Processes," *Industrial Engineering and Chemistry Research* 56 (29), 8375–8384, https://doi.org/10.1021/acs.iecr.7b01657.
- Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin (2017a) "Stiffness Characterization of Asphalt Mixtures with High RAP/RAS Contents and Recycling Agents," *Transportation Research Record* 2633, 58–68, http://dx.doi.org/10.3141/2633-08.
- Yin, F., F. Kaseer, E. Arámbula-Mercado, and A. Epps Martin (2017) "Characterizing the Long-Term Rejuvenating Effectiveness of Recycling Agents on Asphalt Blends and Mixtures with High RAP and RAS Contents," *Road Materials and Pavement Design* 18 (Sup 4), 273–292, http://dx.doi.org/10.1080/14680629.2017.1389074.
- Carvajal Munoz, J. S., F. Kaseer, E. Arámbula, and A. Epps Martin (2015) "Use of the Resilient Modulus Test to Characterize Asphalt Mixtures with Recycled Materials and Recycling Agents," *Transportation Research Record* 2506, 45–53, http://dx.doi.org/10.3141/2506-05.

1.5 Experiment Design

This section provides the experiment design in terms of field projects and associated materials and of selected laboratory tests and specimen fabrication protocols. Different materials and testing combinations were used for each issue explored and each tool developed, as described in Chapter 5 based on the results presented in Chapter 2, Chapter 3, and Chapter 4.

1.5.1 Field Projects and Materials

In selecting field projects for use in the Phase 2 laboratory experiments and the Phase 3 field experiments, consideration was given to obtaining a range in each of the following factors to make the conclusions of this study as comprehensive as possible:

- Recycling agents by category, as defined in Table 7, for comparison of types;
- RAPBR and RASBR;
- Environmental zone, as defined by the SHRP Long-Term Pavement Performance Program (SHRP-LTPP) and shown in Figure 2; and
- Traffic volume.

Since the laboratory experiments were tied to field projects to facilitate Phase 3, selection of a field project in a specific environment simultaneously resulted in selection of the materials (aggregate; base binder; recycled materials; and any additives, including recycling agents) based on the materials selected by the respective DOT. Other eligibility requirements for field projects besides location on a highway, arterial, or collector facility in North America included the following:

- A high RBR between 0.3 and 0.5;
- A virgin test section (with no recycled materials) if possible;
- A DOT control test section (with recycled materials but without recycling agents) at the maximum allowed by the DOT without recycling agents;
- Multiple recycling agents if possible; and
- A minimum number of WMA, anti-stripping, and other additives.

Construction of a new asphalt mixture layer was required for this study because it provided the only opportunity for fabrication of reheated plant-mixed, laboratory-compacted (RPMLC) specimens that capture field blending of base binders, recycled materials, and recycling agents and a starting point for tracking performance of cores to validate laboratory aging protocols critical to evaluating mixture cracking resistance and its evolution with aging.

Table 7. Recycling-agent categories and types (Willis and Tran 2015).

Category	Types	Description
Paraffinic oils	Waste engine oil Waste engine oil bottoms Valero VP 165® Storbit®	Refined used lubricating oils.
Aromatic extracts	Hydrolene® Reclamite® Cyclogen L® ValAro 130A®	Refined crude oil products with polar aromatic oil components.
Napthenic oils	SonneWarmix RJ™ Ergon HyPrene®	Engineered hydrocarbons for asphalt modification.
Triglycerides and fatty acids	Waste vegetable oil Waste vegetable grease Brown grease Oleic acid	Derived from vegetable oils.
Tall oils	Sylvaroad™ RP1000 Hydrogreen®	Paper industry by-products. Same chemical family as liquid antistrip agents and emulsifiers.

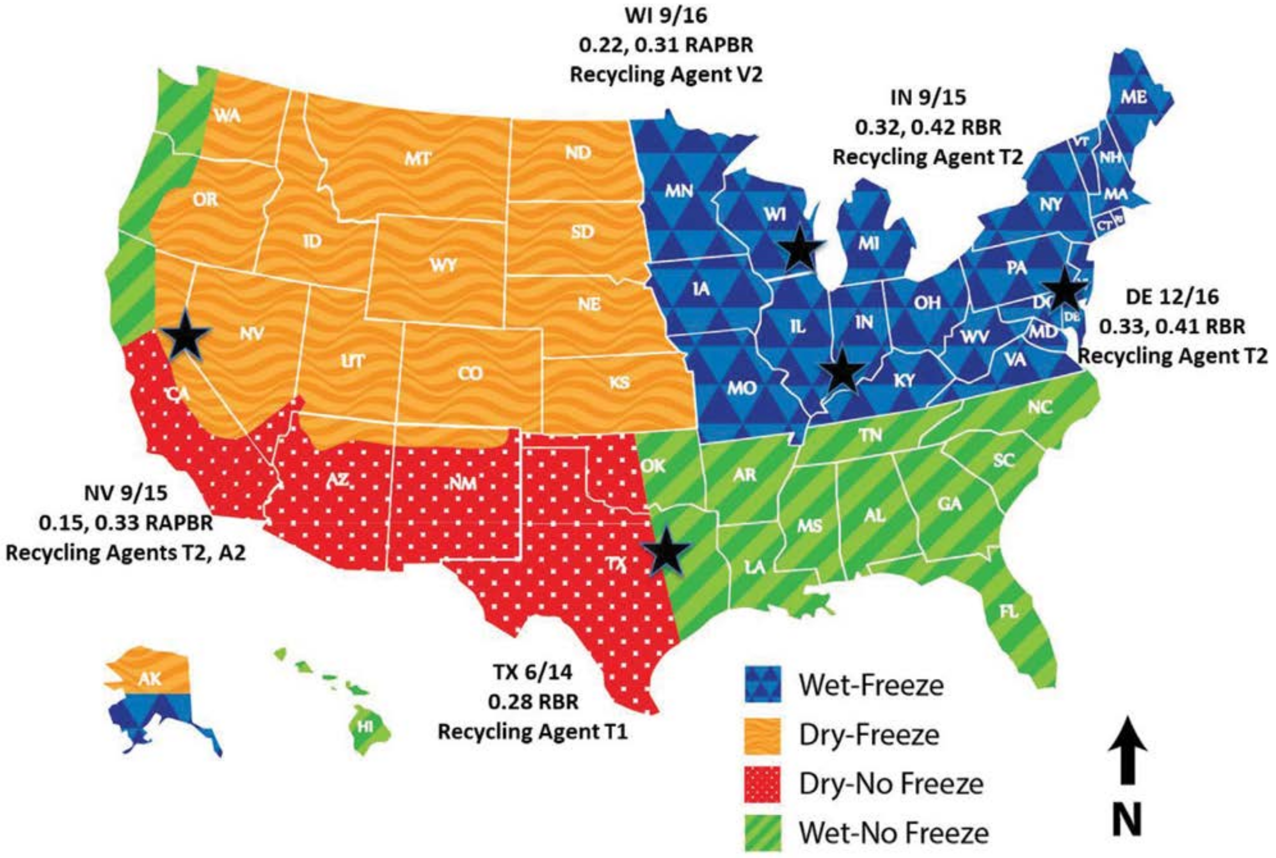


Figure 2. SHRP-LTPP environmental zones and constructed field projects.

Table 8 through Table 12 provide details for the test sections in the field projects constructed in TX, NV, IN, WI, and DE (Figure 2), respectively, which include those used in Phase 2 from TX, NV, and IN and in Phase 3 from WI and DE. Construction reports for the TX, NV, IN, WI, and DE field projects are presented in Appendices A through E, respectively. Each of these field projects provided the following key elements that facilitated the development of evaluation tools for assessing the effectiveness of recycling agents initially and with aging for binder blends and corresponding mixtures with high RBRs in different environmental zones:

- TX—constructed early in study, poor softer (substitute) binder;
- IN—high RASBR, high RBR, poor softer (substitute) binder;
- NV—polymer-modified binder [no softer (substitute) binder], two recycling agents;
- WI—engineered recycling agents; and
- DE—WMA additive, high RBR, no softer (substitute) binder.

Field activities for the constructed field projects included gathering component materials (virgin aggregate; base binder; recycled materials; and any additives, including recycling agents) and plant mix for fabrication of laboratory-mixed, laboratory-compacted (LMLC) and RPMLC specimens, respectively, and procuring cores at construction and after approximately 1 year to verify specimen fabrication and aging protocols, validate relationships between binder and mixture properties, and evaluate the effectiveness of recycling agents with aging. A third set of pavement cores for the TX, NV, and IN field projects after approximately 2 years were procured in Phase 3. All of these materials were available through cooperation with the state DOTs, contractors, and state asphalt paving associations. A general field-performance assessment by visual survey was completed at each coring period in cooperation with the associated DOTs, and a summary is provided in Chapter 3.

Table 8. Mixture characteristics for the TX field project.

Mixture Type/Test Section	Virgin	DOT Control (0.28 RBR) +0.5% WMA	Rejuvenated (0.28 RBR) +2.7% T1
Binder PG	70-22P	64-22	64-22
Binder content[a]	4.9%	4.9%	4.9%
RAP/RAS content	—	10% RAP/ 5% MWAS	10% RAP/ 5% MWAS
RBR	—	0.28 *(0.1 RAP + 0.18 RAS)*	0.28 *(0.1 RAP + 0.18 RAS)*
Recycling-agent type and dose[b]	—	—	2.7% T1
WMA dose[b]	—	0.5	—

NOTE: — = not applicable.

[a] Total binder in the mixture (virgin/base + recycled).

[b] By percentage of total binder in the mixture.

Table 9. Mixture characteristics for the IN field project.

Mixture Type/Test Section	Virgin	DOT Control (0.32 RBR)	Rejuvenated (0.42 RBR) +3% T2
Binder PG	64-22	58-28	58-28
Binder content[a]	5.9%	5.8%	5.8%
RAP/RAS content	—	28% RAP/ 2% MWAS	16% RAP/ 8% MWAS
RBR	—	0.32 *(0.25 RAP + 0.07 RAS)*	0.42 *(0.14 RAP + 0.28 RAS)*
Recycling Agent Type and Dose[b]	—	—	3% T2

NOTE: — = not applicable.

[a] Total binder in the mixture (virgin/base + recycled).

[b] By percentage of total binder in the mixture.

Table 10. Mixture characteristics for the NV field project.

Mixture Type/Test Section	Virgin	DOT Control (0.15 RBR)	Recycled Control (0.33 RBR)	Rejuvenated (0.33 RBR) +2% T2	Rejuvenated (0.33 RBR) +2% A2
Binder PG	64-28P	64-28P	64-28P	64-28P	64-28P
Binder content[a]	5.37%	5.04%	4.6%	4.5%	4.6%
RAP content	—	15%	33%	33%	33%
RBR	—	0.15	0.33	0.33	0.33
Recycling-agent type and dose[b]	—	—	—	2% T2	2% A2

NOTE: — = not applicable.

[a] Total binder in the mixture (virgin/base + recycled).

[b] By percentage of total binder in the mixture.

Table 11. Mixture characteristics for the WI field project.

Mixture Type/Test Section	DOT Control (0.22 RBR) (PG 58-28)	Recycled Control (0.31 RBR) (PG 58-28)	Recycled (0.31 RBR) (PG 52-34)	Rejuvenated (0.31 RBR) (PG 58-28) +1.2% V2
Binder PG	58-28	58-28	52-34	58-28
Binder content[a]	5.6%	5.4%	5.4%	5.4%
RAP content	27%	36%	36%	36%
RBR	0.22	0.31	0.31	0.31
Recycling-agent type and dose[b]	—	—	—	1.2% V2

NOTE: — = not applicable.
[a] Total binder in the mixture (virgin/base + recycled).
[b] By percentage of total binder in the mixture.

For the laboratory experiments, materials were selected from those used in the field projects and expanded with additional base binders from NH and MN; RAP from NH; TOAS from TX and CA; and A1, V1, V3, B1, B2, and P recycling agents as shown in Table 1 and summarized as follows:

- Phase 2A:
  - High 0.3 to 0.5 RBRs with all RAP and RAP/RAS combinations with equivalent RAPBR and RASBR.
  - Traditional aromatic (A1, A2) and greener alternative tall oil (T1, T2) recycling agents.
  - TX field project materials (expanded with additional base binders, recycled materials, and recycling agents): TX PG 70–22P, TX PG 64–22, NH PG 64–28, and NV PG 64–28P base binders; TX RAP, TX MWAS, and TX TOAS; T1 and A1.
  - NV field project materials: NV PG 64–28P base binder, NV RAP, and T2 and A2 for binder and mortar experiments only.
- Phase 2B:
  - High 0.3 to 0.5 RBRs with all RAP and balanced RAP/RAS combinations based on PGH.
  - Improved and softer IN PG 64–22, MN PG 58–28, and IN PG 58–28 base binders.
  - Aromatic extract (A2), tall oil (T2), vegetable oil (V1), modified vegetable oil (V2), and reacted bio-based oil (B1) recycling agents.

Table 12. Mixture characteristics for the DE field project.

Mixture Type/Test Section	DOT Control (0.33 RBR) +0.4% WMA	Rejuvenated (0.41 RBR) +0.8% T2	Rejuvenated (0.41 RBR) +0.8% T2 +0.25% WMA
Binder PG	64-28	64-28	64-28
Binder content[a]	5.4%	5.4%	5.4%
RAP/RAS content	20% RAP/ 4% MWAS	29% RAP/ 4% MWAS	29% RAP/ 4% MWAS
RBR	0.34 *(0.17 RAP + 0.17 RAS)*	0.41 *(0.24 RAP + 0.17 RAS)*	0.41 *(0.24 RAP + 0.17 RAS)*
Recycling-agent type and dose[b]	—	0.8% T2	0.8% T2
WMA dose[b]	0.4%	—	0.25%

NOTE: — = not applicable.
[a] Total binder in the mixture (virgin/base + recycled).
[b] By percentage of total binder in the mixture.

  - NV field project materials: NV PG 64–28P base binder, NV RAP, and T2 and A2.
  - IN field project materials: IN PG 64–22 and IN PG 58–28 base binders, IN RAP and IN MWAS, and T2.
- Phase 3:
  - High 0.3 to 0.5 RBRs with all RAP and balanced RAP/RAS combinations based on PGH.
  - Virgin WI mixture.
  - Improved and softer WI PG 52–34 base binders.
  - Aromatic extract (A1), tall oils (T1 and T2), modified vegetable oils (V2 and V3), reacted bio-based oils (B1 and B2), and paraffinic oil (P) recycling agents.
  - WI field project materials: WI PG 58–28 and WI PG 52–34 base binders, WI RAP, and V2.
  - DE field project materials: DE PG 64–28 base binder, DE RAP and DE MWAS, and T2.

1.5.2 Laboratory Tests and Specimen Fabrication Protocols

The laboratory parameters and tests shown in Table 13, Figure 3, and Figure 4 were selected based on the results from Phase 1 and a continuous review of the literature. For all tests, a minimum of two replicate specimens was utilized with at least three replicates for M_R/FI testing. Air voids (AVs) for all mixture specimens were determined by AASHTO T 166. Mixture specimens included LMLC specimens, RPMLC specimens, and field cores extracted immediately after construction and approximately 1 year, 2 years, and 3 years after construction. Prior to mixture performance testing, specimen fabrication protocols were established for use in the laboratory to address recycling agent incorporation in binders for mixtures and aging. These protocols are described subsequently, followed by additional details for those tests without standards.

1.5.2.1 Recycling-Agent Incorporation Protocol

The most common practice for incorporating recycling agents in mixtures is to follow the producer recommendation for dose and proportion of the recycling agent with respect to the base binder. In most cases, when the recycling-agent dose by weight of total binder is 2.0% or lower, the recycling agent is added to the mixture without modifying the amount of base binder (i.e., by addition), whereas when the recycling-agent dose is more than 2.0%, the base binder content is reduced by the recycling-agent amount (i.e., by replacement). In this study, the replacement practice led to incomplete aggregate coating by the binder in mixtures containing RAS at recycling agent doses as low as 5.5%.

Thus, for two mixtures at high recycling-agent doses, three recycling-agent incorporation protocols that ranged from 100% replacement to 100% addition were evaluated in terms of aggregate coatability using a modified water absorption method developed in NCHRP Project 09–53, "Properties of Foamed Asphalt for Warm Mix Asphalt Applications" (Newcomb et al. 2015b). This method is based on the assumption that a completely coated aggregate submerged in water for a short period of 1 h cannot absorb water because water cannot penetrate through the binder film covering the aggregate surface. Conversely, a partially coated aggregate is expected to have detectable water absorption because water can penetrate and be absorbed by the uncoated portions of the particle. The resulting CI is calculated as the relative difference in saturated surface dry (SSD) water absorption for the uncoated and coated coarse aggregate fraction (larger than 9.5 mm). Larger CI values indicate better aggregate coating.

Figure 5 presents the CI results for a 0.4 RBR mixture with PG 64–22 base binder, TX RAP, and 9.5% A1, and a 0.5 RBR mixture with PG 64–28 base binder, TX RAP at 0.25 RAPBR, TX TOAS at 0.25 RASBR, and 12.5% T1. For the 0.4 RBR mixture, the CI values remained at 100% even after replacing the base binder by half the recycling-agent amount, and above 95% for replacing the base binder by the full recycling-agent amount. However, for the 0.5 RBR mixture, the CI value decreased significantly, especially when replacing the base binder by the

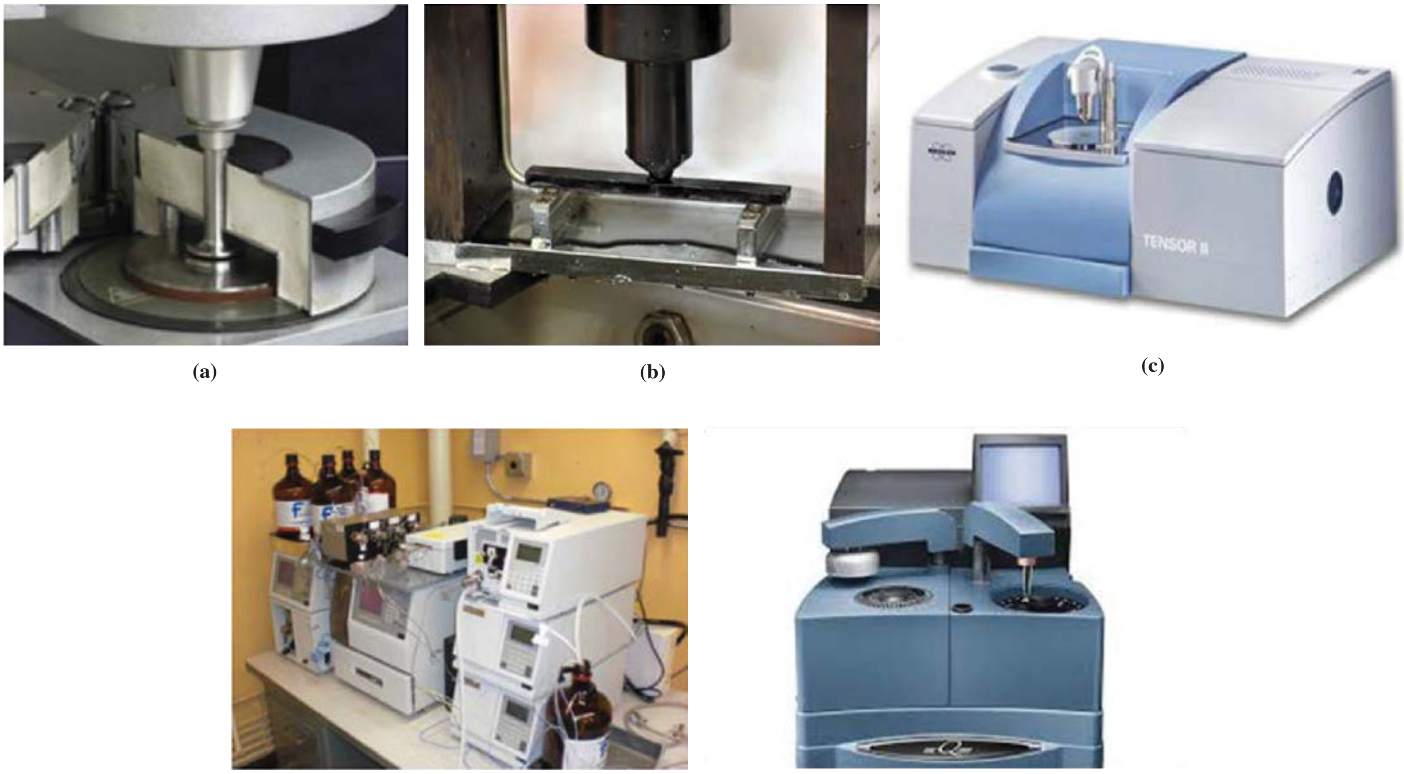
Table 13. Laboratory parameters and tests.

Performance Issue	Binder Parameter and Test	Mortar Parameter and Test	Mixture Parameter and Test
Recycling-agent dose selection	PGH after S Aging, PGL after L Aging per AASHTO T 315, T 313, and M 320	—	—
Rheological balance and effectiveness evolution with aging	PGH after S Aging per AASHTO T 315 & M 320 ΔT_c @ T_{low} after L Aging per AASHTO PP 78 G-R & $T_{\delta=45°}$ @ T_{int} with Aging by DSR Master Curve per AASHTO T 315 CA Growth by FT-IR with Aging Oxidation Kinetics and G-R/CA_g HS by FT-IR and DSR Master Curve	ΔT_c @ T_{low} after L Aging per AASHTO PP 78	M_R @ T_{int} after S, L Aging per ASTM D7369 Externally across Diameter |E*|, φ @ T_{high}, T_{int} and T_{low} after S, L Aging per AASHTO T 342 G-R_m @ 20°C, 5 Hz
Rutting resistance and balanced mixture	PGH after S Aging per AASHTO T 315 and M 320	PGH after S Aging per Draft AASHTO	$N_{12.5}$ by HWTT^ & APA Jr^ @ T_{high} after S Aging per AASHTO T 324
Fatigue cracking resistance	G-R @ T_{int} with Aging by DSR Master Curve per AASHTO T 315	PGI after L Aging per Draft AASHTO	FI & CRI by I-FIT @ T_{int} after S and L Aging per AASHTO TP 124 D^R & N_f@G^R = 100 by S-VECD and |E*| @ T_{int} after L Aging per AASHTO TP 107
Low-temperature cracking resistance	PGL after L Aging per AASHTO T 313 and M 320	PGL after L Aging per Draft AASHTO	CRI_{Env} by |E*| and UTSST @ T_{low} after L Aging per AASHTO T 342 and Draft AASHTO S_m & m-$value_m$ by BBR_m @ T_{low} after L Aging per AASHTO TP 125
Chemical compatibility	CII and TPA by SAR-AD T_g and T_g End by MDSC CA Growth by FT-IR with Aging	—	—

NOTE: S = short-term aging; L = short- and long-term aging; HS = hardening susceptibility; — = not applicable.
^ For limited number of mixtures.

full recycling agent amount and thus reducing the base binder content from 4.9% to 4.3% and resulting in a significant number of coarse aggregate particles left visibly uncoated (Figure 6).

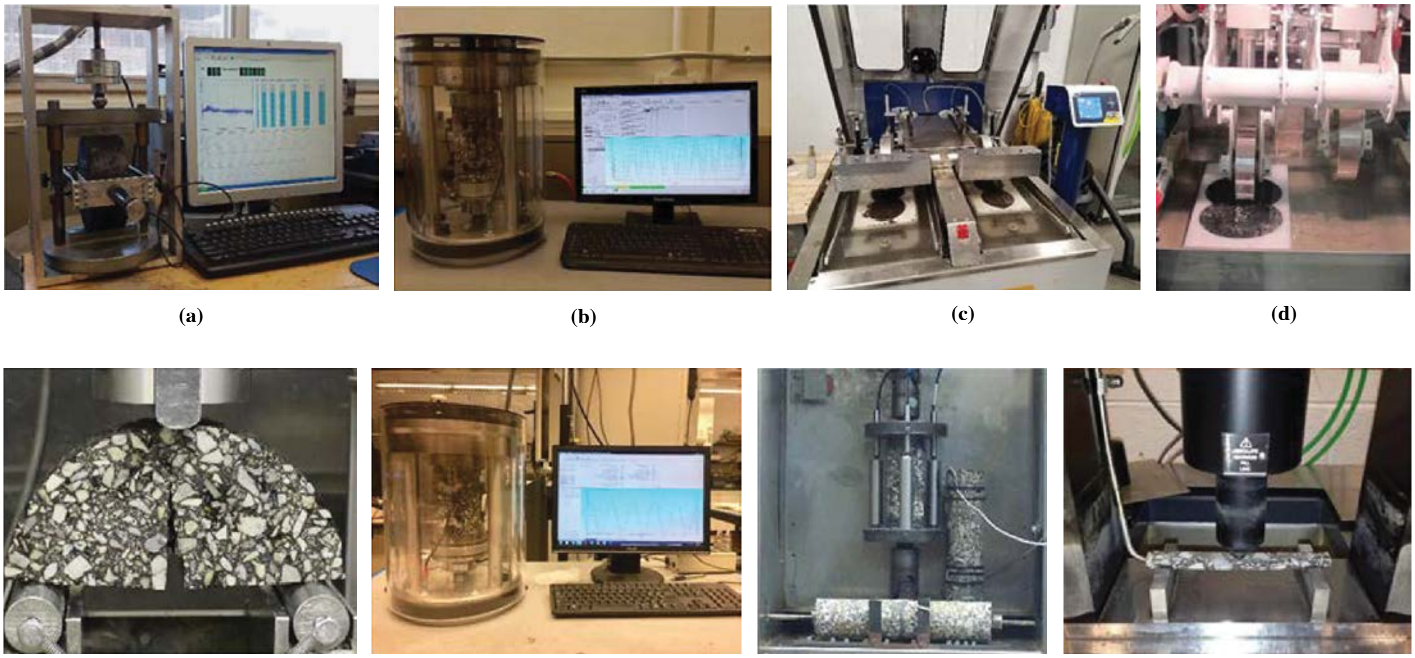
Based on these limited coatability observations and practicality concerns, the recommended practice for incorporation of recycling agents in mixtures with RAS and more than 5.0% recycling agent is addition of the full recycling agent amount (i.e., by addition) with a mandatory requirement to ensure adequate mixture rutting resistance. For mixtures with only RAP or those with RAS and less than or equal to 5.0% recycling agent, the recommended practice for incorporation of recycling agents is reduction of the base binder by the full recycling-agent amount (i.e., by replacement). Additional validation of the recommended 5.0% recycling-agent dose threshold for mixtures with RAS should be completed for mixtures with various optimum binder contents since the amount of total binder in the mixture and other factors, such as binder availability/contribution of the recycled materials and RBR, will likely have an effect on the CI. Additional details are included in Arámbula-Mercado et al. (2018b).



(a) (b) (c)

(d) (e)

Figure 3. Binder tests: (a) DSR for PGH, G-R parameter, $T_{\delta=45°}$, and G-R/CA$_g$ HS; (b) BBR for ΔT_c; (c) FT-IR for G-R/CA$_g$ HS; (d) SAR-AD for CII and TPA (Boysen and Schabron 2015); and (e) MDSC for T_g and T_g End (TA Instruments 2012).



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 4. Mixture tests: (a) M_R; (b) |E*| for G-R$_m$, S-VECD, UTSST; (c) HWTT for $N_{12.5}$; (d) APA for $N_{12.5}$; (e) I-FIT for FI and CRI (Al-Qadi et al. 2015); (f) S-VECD for D^R and $N_f@G^R = 100$; (g) UTSST for CRI$_{Env}$; and (h) BBR$_m$ for S_m and m-value$_m$.

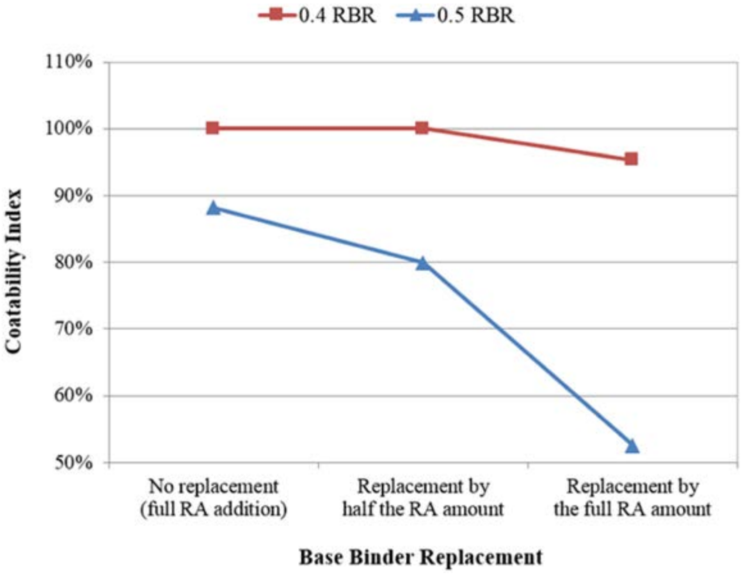


Figure 5. Coatability index for 0.4 RBR and 0.5 RBR mixtures.

Table 14 provides a summary of the specimen fabrication aging protocols and guidelines for recycling-agent blending by addition or replacement.

As an example, for a mixture with 30% RAP ($Pb_{RAP} = 5.0\%$) and 3% RAS ($Pb_{RAS} = 18\%$) or 0.28 RAPBR and 0.1 RASBR, 5.4% total binder content, and a 10 kg batch weight:

total binder = 540 g (10,000 × 5.4%)
= 150 g RAP binder (540 × 0.28) + 54 g RAS binder (0.1 × 0.1) + 336 g base binder
<u>IF recycling-agent dose = 4%</u> (100% replacement):
recycling agent = 22 g (540 × 4%)
base binder = 314 g (336 g – 22 g)
total binder = 540 g
<u>IF recycling-agent dosage = 9%</u> (100% addition + ensure adequate mixture rutting resistance):
recycling agent = 49 g (540 × 9%)
base binder = 312 g (336 – ½ × 49)
total binder = 564 g (540 + ½ × 49)

Figure 6. Coatability results for various recycling-agent incorporation methods: virgin aggregate (left), aggregates after replacing the base binder by the full recycling-agent amount (middle), and aggregates with no replacement of the base binder (right).

Table 14. Specimen fabrication protocol for preparing high RBR mixtures.

Mixing	Dry RAP and RAS for 6 h to 8 h at 60°C (140°F)
	Dry virgin aggregates overnight at mixing temperature
	Mix RAP and RAS with virgin aggregates
	Heat base binder and RAP/RAS/aggregate blend at mixing temperature 2 h before mixing
	Blend recycling agent with base binder using the 100% addition method when recycling agent dose is greater than 5.0% and RAS is used with a mandatory requirement to ensure adequate mixture rutting resistance; otherwise, use the 100% replacement method
	Heat base binder/recycling-agent blend at mixing temperature for 10 min before mixing
	Mix RAP/RAS/aggregate blend with base binder/recycling-agent blend
Short-term conditioning	Condition the loose mix for 2 h at 135°C (275°F) for HMA and WMA with recycling agent or 2 h at 116°C (240°F) for WMA without recycling agent
Compaction	Compact the loose mix to the target AV at 135°C (275°F)
Long-term aging	Age the compacted specimens for 5 days at 85°C (185°F)
Cutting/Coring	Cut/core specimens to final testing dimensions

1.5.2.2 Aging Protocols

Critical or representative aging protocols were used for specimen fabrication for each laboratory test across the pavement temperature spectrum, with short-term aged binders (after RTFO) or mixtures (short-term oven aging [STOA]) evaluated for stiffness, cracking resistance at intermediate temperatures, and rutting resistance at high temperatures, and long-term aged binders (RTFO and PAV) or mixtures (STOA and LTOA) evaluated for stiffness and cracking resistance at intermediate and low temperatures. Standard AASHTO T 240 and AASHTO R 28 binder aging protocols in the RTFO and 20-h PAV at 100°C, respectively, were used in the laboratory experiments, along with an extended 40-h PAV aging at 100°C for tracking recycling agent effectiveness with aging. Recommended revisions to AASHTO R 30 from NCHRP Project 09–52, “Short-Term Laboratory Conditioning of Asphalt Mixtures” (Newcomb et al. 2018) that include mixture oven-aging protocols of 2 h at 135°C (275°F) on loose mix for STOA prior to compaction and an additional LTOA of 5 days at 85°C (185°F) per AASHTO R 30 for compacted specimens were utilized. This STOA protocol developed and verified in NCHRP Project 09–49, “Performance of WMA Technologies: Stage 1—Moisture Susceptibility” and NCHRP 09–52 by Epps Martin et al. (2014), Yin et al. (2013), Yin et al. (2014a), and Yin et al. (2015) was further verified for mixtures with recycling agents by comparing M_R results at 25°C (77°F) for LMLC specimens after laboratory aging with those for cores at construction and after 1 year of field aging, as described in the first interim report (Epps Martin et al. 2015).

1.5.2.3 Laboratory Tests

For binders, the influence of recycling agents on rheological balance and recycling agent effectiveness with aging was assessed using standard PGH and PGL temperatures per AASHTO M 320 and other chemical, physicochemical, and rheological properties. Chemical oxidation was tracked using changes in the FT-IR spectrum, and chemical compatibility was evaluated using the SAR-AD and an MDSC. For each aging state, an attenuated total reflectance FT-IR spectrometer was used to collect absorbance data from 600 cm^{-1} to 4,000 cm^{-1}, and changes in this spectrum were monitored with an emphasis on the carbonyl and sulfoxide regions with peaks at 1,700 cm^{-1} and 1,032 cm^{-1}, respectively.

The SAR-AD technique divides the binder blend by polarity into an expanded set of eight chemical fractions (two saturates, three asphaltenes, two aromatics, and resins) as compared to the traditional four by ASTM D4124 (Boysen and Schabron 2013, 2015). The asphaltene determinator separates the asphaltenes into three fractions by solubility using an evaporative light scattering (ELS) detector and a variable wavelength absorbance detector set at 500 nm. The least soluble fractions are presumed to represent larger asphaltene agglomerations. The CII and the TPA were calculated as follows, with lower chemical compatibility associated with a larger CII and TPA indicating the total amount of asphaltenes in the binder:

$$CII = \frac{Saturates + Asphaltenes}{Aromatics + Resins} \qquad \text{[Equation 4]}$$

$$TPA = \frac{Asphaltenes\ ELS}{Asphaltenes\ 500nm} \qquad \text{[Equation 5]}$$

MDSC testing was conducted by cooling from 165°C (329°F) to −90°C (−130°F) at 0.5°C per minute and then heating again to 165°C (3,295°F) at 0.5°C per minute. Output parameters from the MDSC results included glass transition temperature (T_g) determined by inflection and the high-end temperature of the glass transition (T_g End).

In an extensive binder aging evaluation, binder blends were characterized by CA growth rate by FT-IR after standard 20-h PAV aging per AASHTO R 28, for an extended 40-h PAV, and in a forced draft oven at different temperatures and for multiple durations. CA was calculated as the area beneath the FT-IR spectrum from 1,650 cm^{-1} to 1,820 cm^{-1} with a baseline from 1,524 cm^{-1} to 1,820 cm^{-1}. CA growth (CA_g) was then determined as the difference between CA at a specific aging state and CA for a reference or tank (CA_{tank}) condition. For long-term aging evaluations in this study, CA_{tank} was defined as after RTFO aging. The binders were also tested in a DSR to determine master curves of shear complex modulus (|G*|) and binder phase angle (δ) by conducting isothermal frequency sweeps at different temperatures. These chemical and rheological results were used together to develop and assess the effects of recycling agents on binder oxidation kinetics and resulting HS, which are key inputs for modeling binder aging during the in-service life of a pavement.

Rheological indices such as the G-R parameter and crossover temperature ($T_{\delta = 45^\circ}$) were also calculated from DSR master curves at intermediate temperatures to evaluate the effectiveness of recycling agents initially and with aging. $T_{\delta = 45^\circ}$ was determined from DSR master curves at 10 rad/s as the temperature at which the storage modulus (G′) is equal to the loss modulus (G″) and the phase angle is 45 degrees. The G-R parameter was calculated as follows at 15°C and 0.005 rad/s from both DSR properties (|G*| and δ) that can be plotted in Black space to assess both the effects of adding aged recycled materials and partially restoring the stiffness and flexibility by the inclusion of recycling agents:

$$G - R = \frac{G^* (cos\delta)^2}{sin\delta} \qquad \text{[Equation 6]}$$

These testing conditions were used to tie with inadequate ductility of 5 cm to 3 cm that correlates to G-R parameter values between 180 and 600 kPa, respectively, and relates to cracking onset and significant cracking, respectively, in the field (Kandhal 1977). At low temperatures, the difference between the S-controlled and m-controlled PGL grades (ΔT_c) that Anderson et al. (2011) found correlated with the G-R parameter was also determined as an indicator of base binder quality and thus the starting point in evaluating recycling agent effectiveness with aging by G-R in Black space.

Finally, the G-R/CA_g HS binder parameter combines chemical oxidative aging and its effect on rheology (both stiffness and embrittlement) and is calculated as follows:

$$G - R\ HS = {\Delta[Log(G - R)]} \big/ {\Delta[CA_g]} \qquad \text{[Equation 7]}$$

Since some of the selected recycling agents contain large amounts of carbonyl, CA_g was monitored during aging to define oxidative changes, rather than the more traditional CA, which represents the total carbonyl peak area.

For mortars, laboratory testing followed the latest draft of test method AASHTO T XXX-12 Estimating Effect of RAP and RAS on Blended Binder Performance Grade without Binder Extraction (www.arc.unr.edu/Outreach.html). In this procedure, mortar and binder samples are tested in the DSR and BBR by AASHTO T 315 and T 313, respectively, to quantify the effect of blending recycled binder with base binder in terms of continuous PG grade, allowing for an estimation of binder blend properties at critical pavement temperatures with commonly available equipment and without the need for the time-consuming and hazardous binder extraction and recovery process that may impact binder properties. The following three samples are each tested at low, intermediate, and high critical PG temperatures after appropriate or critical aging in the RTFO or RTFO and PAV:

- Base binder;
- Voidless Mortar A with the same base binder and a single size RAP (or RAS) from a single source; and
- Voidless Mortar B with the same base binder, the same total binder content as Mortar A, and recovered aggregate from the same RAP (or RAS) material (using the ignition oven).

With known base binder properties, this procedure determines the change in continuous PG grade of the binder blend with the addition of recycled materials. The effect of recycling agents on selected binder properties was also evaluated by adding this component to the base binder and both mortars. In addition to PG, ΔT_c was also determined for mortars.

For mixtures, the influence of recycling agents on rheological balance and recycling-agent effectiveness evolution with aging were assessed using standard M_R stiffness tests at 25°C (77°F) per ASTM D7369, with linear variable differential transformers (LVDTs) externally attached across the diameter and standard HWTT per AASHTO T 324 and APA Junior tests per AASHTO T 340 at 50°C.

The evolution of recycling agent effectiveness in improving cracking resistance of mixtures with high RBRs was evaluated with respect to intermediate-temperature rheology and cracking resistance, respectively, using $|E^*|$ at 20°C and 5 Hz per AASHTO T 342 to explore mixture Black space and $G\text{-}R_m$ by Equation 8, the standardized S-VECD approach per AASHTO TP 107 with the asphalt mixture performance tester (AMPT), and the I-FIT at 25°C (77°F) per AASHTO TP 124 (Al-Qadi et al. 2015).

$$G - R_m = \frac{|E^*|(cos\phi)^2}{sin\phi} \qquad \text{[Equation 8]}$$

The conditions for determining $G\text{-}R_m$ were different from those for the binder for practicality such that master curves are not required, for consistency with a frequency selected close to the inflection point (peak of mixture phase angle master curve), and for analysis purposes to allow for statistical evaluation (Mensching et al. 2015, Mensching et al. 2016a, Mensching et al. 2016b).

To overcome the limitations of the FI per AASHTO TP 124, including difficulty in determining the inflection point, moderate variability, and inability to characterize brittle mixtures, an alternative SCB cracking parameter to rank mixture cracking resistance at intermediate temperatures was also developed and used in this study using the same I-FIT test procedure and data. The CRI was calculated as follows:

$$CRI = \frac{G_f}{P_{\max}} \qquad \text{[Equation 9]}$$

$$G_f = \frac{W_f}{A} = \frac{\int (P)du}{A} \qquad \text{[Equation 10]}$$

where

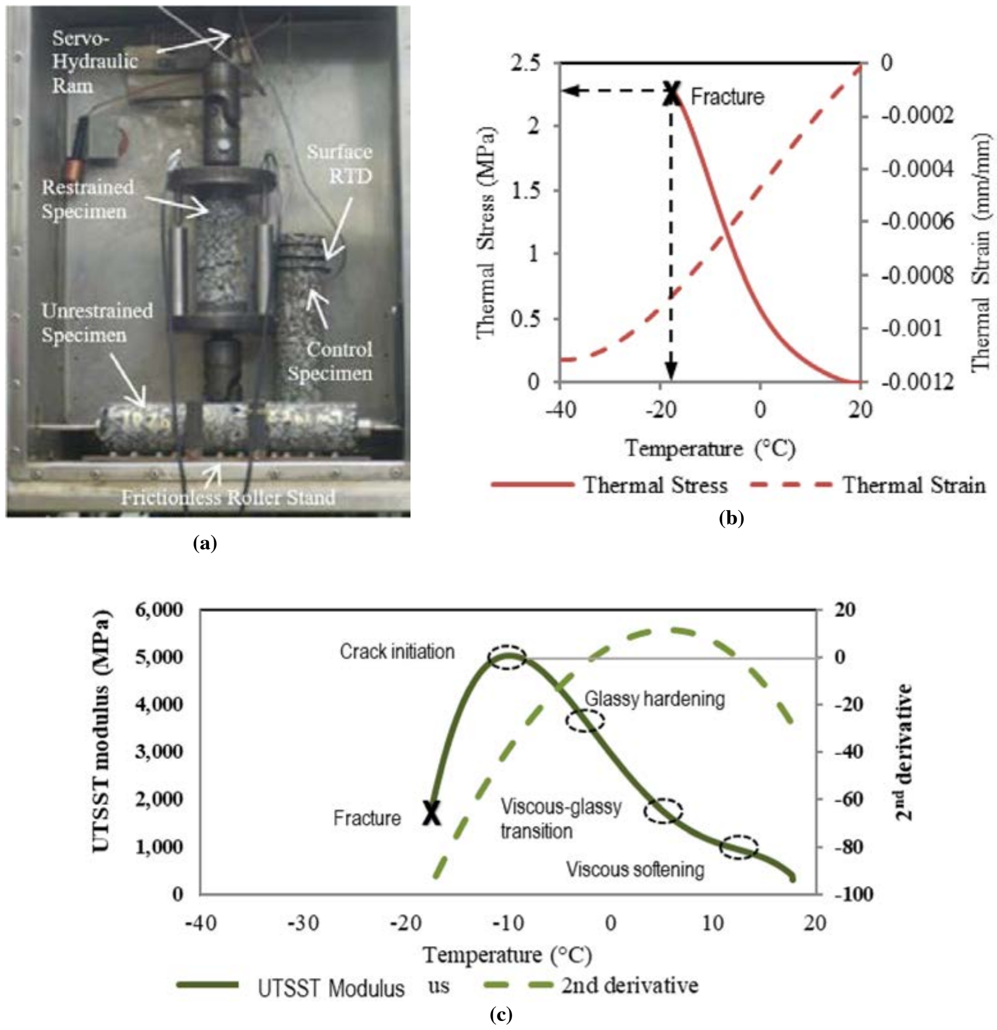
W_f = work of fracture (Joules),
P = load (kN),
U = load-line displacement (mm),
A = ligament area (mm) = the ligament length × the thickness of the specimen, and
P_{max} = peak load (kN).

This alternate parameter includes peak load to differentiate mixtures that may have similar W_f and G_f values but exhibit different behavior in terms of embrittlement. Brittle mixtures with low G_f and/or high P_{max} will have lower CRI. Additional details on the development of the CRI are presented in Kaseer and Yin et al. (2018c).

The evolution of recycling agent effectiveness in improving cracking resistance of mixtures with high RBRs was preliminarily evaluated with respect to low-temperature cracking using the BBR mixture (BBR_m) or sliver test per AASHTO TP 125 to produce a low-temperature mixture Black space and the UTSST. This recently developed UTSST test enhanced the traditional TSRST per AASHTO TP 10 that measures only thermal stress under a constant cooling rate in a restrained mixture specimen until fracture. The development of the UTSST methodologies permits the determination of thermo-volumetric (i.e., coefficient of thermal contraction), thermo-viscoelastic (i.e., stiffness–temperature relationship), crack initiation, and fracture properties of asphalt mixtures using thermal stress and thermal strain measurements (ASTM 2018). More detailed information regarding the test setup, sample fabrication, and mixture results can be found in the literature (Alavi et al. 2013; Hajj et al. 2013b; Mensching et al. 2014; Morian 2014). Figure 7(a) presents the layout of the UTSST apparatus. Briefly, the thermal stress and thermal strain measurements are obtained, respectively, from restrained and unrestrained specimens simultaneously subjected to a cooling rate of 10°C/hr starting from an initial temperature of 20°C. A minimum of two replicates for the restrained specimen were tested for each evaluated mixture, and the same unrestrained specimen was tested twice, once for each of the restrained specimen replicate tests. The following five characteristic stages of material behavior are identified from the stiffness-temperature relationship and thermal stress curve (Figure 7[b], Figure 7[c]):

- Viscous softening: From this stage, the relaxation modulus of the asphalt mixture increases rapidly with decreasing temperature.
- Viscous-glassy transition: At this stage, the glassy properties of the material overcome the viscous properties.
- Glassy hardening: At this stage, the behavior of the material is purely glassy.
- Crack initiation: In this stage, micro-cracks occur in the specimen due to the induced thermal stresses while the material behavior is glassy.
- Fracture: At this stage, the asphalt mixture specimen breaks due to the propagation of micro-cracks by the induced thermal stresses (i.e., macro or global failure).

In this study, the primary evaluation was performed by examining the stresses and temperatures corresponding to the fracture, crack initiation, and viscous softening stages. Further information regarding the thermo-viscoelastic properties and the stiffness-temperature relationship can be found in the literature (Alavi et al. 2013; Hajj et al. 2013b; Morian et al. 2014; Alavi and Hajj 2014; Mensching et al. 2014; Alavi and Morian et al. 2015).



(a)

(b)

(c)

Figure 7. (a) UTSST setup; (b) measured thermal stress and strain; (c) calculated UTSST modulus and associated characteristic stages.

Additional characterization resulting from the UTSST measurements was also developed to summarize mixture low-temperature cracking resistance and combine specific aspects of the thermal stress and thermal strain relationships with those of the thermos-viscoelastic property regions and recognize the benefits of certain mixture characteristics. A cracking resistance index (CRI_{Env}) was determined through calculations based on the measured thermal stress and strain plots, as indicated in Figure 8(a) and Equation 11, including an environmental correction factor, F_{Env}, as defined in Equation 12, that relates mixture cracking resistance to that required by the environment, as shown in Figure 8(b) and Figure 8(c).

$$CRI_{Env} = \frac{A_v + A_i\left(1 + \frac{A_v}{A_v + A_i} + \frac{A_p}{A_p + A_i}\right)}{\left(\sigma_{vgt} / \sigma_f\right)} \times F_{Env} \qquad \text{[Equation 11]}$$

$$F_{Env} = \frac{A_{vgt-F}}{A_{vgt-crit}} \qquad \text{[Equation 12]}$$

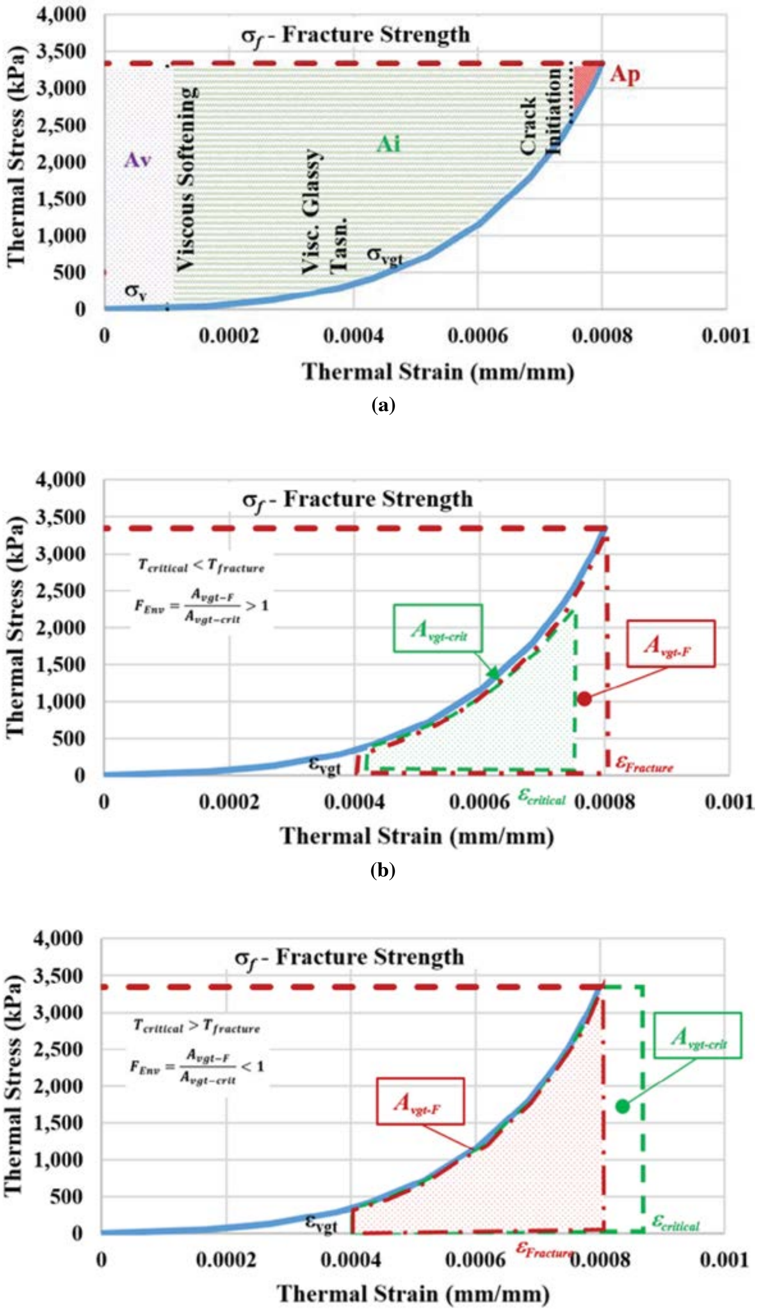


***Figure 8.** (a) Thermal stress and strain plots with CRI parameters; (b) environmental adjustment parameters when $T_{critical} < T_{Fracture}$; (c) environmental adjustment parameters when $T_{critical} > T_{Fracture}$.*

where

CRI_{Env} = UTSST cracking resistance index including the environmental adjustment factor;
A_v = area of viscous behavior, i.e., area of stress–strain up to viscous softening;
A_i = area of crack initiation, i.e., area of stress–strain from viscous softening up to crack initiation;
A_p = area of crack propagation, i.e., area of stress–strain from crack initiation up to ultimate fracture;
σ_{vgt} = thermal stress at viscous–glassy transition;
σ_f = thermal stress at fracture;
$A_{vgt\text{-}F}$ = area under the thermal stress–strain plot between the viscous–glassy transition temperature and the fracture temperature of the restrained UTSST specimen; and
$A_{vgt\text{-}crit}$ = area under the thermal stress–strain plot between the viscous–glassy transition temperature and the required environmental temperature at a given location.

In this configuration, increased levels of low-temperature cracking resistance are indicated by larger values of the CRI_{Env}. For instance, a mixture may exhibit limited resistance to crack propagation (i.e., low A_p) but may show higher levels of overall cracking resistance (i.e., CRI) if the mixture exhibits a high level of crack initiation resistance (i.e., A_i).

By similar logic, the cracking resistance of a mixture would increase with larger measured fracture stress, σ_f. However, the overall resistance would be reduced by an elevated stress level at the viscous–glassy transition stage, σ_{vgt}, which would indicate increased stress levels coupled with glassy or brittle behavior.

The addition of the environmental factor, F_{Env}, provides a simplified correction to acknowledge if the mixture will fracture above or below the required environmental temperature, defined as the DOT-selected PGL for the respective field projects (−22°C for TX, NV, and IN; −28°C for WI and MN).

CHAPTER 2

Key Results from Phase 2

Chapter 2 provides key results obtained in Phase 2 that were not expanded in Phase 3, including development of a recycling-agent dose selection method used throughout the study; fundamental evaluations toward engineering balanced binder blends that include chemical compatibility, rheological balance, and representative blending; investigation of mixture cracking resistance by S-VECD; and comparison of specimen types.

2.1 Development of Recycling-Agent Dose Selection Method

For a specific combination of base binder, recycled binder from RAP/RAS, and recycling-agent, selection of a recycling-agent dose that balances performance in terms of cracking and rutting resistance based on binder blend testing must be completed prior to mixture validation testing. Low recycling-agent doses will fail to provide the mixture with sufficient fatigue and low-temperature cracking resistance. Conversely, high recycling-agent doses will be costly and potentially detrimental to the rutting performance of the mixture, especially during its early life. In the literature, many approaches are used to select a recycling-agent dose. These approaches include using binder blending charts based on viscosity and/or penetration or employing the PG system by evaluating the changes in binder PG grade due to the addition of a recycling agent. However, no standard method is currently available for recycling-agent dose selection.

A preliminary recycling-agent dose selection approach was formulated in Phase 2A for a specific combination of materials including the TX PG 64–22 base binder (ΔT_c of −4.6), 0.28 RBR (0.1 TX RAP and 0.18 TX MWAS), and two recycling-agent types (T1 and A1) at multiple recycling-agent doses (0%, 2%, and 10%). These results verified a linear relationship between recycling-agent dose and the PGH and PGL of the recycled binder blends. The combination of materials was expanded in Phase 2B as shown in Table 15, and two additional recycling-agent dose selection approaches were also explored in an effort to develop a standard recycling-agent dose selection method. All three approaches are summarized in this section, followed by a description of a simplified method for the selected approach. Table 15 and Table 16 provide the recycling-agent doses, ΔT_c values, and resulting PG grades for more than 45 materials combinations prepared in Phase 2A and Phase 2B including six types of base binders, eight types of recycled materials, four combinations of RBRs, and seven types of recycling agents. Additional data and details are included in Arámbula-Mercado and Kaseer et al. (2018b).

2.1.1 Restore PGL (and Verify PGH)

In the first approach originally formulated in Phase 2A, the selected recycling-agent dose was the one that restores the PG grade of the recycled binder blend to that of the target binder needed

Table 15. Binder blends test plan and recycling-agent doses for Phase 2A.

Field Project Target PG	Binder Source and PG	Binder ΔT_c	RBR	RAPBR and Source	RASBR and Source	Recycling Agent	% Recycling-Agent Dose (ΔT_c#) [PG]: Restore PGL, Verify PGH	% Recycling-Agent Dose (ΔT_c#) [PG]: Achieve $\Delta T_c = -5.0$	% Recycling-Agent Dose (ΔT_c#) [PG]: Restore PGH
TX 70-22	TX 64-22	–4.6	0.28	0.1 TX	0.18 TX MWAS	T1	4.5 (–10) [72-22]	12.5 [58-32]	6 (–9) [70-23]
						A1	5.5 (–8) [71-22]	9.5 [66-27]	6.5 (–8) [70-23]
			0.4	0.4 TX	—	T1	7.5 (–8) [69-22]	13.0 [57-30]	7.5 (–8) [69-22]
						A1	10.0 (–6) [73-22]	11.0 [71-23]	12.0 (–5) [70-24]
			0.5	0.25 TX	0.25 TX MWAS	T1	8.0 (–9) [72-22]	11.5 [65-28]	9.0 (–8) [70-24]
				0.25 TX	0.25 TX TOAS	T1	11.5 (–9) [74-25]	14.5 [65-32]	13.5 (–6) [70-30]
	NH 64-28	+1.2	0.4	0.4 TX	—	A1	6.0 (–5) [75-23]	6.0 [75-23]	9.5 (–3) [70-26]
			0.5	0.25 TX	0.25 TX TOAS	T1	12.5 (–5) [75-27]	12.5 [75-27]	15.5 (–4) [70-30]
	NV 64-28P	–3.6	0.5	0.25 TX	0.25 TX TOAS	T1	13.5 (–5) [75-30]	13.5 [75-30]	16.0 (–4) [70-33]
NV 64-28P	NV 64-28P	–3.6	0.3	0.3 NV	—	T2	1.5 (–4) [68-28]	—	3.0 (–2) [64-31]
						A2	2.0 (–2) [69-29]	—	5.5 (+3) [64-33]
IN 64-22	IN 58-28	–8.0	0.42	0.14 IN	0.28 IN MWAS	T2	3.5 (–8) [69-24]	6.5 [63-29]	6.0 (–5) [64-29]

NOTE: — = not applicable.

to satisfy climate and traffic requirements (i.e., PG 70–22 for TX). The PGL of the target binder was used to set the recycling-agent dose for the recycled binder blend. Then the resulting PGH of the binder blend at the selected dose was verified against the PGH of the target binder and adjusted (increased) if needed, while still maintaining the PGL of the target binder.

The recycling-agent doses from this approach were evaluated to assess the rejuvenating effectiveness via changes in Black space (log |G*| versus δ) with aging (after RTFO, 20 h PAV, and 40 h PAV). The Black space results for the recycled blends with 0.28 RBR; T1, A1, V1, and B1 at the selected dose; and the TX PG 64–22 base binder ($\Delta T_c = -4.6$) are shown in Figure 9. at 15°C and 0.005 rad/s.

For each blend in Figure 9, the three markers from right to left represent RTFO, RTFO plus 20-h PAV, and RTFO plus 40-h PAV, respectively. The results after RTFO (0-h PAV) aging indicated improved cracking resistance for the recycled binder blends with the selected recycling-agent dose compared to the DOT control blend. However, after 40-h PAV aging, the recycled

Table 16. Binder blends test plan and recycling-agent doses for Phase 2B.

Field Project Target PG	Base Binder Source & PG	Binder ΔT_c	RBR	RAPBR and Source	RASBR and Source	Recycling Agent	% Recycling-Agent Dose ($\Delta T_c^{\#}$) [PG]		
							Restore PGL, Verify PGH	Achieve ΔT_c = −5.0	Restore PGH
TX 70-22	TX 64-22	−4.6	0.28	0.1 TX	0.18 TX MWAS	T1	4.5 (−10) [72-22]	12.5 [58-32]	6 (−9) [70-23]
						A1	5.5 (−8) [71-22]	9.5 [66-27]	6.5 (−8) [70-23]
						V1	4.0 (−10) [74-22]	8.5 [64-32]	5.5 (−8) [70-26]
						B1	4.0 (−8) [74-22]	7.0 [69-28]	6.5 (−8) [70-27]
	IN 64-22	−1.2	0.28	0.1 TX	0.18 TX MWAS	—	—	—	—
						T1	2.0 (−4) [74-22]	—	5.0 (−3) [70-25]
						A1	2.0 (−5) [75-22]	2.0 [75-22]	6.5 (−4) [70-25]
						V1	1.0 (−5) [75-22]	1.0 [75-22]	3.5 (−5) [70-25]
						B1	1.0 (−5) [75-22]	1.0 [75-22]	4.0 (−3) [70-26]
	NH 64-28	+1.2	0.5	0.25 TX	0.25 TX TOAS	T1	12.5 (−5) [75-27]	12.5 [75-27]	15.5 (−4) [70-30]
						A1	>20.0	>20.0	>20.0
						V1	15.0 (−4) [75-37]	11 [82-30]	17.5 (−3) [70-41]
						B1	17 (−1) [75-37]	8.0 [89-24]	20.0 (+1) [70-40]
IN 64-22	NH 64-28	+1.2	0.5	0.4 NH	0.1 CA TOAS	T1	10.5	N/A	13
						V2	11.5	N/A	13
			0.7	0.7 NH	—	B1	9 (−1) [69-29]	0	11.5 (−1) [64-32]
TX 70-22	MN 58-28	0.0	0.28	0.1 TX	0.18 TX MWAS	—	—	—	—
						T1	0.0 (−3) [71-23]	—	0.5 (−3) [70-24]
						A1	0.0 (−4) [71-23]	—	0.5 (−3) [70-24]
						V1	0.0 (−2) [70-24]	—	—
						B1	0 (−4) [70-23]	—	—

NOTE: — = not applicable.

Table 16. (Continued).

Field Project Target PG	Base Binder Source & PG	Binder ΔT_c	RBR	RAPBR and Source	RASBR and Source	Recycling Agent	% Recycling-Agent Dose $(\Delta T_c^{\#})$ [PG] Restore PGL, Verify PGH	Achieve ΔT_c = −5.0	Restore PGH
TX 70-22	MN 58-28	0.0	0.5	0.25 TX	0.25 TX TOAS	—	—	—	—
				0.25 TX	0.25 TX TOAS	T1	13.5 (−5) [70-24]	13.5 [70-24]	16.5 (−5) [70-26]
				0.25 TX	0.25 TX TOAS	A1	16.5 (−8) [75-22]	>20.0	20.0 (−8) [70-24]
				0.25 TX	0.25 TX TOAS	V1	13.5 (−10) [75-30]	>20.0	16.5 (−10) [70-34]
				0.25 TX	0.25 TX TOAS	B1	13.0 (−6) [75-30]	16.0 [70-34]	16.0 (−5) [70-34]
IN 64-22	IN 58-28	−8.0	0.32	0.25 IN	0.07 IN MWAS	—	—	—	—
			0.42	0.14 IN	0.28 IN MWAS	T2	3.5 (−8) [69-24]	6 [64-29]	6 (−5) [64-29]
			0.42	0.28 IN	0.14 IN MWAS	T2	N/A	N/A	8
			0.5	0.36 IN	0.14 IN MWAS	T2	N/A	N/A	9.5
			0.7	0.7 IN	—	T2	N/A	N/A	10

NOTE: — = not applicable.

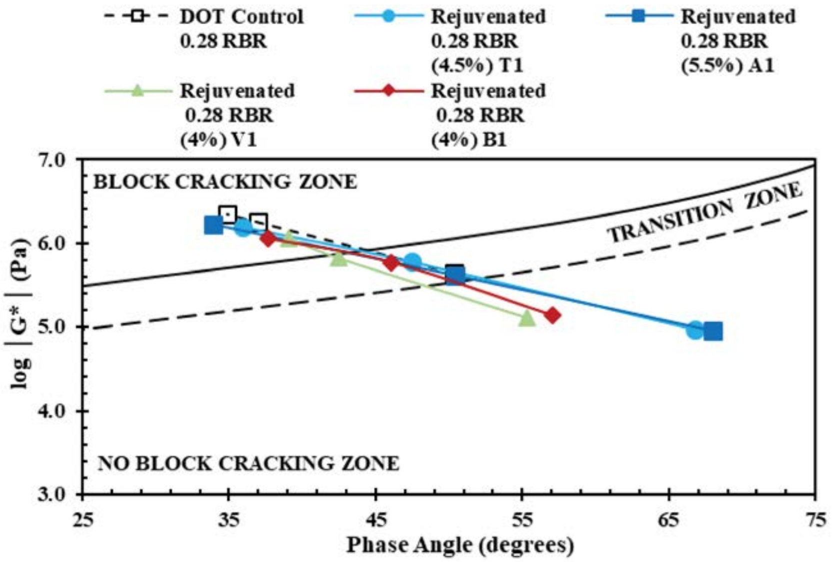


Figure 9. Black space results for 0.28 RBR recycled blends with TX PG 64–22 and recycling agent at the selected dose to restore PGL.

binder blends at the selected recycling agent dose were comparable to the corresponding DOT control blend in terms of stiffness and phase angle and were all within the cracking zone. The no-cracking, transition, and cracking zones in Black space were used to evaluate the results, despite the fact that an adjustment to account for the target PG 70–22 climate versus the PG 58–28 used to generate these thresholds should probably be considered. Nevertheless, these example results showed that the selected recycling-agent doses by the first approach to restore the PG grade to that of the target PG were insufficient to maintain effectiveness with aging.

2.1.2 Achieve $\Delta T_c = -5.0$

Recent work by Anderson et al. (2011) suggested a maximum ΔT_c threshold of −5.0 after 40-h PAV aging to minimize the risk of age-related cracking. However, using this ΔT_c threshold would result in excessively high recycling-agent doses that would be costly and likely result in poor mixture rutting resistance. Thus, the dose to achieve a ΔT_c value of −5.0 after the standard 20-h PAV aging was selected in the second approach to increase the recycling-agent dose and possibly increase its effectiveness with aging. Compared to the first approach, the recycling-agent doses increased for the recycled binder blends with the TX PG 64–22 base binder but did not change for the recycled binder blends with the IN PG 64–22 base binder since the doses from the first approach also yielded ΔT_c values of at least −5.0 (or less negative) after 20-h PAV aging. The Black space results for the recycled binder blends with the TX PG 64–22 base binder shown in Figure 10 were promising, demonstrating lower $|G^*|$ and higher δ for the recycled binder blends, especially compared to the DOT control blend. In addition, all recycled blends were on or below the transition zone significant cracking threshold after 40-h PAV aging.

However, the recycling-agent dose determined with this second approach resulted in recycled blends with low PGH values (i.e., 58°C to 69°C, as shown in Table 16), which could indicate rutting issues at the mixture level. This was confirmed by the Black space results after RTFO, which indicated that the binder blends were likely oversoftened and would possibly result in rutting of corresponding mixtures. Therefore, HWTT testing was performed on the mixture with the highest recycling-agent dose (12.5% T1 shown in the bottom right corner in Black space in

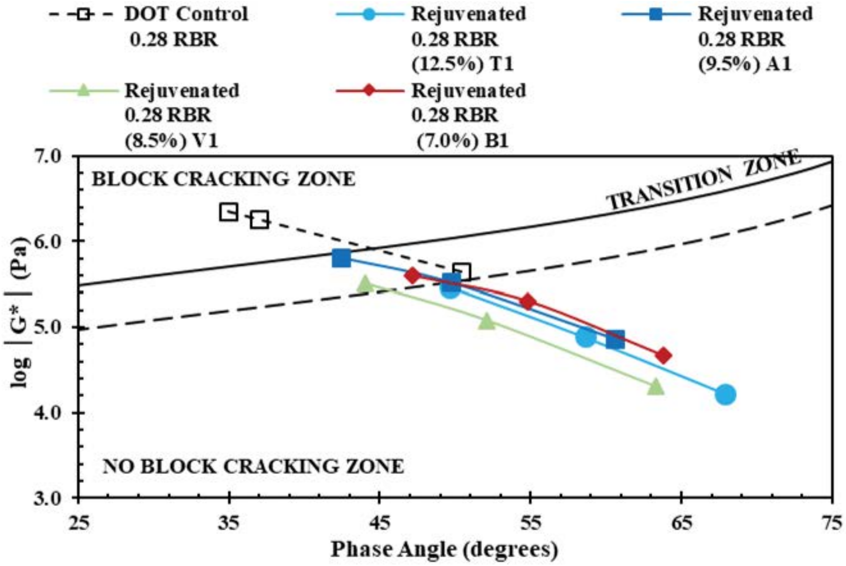


Figure 10. Black space results for 0.28 RBR recycled blends with TX PG 64–22 and recycling agent at the selected dose to achieve ΔTc = −5.0.

Figure 11), and the mixture failed by reaching a rut depth of 12.5 mm (at 50°C) after 2,300 load cycles. These example results showed that for the TX PG 64–22 base binder, the selected recycling-agent doses by the second approach to achieve a ΔT_c value of −5.0 were excessive.

In the case of the IN PG 64–22 base binder, the Black space results shown in Figure 11 demonstrated different trends compared to those for the TX PG 64–22 base binder, most likely because of the difference in quality, as indicated by ΔT_c (i.e., −4.6 versus −1.2, respectively). This higher quality IN PG 64–22 required less recycling agent to restore PGL and simultaneously meet the $\Delta T_c = -5.0$ threshold. The Black space results after 20-h PAV aging were within the transition zone, and the results after 40-h PAV aging were in the cracking zone for all recycled blends. Still, there was a clear distinction between the Black space results for the DOT control blend versus the recycled blends (especially with respect to phase angle) despite the low recycling-agent dose used in the recycled blends between 1.0% and 2.0%. These results indicate that even though the use of a higher-quality base binder (with a less negative ΔT_c value) yielded lower recycling-agent doses and partially restored the phase angle of the recycled blend, the second approach to achieve $\Delta T_c = -5.0$ was still inadequate in terms of determining a recycling-agent dose with prolonged effectiveness on aging.

2.1.3 Restore PGH (Match Continuous PGH)

The third approach for selecting a recycling-agent dose provided values between those of the first and second approaches and followed a methodology similar to that used in mix design where as much binder (or in this case, recycling agent) as possible is included for durability and cracking resistance as long as rutting resistance is maintained. For the first approach (restore PG to that of the target binder, which for TX was a PG 70–22), the resulting continuous PGH was checked and reduced if necessary to just meet a PG 70 grade with a PGH close to 75°C. The third approach was to further increase the recycling-agent dose to a PGH of 70°C in the hopes of improving the effectiveness with aging. Compared to the other two approaches, this third approach was based only on DSR results and accounted for the combined effects of the aging state of the recycled materials (RAP and RAS) and the recycled material combination (RAPBR

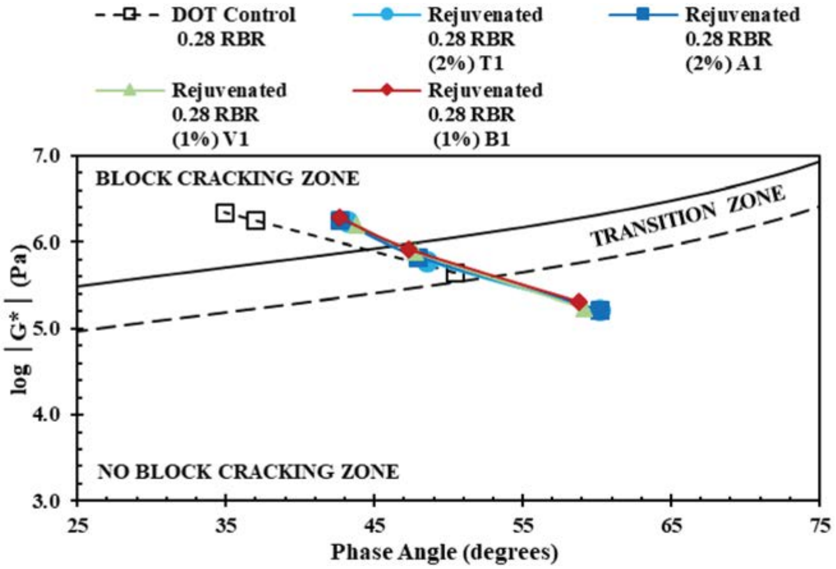


Figure 11. Black space results for 0.28 RBR recycled blends with IN PG 64–22 and recycling agent at the selected dose to achieve $\Delta Tc = -5.0$.

and RASBR). In addition, with this approach, the PGL was restored to that of the target binder or improved further (more negative) for all binder blends, as shown in Table 15.

The Black space results for the third approach for the recycled binder blends with the TX PG 64–22 base binder shown in Figure 12 seemed promising, demonstrating low G* and high δ for the recycled binder blends with different recycling-agent types at all aging levels. Blends with T1, A1, and V1 barely reached the transition zone cracking onset threshold after 20-h PAV aging and showed much better performance compared to the DOT control blend. In addition, the RTFO results were not as close to the bottom right corner in Black space as those from the second approach. To verify rutting resistance, HWTT testing was performed on the mixtures with the TX PG 64–22 and IN PG 64–22 base binders, 0.28 RBR (0.1 TX RAP and 0.18 TX MWAS), and A1 that yielded the highest recycling-agent dose by this approach (i.e., 6.5%). The mixture with the TX PG 64–22 base binder reached 10,300 load cycles before exhibiting 12.5-mm rut depth, while the mixture with the IN PG 64–22 base binder reached the same threshold after 5,000 load cycles. Usually, mixtures with a target PG 70-XX are required to sustain at least 15,000 load cycles before achieving 12.5-mm rut depth at 50°C. Thus, although both of these mixtures would fail this criterion, a significant improvement was observed with respect to the performance of the TX PG 64–22 mixture with 12.5% T1 (which failed at 2,300 load cycles). In addition, based on the results and an alternate analysis proposed by Yin et al. (2014b), the rutting resistance could not be separated from moisture susceptibility.

The third approach was also used for the blends with 0.5 RBR (0.25 TX RAP and 0.25 TX TOAS) for both the NH PG 64–28 (with $\Delta T_c = +1.2$) and the MN PG 58–28 (with $\Delta T_c = 0.0$) base binders. For the blends with the NH PG 64–28 base binder, the recycling-agent doses to match continuous PGH were high but reasonable for the binder blends with T1, V1, and B1; but the recycling-agent dose was excessive with A1 (> 20%). This may be an indication of incompatibility or an unbalanced recycled materials combination. For the binder blends with the MN PG 58–28 base binder, the recycling-agent doses to match continuous PGH were reasonable for all recycling-agent types. However, the ΔT_c values for these binder blends were still more negative compared to those with the NH PG 64–28 base binder, probably due to the better quality based on ΔT_c of the NH PG 64–28 base binder.

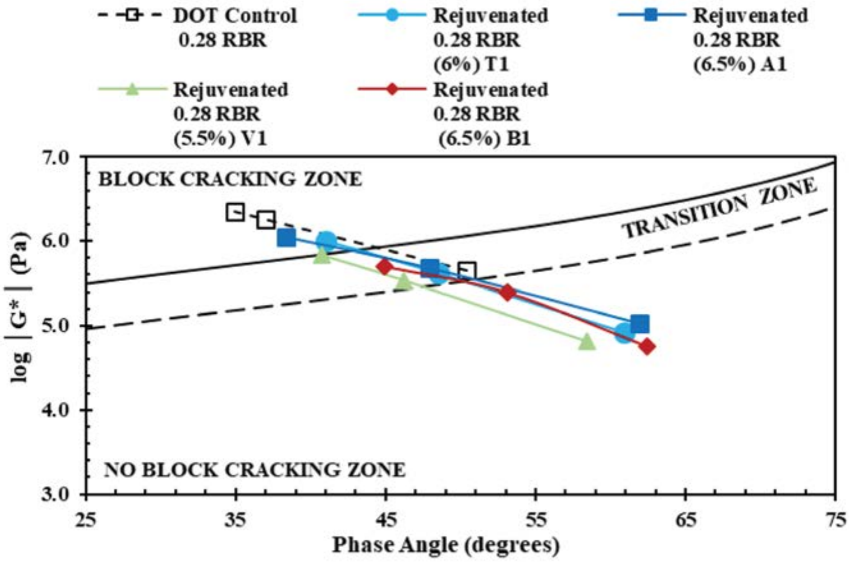


Figure 12. Black space results for 0.28 RBR recycled blends with TX PG 64–22 base binder and recycling agent at the selected dose to restore PGH.

The Black space results for these blends with T1 and V1 shown in Figure 13 were promising, demonstrating low |G*| and high δ for the recycled binder blends at all aging levels. The recycled blends with T1 reached or were on the threshold of the cracking zone after 40-h PAV aging. The other recycled blends with V1 did not reach the transition zone cracking onset threshold after 40-h PAV aging. Based on these results, the third approach to match continuous PGH is recommended for recycling-agent dose selection.

2.1.4 Simplified Recycling-Agent Dose Selection Method

The recycling-agent doses from the selected method to match continuous PGH of the binder blends with 0.5 RBR (0.25 TX RAP and 0.25 TX TOAS) were high (15.5 to 17.5 percent). In addition to the fact that these mixtures may have inadequate rutting resistance, these high recycling-agent doses may not be cost effective based on the economic analysis provided in Appendix G; in addition, they likely indicate incompatibility or an unbalanced materials combination because of insufficient availability and blending of the recycled binder, particularly from the RAS, that is exacerbated in corresponding mixtures. In recycled mixtures, part of the recycled binder is not available during mixing, particularly for stiffer materials such as those containing MWAS; in some cases, like in TOAS, the recycled binder is likely a black rock. For example, the PGH of TX TOAS is 178°C, and it is expected that most of the TOAS binder will not be blended with the base binder when preparing mixtures at common mixing temperatures that range from 132°C to 162°C (270°F to 325°F), or even lower for mixtures with WMA additives. With less available recycled binder and incomplete blending, a high recycling-agent dose determined based on completely blended binder testing may oversoften the base binder and result in mixture rutting. Therefore, maximum RBR should be controlled, particularly maximum RASBR from TOAS, to ensure adequate performance at reasonable recycling-agent doses up to approximately 10%–15% based on the economic analysis in Appendix G. This analysis indicates that the use of recycling agent at these doses is reasonable to double the RAP content from 20% to 40% and save from $6 to $8 per ton HMA/WMA or from $0.30 to $0.40 per 1% RAP when virgin material costs are relatively high. This represents approximately 7% to 10% of in-place prices for HMA/WMA.

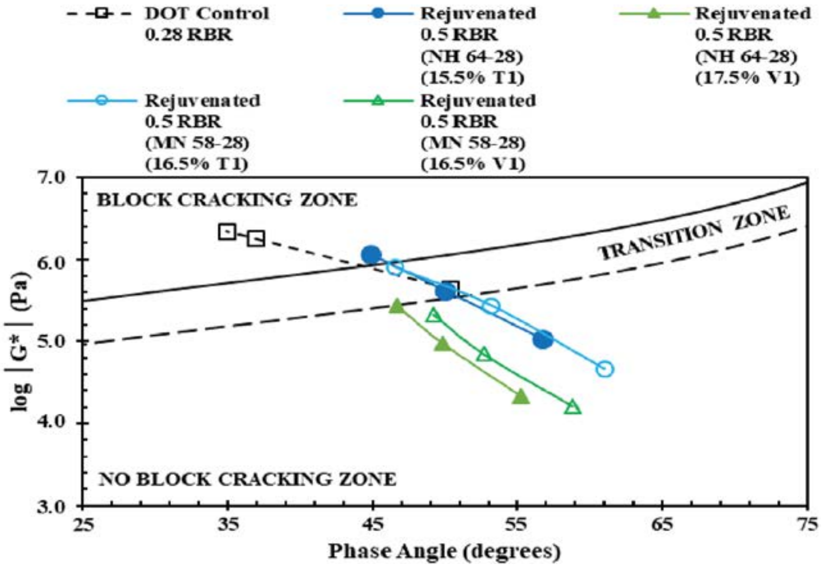


Figure 13. Black space results for 0.5 RBR recycled blends with NH PG 64–28 and MN PG 58–28 base binders and recycling agent at the selected dose to restore PGH.

To limit the RBR and thus recycling-agent dose, the PGH of the blend of base and recycled binders can be controlled through the use of blending charts. Figure 14 presents example blending charts for recycled binder blends with 0.31 RBR and 0.5 RBR (0.31 and 0.5 WI RAP) with the WI PG 58–28 base binder that are verified by the measured data shown. The following linear relationship can be used to establish the blending chart and calculate the PGH of a binder blend (Equation 13):

$$PGH_{Blend} = (RAPBR \times PGH_{RAP}) + (RASBR \times PGH_{RAS}) + (BaseBR \times PGH_{Base\ binder}) \quad \text{[Equation 13]}$$

where

$RAPBR$ = RAP binder ratio,
$RASBR$ = RAS binder ratio, and
$BaseBR$ = base binder ratio.

To validate the blending chart based on Equation 13, the measured PGH of the binder blends without recycling agent in Table 15 and Table 16 were compared to the corresponding calculated PGH as shown in Figure 15. A strong correlation was observed, with only the binder blends with TX MWAS having slightly lower measured PGH than calculated values. Therefore, the blending charts based on Equation 13 can be used to estimate PGH of the recycled binder blends without testing.

The PGHs of recycled binder blends in Table 15 and Table 16 (including multiple base binders, recycled materials, and RBRs) were then plotted versus the recycling-agent dose (for multiple recycling-agent types) required to match continuous PGH to that of the target binder. These plots contain many different material combinations that are categorized by the groups shown in the legends. Figure 16 illustrates the recycling-agent dose required to restore the PGH to 70°C and 64°C for each of four types of recycling agent (T1/T2, A1/A2, V1/V2, and B1). Since the slopes of the relationships (for T1, V1, and B1) shown in Figure 16 are similar, they were combined in Figure 17 to match the continuous PGH of different binder blends to targets of 70°C

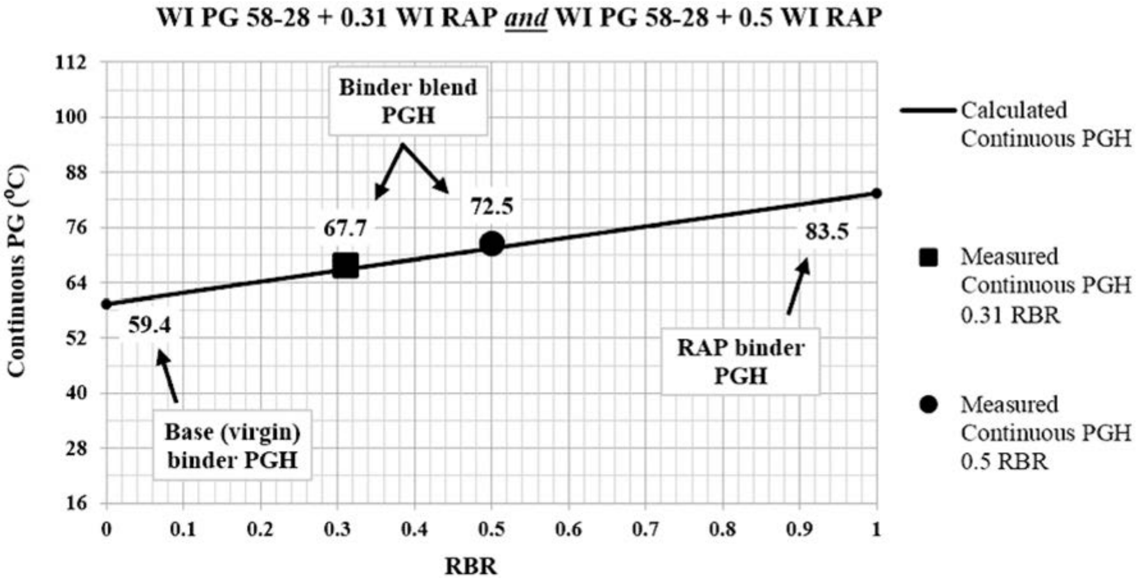


Figure 14. Binder blending chart for 0.31 and 0.5 RAP RBR recycled blends with WI PG 58–28.

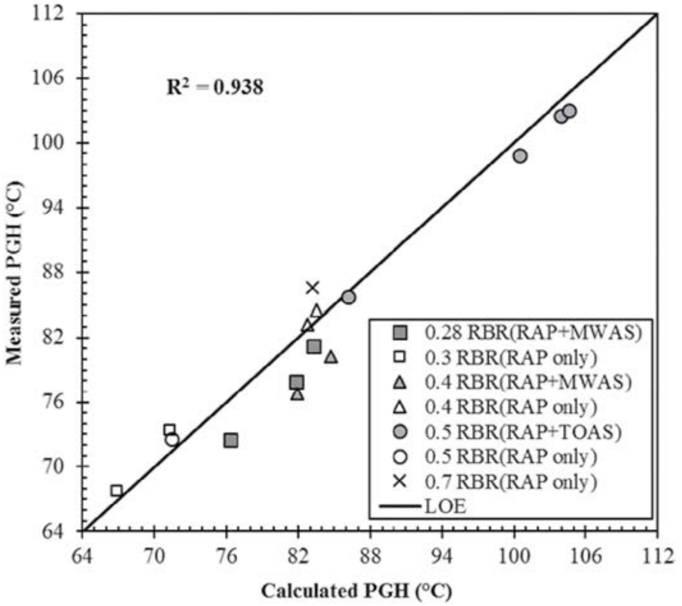


Figure 15. Calculated versus measured PGH of the recycled blends without recycling agent.

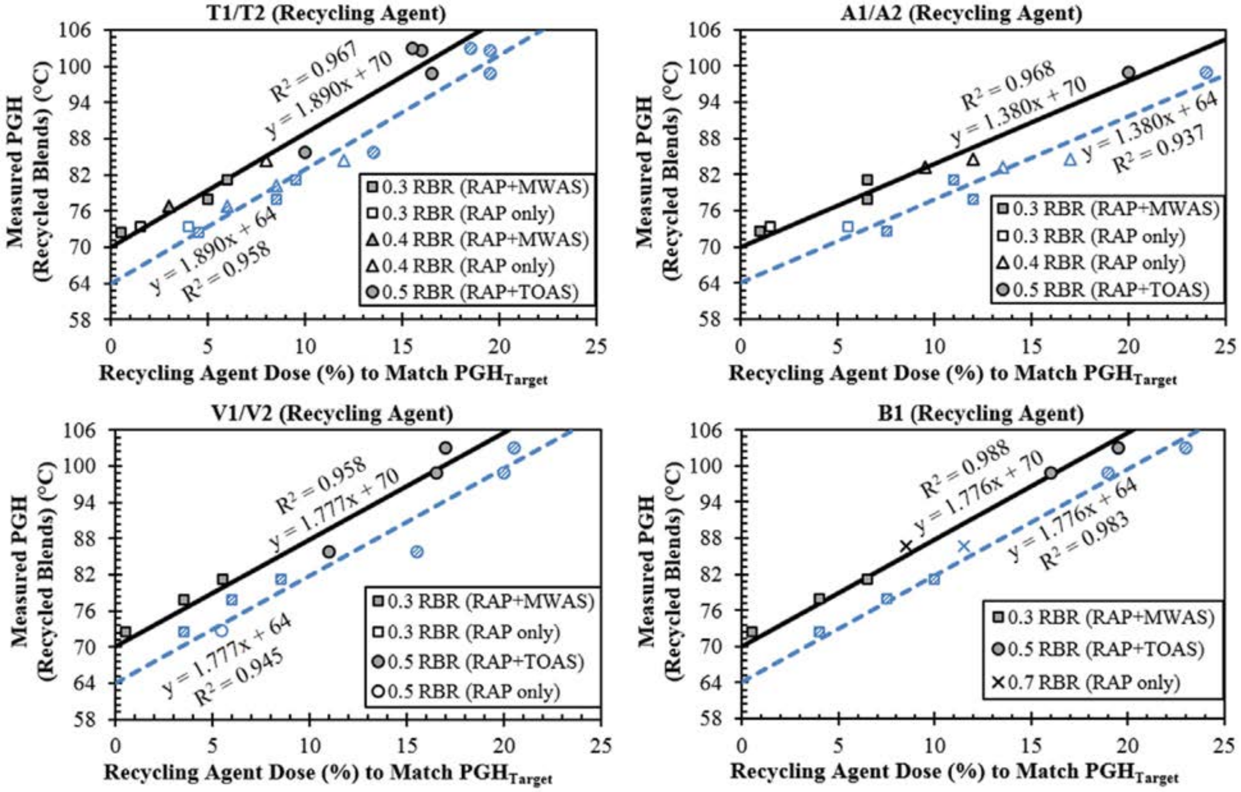


Figure 16. Recycling-agent dose to restore the PGH of the recycled blend to 70°C and 64°C for four recycling-agent types.

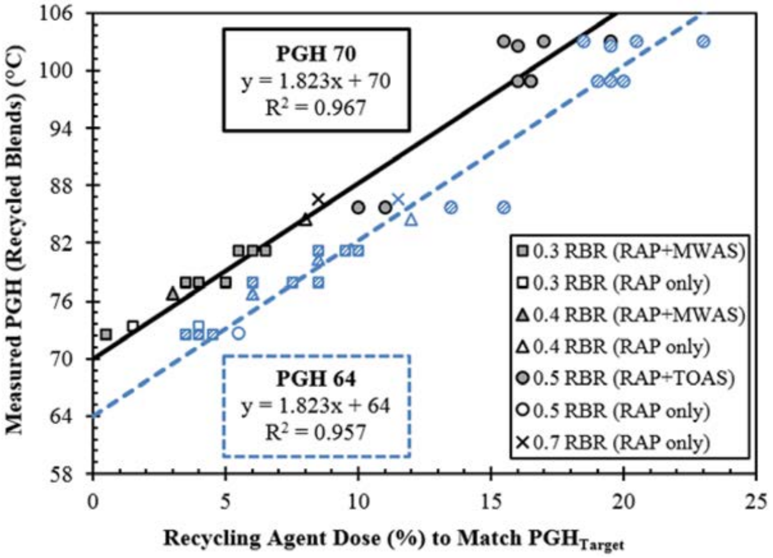


Figure 17. Recycling-agent dose to match the continuous PGH of the recycled blend to 70°C and 64°C.

and 64°C to provide a more universal recycling-agent dose estimation method. The petroleum products (A1/A2) were excluded since these recycling agents exhibited a flatter slope (1.38) compared to other recycling agents (1.89, 1.77, and 1.77 for T1/T2, V1/V2, and B1, respectively), as illustrated in Figure 16. Therefore, removing A1/A2 reduced the variability in Figure 17 and will minimize the risk of oversoftening the binder blends since A1/A2 requires the highest doses to match continuous PGH. Specific recycling-agent dose blending charts from recycling-agent suppliers such as those shown in Figure 16 should be used if available. Additional data and details are included in Kaseer and Garcia Cucalon et al. (2018b).

The results shown in Figure 17 are promising and show a strong relationship between the PGH of the blend of base and recycled binders (which can be estimated with Equation 13 without testing) and the recycling-agent dose to restore to the target PGH, regardless of the base binder, recycled materials, RBR, or recycling-agent type. Results also illustrate the recycling-agent rejuvenation capacity of the seven types of recycling agents evaluated, with an approximate average of 1% recycling agent to reduce the PGH by 1.8°C. Equation 14 can be used to estimate the recycling-agent dose to restore the continuous PGH of the recycled blend with a recommended slope rate or rate of reduction in PGH of 1.82 for tall oils (T), vegetable oils (V), and reacted bio-based oils (B) evaluated in this study. For aromatic extracts (A), a lower slope rate of 1.38 is recommended based on the materials evaluated in this study.

$$\%Recycling\ Agent = (PGH_{Blend} - PGH_{Target})/Slope\ Rate \qquad \text{[Equation 14]}$$

where $\%Recycling\ Agent$ = estimated recycling-agent dose to match continuous PGH.

The slope rate can be determined (or the estimated recycling-agent dose can be verified) by preparing recycled blends with 0%, 2% or 5%, and 10% recycling agent and measuring PGH and PGL using the DSR and BBR, respectively, if component materials are available. An example of determining recycling-agent dose (and slope rate or rate of reduction in PGH) using these data is illustrated in Figure 18.

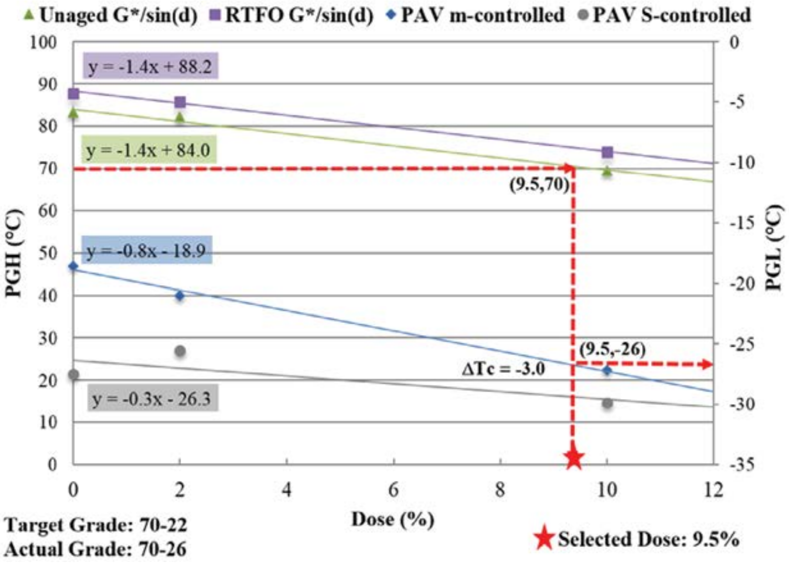


Figure 18. Example of optimum recycling-agent dose verification.

2.2 Chemical Compatibility of Binder Blends

Recycling heavily aged RAP/RAS into new asphalt pavements while maintaining sufficient durability is challenging because recycled binders have a larger asphaltene content (and larger size asphaltene agglomerations) compared to base binders and are therefore significantly stiffer and more brittle. Depending on the RBR and resulting PGH of the binder blend, the target PG for a specific field project can be met by blending with a softer (substitute) base binder and/or by incorporating a recycling agent. Rejuvenation by inclusion of a recycling agent is generally attributed to a combination of the following mechanisms:

- Softening from blending with a recycling agent,
- Reduction of the size of asphaltene agglomerations, given that the recycling agent may break apart strong polar bonds or aromatic pi-pi interactions, and
- Improvement in the dispersive power of the continuous maltene phase by inclusion of a recycling agent.

The challenge becomes further complicated considering that aging of rejuvenated binder blends could result from a combination of the following mechanisms that are not necessarily common to base binders:

- Formation of pericondensed asphaltenes and related changes in compatibility with maltenes,
- Reagglomeration of asphaltene agglomerates that may have initially been dispersed during blending with the recycling agent, and
- Chemical changes in the recycling agent with aging that may result in reduced dispersive power of the maltene phase.

Chemical compatibility of binder blends was evaluated to do the following:

- Provide fundamental insight into the mechanisms of rejuvenation when recycling agents are included, with specific interest on the impact of recycling agents on asphaltene agglomerations; and

- Assess rheological and physicochemical changes upon rejuvenation and aging of binder blends considering the materials combinations presented in Table 17.

Rheological characterization was conducted using the DSR and BBR to determine PGH and PGL and the G-R parameter with aging. Physicochemical aspects of recycling and rejuvenation were evaluated by MDSC and SAR-AD. Tracking of oxidation products was performed using FT-IR. Additional data and details are included in Garcia Cucalon et al. (2017).

The materials combinations considered included two different base binders (TX PG 64–22 and NH PG 64–28), three types of recycled materials (RAP, MWAS, and TOAS from TX), and two types of recycling agents (T1 and A1) at different doses by weight of total binder. The DOT control blend used in the field (0.3 control) included RAP with a PGH of 107 and MWAS with a PGH of 133. Alternatives to the blend used in the field included consideration of the effect of recycling agent type (T1 and A1), inclusion of higher RBR (0.5) and a more oxidized TOAS (PGH of 178), and use of a higher-quality base binder (NH PG 64–28). The recycling-agent doses for the blends considered in this experiment were optimized to restore PGL of the target binder (PG 70–22) as previously described, and the resulting PG grades of the binders and binder blends are presented in Table 17.

MDSC evaluation was conducted primarily to characterize glass transition temperature (T_g) and the high-end temperature of the glass transition (T_g End) for base binders and binder blends after inclusion of recycled binders and recycling agents. This second parameter changes more significantly with aging (Huang et al. 2015), with an increased T_g End being undesirable because it indicates the glass transition and potentially embrittlement extends to higher temperatures. In this experiment, the inclusion of recycled binders resulted in small changes in T_g but more significant increases in T_g End. Conversely, the inclusion of a recycling agent reduced both T_g and T_g End significantly, with greater improvement at higher recycling-agent doses. These results were expected since softening/rejuvenating additives (including recycling agents) are significantly less

Table 17. Chemical compatibility materials combinations.

Binder/Binder Blend	Blend Proportions[a]			Recycling Agent[b]	Continuous PG	
	Base Binder	TX RAPBR	TX RASBR	Dose	PGH	PGL
TX PG 64-22	PG 64-22	—	—	—	69.4	−24.6
NH PG 64-28	PG 64-28	—	—	—	66.9	−28
0.28 Control	0.7 PG 64-22	0.1	0.18 MWAS	—	81	−15.6
0.28 + 4.5% T1	0.7 PG 64-22	0.1	0.18 MWAS	R4444.5% T1	73	−22.0
0.28 + 5.5% A1	0.7 PG 64-22	0.1	0.18 MWAS	5.5% A1	71	−22.3
0.5 Control MWAS	0.5 PG 64-22	0.25	0.25 MWAS	—	88	−10.6
0.5 MWAS + 7.5% T1	0.5 PG 64-22	0.25	0.25 MWAS	7.5% T1	73	−21.7
0.5 Control TOAS	0.5 PG 64-22	0.25	0.25 TOAS	—	102	−2.1
0.5 TOAS + 11.5% T1	0.5 PG 64-22	0.25	0.25 TOAS	11.5% T1	74	−25.8
0.5 Control TOAS 64-28	0.5 PG 64-28	0.25	0.25 TOAS	—	101	−12.7
0.5 TOAS 64-28 + 12.5% T1	0.5 PG 64-28	0.25	0.25 TOAS	12.5% T1	75	−27.1

NOTE: — = not applicable.
[a] By weight of total blend.
[b] By weight of total binder.

viscous and can exhibit much lower T_g compared to base binders, and therefore significantly lower T_g and PGL in corresponding binder blends (Lei et al. 2016).

The SAR-AD CII and total TPA indices indicated a detrimental effect on compatibility when including recycled materials in a binder blend. The benefit of adding a recycling agent was not clear based on these indices for the recycling-agent doses evaluated, but complete rebalancing of the SAR-AD fractions to proportions comparable to those of base binders is not likely at any dose. The asphaltene determinator from this test was further utilized to investigate the possible recycling-agent rejuvenation mechanism by dissociation of asphaltene agglomerations. Figure 19 presents the asphaltenes observed by the 500-nm detector in terms of fractions soluble in cyclohexane (CyC_6), toluene, and methylene chloride:methanol (CH_2Cl_{12}:MeOH). Incorporation of recycled materials resulted in increased asphaltene content, as expected. However, SAR-AD only captured a very minor decrease in asphaltene content when A1 was included and even an increased asphaltene content for blends with TOAS, including 11.5% and 12.5% T1. This was unexpected, considering that T1 does not contain any of the polycyclic aromatic molecules thought to create the molecular associations called asphaltenes. On further consideration, the fatty acid group on the tall oil molecule must have enough polarity to bond with other polar molecules in the asphaltenes. A strong fatty acid–asphaltene polar interaction may be the mechanism by which the recycling agent provides improved molecular mobility of the large asphaltene agglomerates.

Rheological evaluation with aging was also conducted for the base binders, DOT control blend (0.28 control), and rejuvenated binder blends. G-R parameters are presented in Figure 20 with the corresponding cracking onset (180 kPa) and significant cracking (600 kPa) thresholds that define the G-R transition zone in Black space. The DOT control blend (0.28 control) was excessively brittle based on the two damage thresholds after RTFO and PAV aging. Comparing both base binders, the TX PG 64–22 reached the durability thresholds significantly faster than the NH PG 64–28. All the rejuvenated binder blends with short-term aging (RTFO) ranked between both base binders and exhibited improved performance compared to the DOT control blend (0.28 control). After 20-h PAV aging, all the rejuvenated binder blends exceeded the

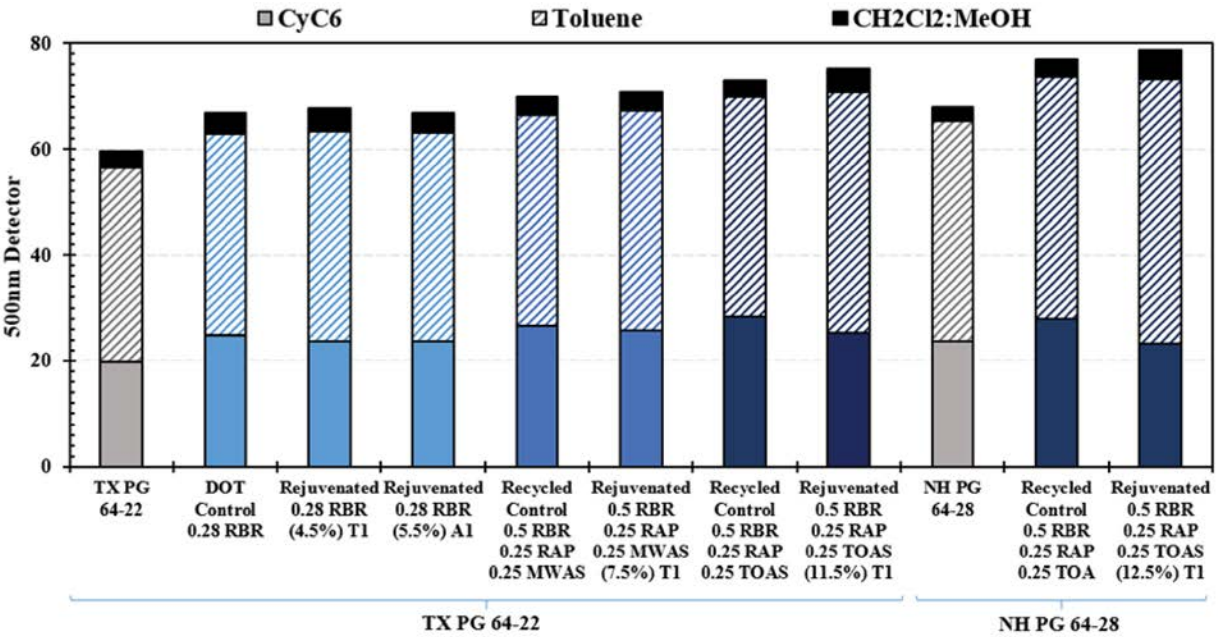


Figure 19. SAR-AD results—asphaltene determinator 500 nm.

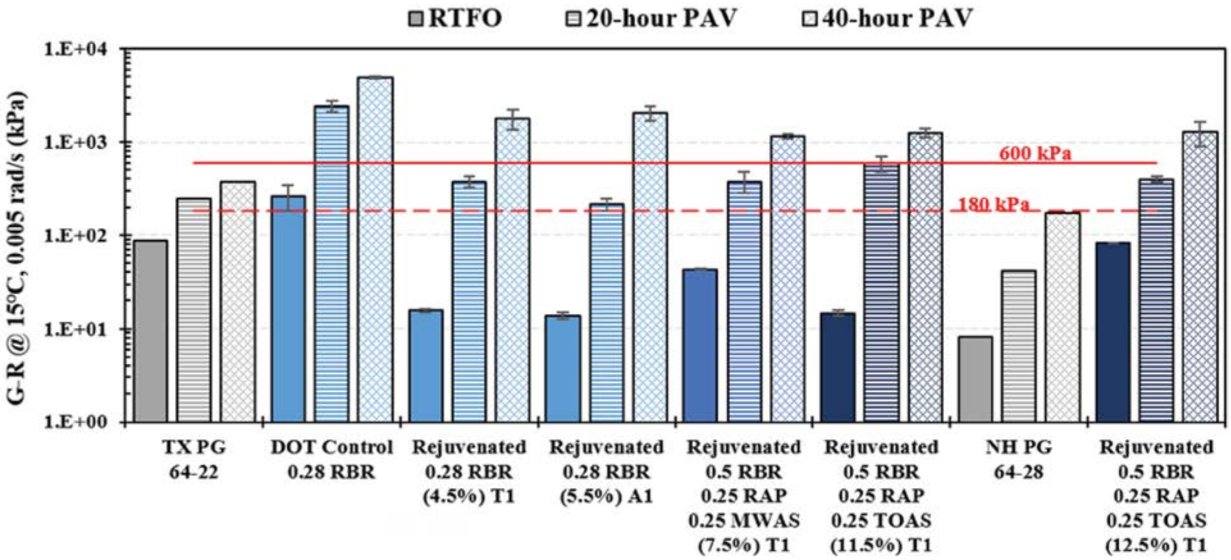


Figure 20. G-R with aging.

cracking onset threshold and exhibited similar or slightly worse performance compared to the poor-quality TX PG 64–22 base binder. After 40-h PAV aging, all rejuvenated binder blends would be expected to have significant cracking based on G-R thresholds.

The aging and associated stiffening and embrittlement of these rejuvenated binder blends may be related to chemical changes different to those common for base binders. In addition to formation of common oxidation products, it is possible that with time, the binder blend loses compatibility due to reagglomeration of asphaltene clusters that may have initially been dispersed during blending with recycling agents, and/or chemical changes in the recycling agents with aging may affect rheology. Analysis of the FT-IR spectrum with aging showed increases in peaks at 1,743 cm^{-1}, 1,700 cm^{-1}, and 1,032 cm^{-1}, associated with formation of esters, ketones/carboxylic acids, and sulfoxides, respectively. Changes in the 1,743 cm^{-1} and 1,700 cm^{-1} peaks may be associated with changes in recycling agents as well as the common oxidation process of asphalt binders. Further evaluation of chemical changes in recycling agents with aging and their impact on the chemistry and rheology of rejuvenated binder blends was completed in Phase 3 and described subsequently.

This experiment provided fundamental insight to the mechanisms of rejuvenation and aging of binder blends with a recycling agent through rheological and physicochemical characterization. The main findings can be summarized as follows:

- Rheological (PG and G-R) and physicochemical (MDSC Tg and Tg End) measurements confirm that there is a rejuvenation effect from inclusion of recycling agents.
- With long-term aging, rejuvenation effectiveness is diminished, especially after 40-h PAV aging. Nevertheless, all rejuvenated binder blends continued to show improved performance compared to the DOT control blend without any recycling agent, corroborating the added value of using a recycling agent to increase RBR.
- SAR-AD indices may allow evaluation of the evolution of compatibility with aging but may not have equivalent relevance as a tool to evaluate the effectiveness of different recycling agents in partially restoring binder rheology.
- Chemical analysis by SAR-AD did not confirm or deny the hypothesis regarding the reduction of asphaltene agglomerates by inclusion of recycling agents but did provide evidence

of a strong polar interaction between asphaltenes and T1 that may contribute to increased molecular mobility and restoration of rheological properties as observed.

- Considering the large number of recycling agents available on the market, it is important to understand the chemical changes typically observed in the different recycling-agent types that may compromise durability of binder blends.

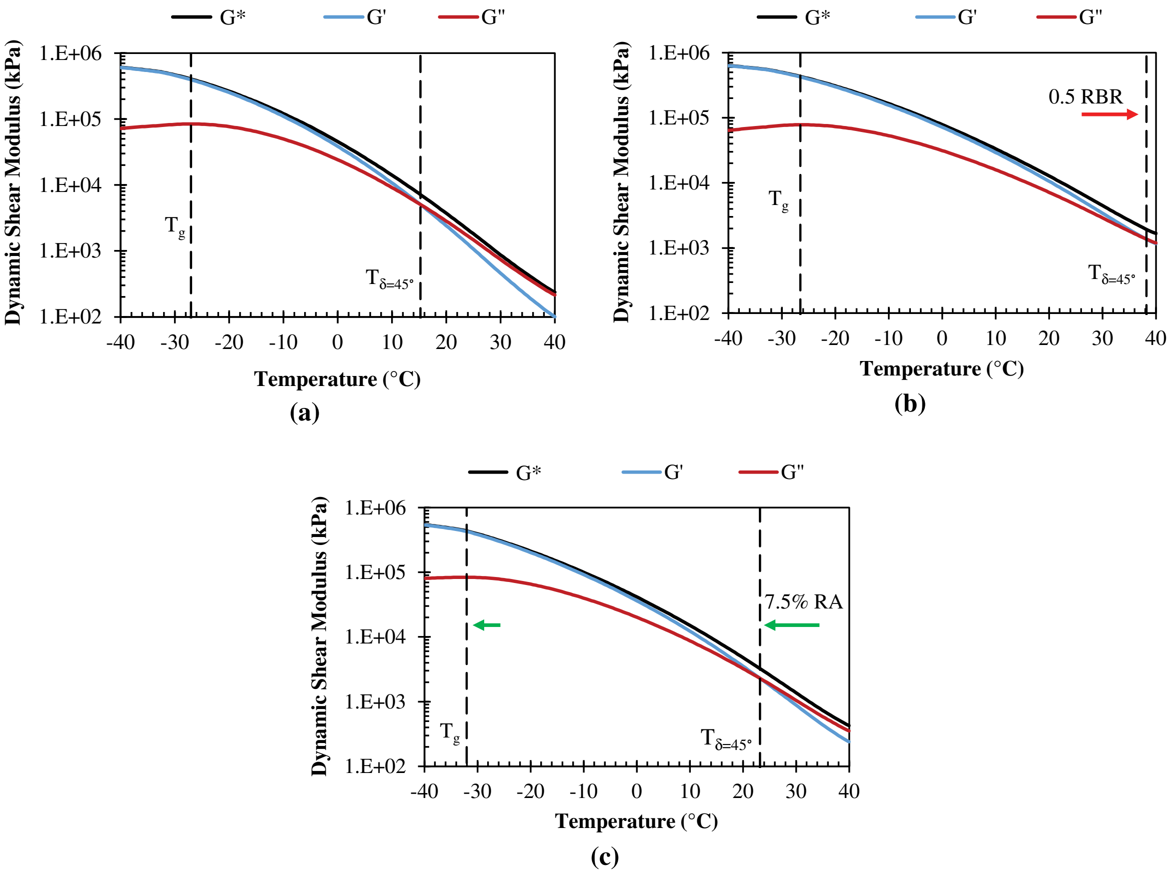
A complementary study was conducted in partnership with Texas A&M University at Qatar exploring microstructural and rheological changes upon aging, rejuvenation, and further aging. Menapace et al. (2018b) found that the improved flow properties observed rheologically (by PG and G-R) were detected in atomic force microscopy (AFM) as a reduction in surface roughness, smoother borders of dispersed domains, increased matrix area, and better dispersion of domains in the rejuvenated binders. Note that the dispersed domains observed with AFM were on the order of microns, which is orders of magnitude larger than what the literature reports on size of asphaltene aggregates/clusters. Additional data and details are included in Menapace et al. (2018b).

2.3 Rheological Balance of Binder Blends

In developing the recycling-agent dose selection method, three approaches were evaluated, and the final recommendation was to increase recycling-agent dose without sacrificing PGH (dose to match PGH). Blending charts investigated limits on recycled materials and the balance between base binders and recycled binders to improve the potential for effective rejuvenation by recycling agents at selected doses. Evaluation of chemical compatibility provided fundamental insight on rejuvenation mechanisms contributing to the observed changes in rheology, changes in temperature transition parameters observed by MDSC, and rejuvenation effectiveness with aging in terms of the intermediate-temperature G-R parameter. Based on limitations of and practicality concerns associated with the physicochemical characterization methods, an additional rheological parameter was explored at intermediate temperatures to capture the solid- to fluid-like transition. Considering early life rutting potential and the effects of rejuvenation and aging in intermediate (solid- to fluid-like transition) and cold temperature (ΔT_c) compatibility, it was possible to engineer or better select rheologically balanced binder blends.

Figure 21 illustrates the temperature dependency of binders and binder blends, including two transition parameters, the rheological glass transition (T_g) defined as the maximum G'' and the crossover temperature or solid- to fluid-like transition temperature ($T_{\delta = 45°}$). Above $T_{\delta = 45°}$, the binder (or blend) exhibits primarily fluid-like viscous behavior ($G'' > G'$); therefore, under load it is more likely to flow and dissipate energy instead of cracking. Below $T_{\delta = 45°}$, cracking is of concern since the binder (or blend) exhibits primarily solid-like viscoelastic behavior ($G' > G''$) and it is thus more likely to store energy instead of relax stress. Typically for unmodified binders, a more solid-like behavior (lower phase angle) is associated with increased brittleness (Ruan et al. 2003). Both of these transition parameters (T_g and $T_{\delta = 45°}$) are related to molecular motion and are thus frequency-dependent phenomena, but in this experiment, $T_{\delta = 45°}$ was determined at the standard DSR frequency of 10 rad/s.

A limited set of materials combinations were characterized using a DSR temperature-sweep conducted at 10 rad/s with a constant cooling rate of 0.5°C/min from 40°C to −40°C to determine $T_{\delta = 45°}$ and highlight its utility. The effect of recycled materials on this parameter is shown by comparing the TX PG 64–22 base binder (Figure 21*a*) and the recycled PG 88–10 binder blend (Figure 21*b*). Both have a similar T_g, while $T_{\delta = 45°}$ is significantly shifted (increased) by the inclusion of aged recycled materials. The effect of rejuvenation by recycling agent is presented in Figure 21*c*, with both T_g and $T_{\delta = 45°}$ decreasing compared to the recycled binder blend shown in Figure 21*b*. The resulting PG 73–22 rejuvenated binder blend met the climatic requirements



(a)

(b)

(c)

Figure 21. Temperature dependency of binder and binder blends for (a) TX base (PG 64–22), (b) TX recycled blend (PG 88–10), and (c) TX recycled blend + 7.5% recycling agent (PG 73–22).

for TX (PG 70–22), with PGL and T_g decreased due to the low viscosity and low T_g characteristic of typical recycling agents. $T_{\delta = 45°}$ was decreased but not restored to that of the base binder (Figure 21*a*), even though all binders and binder blends met the associated intermediate-temperature PG specification at 25°C and 28°C for PG 64–22 and PG 70–22, respectively. The |G*| sinδ (G″) parameter and specification threshold may not be sufficient to capture the effects of binder embrittlement with recycled materials and rejuvenation by recycling agent since it only considers changes in the viscous component of the complex modulus. Crossover temperature ($T_{\delta=45°}$) at 10 rad/s is an alternate intermediate-temperature parameter that can also be obtained from DSR master curves, with the simplest approach shifting the crossover frequency (ω_c) to 10 rad/s by applying time-temperature superposition principles, resulting in a robust parameter for tracking the effect of binder aging and rejuvenation.

As detailed in Garcia Cucalon et al. (2018), DSR master curve data for calculating $T_{\delta=45°}$ were available for the materials combinations shown in Table 1 that included four base binders, five recycled materials, five recycling agents, and five aging conditions in different combinations. Thresholds tied to field performance and laboratory failure tests (ductility) are not available for $T_{\delta=45°}$ as they are for the G-R parameter, but a strong relationship was found between these two intermediate-temperature parameters, as shown in Figure 22, for many binders and binder blends, including those with WMA additives, polymers, and recycling agents, over multiple aging conditions. Considering the G-R thresholds previously introduced, preliminary crossover temperature ($T_{\delta = 45°}$) durability thresholds were set at 32°C and 45°C for inadequate performance with aging.

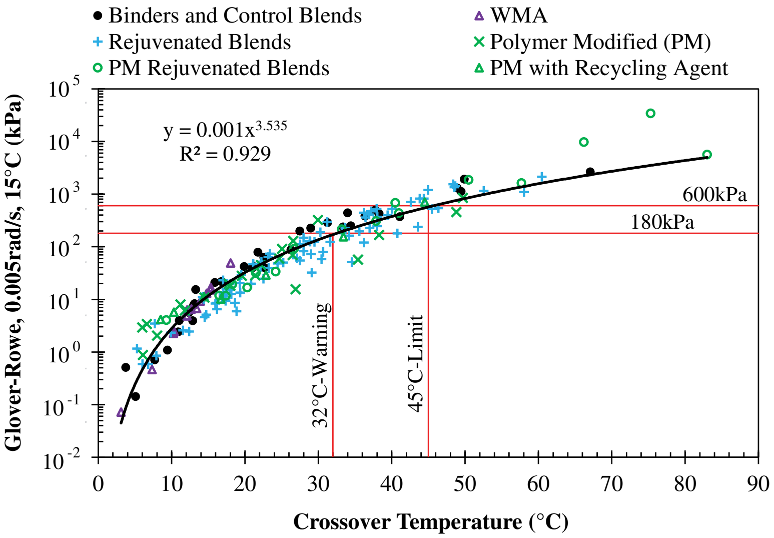


Figure 22. Defining trial durability thresholds for $T_{\delta=45^\circ}$.

Figure 23 presents a summary graph highlighting the approach to engineering rheological balance by optimizing PGH and tracking $T_{\delta=45^\circ}$ with aging. The factors evaluated include two base binders with their corresponding DOT control blends (0.28 RBR), two recycling-agent types/doses, and a very high RBR. The NH PG 64–28 base binder is of better quality compared to the TX PG 64–22 base binder based on ΔT_c, as discussed previously, PG useful temperature interval (UTI), SAR-AD CII, and G-R with aging. The crossover temperature ($T_{\delta=45^\circ}$) results with aging provide the same conclusion. Furthermore, the quality of base binders is reflected in the DOT control blends (with the same RAP/RAS combination), where the control blend with the NH PG 64–28 base binder had better $T_{\delta=45^\circ}$ before and after aging than that with the TX PG 64–22 base binder. Two recycling-agent types (V1 and T1) at different doses were incorporated in the 0.28 RBR DOT control blend with TX PG 64–22 base binder. Increasing the recycling-agent dose resulted in improved (lower) crossover temperature ($T_{\delta=45^\circ}$) with aging, but the PGH was lower than the 70°C requirement for TX. Increased recycling-agent doses were best for long-term

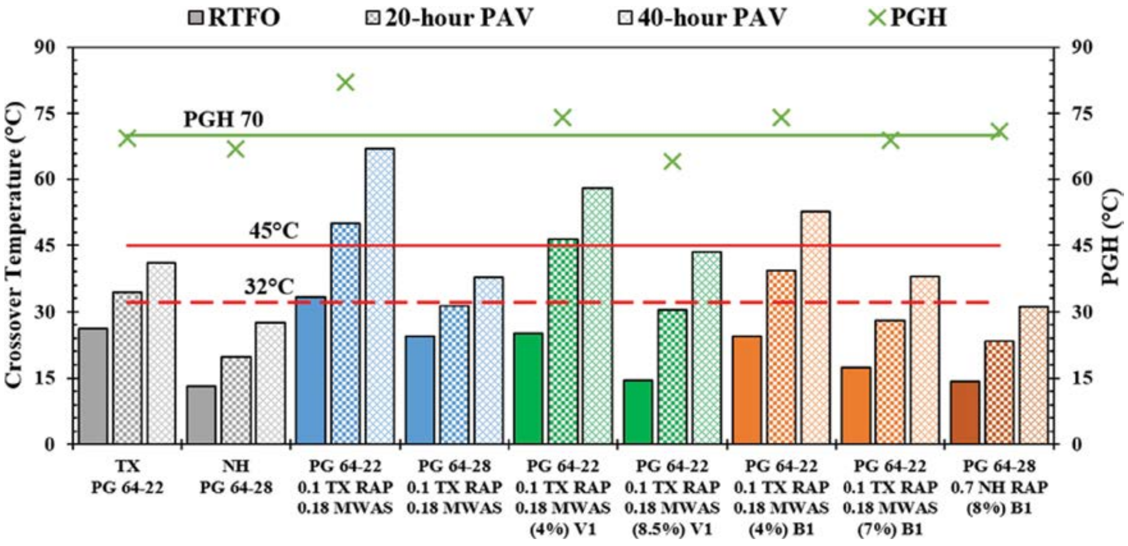


Figure 23. Engineering balanced recycled binder blends.

durability, but rutting susceptibility must also be considered to achieve rheologically balanced blends. Based on these results, B1 was the most effective in rejuvenating the 0.28 RBR blends with TX materials. Finally, B1 was added to a very high RBR blend with 0.7 NH RAP and 0.3 NH PG 64–28 base binder to meet a 70 PGH and was able to maintain a low crossover temperature ($T_{\delta = 45°}$) after aging, highlighting the importance of appropriate materials selection and their combinations to facilitate the use of high RBR.

Garcia Cucalon et al. (2018) provided additional insight on the importance of selection of better-quality base binders (including polymer modified) for recycling applications and optimization of components for improved compatibility of recycled and rejuvenated blends. The parameter ΔT_c, an indicator of low-temperature compatibility, was also evaluated for base binders, recycled blends, and rejuvenated blends and correlated linearly to $T_{\delta = 45°}$ with an R^2 of 0.61.

An alternative approach toward engineering balanced recycled binder blends was explored with an intermediate-temperature transition parameter, crossover temperature ($T_{\delta = 45°}$), in combination with more commonly used parameters PGH and ΔT_c. The main findings can be summarized as follows:

- In combination with PGH and ΔT_c, $T_{\delta = 45°}$ was useful in evaluating rejuvenation and aging processes with respect to early rutting and long-term durability. This study confirmed the importance of selecting high-quality base binders in recycling construction projects. The type of recycled materials and recycling-agent type/dose can also be optimized for improved rheological balance.
- Despite the potential differences in the fundamental aging mechanisms operating within polymer-modified systems, the characteristic behavior and evaluation framework outlined for unmodified binders was demonstrated as applicable to polymer-modified systems.
- The correlation presented resulted in guidelines for initial threshold selections for $T_{\delta = 45°}$ that should be adjusted in future studies by considering asphalt mixture properties and climate. $T_{\delta = 45°}$ data were presented in terms of temperature, thus facilitating climate-based adjustments and alignment to PG specifications.

2.4 Representative Binder Blending

The influence of recycled materials and recycling agents on the continuous PG of the material combinations shown in Table 1 was evaluated using the mortar procedure in the latest draft AASHTO standard test method for *Estimating Effect of RAP and RAS on Blended Binder Performance Grade without Binder Extraction* (www.arc.unr.edu/Outreach.html). Figure 24 through Figure 27 indicate the high-, intermediate-, and low-temperature continuous PG for the various binder blends and mortars for the TX recycled materials and T1 (Figure 24 through Figure 26) and for the NV recycled materials and A2 and T2 (Figure 27) at the respective RBRs and recycling-agent doses from the corresponding field projects.

The results with the TX PG 70–22 target binder in Figure 24 suggest that T1 influenced PGH more than PGL, with a more pronounced effect in restoring the controlling m-value PGL compared to the stiffness PGL. For the mortars containing either RAP or MWAS separately, T1 at the selected dose restored the PGL to the target of −22°C. However, it did not fully restore the PGL to the target of −22°C when the recycled materials were added together at the field combination of 0.28 RBR (0.1 RAP + 0.18 MWAS).

Figure 25 shows the results for the binder blends and mortars with the TX PG 64–22 softer (substitute) binder. T1 again had a more significant effect in restoring the controlling m-value PGL compared to the stiffness PGL for the materials combinations containing MWAS.

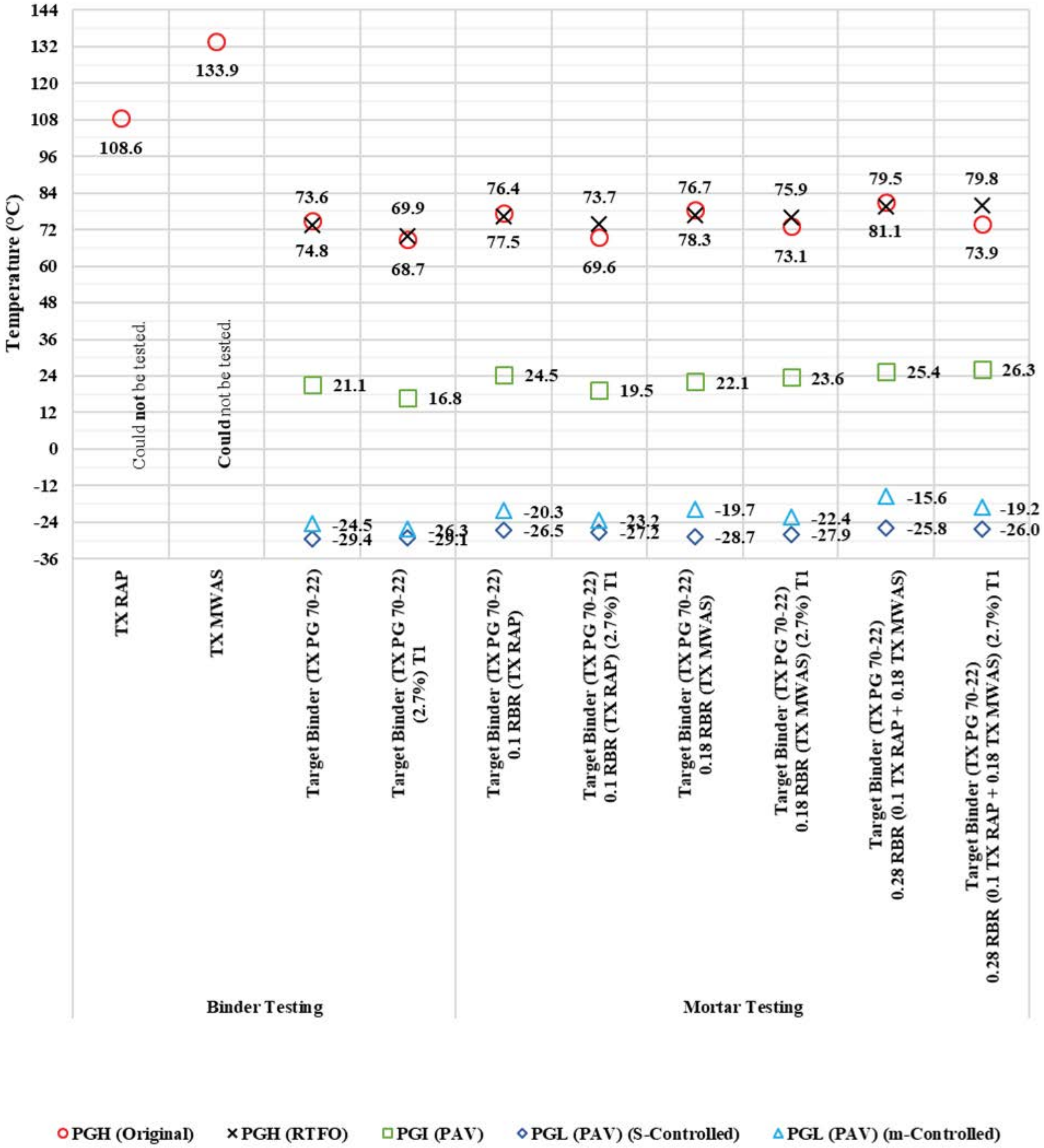


Figure 24. Effect of recycling and recycling agent on continuous PG for binder blends and mortars with TX PG 70–22 target binder, T1, and TX recycled materials.

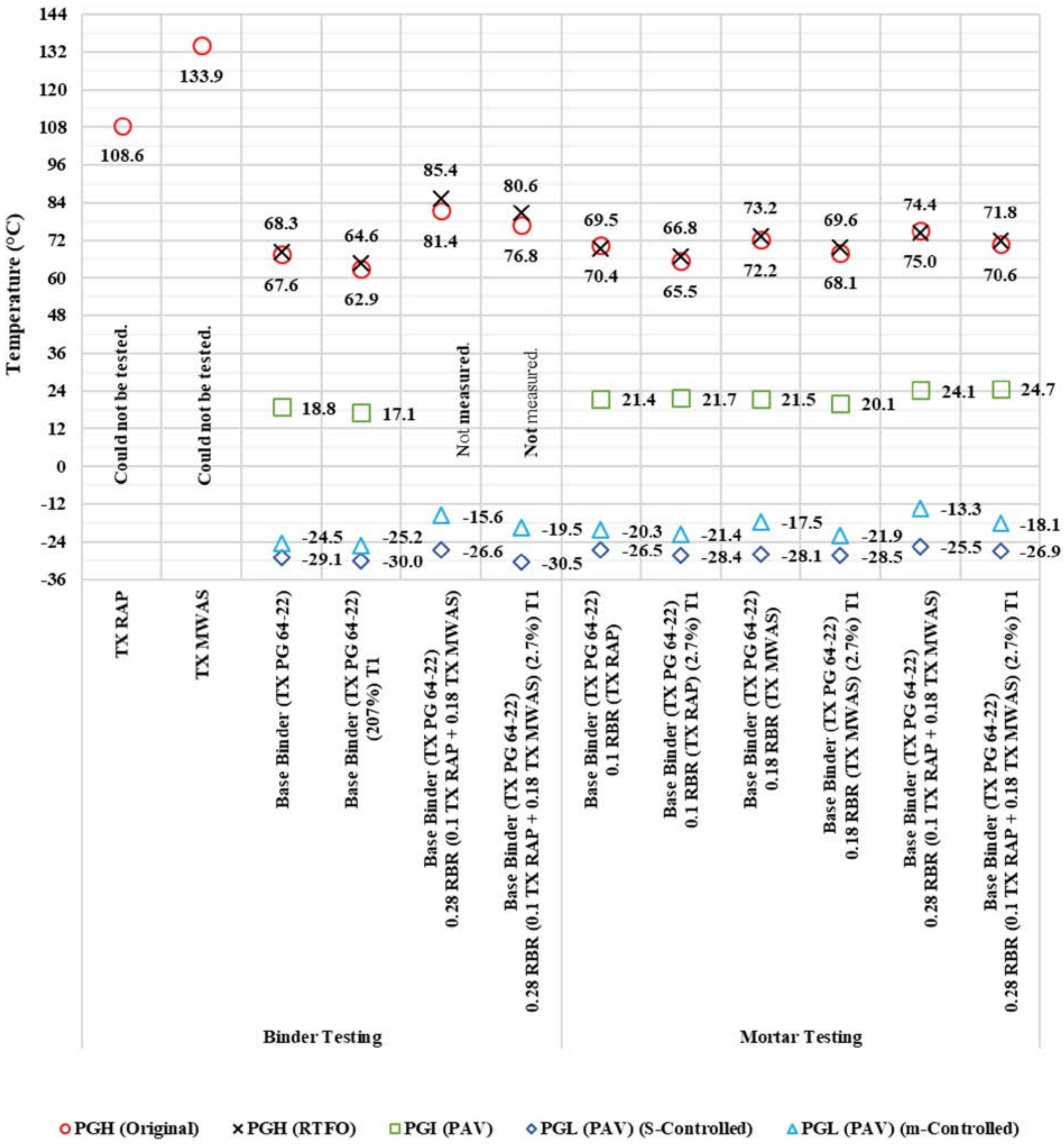


Figure 25. Effect of recycling and recycling agent on continuous PG for binder blends and mortars with TX PG 64–22 softer (substitute) binder, T1, and TX recycled materials.

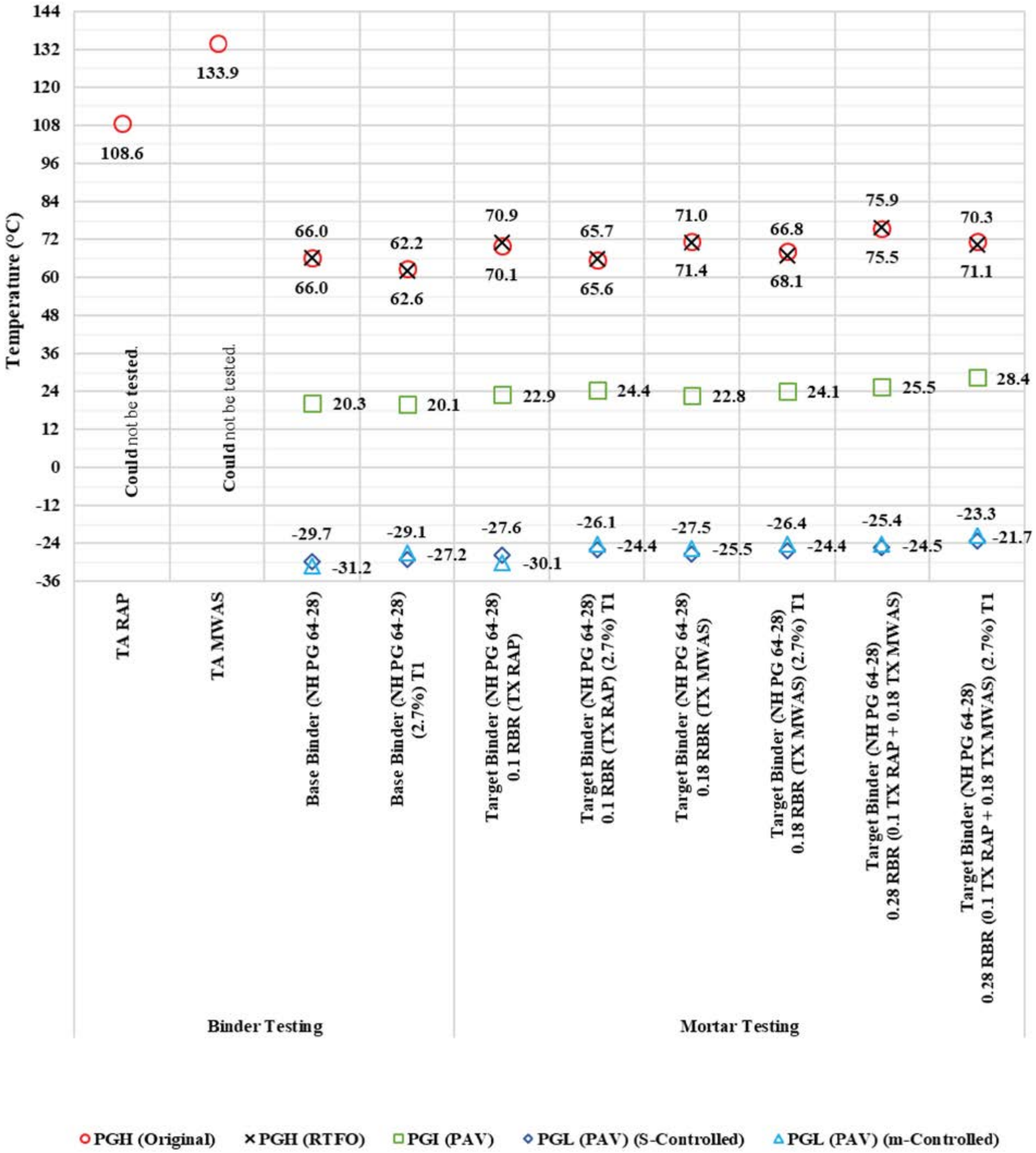


Figure 26. Effect of recycling and recycling agent on continuous PG for binder blends and mortars with NH PG 64–28 softer (substitute) binder, T1, and TX recycled materials.

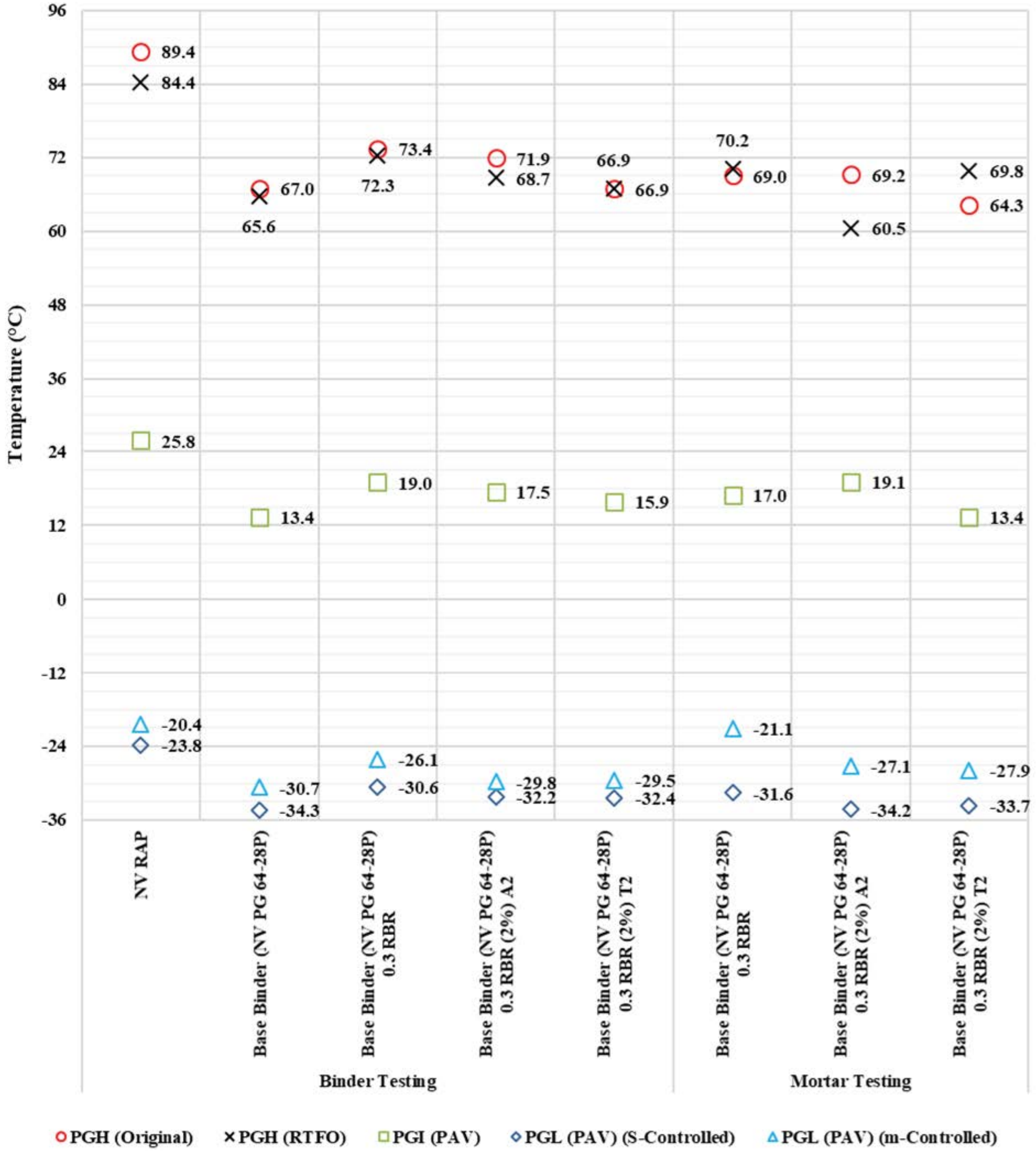


Figure 27. Effect of recycling and recycling agent on continuous PG for binder blends and mortars with NV PG 64–28P target binder, A2 and T2, and NV recycled materials.

However, T1 at the selected dose was only able to partially restore the PGL (to the target of −22°C) when either RAP or MWAS was added separately or when the recycled materials were added together at the field combination of 0.28 RBR (0.1 RAP + 0.18 MWAS). These results suggest that a higher recycling-agent dose might be required for these materials combinations.

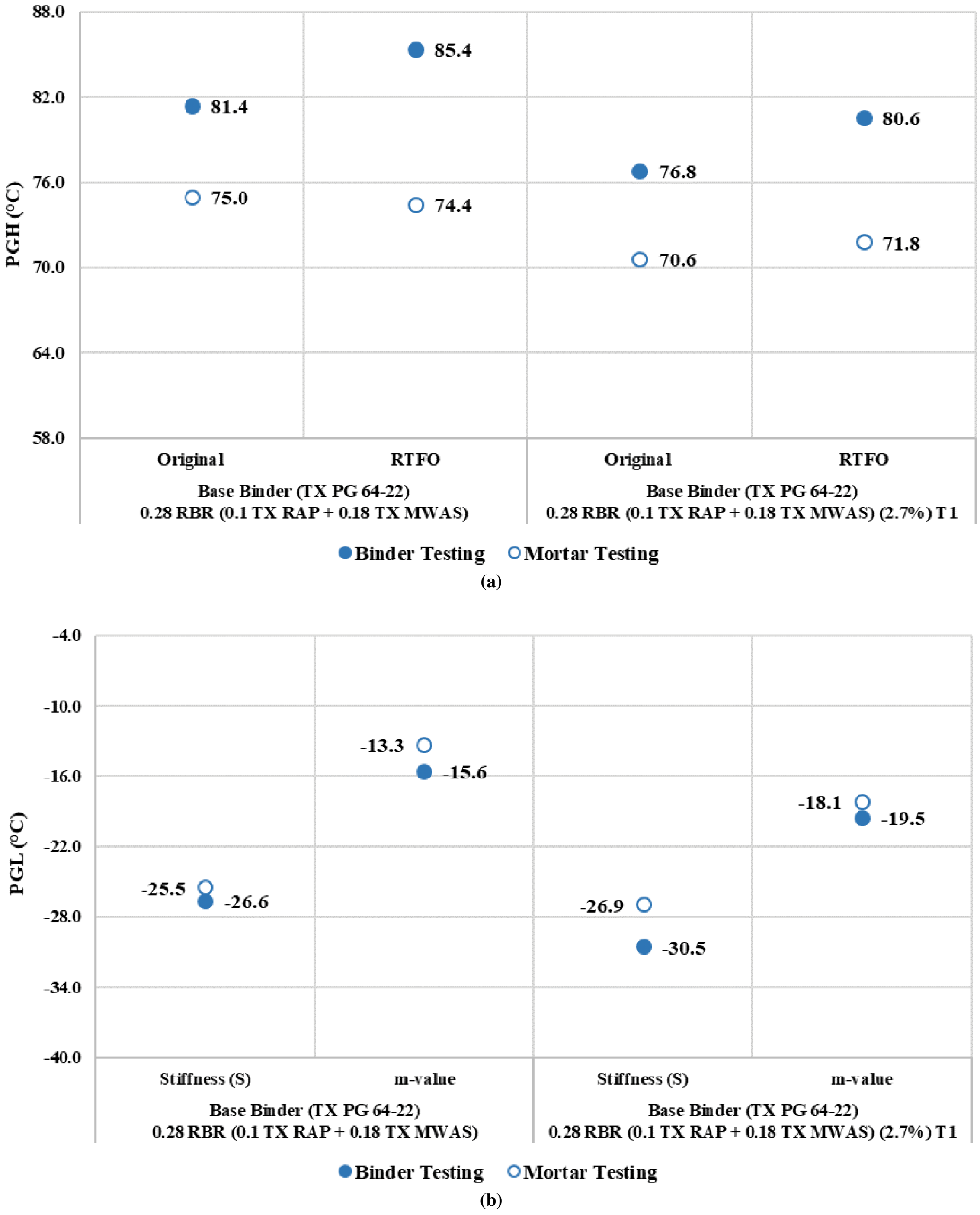
Similar test results are presented in Figure 26 for the NH PG 64–28 softer (substitute) binder. In all cases, the use of an improved base binder (with a less negative or positive ΔT_c) facilitated the addition of RAP, MWAS, or the combination of both recycled materials, with or without the use of T1, with PGL values less than or equal to the target of −22°C. In these cases, when a recycling agent was not needed, the use of T1 at the selected dose was detrimental with a reduction in PGH and an increase in PGL.

Two different recycling agents were used with the NV PG 64–28P target binder for the NV recycled materials, as shown in Figure 27. Both binder blends with 0.30 RAPBR and A2 or T2 at the selected doses met the target PGH of 64°C, but T2 reduced PGH more than A2. For the mortars with more representative blending, A2 reduced PGH more than T2 such that the mortar with A2 did not meet the target PGH of 64°C. The NV PG 64–28P binder blend results also showed that the use of A2 or T2 at the selected doses was effective in restoring the PGL to the target of −28°C, with a more pronounced effect in restoring the controlling m-value PGL compared to the stiffness PGL. Again, the mortars with more representative blending indicated different results, with the recycling agent only able to partially restore the m-value PGL.

Figure 28 and Figure 29 show a comparison between binder blends with complete blending and mortars with more realistic blending in terms of PGH and PGL for the TX PG 64–22 softer (substitute) binder with TX field project materials and the NV PG 64–28P target binder with NV field project materials, respectively. For the TX PG 64–22 softer (substitute) binder, the PGH from the mortar procedure was significantly lower (6.2°C to 11.0°C colder) than the PGH for the binder blend, resulting in a narrower UTI. The PGL from the mortar procedure also resulted in a narrower UTI (with PGL values 1.1°C to 3.6°C warmer) compared to that for the binder blend. For the NV PG 64–28P target binder, the PGH from the mortar procedure was again lower (2.1°C to 8.2°C colder) than that for the binder blends for all controlling cases. The PGL from the mortar procedure also resulted in a narrower UTI (with PGL values 1.6°C to 5.0°C warmer) for the controlling m-value cases, but a wider UTI was realized (with PGL values 1.0°C to 2.0°C colder) for the stiffness PGL. For both base binders and all mortars and binder blends, the PGL was controlled by m-value.

Figure 30 through Figure 33 show ΔT_c values for binder blends and mortars whose results were in general agreement with each other. For the TX PG 70–22 target binder, T1 was effective in increasing the ΔT_c when RAP, MWAS, or the combination of both recycled materials was used at the selected RBR values. For the TX PG 64–22 softer (substitute) binder, T1 was also effective in increasing (or not decreasing) the ΔT_c for the materials combinations containing MWAS. For the NH PG 64–28 softer (substitute) binder, when a recycling agent was not needed per the previous discussion, the use of T1 at the selected dose was detrimental with a decrease in ΔT_c for all materials combinations except that with MWAS only. For the NV PG 64–28P target binder, both A2 and T2 were effective in increasing the ΔT_c.

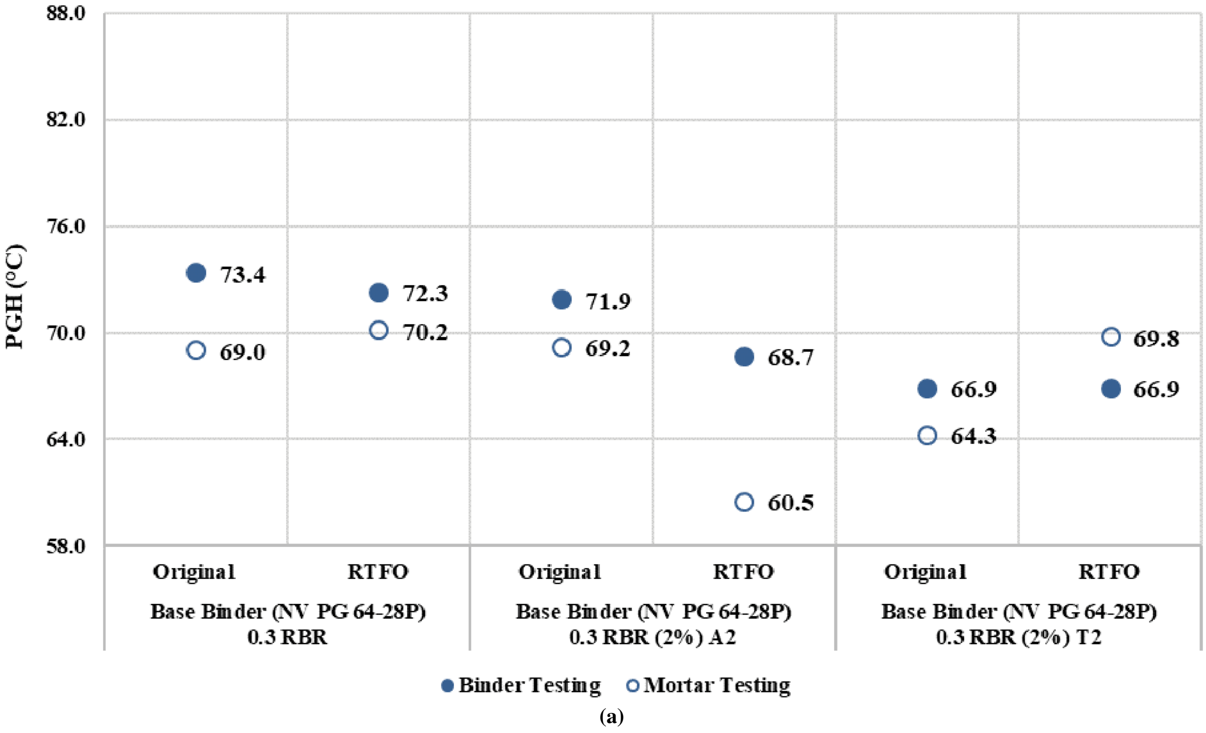
Results for binder blends and mortars indicated that recycling agents reduce both PGH and PGL. In general, complete blending with the binder blends resulted in overestimation of both the PGH (warmer by 3°C–8°C for NV and 6–7°C for TX) and the PGL (colder by 2°C–5°C for NV and 1°C–2°C for TX) and suggests that perhaps an adjustment is needed to binder blend continuous PG results to account for representative incomplete blending. The more representative mortar results also showed increased recycling-agent effectiveness in terms of ΔT_c for both the TX and NV field project materials combinations. Thus, the mortar procedure can be used to provide useful insights for these complex materials combinations.



(a)

(b)

Figure 28. Comparison between binder blends and mortars for TX PG 64–22 softer (substitute) binder, T1, and TX recycled materials: (a) PGH, and (b) PGL.



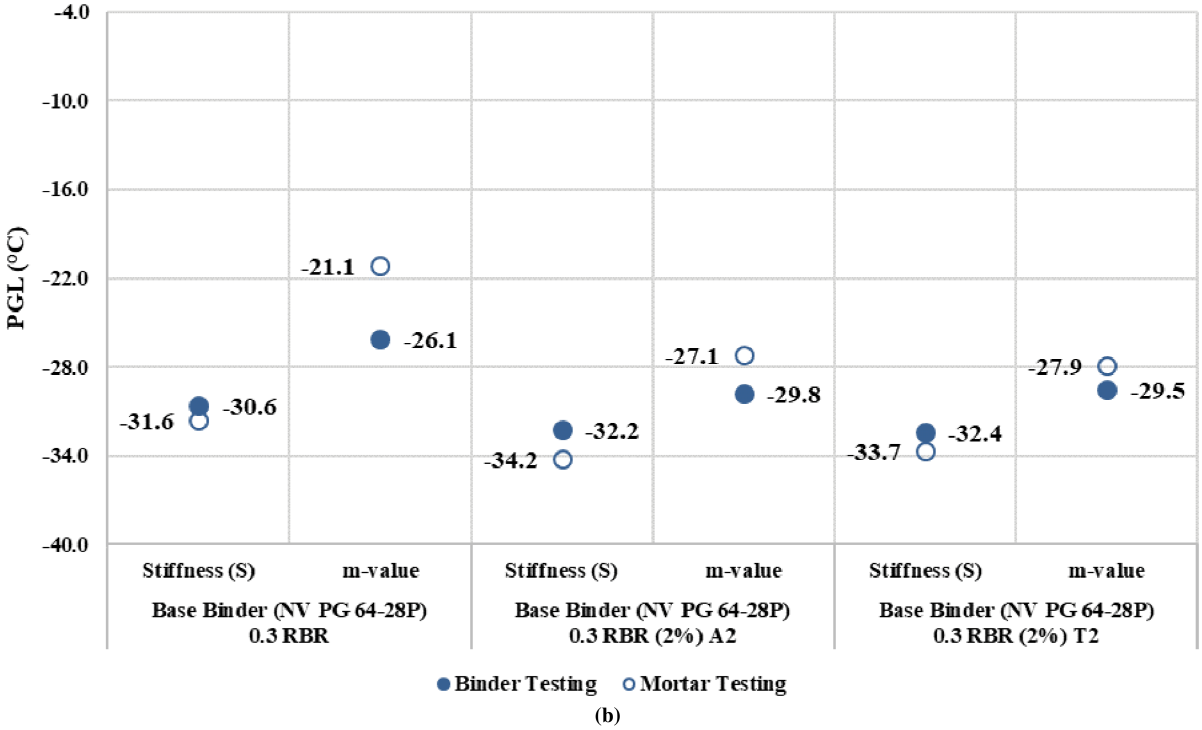


Figure 29. Comparison between binder blends and mortars for NV PG 64–28P target binder, A2 and T2, and NV recycled materials: (a) PGH, and (b) PGL.

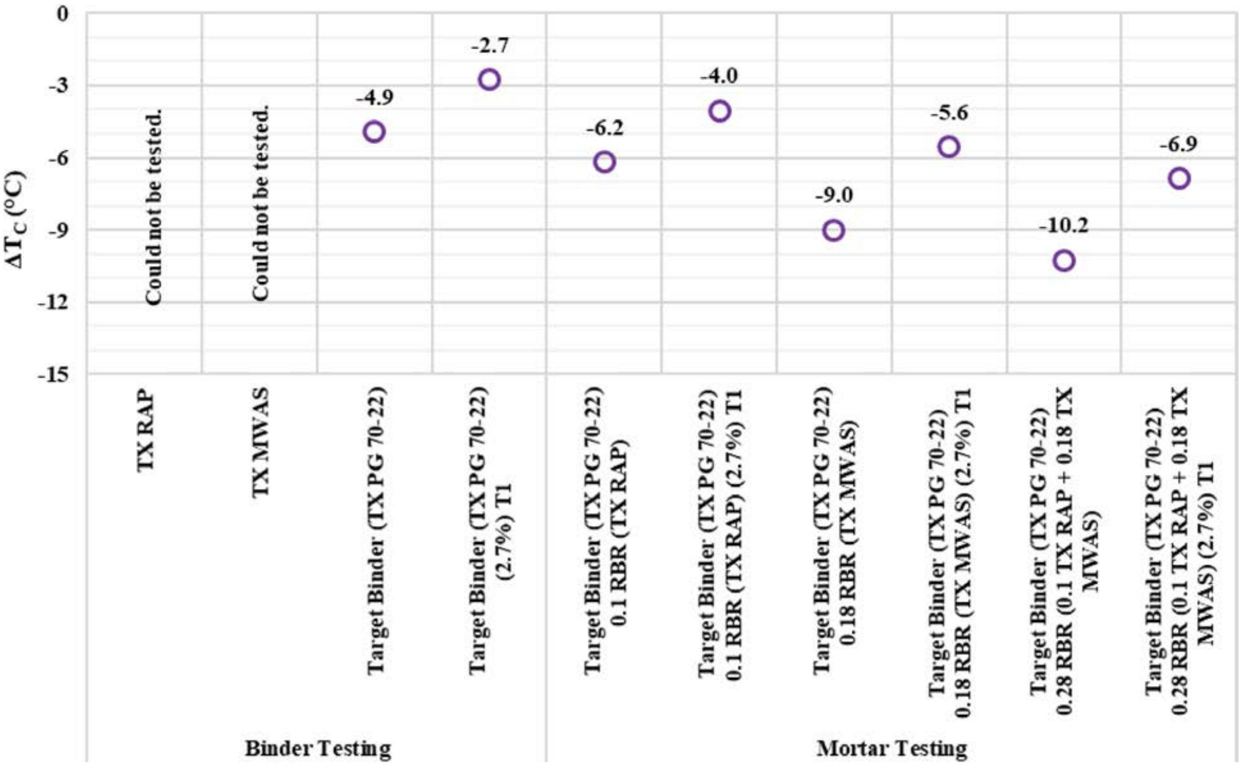


Figure 30. Effect of recycling and recycling agent on ΔT_c for binders and mortars with TX PG 70–22 target binder, T1, and TX recycled materials.

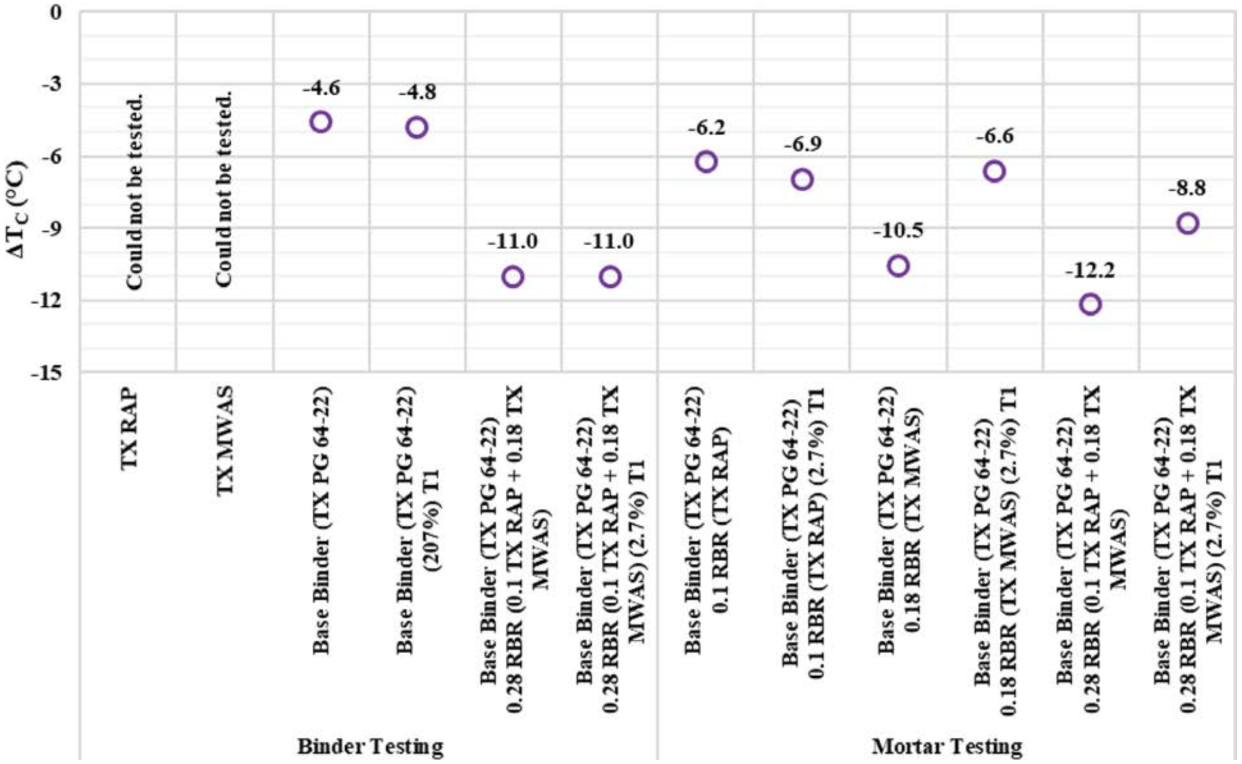


Figure 31. Effect of recycling and recycling agent on ΔT_c for binder blends and mortars with TX PG 64–22 softer (substitute) binder, T1, and TX recycled materials.

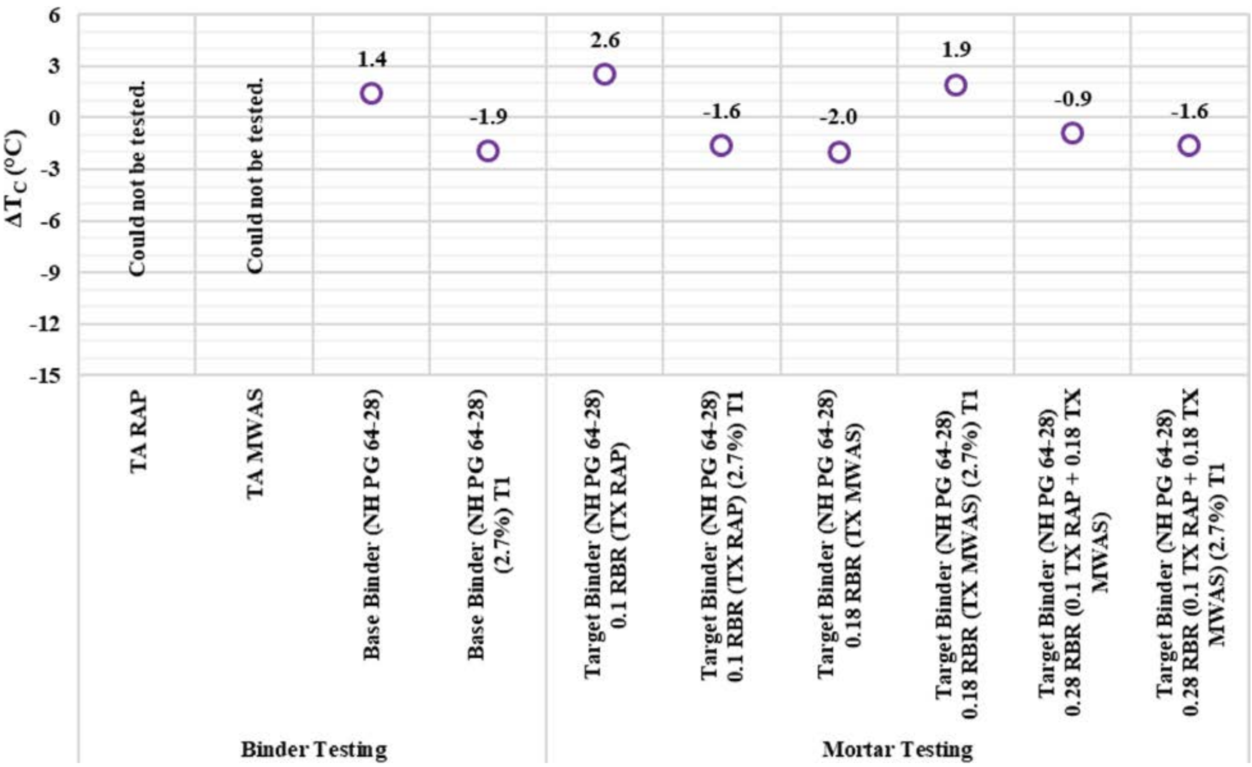


Figure 32. Effect of recycling and recycling agent on ΔT$_c$ for binder blends and mortars with NH PG 64–28 softer (substitute) binder, T1, and TX recycled materials.

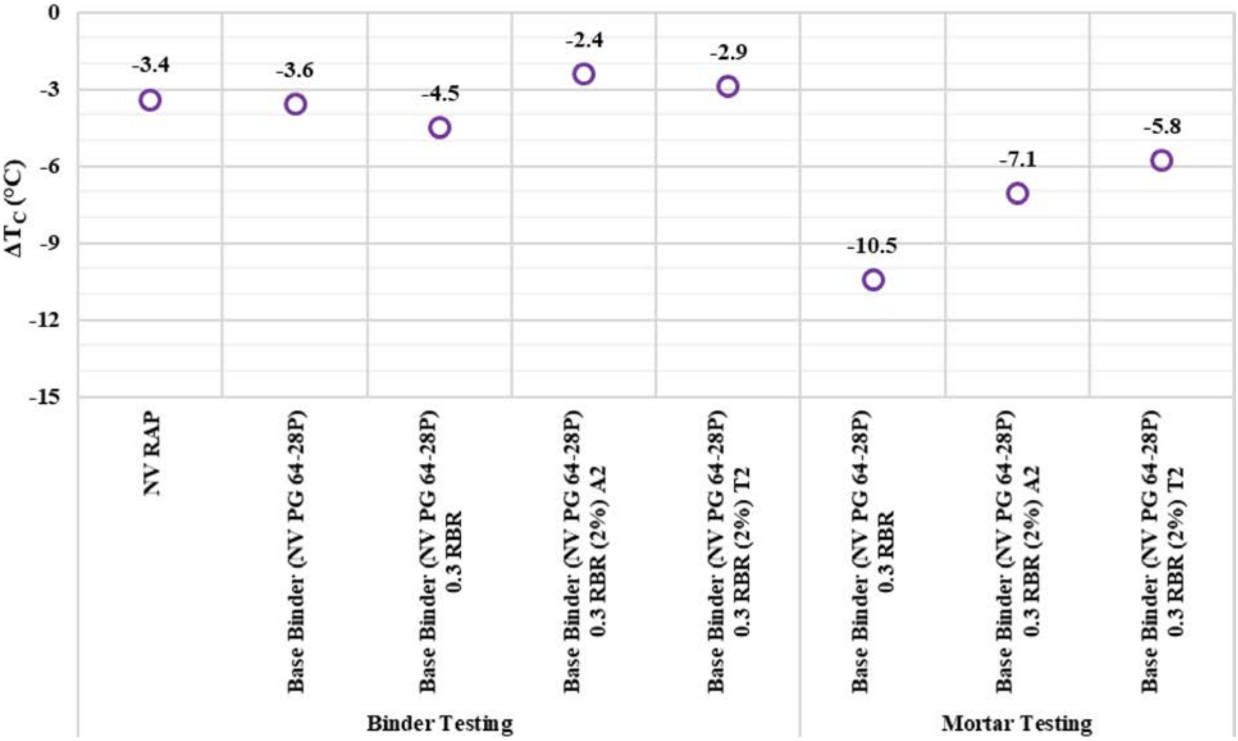


Figure 33. Effect of recycling and recycling agent on ΔTc for binder blends and mortars with NV PG 64–28P target binder, A2 and T2, and NV recycled materials.

2.5 Mixture Cracking Resistance by S-VECD

To assess the possibility of utilizing S-VECD testing and analysis per AASHTO TP 107 with the AMPT to evaluate the evolution of recycling agent effectiveness in improving intermediate-temperature fatigue cracking resistance of mixtures with high RBRs, LMLC and RPMLC specimens were tested. Per AASHTO TP 107, fatigue testing is conducted at temperatures determined by Equation 15:

$$\mathit{Test\ Temperature} = \left[\frac{PGH + PGL}{2} - 3\right] \qquad \text{[Equation 15]}$$

Two failure criteria were employed:

- The rate of pseudo strain energy release (G^R) and
- The average reduction in pseudo stiffness up to failure (D^R).

G^R characterizes the rate of damage accumulation during load application, with higher values indicating faster damage accumulation and therefore less time before the material is expected to fail (Zhang et al. 2013). Sabouri and Kim (2014) found that the correlation between G^R and the traditional fatigue parameter number of cycles to failure (*Nf*) is given in Equation 16:

$$G^R = \gamma N_f^{\delta} \qquad \text{[Equation 16]}$$

where γ and δ are considered material properties.

For simplicity, the number of cycles (N_f) corresponding to G^R of 100 was adopted for ranking mixtures. D^R is given in Equation 17 (Wang and Kim 2017):

$$D^R = \frac{\int_0^{N_f} (1 - C)\,dN}{N_f} \qquad \text{[Equation 17]}$$

where C = the pseudo stiffness, which ranges from 1 (undamaged state) to 0 (damaged state).

Whereas the G^R criterion requires a minimum of three test replicates, the D^R parameter can be evaluated using individual test replicates. A higher value of both parameters suggests better mixture cracking resistance.

Generally, there are three possible types of failures encountered during S-VECD fatigue testing, and each type determines the appropriateness of the data for further analysis:

- Brittle failure: This type occurs when the material is too stiff, causing it to fracture abruptly, and there are insufficient data to evaluate both failure criteria.
- End failure: This type is defined as cracking outside the LVDT gauge length as shown in Figure 34, and there are uncertainties surrounding evaluation of both failure criteria.
- Middle failure: This desired type of failure is defined as cracking within the LVDT gauge length as shown in Figure 34, and data obtained facilitate determination of both failure criteria.

Testing information for TX LMLC specimens and RPMLC specimens from the IN, NV, and WI field projects is summarized in Table 18, Table 19, Table 20, and Table 21, respectively, with the appropriateness of the resulting fatigue data indicated by the following three status colors:

- Green = middle failure,
- Yellow = end failure, and
- Red = brittle failure.

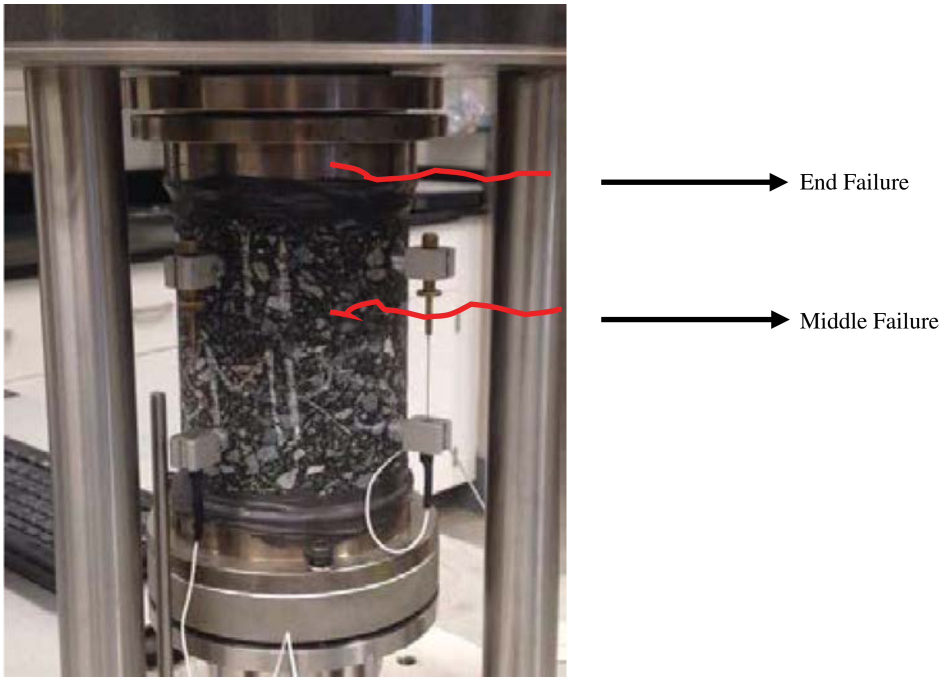


Figure 34. Crack location in specimen.

Table 18. S-VECD testing information for TX LMLC mixtures.

Mixtures	Rep. No.	Actual Temp (PG-Based Temp)	Microstrain	Initial Modulus (Mpa)	Initial Phase Angle (°)	*Nf* (approx.)	Crack Location	Status	Final Phase Angle (°)
Virgin (70-22)	1	21 (21)	300	6,520	16	48,000	Middle	OK	49
	2		350	6,000	17	6,500	Middle	OK	43.5
DOT Control 0.28 RBR	1	18 (18)	300	8,281	5.0	—	Edge	Fracture	—
	2	21 (18)	250	8,850	11.1	230	Edge	Fracture	16
DOT Control 0.28 RBR (WMA)	1	21 (18)	175	6,007	13.3	55,000	Edge	End Fail	25
	2		225	7,984	12.5	260	Edge	End Fail	21
Rejuvenated 0.28 RBR (2.7%) T1	1	21 (18)	150	6,703	11.8	1,200	Edge	End Fail	16
	2	23 (18)	150	7,556	12.4	4,000	Edge	End Fail	17.4
Rejuvenated 0.28 RBR (2.7%) T2 (PG 64-28)	1	23 (15)	200	7,250	16.2	100,000	Middle	OK	32.5
	3		275	7,300	16.3	2,000	Edge	End Fail	27.5
Rejuvenated 0.28 RBR (3.5%) T1	1	23 (18)	150	6,500	12.4	140,000	Middle	OK	25.4
	2	21 (18)	200	7,890	11.6	800	Edge	End Fail	16
	4		150	8,000	11.5	8,000	Edge	End Fail	23.7
Rejuvenated 0.28 RBR (5.5%) A1	20	23 (18)	175	6,450	15.2	62,000	Middle	OK	41.5
	21		225	6,500	15.8	11,000	Middle	OK	42
Rejuvenated 0.5 RBR (12.5%) T1 (PG 64-28)	1	21 (18)	200	9,600	10.1	5,500	Edge	End Fail	22.5
	2		150	9,800	11.3	26,000	Middle	OK	26.5
	3		130	10,700	10.3	140,000	Middle	OK	21.2

NOTE: — = not applicable.

Table 19. S-VECD testing information for Indiana RPMLC mixtures.

Mixtures	Rep. No.	Actual Temp (PG-Based Temp)	Microstrain	Initial Modulus (Mpa)	Initial Phase Angle (°)	*Nf* (approx.)	Crack Location	Status	Final Phase Angle (°)
Virgin (PG 64-22)	1	18 (18)	250	10,000	14.8	21,000	Edge	OK	28
	2		225	9,920	14.8	50,000	Edge	OK	28
	3		275	10,000	14.9	9,000	Middle	OK	29.5
DOT Control 0.32 RBR	1	15 (12)	225	12,000	11.3	24,000	Edge	End Fail	24.6
	2		250	10,700	12.5	19,000	Edge	End Fail	26.9
	3		300	11,580	12.4	140	Edge	End Fail	16
	4		200	11,030	12.1	200,000	No crack	End Fail	25.9
Rejuvenated 0.42 RBR (3%) T2	1	15 (12)	—	14,000	—	—	—	Fracture	—
	2	20 (12)	150	12,000	9	140	Edge	Fracture	11
	3	25 (12)	—	—	—	—	—	Fracture	—
	4	27 (12)	150	11,000	10	200	Edge	Fracture	12

NOTE: — = not applicable.

Testing stiff and brittle mixtures resulting from high RBRs and aged materials, along with the aging gradient induced by LTOA of compacted specimens, resulted in a significant number of brittle and end failures. To reduce the probability of brittle failures, the testing temperatures were often increased from those calculated using Equation 15, and these test temperatures are also indicated in Table 18, Table 19, Table 20, and Table 21.

In spite of the difficulties associated with S-VECD testing, adequate data were obtained for assessing the WI and NV RPMLC mixtures. The failure criteria are presented subsequently in bar graphs with an error bar indicating one standard deviation from the mean value for the

Table 20. S-VECD testing information for Nevada RPMLC mixtures.

Mixtures	Rep. No.	Actual Temp (PG-Based Temp)	Microstrain	Initial Modulus (Mpa)	Initial Phase Angle (°)	*Nf* (approx.)	Crack Location	Status	Final Phase Angle (°)
Virgin	1	15 (15)	300	5,100	22.4	200,000	No Crack	End Fail	47.8
	2		400	5,550	19.5	4,600	Edge	End Fail	41.8
	3		350	5,650	20.1	4,000	Edge	End Fail	38.2
	5		310	5,510	2.1	85,000	Middle	OK	51
	6		330	5,800	19.5	15,000	Middle	OK	47
DOT Control 0.15 RBR	2	18 (15)	250	6,180	19.6	185,000	Middle	OK	49
	3		275	6,180	19.5	110,000	Middle	OK	58
	4		300	6,030	20.2	100,000	Middle	OK	52.5
	5		350	5,880	19.8	23,000	Middle	OK	50.8
	6		375	5,960	19	13,000	Middle	OK	48.5
Recycled 0.3 RBR	1	18 (15)	250	7,700	15.2	145,000	Middle	OK	42.7
	2		300	7,130	15.4	7,000	Edge	End Fail	30
	3		275	7,650	15.7	70,000	Middle	OK	43
	5		300	8,670	14.7	32,000	Middle	OK	43
	8		325	8,350	14.4	14,500	Middle	OK	46
Rejuvenated 0.3 RBR (2%) T2	1	18 (15)	250	7,880	14.9	46,000	Edge	End Fail	31.5
	2		275	8,420	14.9	6,200	Edge	End Fail	30
	3		250	7,440	16	18,000	Edge	End Fail	33
	5		200	7,300	15.5	230,000	Middle	OK	36
	6		260	7,700	15.2	16,500	Edge	End Fail	33
Rejuvenated 0.3 RBR (2%) A2	1	18 (15)	250	7,680	15.9	59,000	Edge	OK	43.4
	2		300	7,020	16.4	50	Edge	Fracture	—
	3		225	7,080	16.1	75,000	Edge	End Fail	34
	5		275	7,070	16.4	52,000	Middle	OK	45.6
	6		290	7,230	15.6	19,000	Edge	End Fail	37
	7		200	7,370	16.6	160,000	Middle	OK	38.5

NOTE: — = not applicable.

Table 21. S-VECD testing information for Wisconsin RPMLC mixtures.

Mixtures	Rep. No.	Actual Temp (PG-Based Temp)	Microstrain	Initial Modulus (Mpa)	Initial Phase Angle (°)	*Nf* (approx.)	Crack Location	Status	Final Phase Angle (°)
DOT Control 0.22 RBR	1	21 (12)	275	6,970	18	24,000	Middle	OK	53
	2		300	7,600	17	10,000	Middle	OK	49
	3		300	7,200	17.6	8,900	Middle	OK	54
	4		260	7,400	17.4	20,000	Middle	OK	54.8
	8		315	7,430	16.8	7,200	Middle	OK	54
Recycled 0.31 RBR	1	18 (12)	250	10,120	13	14,000	Middle	OK	46
	2		275	9,820	13.8	5,700	Edge	End Fail	34
	3		275	9,770	13.6	6,900	Middle	OK	43
	4		300	8,970	14.4	3,100	Edge	End Fail	31
	5	21 (12)	315	7,200	17	6,900	Middle	OK	43
	6		300	8,000	15.8	8,800	Middle	OK	42
Recycled 0.31 RBR (PG 52-34)	2	21 (6)	275	6,710	19.4	16,000	Middle	OK	57.5
	3		300	6,450	20.6	13,000	Middle	OK	54
	4		330	6,040	21	13,000	Middle	OK	57
	6		315	7,060	19.2	9,800	Middle	OK	53.5
Rejuvenated 0.31 RBR (1.2%) V2	1	21 (12)	275	7,680	16.5	14,000	Middle	OK	52.5
	2		300	8,150	16.3	3,100	Middle	OK	48.5
	3		245	7,370	16.8	62,000	Middle	OK	50.5
	4		260	8,190	16	25,000	Middle	OK	54.5

D^R criterion that used more than one replicate and facilitated statistical evaluation. For the WI mixtures, both S-VECD failure criteria (D^R and G^R) in Figure 35 show an improvement with the addition of the field dose of the recycling agent (1.2%) and with the use of a softer base binder (PG 52–34) compared to the 0.31 RBR recycled control mixture. However, neither strategy for increasing RBR restored the parameters to the level of the DOT control mixture (0.22 RBR).

For the NV mixtures with results in Figure 36, the field dose of the recycling agent (2%) provided an increase in the G^R value over the mixture with no recycling agent; however, there was no improvement in the D^R parameter. Neither parameter was restored to the level of the DOT

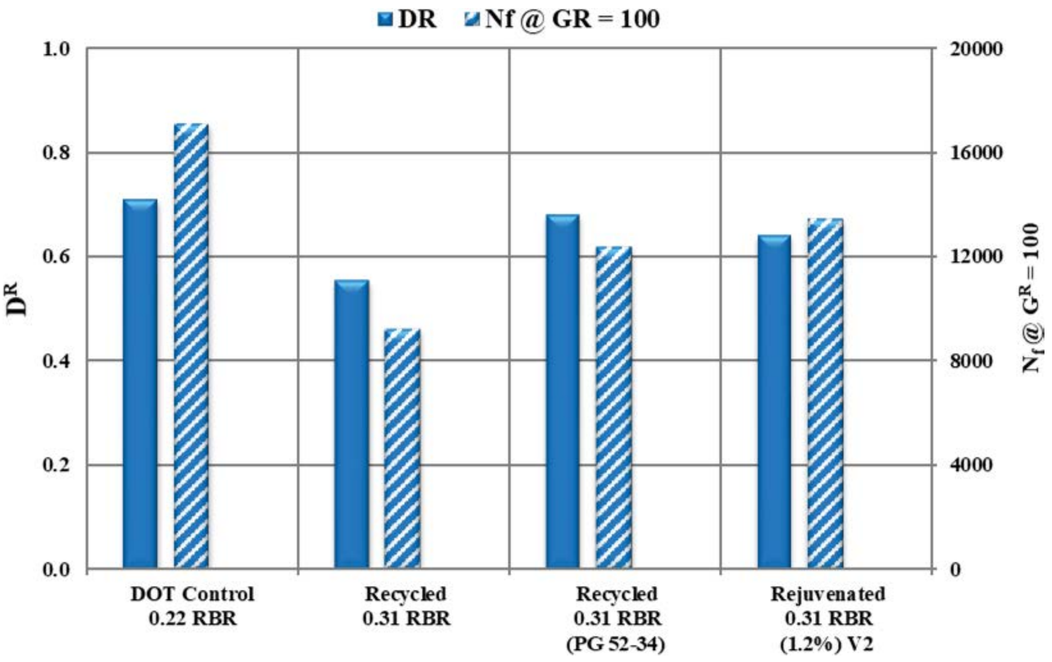


Figure 35. S-VECD criteria for WI RPMLC mixtures.

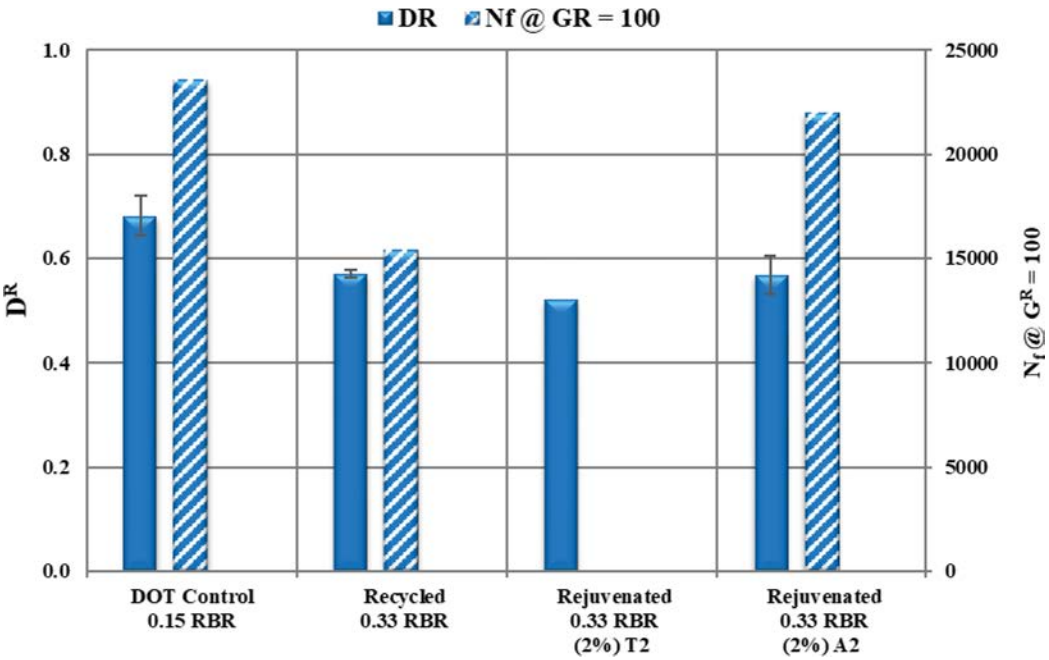


Figure 36. S-VECD criteria for NV RPMLC mixtures.

control (0.15 RBR), indicating that the field dose did not facilitate the use of higher recycled materials content (0.3 RBR).

Because of the limited scope of successful S-VECD results obtained for aged mixtures with high RBRs and the need for additional efforts to determine the best way to use this tool for these types of mixtures, the use of this test and analysis approach is not recommended at this time.

2.6 Comparison of Specimen Types

Figure 37 and Figure 38 present the M_R and I-FIT results for field cores and for LMLC and RPMLC specimens after STOA and LTOA for the WI field project materials combinations. For each mixture, the darker-shaded stacked column represents the M_R and FI after STOA (at construction for the field cores), and the hatched lighter-shaded stacked column represents the M_R and FI after LTOA (at 1 year after construction for the field cores). All specimen types, including the field cores, had AV values within 7 ± 0.5%.

Based on the error bars (+ one standard deviation) for each specimen type in Figure 37, the LMLC specimens after STOA and field cores at construction showed similar stiffness (green and blue bars), and lower stiffness than the RPMLC specimens (red bars). The higher stiffness of the RPMLC specimens was likely due to the reheating of the loose plant mixture, and thus the additional aging introduced in these specimens. Similar trends were also observed after LTOA where both the LMLC specimens and field cores showed similar stiffness, but lower than the RPMLC specimens (except for the DOT control mixture). The I-FIT test results, shown in Figure 38, also indicated that the LMLC specimens and field cores consistently showed similar FI values regardless of aging condition or service time in the field, and both had higher FI values than RPMLC specimens.

These results provide justification for selecting LMLC specimens when possible to evaluate the performance of recycled asphalt mixtures with recycling agents since the additional aging

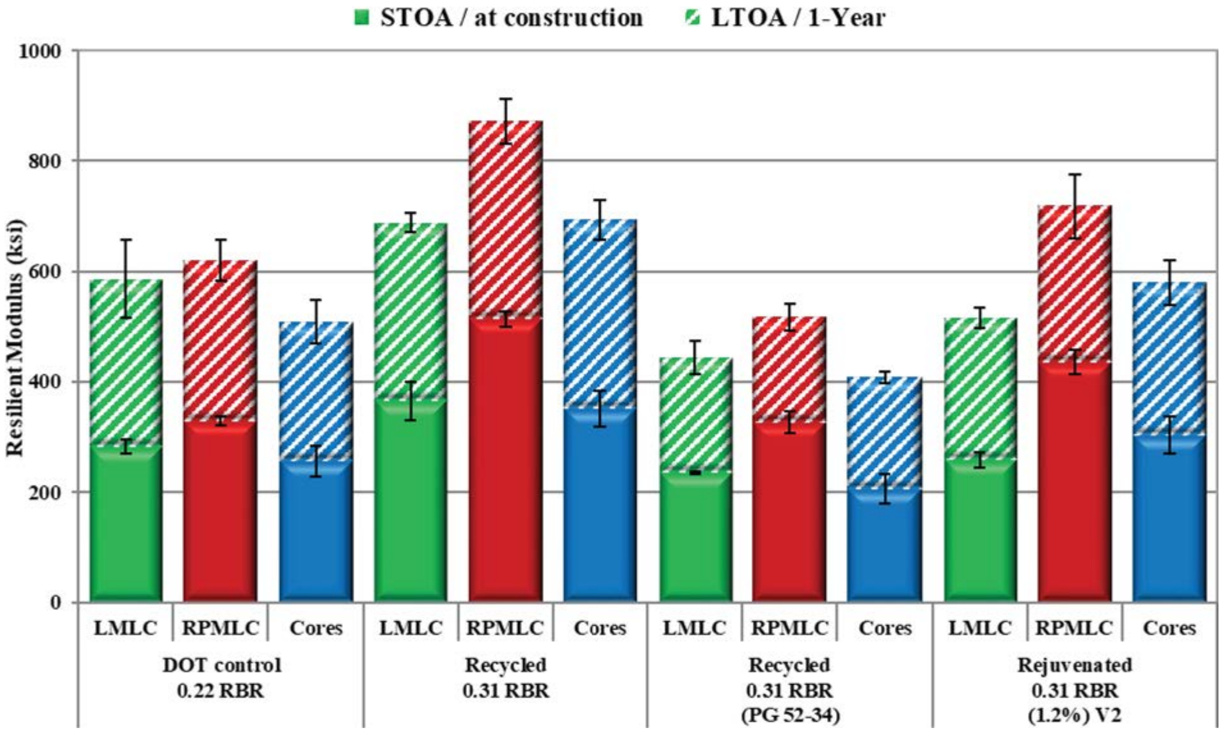


Figure 37. M_R *test results for WI mixtures of different specimen types.*

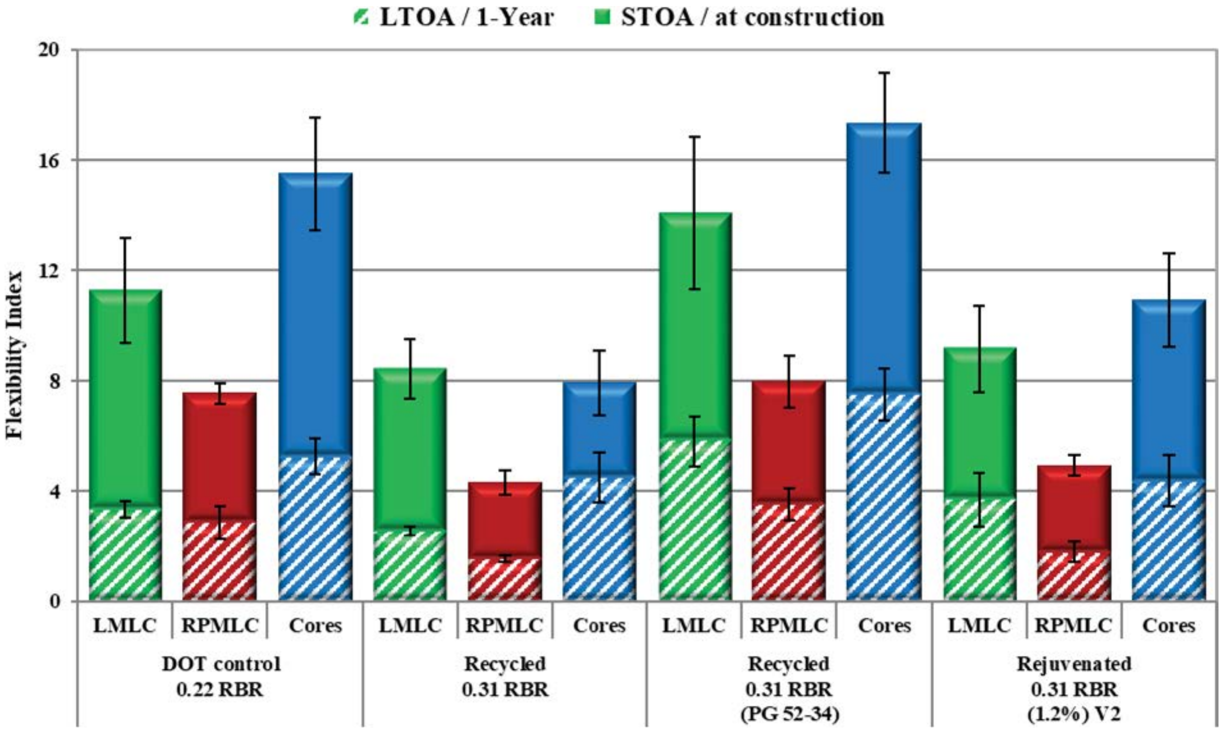


Figure 38. I-FIT test results for WI mixtures of different specimen types.

introduced due to reheating the plant loose mixtures significantly affected the laboratory test results for the RPMLC specimens. In some cases, RPMLC data were utilized when available and appropriate.

2.7 Key Findings

Key findings from this study presented in this chapter from results obtained in Phase 2 that were not expanded in Phase 3 include the following:

- Recycling-agent effectiveness must be characterized in high RBR binder blends initially and with long-term aging to capture initial compatibility and rheological response to oxidation.
- A recycling-agent dose to match continuous PGH for the target climate is required for high RBR binder blends and mixtures to maintain durability with long-term aging, with a lower dose to restore PGL only sufficient with short-term aging.
- Chemical analysis of high RBR binder blends with recycling agents is challenging, and additional evaluation tools are needed.
- Crossover temperature ($T_{\delta = 45°}$) can be used as an alternative approach to the G-R parameter to engineer balanced recycled binder blends.
- Use of high-quality base binders improves performance of high RBR binder blends and mixtures with recycling agents.
- Rejuvenation mechanisms differ by recycling agent type.
- Mortar procedures provide realistic assessment of binder blending and narrow the PG UTI as compared to that of a corresponding binder blend.
- Recycling agents are more effective in rejuvenating less-aged recycled materials (RAP more than RAS and MWAS more than TOAS) in balanced, limited proportions.
- Modifications are needed for testing high RBR mixtures after long-term aging.
- Reheating to produce RPMLC specimens is especially detrimental to high RBR mixtures with recycling agents.
- Standard laboratory fabrication protocols with STOA produce specimens that represent cores for high RBR mixtures with and without a recycling agent.

CHAPTER 3

Field and Laboratory Performance of High RBR Mixtures

Chapter 3 presents field performance of the mixtures included in the field projects and corresponding laboratory performance. Kaseer et al. (2018c) provide additional details.

3.1 Pavement Distress Summary

In order to tie the laboratory test results to field performance, pavement distress surveys were performed and field cores were procured (soon after construction and up to 3 years after construction). Table 22, Table 23, and Table 24 summarize the pavement distress surveys for the TX, IN, and WI field projects, including the quantity and severity of longitudinal, transverse, and alligator cracking for each of the test sections. No cracking was noted on any of the test sections in the NV and DE field projects, possibly because these mixtures were in service for a short period of time, and cracking distresses may take more time to appear. However, a few areas had visible signs of minor mix segregation in the DE test section with 0.41 RBR and 0.8% T2 plus 0.25% WMA, and some cracks started to initiate in the NV test section with 0.33 RBR and 2% T2.

In Table 22, Table 23, and Table 24, and when comparing the quantity and severity of pavement distress of the asphalt mixtures with the field dose of recycling agent against the virgin and/or DOT control mixtures, the following conclusions can be drawn:

- For TX mixtures: The use of 2.7% recycling agent did not facilitate incorporating RAP and RAS compared to the virgin mixture, and the use of WMA additive in the DOT control mixture with 0.28 RBR and a lower production temperature was more effective than the use of a recycling agent.
- For IN mixtures: The use of 3% recycling agent did not facilitate incorporating RAP and RAS compared to the virgin mixture, and did not facilitate increasing the RBR from 0.32 to 0.42 compared to the DOT control mixture.
- For WI mixtures: All mixtures exhibited similar performance in terms of quantity and severity of cracking regardless of their composition, possibly because these mixtures were in service for a short period of time.

3.2 Field Core Results

In addition to pavement distress surveys, field cores were procured from each test section soon after construction and up to 3 years after construction. I-FIT testing was conducted on these cores, and the results are presented in Figure 39, Figure 40, Figure 41, Figure 42, and Figure 43, with the error bars on each column representing ± one standard deviation from the average value based on replicate measurements. Some FI values are missing for certain mixtures

Table 22. Pavement distress summary for the TX field project (2 years after construction).

Distress Type	Distresses Quantity and Severity per Test Section		
	Virgin	DOT Control (0.28 RBR) +0.5% WMA	Rejuvenated (0.28 RBR) +2.7% T1
Transverse Cracking[a]	16.0	15.9	52.7
Longitudinal Cracking[a]	10.9	0.0	40.6
Alligator Cracking[b]	—	—	—
Summary	Low-severity longitudinal and transverse cracking	Low-severity longitudinal and transverse cracking	Moderate-severity longitudinal and transverse cracking

NOTE: — = not applicable.

[a] Total feet per 100 ft of test section.

[b] Percentage of total wheel path.

Table 23. Pavement distress summary for the IN field project (2 years after construction).

Distress Type	Distresses Quantity and Severity per Test Section		
	Virgin	DOT Control (0.32 RBR)	Rejuvenated (0.42 RBR) +3% T2
Transverse Cracking[a]	0.8	1.4	118.4
Longitudinal Cracking[a]	1.0	0.5	4.5
Alligator Cracking[b]	—	0.1	4.4
Summary	Very minimal visible cracking	Very minimal visible cracking	Significant amount of low-severity transverse and longitudinal cracking, and some alligator cracking

NOTE: — = not applicable.

[a] Total feet per 100 ft of test section.

[b] Percentage of total wheel path.

Table 24. Pavement distress summary for the WI field project (1 year after construction).

Distress Type	Distresses Quantity and Severity per Test Section			
	DOT Control (0.22 RBR) (PG 58-28)	Recycled (0.31 RBR) (PG 58-28)	Recycled (0.31 RBR) (PG 52-34)	Rejuvenated (0.31 RBR) (PG 58-28) +1.2% V2
Transverse Cracking[a]	18.3	22.2	28.4	12.8
Longitudinal Cracking[a]	—	—	—	—
Alligator Cracking[b]	—	—	—	—
Summary	Low-severity transverse cracking			

NOTE: — = not applicable.

[a] Total feet per 100 ft of test section.

[b] Percentage of total wheel path.

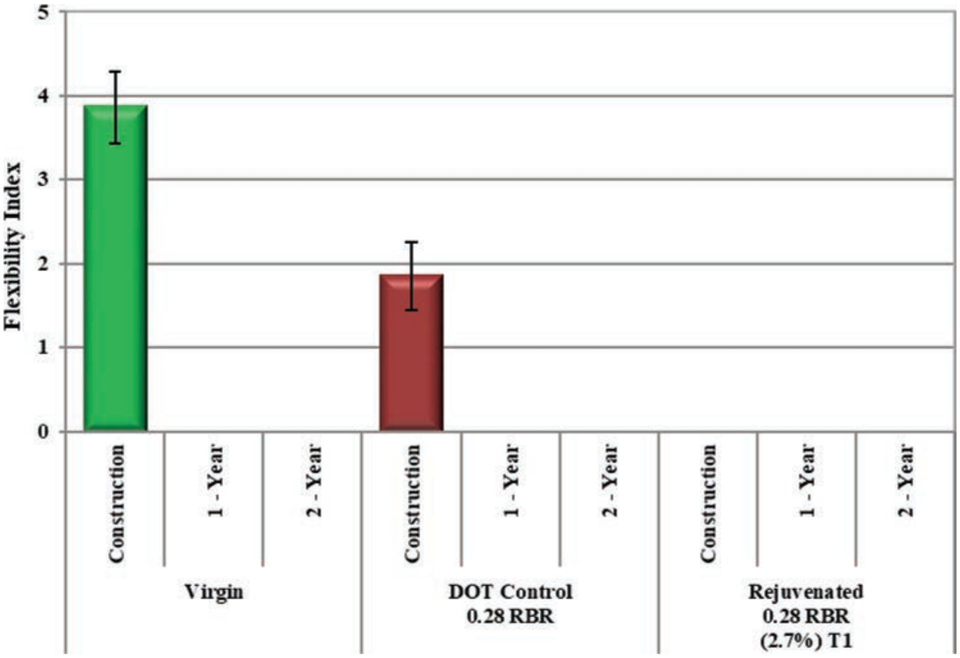


Figure 39. FI results of TX field cores.

because these mixtures were very brittle and did not have post-peak displacement data available to allow determination of the inflection point, and thus FI approaches zero. Figure 39, Figure 40, Figure 41, Figure 42, and Figure 43 demonstrate that all the recycled mixtures with high RBR and with the field dose of recycling agent exhibited lower FI values compared to the virgin and/or DOT control mixtures, indicating that using recycling agents at the low field doses did not adequately improve the cracking resistance of the recycled mixtures.

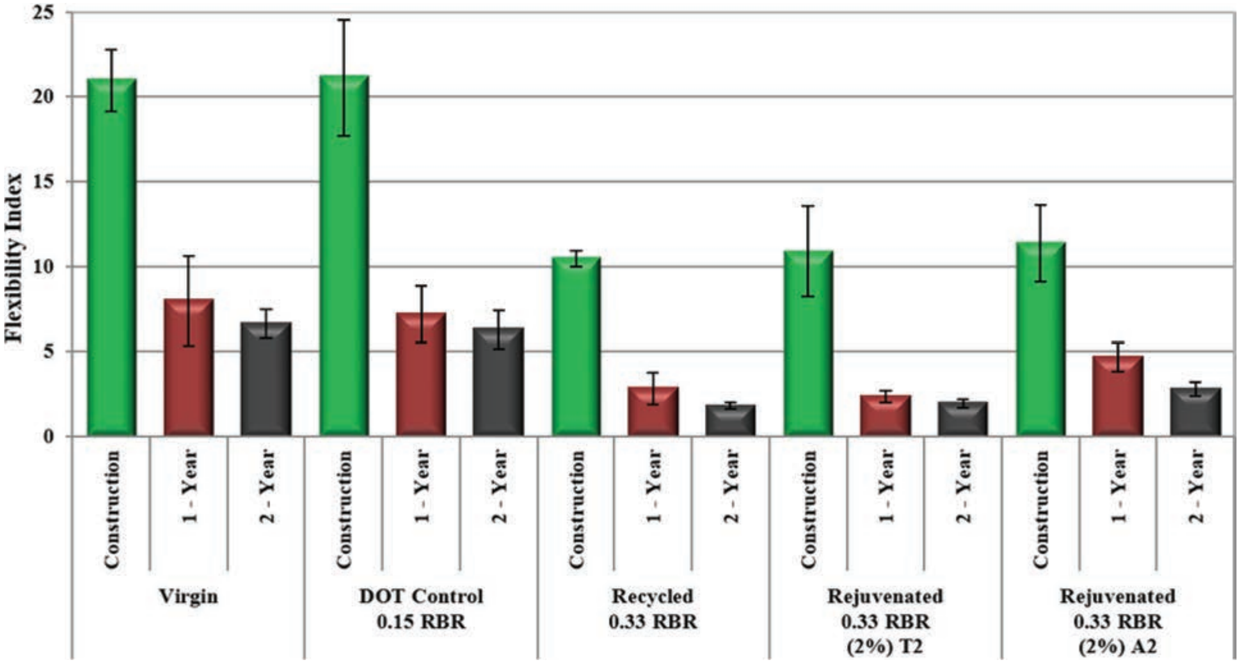


Figure 40. FI results of NV field cores.

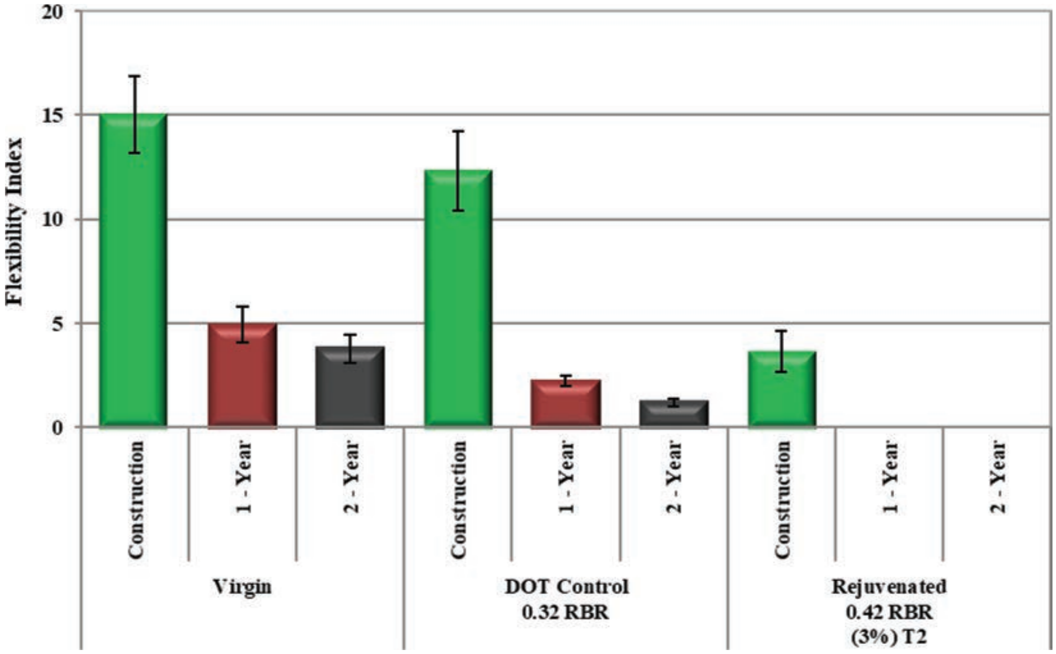


Figure 41. FI results of IN field cores.

NV field cores were tested for UTSST, and the results are presented in Figure 44. The DOT control mixture at lower 0.15 RBR exhibited the highest CRI_{Env} value. The increase in RBR to 0.33 in the recycled control mixture resulted in a decrease in CRI_{Env} by approximately 75%. The effect of recycling agents in the rejuvenated mixtures at the field doses was retained after the first year of service, but after 2 years in service, the effectiveness of the recycling agent started to decrease.

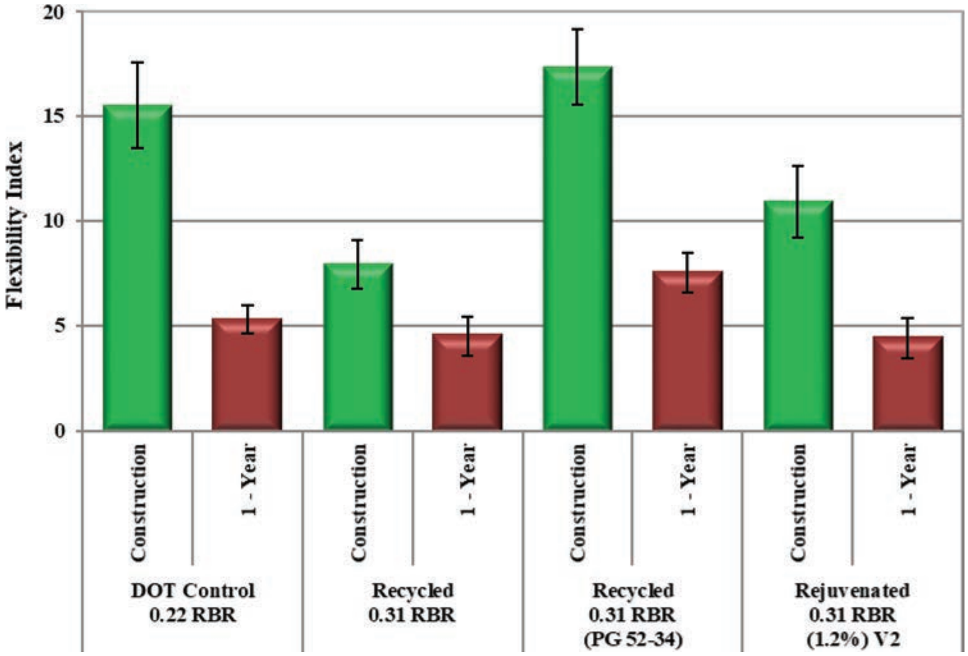


Figure 42. FI results of WI field cores.

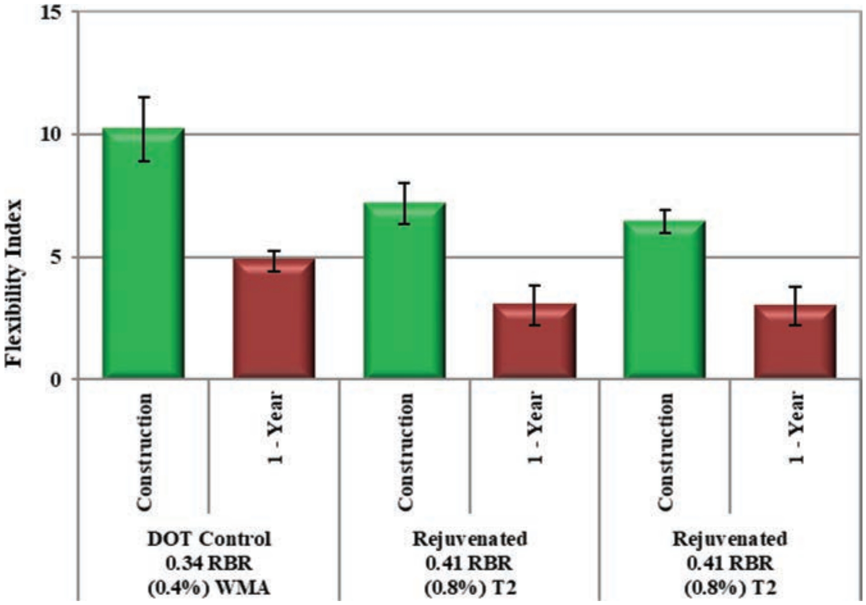


Figure 43. FI results of DE field cores.

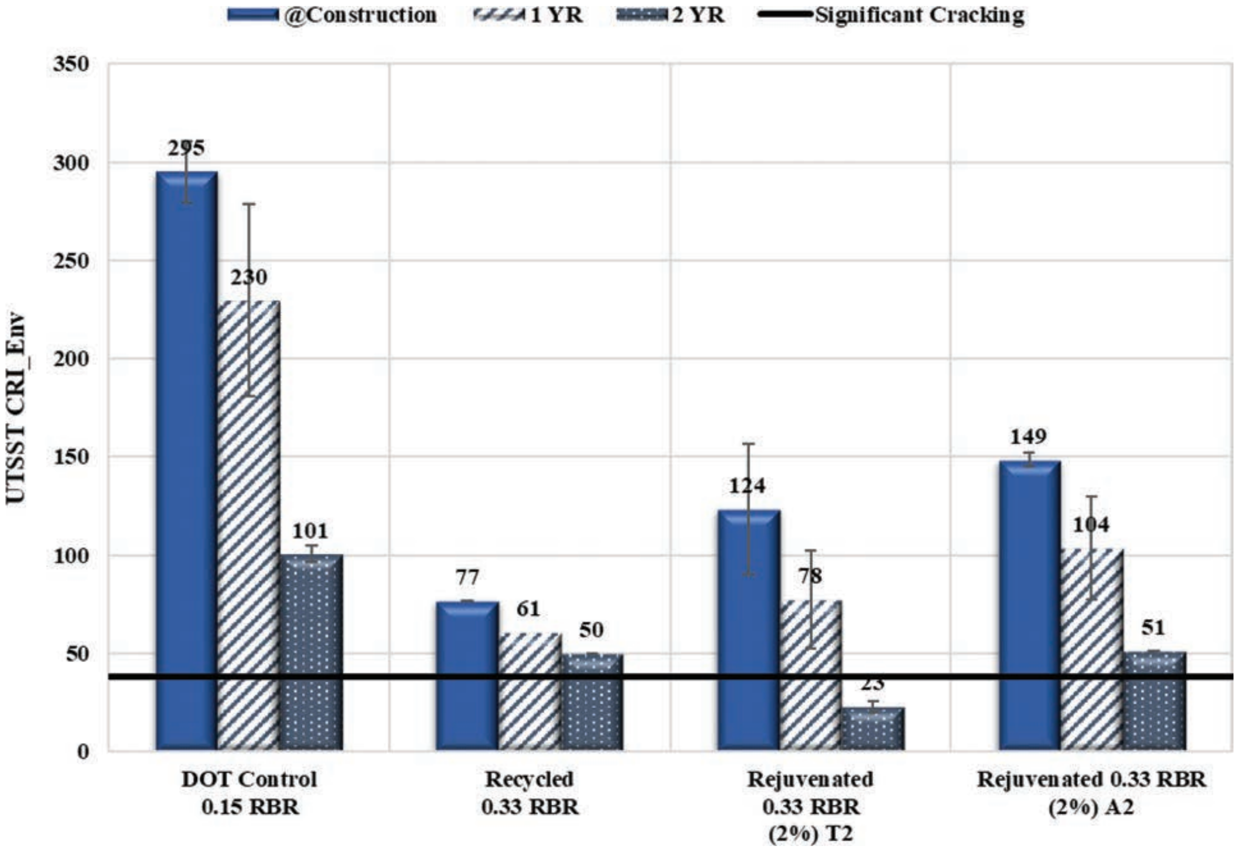


Figure 44. UTSST CRI$_{Env}$ for NV field cores.

3.3 Comparison of Laboratory Results and Field Performance

In order to evaluate the recycling-agent dose selection method developed in this study and facilitate proposing materials selection guidelines, the performance of field-test sections and UTSST and I-FIT results for corresponding laboratory-compacted LMLC and RPMLC specimens was compared in an effort to establish thresholds for determining acceptable mixture performance in terms of both low- and intermediate-temperature cracking resistance.

Previous observations of a low-temperature cracking resistance index similar to CRI_{Env} indicated substantial correlation with field performance, particularly longitudinal and transverse cracking distresses, with details provided in Hajj et al. (2016). Acknowledging the dependency of both UTSST measurements and the field distresses on environmental conditions and specifically the aging or oxidation level, an exhaustive analysis was conducted to properly assess the relationship between the CRI_{Env} of RPMLC specimens and crack density collected from pavement distress surveys at different in-service ages. Crack density was calculated as the measured linear longitudinal and transverse crack length divided by the area of each test section, excluding any construction joints, to normalize distress data for comparison with CRI_{Env}.

RPMLC specimens were used for this comparison since more data were available with consistent correlation to field performance in both cold and warm climates. The RPMLC specimens were also LTOA before being tested in the UTSST to represent worst-case conditions for cracking resistance and an indiscriminate level of in-service aging. Table 25 provides details for the field-test sections considered in this effort, including some from MN not included in the overall study.

Figure 45 presents a comparison between the CRI_{Env} of LTOA RPMLC specimens and their respective crack density. The horizontal line represents the threshold established based on the crack density that corresponds to the average MEPDG (AASHTO 2008) threshold for transverse cracking that delineates adequate (i.e., fair and better) and inadequate (i.e., poor) field performance for interstate and state routes. The vertical line denotes the proposed CRI_{Env} threshold to differentiate mixtures with inadequate and adequate low-temperature cracking resistance. In general, test sections with higher levels of cracking density exhibited lower values of CRI_{Env} after LTOA, and the general lack of measurements in the upper right and lower left corners supports the definition of CRI_{Env} and the proposed threshold developed based on these field projects. The circles on the plot represent the average values for CRI_{Env} and crack density, while horizontal and vertical whiskers represent minimum and maximum values. The circle in the upper left corner is the average value for the mixtures that exhibited inadequate performance, while the circle in the lower right corner is the average value for the mixtures that exhibited adequate field performance based on the crack density threshold of 0.046 m^{-1}. The intercept between the line connecting these two points and the threshold limit for significant cracking (crack density of 0.046 m^{-1}) results in a threshold of 38 for CRI_{Env} based on laboratory results for RPMLC specimens. In other words, a mixture with a CRI_{Env} below 38 after LTOA will likely exhibit significant cracking, as defined by a crack density greater than 0.046 m^{-1}.

Using the same methodology, a threshold of 7 for FI was developed, as shown in Figure 46, for LMLC specimens after STOA. These data were used for this comparison since more data were available for both flexible and brittle mixtures, and STOA results provided greater differentiation among mixtures compared to LTOA results.

Based on the comparison of laboratory test results and field performance, adequate performance in the field may be judged by laboratory tests on recycled asphalt mixtures with high RBR and recycling agents that should show similar or better performance than the DOT control mixtures. Since the DOT control mixtures showed acceptable performance in the field, all recycled

Table 25. Summary of field distress data and CRI_{Env} and FI used to develop thresholds.

Section ID	Mix ID	In-Service Age for Distress Data (Years)	Crack Density (1/m)[a]	Field Performance Condition[b]	FI of LMLC after STOA	CRI_{Env} (kPa) of RPMLC after LTOA
Mn_Olmsted-1	Recycled 0.2 RBR MIF (PG 58-34) (Elvaloy Modified)	5.1	0.018	Adequate (Good)	—	51.9
Mn_Olmsted-2	MIF (PG 58-34) (Elvaloy Modified)		0.024	Adequate (Good)	—	78.8
Mn_Olmsted-3	Canadian Blend (PG 58-28)		0.060	Inadequate (Poor)	—	21.1
Mn_Olmsted-4	Arab Heavy/Arab Medium/Kirkuk Blend with REOB (PG 58-28)		0.128	Inadequate (Poor)	—	15.4
Mn_Olmsted-5	Venezuelan Blend (PG 58-28)		0.016	Adequate (Good)	—	101.4
TX-1	Virgin	2.1	0.074	Inadequate (Poor)	11.1	31.3
TX-2	DOT Control 0.28 RBR (PG 64-22)		0.046	Inadequate (Poor)	3.2	14.0
TX-3	Rejuvenated 0.28 RBR (PG 64-22) (2.7%) T1		0.275	Inadequate (Poor)	3.5	0.7
IN-C	Virgin	2.1	0.005	Adequate (Good)	6.5	25.0
IN-E	Rejuvenated 0.42 RBR (PG 58-28) (3%) T2		0.367	Inadequate (Poor)	4.2	1.0
IN-V	DOT Control 0.32 RBR (PG 58-28)		0.005	Adequate (Good)	5.7	28.5
WI-1	Recycled 0.31 RBR (PG 52-34)	1.1	0.078	Inadequate (Poor)	14.1	40.7
WI-3	Rejuvenated (0.31 RBR) (1.2%) V2		0.035	Adequate (Fair)	9.2	25.0
WI-4	Recycled 0.31 RBR		0.061	Inadequate (Poor)	8.4	22.0
WI-5	DOT Control 0.22 RBR		0.050	Inadequate (Poor)	11.3	36.0

NOTE: — = not available.

[a] Measured linear longitudinal and transverse crack length divided by the area of respective test section, excluding any construction joints.

[b] Based on information from Table 10-8 in Mechanistic-Empirical Pavement Design Guide (MEPDG): A Manual of Practice (AASHTO 2008): adequate (good), crack density $< 0.033\ \text{m}^{-1}$; adequate (fair), crack density $< 0.046\ \text{m}^{-1}$; inadequate (poor), crack density $\geq 0.046\ \text{m}^{-1}$.

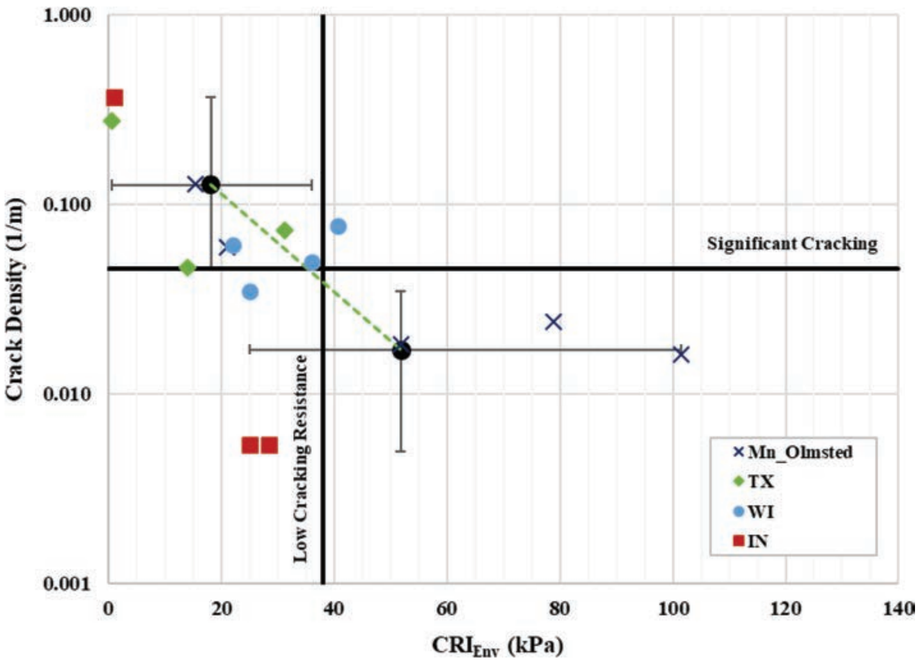


Figure 45. Correlation of CRI_{Env} for LTOA RPMLC specimens with crack density (whiskers represent minimum and maximum observed values).

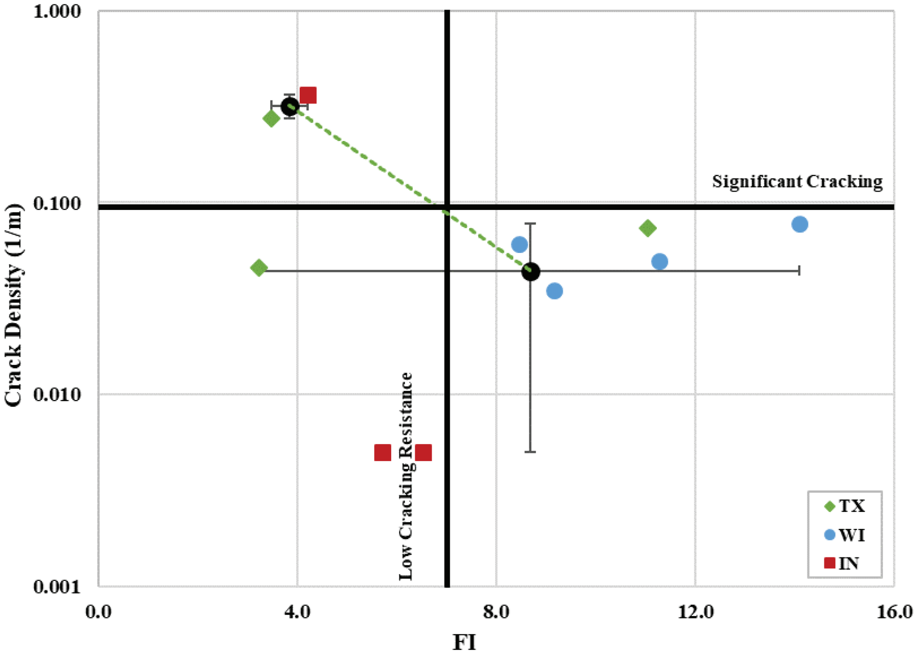


Figure 46. Correlation of FI for STOA LMLC specimens with crack density (whiskers represent minimum and maximum observed values).

asphalt mixtures with recycling agents were directly compared to the DOT control mixtures in this study.

Using DOT control mixtures as reference mixtures for determining acceptable mixture performance in terms of cracking resistance is an alternative if mixture thresholds are not available since these mixtures showed adequate field performance and similar performance to the virgin mixtures. Virgin mixtures were not used as reference mixtures due to the use of different base binders than other mixtures. For most state DOTs, producing virgin asphalt mixtures without recycled materials is no longer a common practice, and the use of recycled materials, predominantly RAP, has become a general practice. In a report published by NAPA in 2017, out of 229 companies (with 1,146 production plants) surveyed in 2016, 98% reported using RAP in asphalt mixture production (Hansen and Copeland 2017).

3.4 Key Findings

The key findings presented in this chapter are based on field performance of the mixtures included in the field projects and corresponding laboratory performance and include the following:

- Recycling-agent doses used in the field projects in this study were insufficient with aging.
- Field performance can be used to establish or verify thresholds for adequate mixture cracking performance or performance of recycled asphalt mixtures with high RBR, and recycling agents can be compared to that of DOT control mixtures.

CHAPTER 4

Expanded Laboratory Performance of High RBR Binder Blends and Mixtures

Chapter 4 presents expanded laboratory performance results for binder blends and mixtures with high RBRs to explore the impact of higher recycling-agent doses than those used in the field projects with respect to the following issues:

- Binder blend rheology with aging,
- Binder blend aging prediction,
- Recycling-agent characterization,
- Mixture performance, and
- Recycled binder availability.

Appendix F provides additional data on binder blend aging prediction, and Appendix G provides additional data on recycling-agent characterization. Additional data and details on mixture performance are included in Kaseer et al. (2018a).

4.1 Binder Blend Rheology with Aging

The effects of recycling, aging, and rejuvenation on binder blend performance at low and intermediate temperatures are discussed in this section using ΔT_c and the G-R parameter in Black space and respective existing thresholds tied to cracking resistance. Figure 47 illustrates the typical direction of the shifts observed in Black space with the inclusion of recycled materials, recycling agents, and aging considering binders without polymer modification. A new asphalt binder without polymer modification has a relatively low $|G^*|$ and high δ, so it is located in the lower right corner of the Black space diagram. The inclusion of recycled materials (labeled "Recycling" in Figure 47) is reflected as an increase in $|G^*|$ and reduction in δ, similar to the effect of laboratory and/or field aging. Conversely, considering rejuvenation as the partial reversal of the impact of aging on asphalt binders from a rheological standpoint, the inclusion of recycling agents is expected to reduce $|G^*|$ and increase δ as an indication of improved ductility.

The selected recycling-agent doses to match continuous PGH for the target climate were evaluated using various base binders, recycled materials, RBRs, and recycling-agent types, taking into consideration different target climates: PG 70–22 (TX), PG 64–22 (IN), PG 64–28 (NV and DE), and PG 58–28 (WI). Table 26, Table 27, Table 28, Table 29, and Table 30 summarize the components and characteristics of the recycled and rejuvenated binder blends evaluated in Black space (and corresponding recycled and rejuvenated asphalt mixtures discussed subsequently). Gray shading indicates field project combinations, and NV binder blends were not evaluated.

In Table 26, Table 27, Table 28, Table 29, and Table 30, the DOT control blends refer to the recycled binder blends without recycling agent with a RAP/RAS binder content within the maximum allowable content per the different state DOT specifications (TX, IN, DE, and WI).

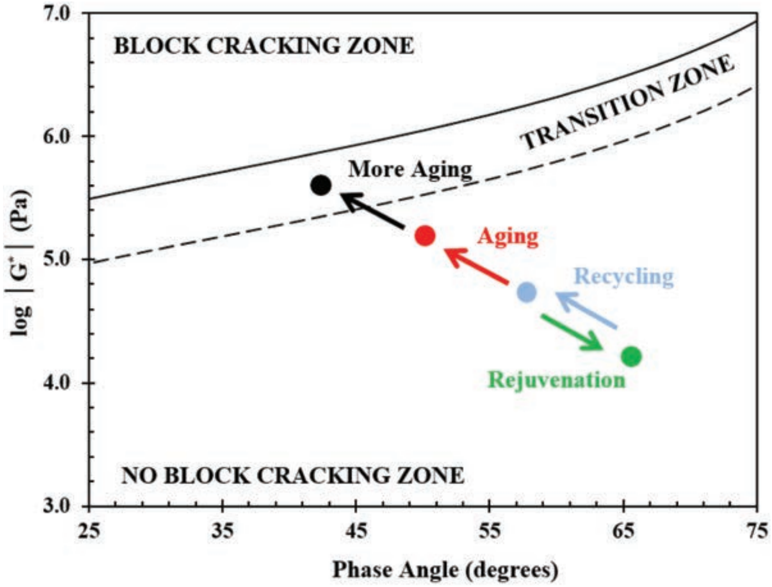


Figure 47. Illustration of |G| and δ changing with recycling, aging, and rejuvenation in Black space.*

Table 26. Characteristics of TX binder blends and asphalt mixtures.

Blend/Mixture	DOT Control (0.28 RBR) +0.5% WMA	Rejuvenated (0.28 RBR) +2.7% T1	Rejuvenated (0.28 RBR) +6% T1	Rejuvenated (0.28 RBR) +6.5% A1
Binder PG	64-22	64-22	64-22	64-22
Binder Content[a]	4.9%	4.9%	4.9%	4.9%
RAP/RAS Content[b]	10% RAP 5% RAS	10% RAP 5% RAS	10% RAP 5% RAS	10% RAP 5% RAS
RBR	0.28 (0.1 RAP + 0.18 RAS)	0.28 (0.1 RAP + 0.18 RAS)	0.28 (0.1 RAP + 0.18 RAS)	0.28 (0.1 RAP + 0.18 RAS)
Recycling-Agent Type and Dose[c]	—	2.7% T1	6% T1	6.5% A1
Warm-Mix Additive Dose[c]	0.5%	—	—	—

NOTE: — = not applicable.

[a] Total binder in the mixture (base binder + recycled binders).

[b] By percentage of total weight of the mixture.

[c] By percentage of total binder in the mixture to match continuous PGH for target climate of PG 70-XX.

Table 27. Characteristics of IN binder blends and asphalt mixtures.

Blend/Mixture	DOT Control (0.32 RBR)	Recycled Control (0.42 RBR)	Rejuvenated (0.42 RBR) +3.5% T2	Rejuvenated (0.42 RBR) +8% T2	Rejuvenated (0.5 RBR) +9.5% T2
Binder PG	58-28	58-28	58-28	58-28	58-28
Binder Content[a]	5.8%	5.8%	5.8%	5.8%	5.8%
RAP/RAS Content[b]	28% RAP 2% RAS	16% RAP 8% RAS	16% RAP 8% RAS	31% RAP 4% RAS	40% RAP 4% RAS
RBR	0.32 (0.25 RAP + 0.07 RAS)	0.42 (0.14 RAP + 0.28 RAS)	0.42 (0.14 RAP + 0.28 RAS)	0.42 (0.28 RAP + 0.14 RAS)	0.5 (0.36 RAP + 0.14 RAS)
Recycling-Agent Type and Dose[c]	—	—	3.5% T2	8% T2	9.5% T2

NOTE: — = not applicable.

[a] Total binder in the mixture (base binder + recycled binders).

[b] By percentage of total weight of the mixture.

[c] By percentage of total binder in the mixture to match continuous PGH for target climate of PG 64-XX.

Table 28. Characteristics of NV asphalt mixtures.

Blend/Mixture	**DOT Control (0.15 RBR)**	**Rejuvenated (0.3 RBR) +2% T2**	**Rejuvenated (0.3 RBR) +2% A2**	**Rejuvenated (0.3 RBR) +3.5% T2**	**Rejuvenated (0.3 RBR) +5.5% A2**
Binder PG	64-28 P[d]	64-28 P	64-28 P	64-28 P	64-28 P
Binder Content[a]	5.0%	4.6%	4.6%	4.6%	4.6%
RAP Content[b]	15% RAP	33% RAP	33% RAP	33% RAP	33% RAP
RBR	0.15 RAP	0.33 RAP	0.33 RAP	0.33 RAP	0.33 RAP
Recycling-Agent Type and Dose[c]	—	2% T2	2% A2	3.5% T2	5.5% A2

NOTE: — = not applicable.

[a] Total binder in the mixture (base binder + recycled binders).

[b] By percentage of total weight of the mixture.

[c] By percentage of total binder in the mixture to match continuous PGH for target climate of PG 64-XX.

[d] Polymer-modified binder.

Table 29. Characteristics of WI binder blends and asphalt mixtures.

Blend/ Mixture	**DOT Control (0.22 RBR) (PG 58-28)**	**Recycled Control (0.31 RBR) (PG 58-28)**	**Recycled 0.31 RBR (PG 52-34)**	**Rejuvenated (0.31 RBR) (PG 58-28) +1.2% V2**	**Rejuvenated (0.31 RBR) (PG 58-28) +5.5% V2**	**Rejuvenated (0.5 RBR) (PG 58-28) +9% V2**
Binder PG	58-28	58-28	52-34	58-28	58-28	58-28
Binder Content[a]	5.6%	5.4%	5.4%	5.4%	5.4%	5.4%
RAP Content[b]	27% RAP	36% RAP	36% RAP	36% RAP	36% RAP	58% RAP
RBR	0.22	0.31	0.31	0.31	0.31	0.5
Recycling-Agent Type and Dose[c]	—	—	—	1.2% V	5.5% V	9% V

NOTE: — = not applicable.

[a] Total binder in the mixture (base binder + recycled binders).

[b] By percentage of total weight of the mixture.

[c] By percentage of total binder in the mixture to match continuous PGH for target climate of PG 58-XX.

Table 30. Characteristics of DE binder blends and asphalt mixtures.

Blend/ Mixture	**DOT Control (0.34 RBR)**	**Rejuvenated (0.41 RBR) +0.8% T2**	**Rejuvenated (0.41 RBR) +0.8% T2 +0.25% WMA**	**Rejuvenated (0.41 RBR) +8.5% T2**	**Rejuvenated (0.5 RBR) +10% T2**
Base Binder PG	64-28	64-28	64-28	64-28	64-28
Binder Content[a]	5.4%	5.4%	5.4%	5.4%	5.4%
RAP/RAS Content[b]	20% RAP 4% RAS	29% RAP 4% RAS	29% RAP 4% RAS	29% RAP 4% RAS	40% RAP 4% RAS
RBR	0.34 (0.17 RAP + 0.17 RAS)	0.41 (0.24 RAP + 0.17 RAS)	0.41 (0.24 RAP + 0.17 RAS)	0.41 (0.24 RAP + 0.17 RAS)	0.5 (0.33 RAP + 0.17 RAS)
Recycling-Agent Type and Dose[c]	—	0.8% T2	0.8% T2	8.5% T2	10% T2
Warm-Mix Additive Dose[c]	0.4%	—	0.25%	—	—

NOTE: — = not applicable.

[a] Total binder in the mixture (base binder + recycled binders).

[b] By percentage of total weight of the mixture.

[c] By percentage of total binder in the mixture to match continuous PGH for target climate of PG 64-XX.

These blends were regarded as the reference blends and compared to other blends of similar or higher RBR with recycling agent to evaluate the effectiveness of the recycling agents at the selected doses in improving the performance of the DOT control blend, and in facilitating the use of higher RBR than currently allowed by the DOTs. In Table 27, the rejuvenated binder blends (and asphalt mixtures) with the selected dose of recycling agent were designed to have a balanced combination of RBR from RAP and RAS. This was accomplished by maximizing RAP and minimizing RAS contents, while maintaining the same total RBR compared to the rejuvenated binder blend (and asphalt mixture) with the field dose of recycling agent.

Figure 48, Figure 49, Figure 50, and Figure 51 present the Black space diagrams for the recycled binder blends for TX, IN, WI, and DE materials with PG 70–22, PG 64–22, PG 64–28, and PG 58–28 target climates, respectively. The three data points represent RTFO, 20-h, and 40-h PAV aging. With aging, all the blends showed the expected increase in |G*| and decrease in δ with aging, indicating loss of ductility.

For the TX blends, the DOT control blend with 0.28 RBR shown in Figure 48 was located within the block cracking zone after 20-h PAV aging exhibiting very high |G*| and low δ. The rejuvenated binder blends with 0.28 RBR and recycling agent had lower |G*| and larger δ values compared to the DOT control, indicating restored ductility. However, the blends with the recycling agent at the selected dose to match continuous PGH for the target climate (6% T1 and 6.5% A1) showed the best reduction in |G*| and improvement in δ. Considering ΔT_c, all blends had poor ΔT_c values (based on existing threshold of −5.0 after 20-h PAV aging), with the blends at the selected recycling-agent dose showing the highest (less negative) ΔT_c values.

For the IN blends shown in Figure 49, the DOT control blend with 0.32 RBR and the recycled control blend at higher 0.42 RBR were located within the transition zone after 20-h PAV aging and within the block cracking zone after 40-h PAV aging with high |G*| and low δ. The rejuvenated binder blend with 0.42 RBR and recycling-agent dose close to the field dose (3.5%) had similar |G*| and δ values, compared to the DOT control, after 40-h PAV aging and was located within the block cracking zone. The two rejuvenated binder blends with balanced recycled materials combinations (0.42 and 0.5 RBR) and the selected recycling-agent dose (8.0% and 9.5% T2) had lower |G*| and larger δ values compared to the DOT control, and they were located within the transition zone.

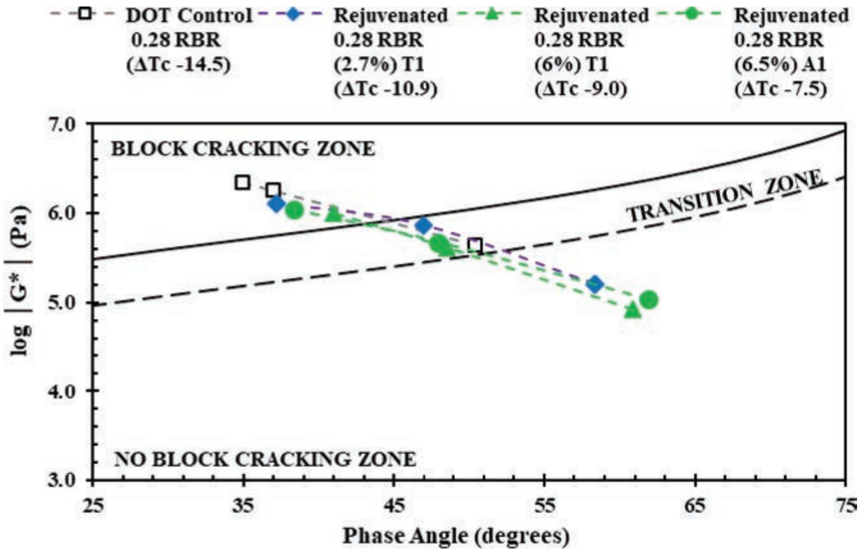


Figure 48. |G| and δ in Black space for TX binder blends (target PG 70–22 climate).*

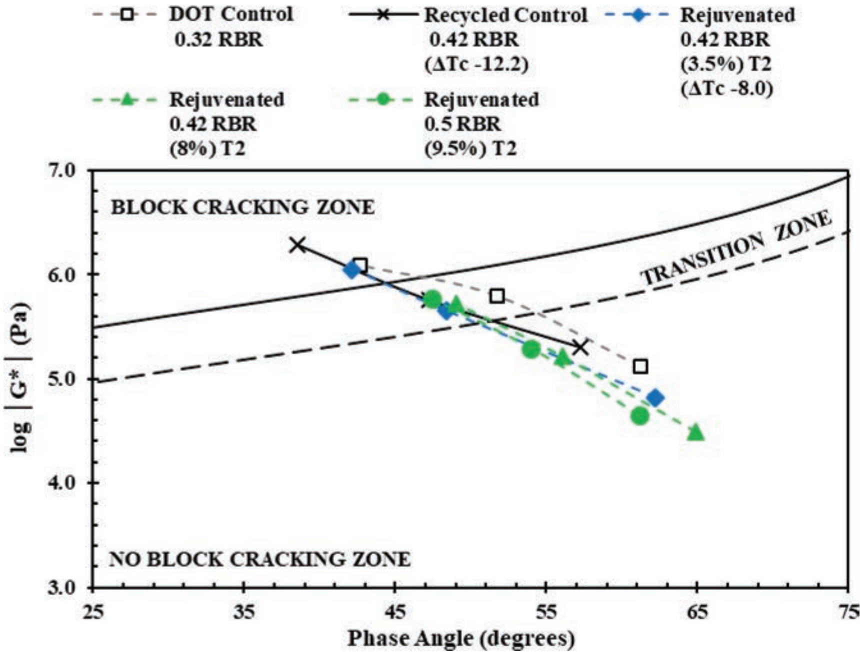


Figure 49. |G| and δ in Black space for IN binder blends (target PG 64–22 climate).*

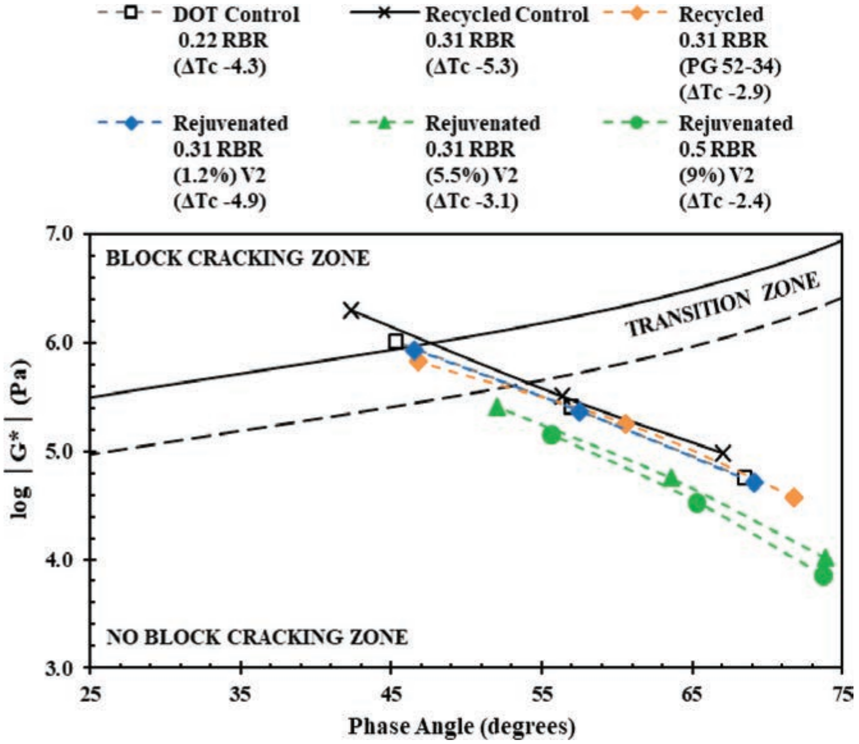


Figure 50. |G| and δ in Black space for WI binder blends (target PG 64–28 climate).*

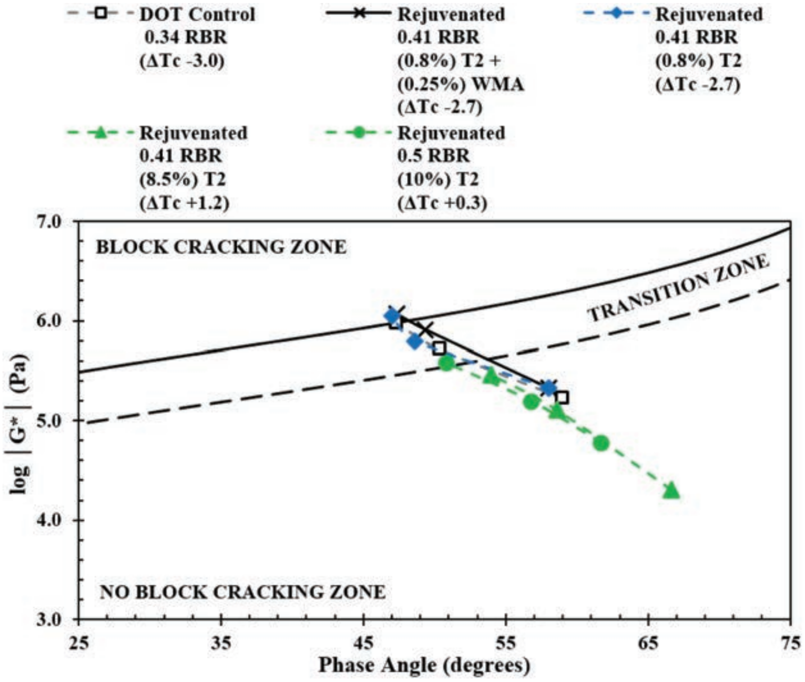


Figure 51. |G| and δ in Black space for DE binder blends (target PG 58–28 climate).*

This behavior indicated improved performance, with use of the recycling agent at the selected dose facilitating higher recycled materials contents compared to that of the DOT control. Considering ΔT_c, all blends had poor ΔT_c values, with the blend with recycling agent at close to the field dose showing a higher (less negative) ΔT_c value. ΔT_c values for the binder blends with the recycling agent at the selected dose were not available.

For the WI blends shown in Figure 50, the DOT control blend with 0.22 RBR and the recycled control blend at higher 0.31 RBR were located within the no block cracking zone after 20-h PAV aging, but within the block cracking zone after 40-h PAV aging. The recycled binder blend with 0.31 RBR with the softer base binder (PG 52–34) or the rejuvenated blend with the recycling agent at the field dose (1.2% V2) had slightly lower |G*| and higher δ values, compared to the DOT control, after 40-h PAV aging. The two rejuvenated binder blends with 0.31 and 0.5 RBR and recycling agent at the selected dose (5.5% and 9% V2, respectively) had much lower |G*| and larger δ values compared to the DOT control, with both blends located in the no block cracking zone after 40-h PAV aging. This again indicated that using the recycling agent at the selected dose facilitated the use of higher recycled materials contents compared to that of the DOT control, with much better performance than using a softer base binder. Considering ΔT_c, all blends had good ΔT_c values (higher than those in the TX and IN binder blends), with the blends at the selected recycling agent dose and the blend with the softer base binder showing the highest (less negative) ΔT_c values.

Finally, the DE binder blends shown in Figure 51 illustrated that the recycled binder blend with 0.41 RBR and the field dose of recycling agent (0.8% T2) had similar |G*| and δ values to those of the DOT control blend with 0.34 RBR, and both were located at the onset of the block cracking zone after 40-h PAV aging. The two recycled binder blends with 0.41 and 0.5 RBR and recycling agent at the selected dose (8.5% and 10% T2) had much lower |G*| and larger δ values compared to the DOT control, and neither blend reached the block cracking zone after 40-h PAV aging. This again indicated that using the recycling agent at the selected dose facilitated the use of higher recycled materials contents compared to the DOT control. Considering ΔT_c, all blends had good ΔT_c values (higher than those in the TX, IN, and WI blends), with the blends at the selected recycling-agent dose showing the highest ΔT_c values.

4.2 Binder Blend Aging Prediction

An extensive binder aging experiment was conducted to gather oxidative aging kinetics data and resulting rheological changes for materials combinations shown in Table 1 under isothermal oven aging at 60°C, 85°C, and 100°C over multiple temperature-specific durations. Then a diffusion-based oxidative aging model (Han 2011) was used to predict CA with depth and in-service time at the TX and WI field project locations from the following inputs:

- Binder aging kinetics (E_a and A [Equation 18]) and hardening parameters (hardening susceptibility [HS] and hardening function constant [m]),
- Binder initial CA at the beginning of constant-rate aging,
- Predicted hourly pavement temperatures at the selected depth in the HMA layer at a specific location from the Temperature Estimate Model for Pavement Structure (TEMPS) (http://www.arc.unr.edu/Software.html#TEMPS), and
- Average representative AV radius and effective aging distance (e.g., binder film).

Some additional data and details are included in Pournoman et al. (2018).

These binder blend aging predictions were explored to capture the materials-specific influence of multiple components in each materials combination. Figure 52 provides an overview of how predicted CA [from the model based on changes in low shear viscosity (LSV)] and corresponding limiting CA values (with the model based on changes in G-R parameter) when G-R cracking onset and significant cracking thresholds are reached were utilized to generate predicted aging times when cracking is of concern. This procedure permitted the hypothetical relative comparison of the binder blends for the selected field project locations using measured chemical and rheological binder properties. Appendix F provides additional details.

The wide spectra of chemical and rheological measurements made in terms of temperatures and durations enabled a robust evaluation of the respective aging path of each materials

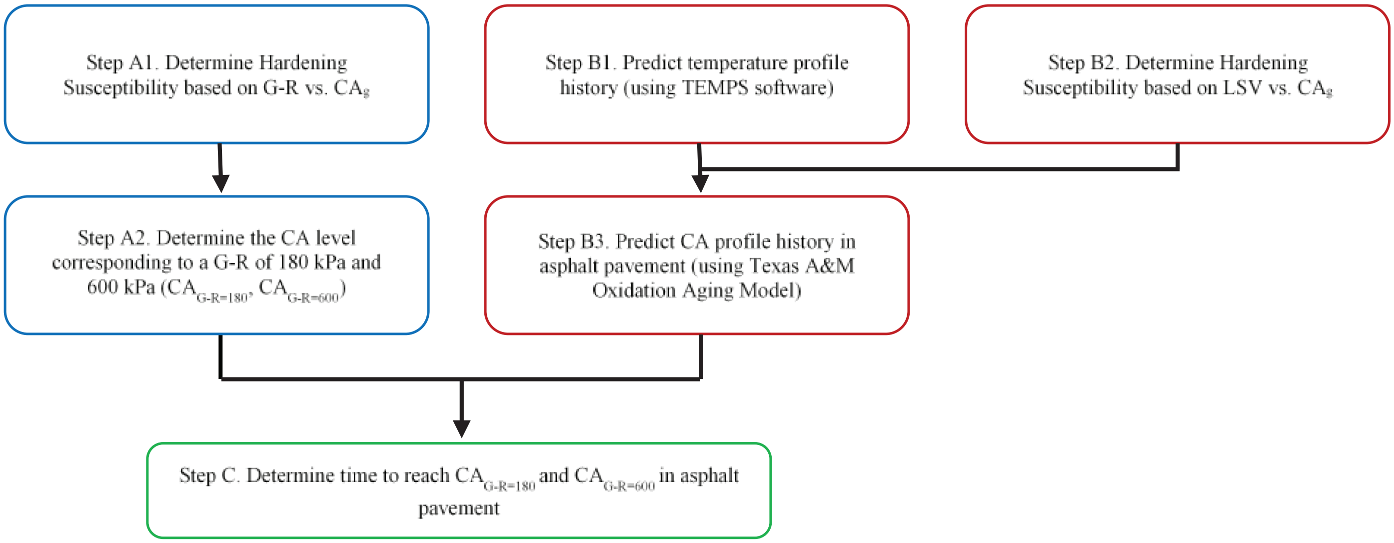


Figure 52. Overview of binder blend aging prediction for selected field project locations.

combination with the prediction of both oxidation and rheological characteristics in service. The oxidation rate along this path was measured in terms of CA growth (CA_g), and oxidation kinetics were modeled by Equation 18.

$$CA_g = M*(1-e^{-k_f t})+k_c t \qquad \text{[Equation 18]}$$

where

CA_g = carbonyl area growth (CA-CA_0),
CA = carbonyl area,
CA_0 = original or tank CA measurement (after RTFO aging for this study),
M = initial jump, magnitude of fast rate reaction in terms of CA_g,
k_f = fast rate of CA_g,
k_c = slow or constant rate of CA_g, and
t = time, days.

The duration of time at the fast rate is much shorter than that for the constant rate as temperature increases, consistent with an Arrhenius reaction function as shown in Equation 19, and both oxidation kinetics parameters or rates (k_f and k_c) are represented as follows:

$$r_{CA_g}(k_f or k_c) = AP^{\alpha} e^{-Ea/RT} \qquad \text{[Equation 19]}$$

where

r_{Cag} = rate of carbonyl area growth (CA_g), either k_f or k_c.
A = pre-exponential factor.
P = absolute oxygen pressure during oxidation, atm.
α = reaction order with respect to oxidation pressure.
E_a = activation energy, kJ/mol.
R = ideal gas constant, 8.3144621 L/mol °K.
T = temperature, °K.

Figure 53 provides an example of constant oxidation rates (k_c) as a function of the inverse of the aging temperature multiplied by the gas constant R for binder blends with the TX PG 64–22 base binder. Appendix F contains additional data for binder blends with four other base binders

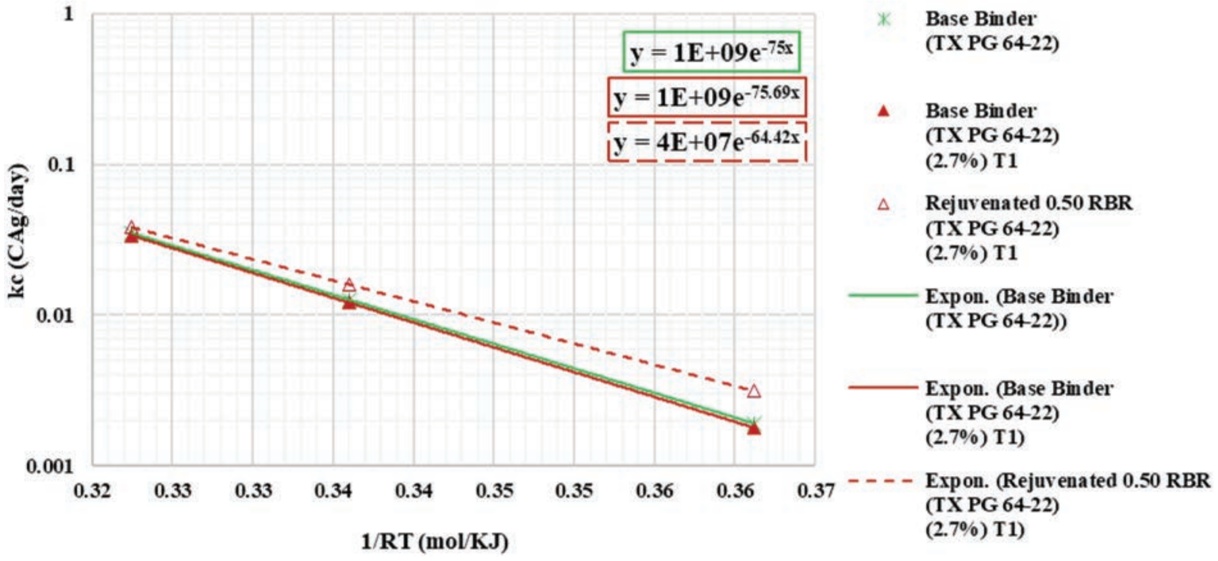


Figure 53. Constant-rate oxidation kinetics for TX PG 64–22 base binder blends.

(NH PG 64–28, NV PG 64–28P, WI PG 58–28, and WI PG 52–34). Evaluation of these k_c plots in Appendix F resulted in the following observations:

- The addition of T1 to the TX PG 64–22 base binder did not change k_c, but the rejuvenated blend with recycled materials and T1 at the low field dose (2.7%) did exhibit increased k_c, possibly due to the low field recycling-agent dose that was unable to counteract the addition of RAP and MWAS.
- The addition of T1 to the NH PG 64–28 rejuvenated blend at the dose to restore PGL (12.5%) for 0.5 RBR significantly reduced k_c when compared to that of the NH PG 64–28 base binder or the rejuvenated blend with the lower dose (2.7%). Conversely, the rejuvenated blend with A1 and only RAP at 0.4 RBR did not show reduced k_c relative to the base binder at the dose to restore PGL (6%). Thus, oxidation kinetics depend on both recycling-agent dose and type and recycled materials content and type.
- The addition of T1 to the NV PG 64–28P base binder at the lower dose (2.7%) or the addition of T1 to the corresponding rejuvenated blend at the higher dose (11%) generally reduced k_c when compared to the base binder and demonstrated that the use of recycling agent can facilitate the use of recycled materials.
- The addition of V2 to the WI PG 58–28 rejuvenated blend at 0.31 RBR did not show reduced k_c relative to the recycled control at 0.31 RBR and the DOT control at 0.21 RBR, but the softer rejuvenated blend with WI PG 52–34 and 0.31 RBR exhibited noticeably lower k_c values, as expected.

Figure 54 provides an example of the rheological response of the binder blends to CA_g in terms of the G-R parameter for the TX PG 64–22 base binder. The slope of this plot is defined as the G-R/CA_g HS. Similar plots are included in Appendix F for binder blends with the NH PG 64–28, NV PG 64–28P, WI PG 58–28, and WI PG 52–34 base binders. For the majority of the binder blends evaluated, the dual-slope model form previously used for fast and constant-rate kinetics provided a better representation of the measurements. Thus, similar to Equation 18 representing the kinetics, G-R/CA_g HS is presented in the form of Equation 20 as follows:

$$ln(G-R) = M\left(1-e^{-k_f' CA_g}\right) + k_c' CA_g + ln(G-R)_0 \qquad \text{[Equation 20]}$$

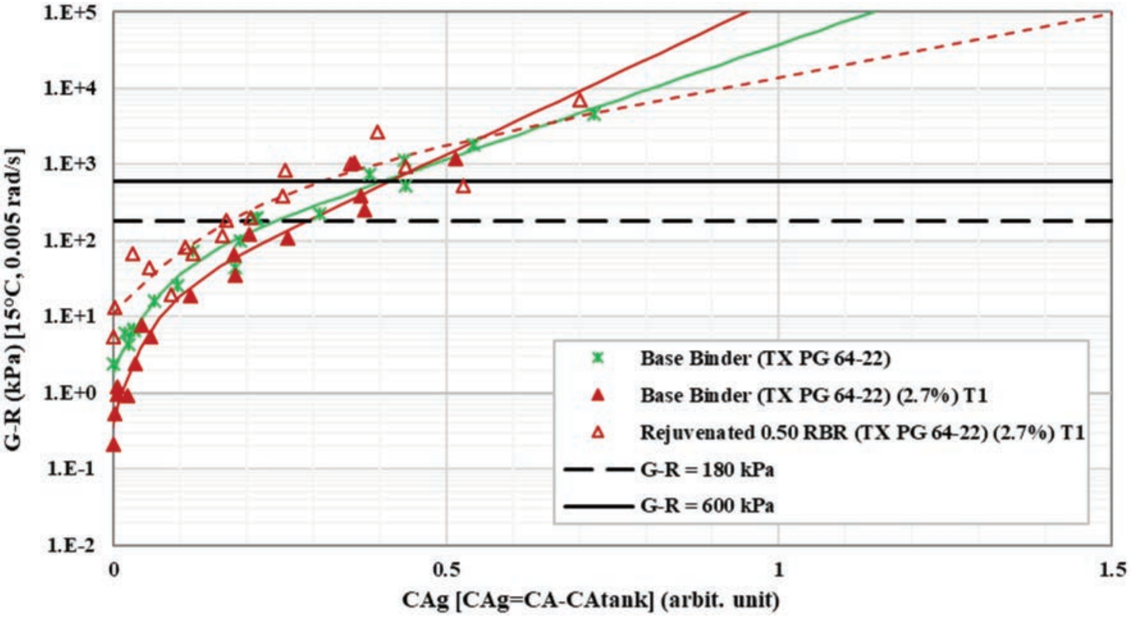


Figure 54. Glover-Rowe parameter at 15°C for PG 64–22 base binder blends.

where

G-R = Glover-Row parameter (kPa) at 15°C and 0.005 rad/s.
$G\text{-}R_0$ = initial Glover-Row parameter (kPa) at 15°C and 0.005 rad/s.
CA_g = carbonyl area growth.
K_f' = fast rate of G-R growth.
K_c' = constant rate of G-R growth.

In this model form with the G-R parameter, the long-term or constant-rate G-R/CA_g HS region of the function is of primary interest since it is expected to represent the material late in its service life. Subsequently, evaluation of the plots in Appendix F resulted in the following observations:

- The addition of the recycling agent to the TX PG 64–22 base binder increased the flexibility of the binder based on lower G-R parameter values at a given CA_g during the early stages of the aging process. However, after a certain level of oxidation, the TX PG 64–22 base binder modified with T1 resulted in higher G-R parameter values, indicating increased stiffness and embrittlement relative to the base binder due to interaction with the recycling agent. The addition of recycled materials (RAP and MWAS) increased the stiffness and reduced the phase angle of the blend, as indicated by the higher G-R parameter. Further, the recycling agent was not effective in fully restoring the rheological properties at the low field dose (2.7%) for at least the early stages of aging. However, as the aging progressed, the T1 in the rejuvenated blend retained more flexibility and eventually resulted in the lowest G-R parameter, below that of either the base binder or the base binder with T1.
- The addition of T1 to the NH PG 64–28 base binder at the lower dose (2.7%) increased the flexibility of the binder, resulting in lower G-R parameter values at a given CA_g. In contrast to the results for the TX PG 64–22 base binder, the G-R/CA_g HS (slope) was relatively unchanged by the addition of T1, but the recycling agent softened the blend. Similar to the results for the TX PG 64–22 base binder, the addition of recycled materials and T1 (even at the higher 12.5% dose to restore PGL) significantly increased the brittleness of the blend at 0.5 RBR, and likewise reduced the G-R/CA_g HS compared to that of the base binder. In a similar comparison, A1 had a similar influence on the NH PG 64–28 base binder at the dose to restore PGL (6%). However, when combined with RAP only at 0.4 RBR, the G-R/CA_g HS for the rejuvenated blend with A1 was significantly reduced compared to the T1 blends with either base binder at different RBRs, possibly due to the fact that no RAS was present.
- The addition of T1 to the NV PG 64–28P base binder slightly increased the flexibility of the binder at the low dose (2.7%), resulting in lower G-R parameter values at a given CA_g. However, the G-R/CA_g HS of the two are similar for this combination compared to those for the other two base binders. When considering the addition of the recycled materials with T1 at the higher dose (11%), a similar response to that for the TX PG 64–22 binder blends was noted. In this case, the initial reduction in flexibility observed at higher G-R parameter values was eventually overcome by the reduced G-R/CA_g HS with the rejuvenated blend. After some level of aging, the G-R parameter values of the rejuvenated blends were lower than those for either the base binder or the blend with only T1.
- The addition of V2 to the WI PG 58–28 rejuvenated blend resulted in an increase in the flexibility of the blend at the same 0.31 RBR, as evidenced by lower G-R parameter values at a given CA_g during the initial stages of aging. Then after a certain level of oxidation, the rejuvenated blend exhibited higher G-R parameter values, which indicated an increase in embrittlement when compared to the blends without recycling agent.
- As a preliminary summary of these G-R/CA_g HS relationships, the recycling agents evaluated reduced the overall stiffness in the initial stages of oxidation. However, differential aging

rates or G-R/CA_g HS were observed between blends with only recycling agent added and rejuvenated blends (with recycling agent and recycled materials) for the TX PG 64–22, NH PG 64–28, and NV PG 64–28P base binders. These differences were not consistent with the type of RAS (i.e., MWAS or TOAS).

Using the measurements of kinetics and LSV/CA_g HS for the selected binder blends facilitated predictions through oxidation modeling of the changes in rheology over simulated in-service time for a given location and subsequent comparisons. Specifically, the model predicted the level of oxidation in terms of CA_g expected in the different binder blends as a function of in-service time, which was then directly correlated to rheological properties afforded by the G-R/CA_g HS relationships. While the previous comparisons used the G-R parameter determined at the standard temperature of 15°C and G-R/CA_g HS, the oxidation prediction models used LSV/CA_g HS due to developed correlations between LSV and oxygen diffusivity of asphalt binders.

Oxidative aging (CA_g) predictions were completed over the analysis period at 0.01 m below the pavement surface using the predicted hourly pavement temperature at the corresponding depth for the TX and WI field project locations and the binder oxidation properties shown in Table 31.

Table 31. Oxidative aging model parameters for the evaluated asphalt binders.

	Binder ID	E_a[a] (kJ.mol^{-1}.°K^{-1})	Pre-exponential Factor[b], AP$^{\alpha}$	LSV/CA_g HS[c] (1/CA_g)	m[d] (ln(poise))	CA_{RTFO}[e] (arbitrary unit)	k_c		
							Temperature (°C)		
							60	85	100
TX[f]	Base (PG 64-22)	75	1.129E+09	11.31	46.91	0.323	0.002	0.013	0.035
	Base (2.7%) T1	76	1.357E+09	13.28	0.12	0.637	0.002	0.012	0.034
	Rejuvenated 0.50 RBR (PG 64-22) (2.7%) T1	64	4.049E+07	11.61	0.29	0.857	0.003	0.016	0.038
NH[f]	Base (PG 64-28)	65	5.189E+07	9.46	201.22	0.131	0.003	0.018	0.042
	Base (2.7%) T1	69	2.354E+08	8.92	6.55	0.420	0.004	0.022	0.056
	Base (6%) A1	70	3.700E+08	8.16	123.22	0.107	0.004	0.021	0.053
	Rejuvenated 0.50 RBR (PG 64-28) (12.5%) T1	70	1.400E+08	8.43	1.00e-05	2.446	0.001	0.009	0.022
	Rejuvenated 0.40 RBR (PG 64-28) (6%) A1	73	8.101E+08	5.93	75.43	0.679	0.003	0.020	0.052
NV[f]	Base (PG 64-28P)	73	5.931E+08	6.53	997.61	0.067	0.002	0.015	0.041
	Base (2.7%) T1	79	4.709E+09	8.90	22.91	0.383	0.002	0.013	0.038
	Rejuvenated 0.50 RBR (PG 64-28P) (11%) T1	86	5.045E+10	6.12	0.01	2.112	0.002	0.013	0.043
WI[g]	DOT Control 0.22 RBR	81	1.0494E+10	9.15	5.453	0.288	0.002	0.014	0.041
	Recycled 0.31 RBR	84	3.0189E+10	6.49	5.482	0.285	0.002	0.016	0.050
	Recycled 0.31 RBR (PG 52-34)	103	8.4628E+12	9.74	6.260	0.295	0.0005	0.007	0.027
	Rejuvenated 0.31 RBR (1.2%) V2	64	3.0880E+07	8.5	6.588	0.227	0.003	0.013	0.031

[a] E_a: activation energy.
[b] AP^{α}: pre-exponential factor.
[c] LSV/CA_g HS: hardening susceptibility, based on LSV.
[d] m: hardening function constant, based on LSV.
[e] CA_{RTFO}: CA after RTFO aging.
[f] TX: environment simulation.
[g] WI: environment simulation.

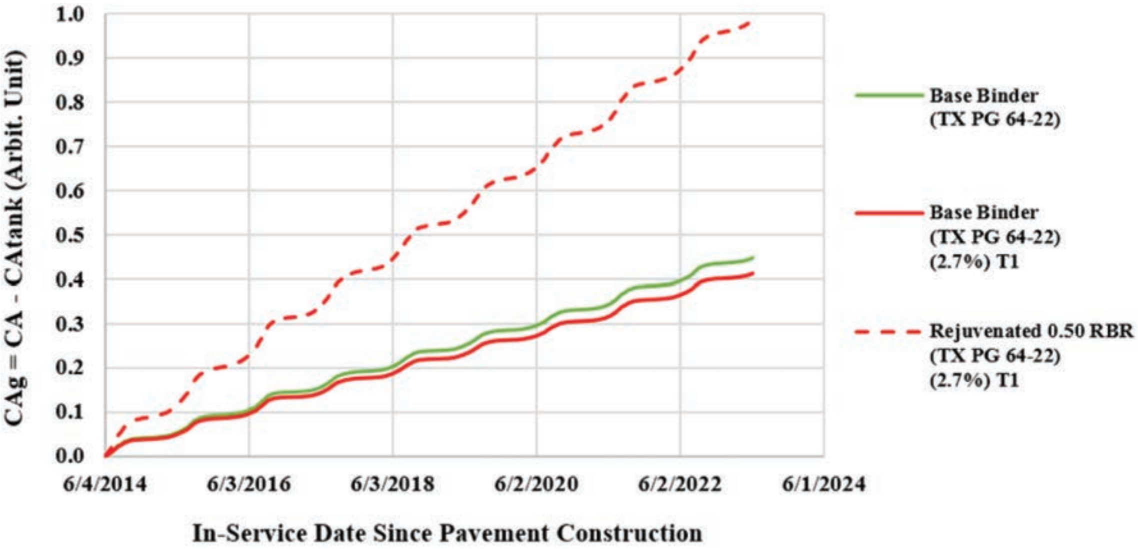


Figure 55. Carbonyl area prediction in mixture surface layer at TX field project.

As an example, a summary of CA_g predictions for the TX PG 64–22 binder blends over the analysis period at 0.01 m below the surface at the TX field project location is provided in Figure 55.

Using the CA_g predictions from all the selected base binder blends resulted in the estimated time to reach the G-R thresholds as a function of in-service time at the TX and WI field projects. These are hypothetical aging simulations using the selected TX and WI field project environmental conditions and the materials-specific binder blend aging characteristics, but only a few of these materials combinations were constructed as part of the TX and WI field projects (Table 8 and Table 11). Consequently, Figure 56, Figure 57, Figure 58, and Figure 59 provide a materials-specific comparison of the base binders from TX, NH, NV, and WI to evaluate the overall ability of the oxidation kinetics and G-R/CA_g HS relationships to identify the simulated time to reach the G-R parameter thresholds for cracking onset (i.e., 180 kPa) and significant cracking

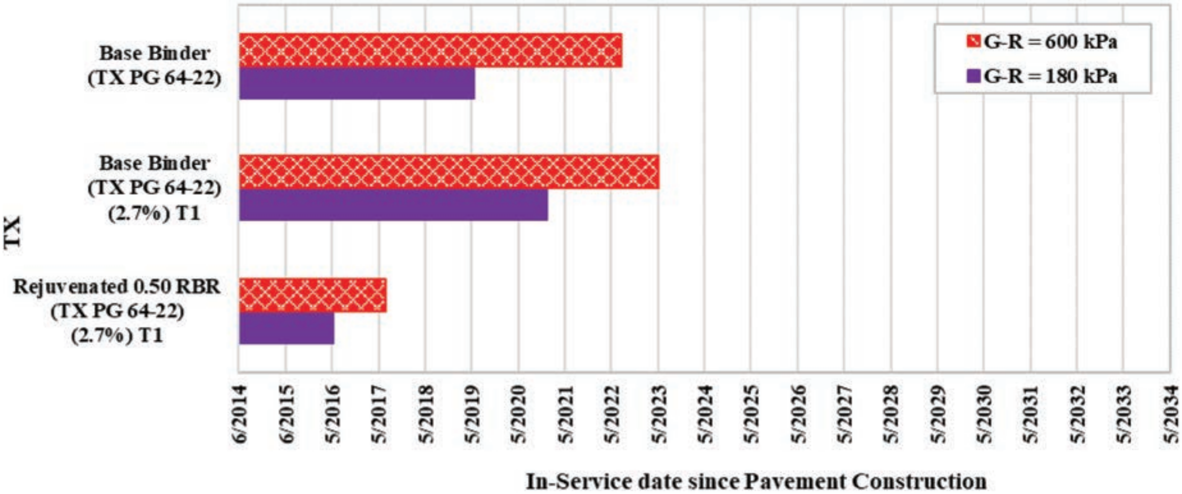


Figure 56. Simulated time to reach G-R = 180 kPa and G-R = 600 kPa in asphalt pavement for TX PG 64–22 base binder blends (in TX field project location).

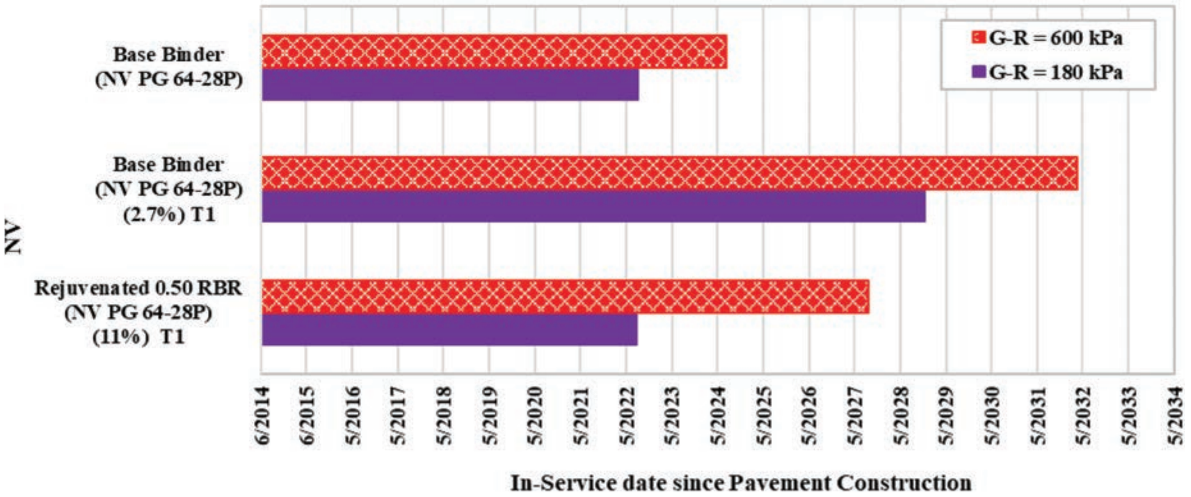


Figure 57. ***Simulated time to reach G-R = 180 kPa and G-R = 600 kPa in asphalt pavement for NV PG 64–28P base binder blends (in TX field project location).***

(i.e., 600 kPa). These results and subsequent interpretations highlight the complex nature of the potential interactions between the different components in these binder blends.

Considering the binder blends with TX PG 64–22 base binder, as shown in Figure 56, there was a systematic influence of the added components. The addition of T1 at the field dose softened the blend and restored some of the flexibility as demonstrated by longer durations to meet the respective G-R parameter thresholds. Addition of the recycled materials (RAP and MWAS) resulted in a drastic reduction in the softening effect of the T1 and thus a reduction in the simulated durations to the G-R parameter thresholds to less than those for the TX PG 64–22 base binder. These data clearly indicate that the T1 field dose was inadequate.

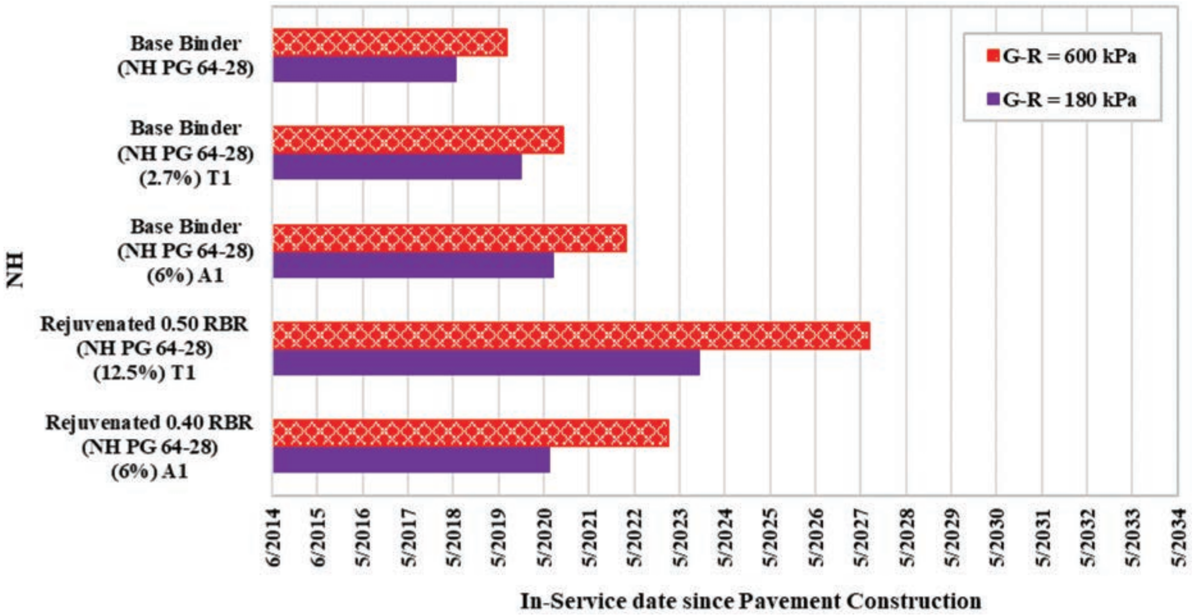


Figure 58. ***Simulated time to reach G-R = 180 kPa and G-R = 600 kPa in asphalt pavement for NH PG 64–28 base binder blends (in TX field project location).***

Figure 59. Simulated time to reach G-R = 180 kPa and G-R = 600 kPa in asphalt pavement for WI binder blends (in WI field project location).

Consideration of the NV PG 64–28P binder blends shown in Figure 57 resulted in similar findings for the respective influences of the various components. The exception noted with this polymer-modified blend was found with the cracking onset threshold of 180 kPa for the rejuvenated blend, which was observed at a time similar to that for the NV PG 64–28P base binder, while the significant cracking threshold of 600 kPa was predicted to occur substantially after that for the base binder. Numerically, this was the result of the slightly lower oxidation rate (k_c) combined with the lower G-R/CA_g HS or flatter slope noted with the rejuvenated blends. These results provide examples of similar or improved performance for the rejuvenated blend with an effective T1 dose relative to the base binder.

A nearly identical discussion for the NH PG 64–28 base binder results presented in Figure 58 with A1 and RAP at 0.4 RBR is also appropriate. An increase in the time to reach the G-R parameter thresholds was observed when either T1 (at a low 2.7% dose) or A1 (at a higher selected dose to restore PGL) was added to the NH PG 64–28 base binder. The addition of recycled materials at 0.5 RBR to this base binder with T1 at the selected dose to restore PGL resulted in an increase in the time to reach the G-R parameter thresholds, thus demonstrating the efficiency of T1 when used at the higher selected dose. The addition of recycled materials at 0.4 RBR to this base binder with the A1 resulted in similar behavior to that of the base binder with only A1 at the same dose. Considerations of the diffusion limitation potential became even more prominent with the NH PG 64–28 base binder and respective rejuvenated blends with T1. In this case, both the k_c and G-R/CA_g HS for the rejuvenated blend were lower than those for the base binder with only T1 or even the NH PG 64–28 base binder, thus indicating a restricted oxidation path with these materials, both of which combined to simulate much slower oxidation and thus longer time durations to reach the G-R parameter thresholds. It is also important to note the differences in the doses between the blend of the NH PG 64–28 base binder and T1 only (i.e., at the low dose of 2.7%) compared to the selected T1 dose of 12.5% to restore PGL when TX RAP and TX TOAS were included. Despite the similarities in the dose of T1 as well as the TOAS in both the NH PG 64–28 and NV PG 64–28P blends, the influence of those components was not consistent.

Figure 59 provides results for the WI binder blends in the WI field project location that is significantly milder in terms of temperature and other climatic parameters required as inputs for the oxidation model relative to the TX field project location. After a 20-year simulation, none of the recycled blends with recycled materials (and either base binder) reached either of the G-R parameter thresholds, but the rejuvenated blend with V2 reached these thresholds after shorter durations. However, these observations are not consistent with the early field distress data collected, where all mixtures showed low-severity transverse cracking mainly as a result of cracks reflected from the existing underlying concrete slabs.

Several reasons might have contributed to the observed discrepancies between laboratory and field data from the WI field project. For instance, neither the aging prediction model nor the G-R parameter thresholds take into consideration reflective cracking from an existing concrete layer. The G-R parameter thresholds of 180 kPa and 600 kPa were originally developed to control cracking in the asphalt binder due to an increase in stiffness and a reduction in phase angle as a result of oxidative aging. Furthermore, these cracking thresholds were developed based on a specific binder aging to this level and not based on rheological changes due to modification processes such as polymer modification or the addition of recycled materials. Accordingly, the standard testing conditions of 15°C and 0.005 rad/s for G-R parameter determination may introduce a bias in the results when dealing with binders subjected to different modification processes. In addition, the aging predictions are based on assumed full blending between base and recycled binders, which is likely not representative of field-produced mixtures. Thus, while binder testing can help screen and preclude the use of materials combinations likely to perform inadequately in the field, it is still important to evaluate mixture performance and resistance to critical distresses.

In summary, both T1 and A1 showed beneficial effects, with larger doses resulting in a more substantial benefit. However, this consistent trend was not shown for V2. This is not unexpected, considering the highly materials-specific interactions observed previously with these materials combinations. The simulated oxidative aging predictions generally provided the following conclusions:

- The field dose of T1 (2.7%) in the TX PG 64–22 rejuvenated blend with 0.28 RBR mixture (0.1 RAP + 0.18 MWAS) was not sufficient to restore the binder blend to be rheologically similar to the base binder.
- The NH PG 64–28 rejuvenated blend with a selected dose of 12.5% T1 to restore PGL and 0.5 RBR (0.25 RAP + 0.25 TOAS) almost restored the binder blend to be similar to the base binder. Similarly, the NH PG 64–28 rejuvenated blend with A1 at the selected dose of 6% to restore PGL and 0.4 RBR (0.4 RAP) exhibited slightly better restoration. These results imply that using a recycling agent at the selected dose can have a positive influence in restoring binder rheology.
- The NV PG 64–28P rejuvenated blend contained 0.5 RBR (0.25 RAP + 0.25 TOAS) and a higher T1 dose of 11%. This dose not only restored the binder blend life prediction to that of the base binder but also improved it for almost an additional 6 years.
- The WI PG 58–28 rejuvenated blend with 0.31 RBR (0.31 RAP) and 1.2% V2 exhibited a reduction in the time to reach the established cracking thresholds. Thus, the field dose of V2 may not be sufficient to restore binder rheology.

The resulting durations to reach the G-R parameter thresholds for the base binders stem from the influence of the determined k_c rates combined with the relative differences in G-R/CA_g HS. Specifically, there was a minor reduction in the k_c values of the NV PG 64–28P base binder relative to the NH PG 64–28 and the TX PG 64–22 base binders (particularly at the lower temperatures, i.e., higher 1/RT values). Similar k_c terms for the NH PG 64–28 and TX PG 64–22 base binders yielded modest differences in durations when compounded by the minor discrepancies noted in the G-R/CA_g HS between the two. These conditions were further exemplified by the lower G-R/CA_g HS for the NV PG 64–28P base binder resulting in the longest simulated durations among these base binders. For the WI binder blends, different environmental conditions yielded longer durations despite the similarities in k_c rates when compared with the other blends.

4.3 Recycling-Agent Characterization

Throughout this study, results indicated that initial compliance with target PG requirements is not sufficient to ensure long-term effectiveness of rejuvenated binder blends. PGH increases with the addition of recycled materials (or oxidation) in these blends, and recycling agents can be formulated to restore PGL (after 20-h PAV) for the target climate. Because phase angles of rejuvenated binder blends are relatively low, the PGI requirement is usually also met. However, cracking continues to be a problem for corresponding rejuvenated mixtures, especially at high RBRs.

Restoring the rejuvenated binder blend to a predetermined stiffness is necessary, but not sufficient, to preclude cracking. Oxidative aging seriously restricts molecular motion, leading to a rapidly decreasing phase angle. Recycling agents must be evaluated based on their ability to restore rheology both in terms of decreasing stiffness and increasing phase angle at low and intermediate temperatures. In this study, Black space analysis and the calculated G-R parameter were utilized to rank recycling agents in binder blends initially and with aging, with the more effective recycling agent exhibiting a higher phase angle at any given |G*| (data point further to the right).

To further explore the rejuvenating mechanism of different types of recycling agents while comparing the evolution of their effectiveness with aging, recycling-agent characterization experiments were conducted. The primary experiment evaluated both rheological and chemical changes in rejuvenated binder blends after short- and long-term aging. Since aging of these blends may result in chemical changes in the recycling agent itself and subsequent reduction in the dispersive power of the maltene phase, a second experiment was completed to examine the effect of oxidation on recycling agents themselves. A third experiment was completed to compare binder blends after two different conditioning sequences: one with rejuvenation prior to aging (RTFO and 20-h PAV) and the other with aging prior to rejuvenation. Finally, corresponding mixture tests were completed for comparison with the binder blend results.

Rejuvenated binder blends were prepared by combining the DE base binder (PG 64–28), DE RAP at 0.5 RBR, and one of seven recycling agents (aromatic extract A1, reacted bio-based oils B1 and B2, paraffinic oil P, tall oil T1, and modified vegetable oils V2 and V3). The dose of recycling agent in each blend was selected to match the continuous PGH required by climatic and traffic conditions at the DE field project. The rejuvenated binder blend with A1 required 13.5% recycling agent, the highest to match continuous PGH, followed by the binder blend with P at 11%, the blend with B2 at 10.5%, the blend with V2 at 9%, the blend with T1 at 8.5%, and the blends with B1 and V3 at 8%. These results are in agreement with the literature (Zaumanis et al. 2014), with petroleum-based recycling agents (including A and P types in this study) requiring higher doses than their bio-based counterparts (including T, V, and B types in this study). The rejuvenated binder blends and the pure recycling agents were subjected to four aging levels:

- Unaged,
- RTFO,
- RTFO and 20-h PAV, and
- RTFO and 40-h PAV.

For each binder blend or recycling agent at each aging level, rheological evaluation in Black space and calculation of the G-R parameter and chemical analysis using FT-IR spectra were completed.

The basic rejuvenation mechanism by the selected recycling agents is the addition of strongly polar compounds that help to polarize asphaltene clusters in recycled binders and compatibilize them with maltenes, thus breaking up the large asphaltene clusters. Recycling agents with these strongly polar compounds are classified as rejuvenators, and their addition reduces stiffness (|G*|) and increases phase angle (δ), shifting the Black space plot to the bottom right. Recycling agents without these compounds, like paraffinic oil P, are classified as softening agents, which only decrease stiffness (|G*|) without sufficiently reducing phase angle (δ). However, this also makes them the least susceptible to aging. The other recycling agents under consideration were rejuvenators that had strong polar groups including aromatics in A1, fatty acids in T1, a mixture of glycerides in V2 and V3, and glycerides stabilized through crosslinking and/or ester and amide bonds in B1 and B2.

A Black space diagram for the aged blends is shown in Figure 60, with calculated G-R parameters provided in Appendix G. Similar in effect to paraffinic-like recycled engine oil bottoms (REOBs), addition of the paraffinic oil P produced blends that are far more brittle with low phase angles compared to blends with the other six recycling agents. The corresponding G-R parameter value of 197 kPa after 40-h PAV indicated this as the only rejuvenated blend that extended into the transition zone. This poor effectiveness exhibited by the P recycling agent is generally attributed to problematic compatibility between aromatic asphaltenes and the high concentration of non-aromatic non-polar paraffins in the continuous phase of the binder. Paraffinic oils are not generally used as asphalt additives or recycling agents, and this result makes a clear case supporting previous concerns that excess paraffin concentrations may accelerate cracking even when aliphatic molecules might be non-crystalline at low temperatures. The bio-based recycling agents (including T, V, and B types in this study) led to rheological properties before and after aging that are slightly better than the aromatic oil traditionally used for rejuvenation. The two bio-oils (B1, B2) and the two modified vegetable oils had similar G-R values after 40-h PAV

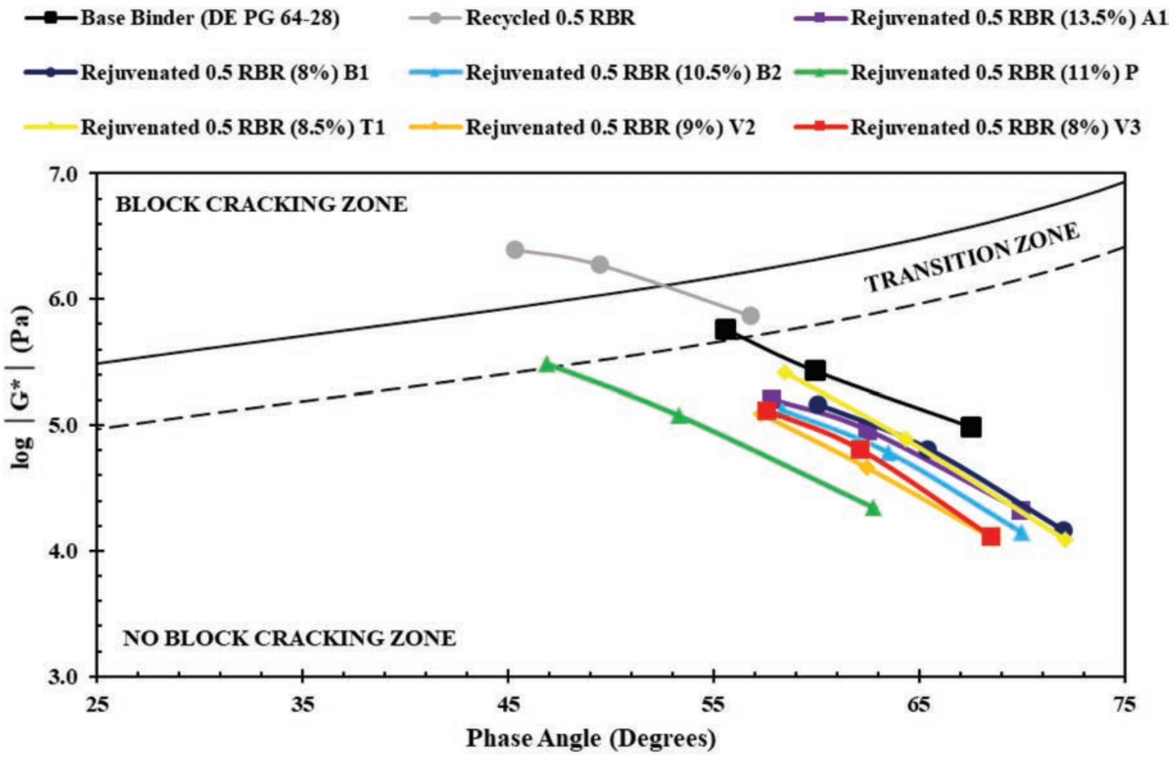


Figure 60. Black space diagram for binder blends with different recycling agents.

ranging from 42 kPa to 45 kPa, whereas the aromatic extract A1 was slightly higher at 55 kPa, and the tall oil exhibited more sensitivity to aging with a G-R value of 84 kPa. A Glover-Rowe long-term aging index was also calculated as the logarithm of the ratio of the G-R parameter for the blend after 40-h PAV to that after RTFO. The blend with T1 exhibited the highest aging index (1.84), followed by the blend with P (1.58); the blend with B1 (1.46); the blends with V2, V3, and B2 (1.38); and the blend with A1 with the smallest aging index (1.31). This aging index for the base binder (1.17) and that for the recycled blend with no recycling agent (0.82) were significantly less than those for the rejuvenated blends, but they were both shifted to the upper left corner in Black space because neither contained a recycling agent.

FT-IR spectra provide a fingerprint for asphalt binder chemical functionality, with primary emphasis on the CA around 1710 cm^{-1} to define oxygen uptake during aging. However, bio-based recycling agents (including T, V, and B types in this study) as used for rejuvenation contain high concentrations of fatty acids, either alone or as part of mono-, di-, and triglycerides that create ester functionality in vegetable oils. Fatty acids may be further reacted or derivatized to change their chemical stability and rheological behavior. As the immediate chemical environment changes, the carbonyl IR absorbance bands may shift somewhat, but the carbonyl itself will almost always remain even when the recycling agents have been chemically stabilized in some manner to resist further aging. Thus, most bio-based recycling agents (including T, V, and B types in this study) will contain high concentrations of carbonyl functionality even before any oxidative aging occurs. Depending on the source and any chemical reactions used to stabilize or upgrade the recycling agent, the carbonyl functionality may be in the form of fatty acids, esters, fatty anions, or even amides or imidazolines. The specific chemical functionality surrounding it will cause the energy of maximum IR absorbance for the carbonyl to shift somewhat, but IR absorbance for carbonyl usually remains within the range of 1,650 cm^{-1} to 1,820 cm^{-1}.

When blending 0.50 RBR blends with bio-based recycling agents (including T, V, and B types in this study), FT-IR spectra for unaged rejuvenated binder blends, as shown in Figure 61, reveal significant information even without further RTFO or PAV oxidation. However, it can

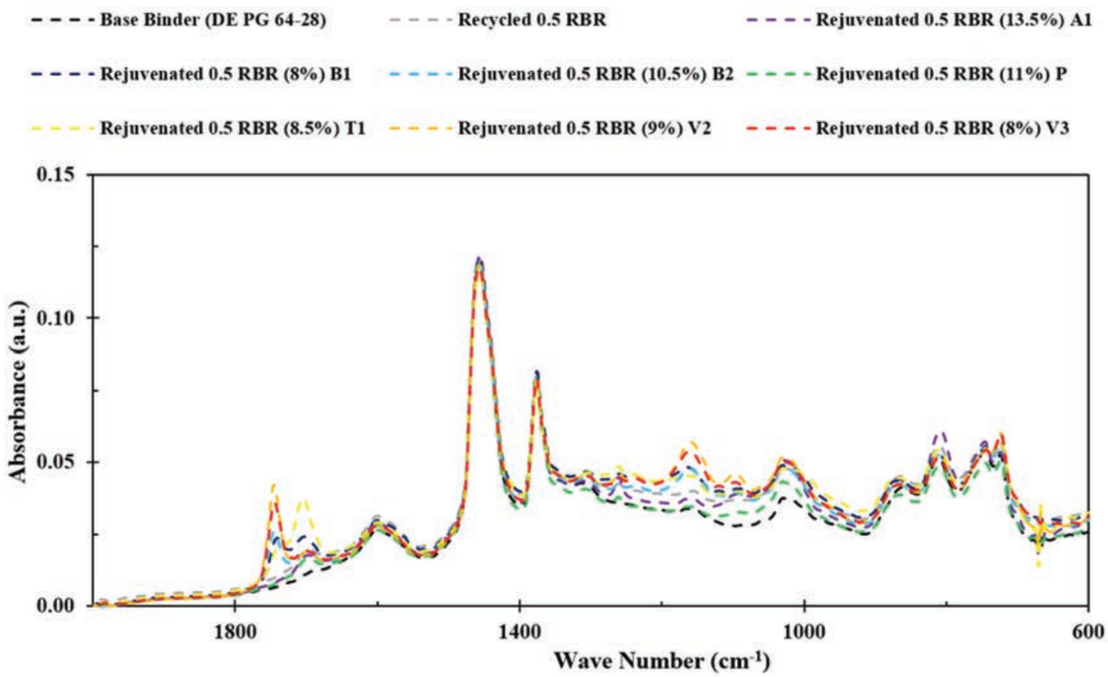


Figure 61. FT-IR spectra for unaged binder blends with different recycling agents.

be difficult to differentiate and quantify the overlapping peaks, especially for those blends with bio-based recycling agents (including T, V, and B types in this study). The oxidized carbonyl ketones in asphalt absorb IR light near 1,700 cm^{-1} and fatty acids absorb near 1,710 cm^{-1}, causing peaks to overlap with carbonyl peaks from asphalt oxidation. Ester peaks are formed when the fatty acids from bio-based recycling agents remain attached to glycerin, or when fatty acids are converted to esters through reactions with alcohols. The carbonyl groups in esters should show maximum IR absorbance near 1,750 cm^{-1}, making them easier to quantify in the presence of oxidized asphalt than their fatty acid counterparts. Other bands are also valuable for differentiating the presence of bio-based recycling agents from the carbonyls from asphalt oxidation. In particular, carbon-oxygen bonds are present for both esters and fatty acids, but only in small amounts for oxidized asphalt binder.

Additional FT-IR spectra for the aged binder blends are provided in Appendix G. In this study, CA and CA_g were determined from the FT-IR spectra to capture chemical changes due to oxidative aging. This chemical analysis is complicated by the presence of competing carbonyl peaks from fatty acids and esters as found in bio-based recycling agents, but these could be subtracted out if comparable aged and unaged binder blends are available.

To combine the chemical analysis and rheological response of the rejuvenated binder blends, G-R/CA_g HS was defined and tabulated as shown in Appendix G. The G-R parameter was utilized instead of more traditional LSV to capture rheology in terms of both stiffness and embrittlement as indicated by phase angle. Figure 62 provides log G-R versus CA_g with the slopes provided as G-R/CA_g HS values for the aged rejuvenated blends, plus the base binder and corresponding recycled binder blend without recycling agent. As expected, the rejuvenated binder blend with P had a significantly higher G-R/CA_g HS than the blends with all other recycling agents. This finding supports other evidence that the paraffinic oil P was least sensitive to oxidation as measured

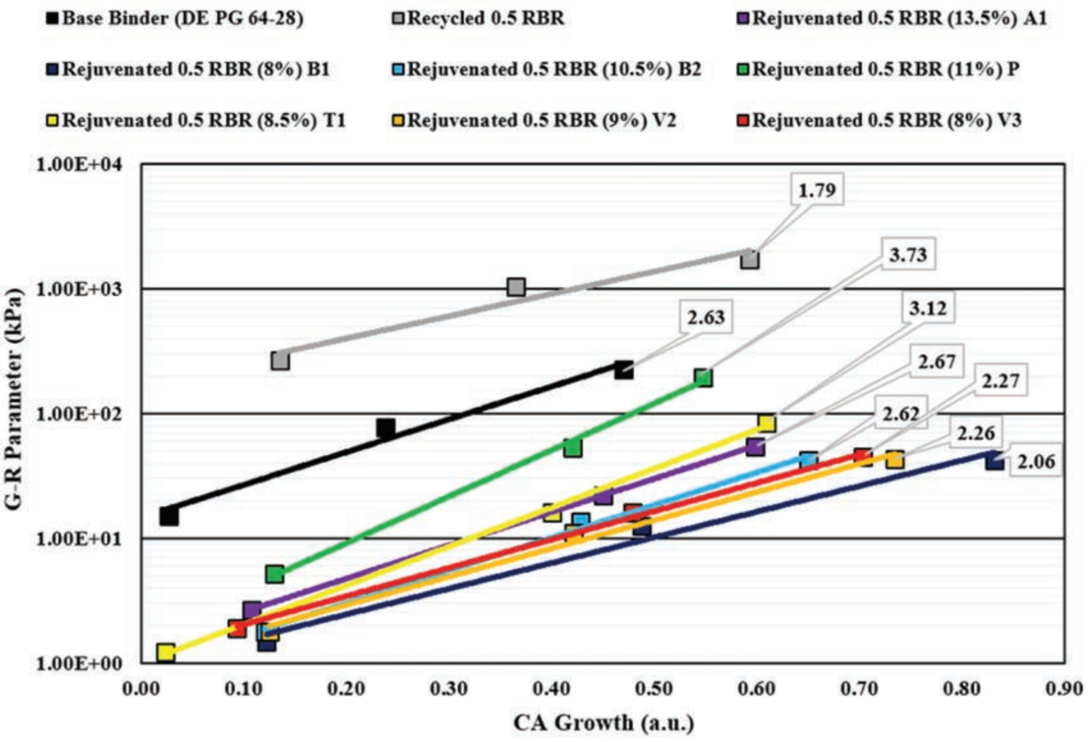


Figure 62. G-R/CA_g HS (provided as slope of trendlines) for binder blends with different recycling agents.

by CA_g, but the blend experienced substantial increases in G-R due to a rapid deterioration in compatibility between a saturate-rich maltene phase and increasingly larger and more polar asphaltenes. This parameter would likely show the same deficiencies for REOB modified binders, given previous reports from Reinke (2015) and Reinke et al. (2015) noting dramatic losses in ΔT_c when REOB was blended with asphalt binder at similar concentrations. The rejuvenated blends with various bio-based recycling agents (including T, V, and B types in this study) contain double bonds and therefore exhibit considerably more CA_g than the blend with P. However, those same double bonds encourage molecular motion, leading to higher phase angles and lower G-R parameter values. For the bio-based recycling agents, the blend with tall oil T1 had a relatively high G-R/CA_g HS due to a higher G-R parameter value. The other four bio-based recycling agents (V2, V3, B1, and B2) had almost identical G-R parameter values, but G-R/CA_g HS values differed with varying CA_g values.

G-R/CA_g HS provides a necessary, but not sufficient, parameter for evaluating recycling agents as it indicates the rate of rheological change with chemical oxidative aging. Location in Black space is also important with respect to cracking resistance in corresponding mixtures. For example, the blends with aromatic extract A1 and reacted bio-based oil B2 were almost equivalent to the base binder in terms of G-R/CA_g HS, but their locations in Black space and G-R parameter value were different (Figure 60). In addition, the lowest G-R/CA_g HS value was exhibited by the recycled blend without recycling agent due to significant previous aging, which is also shown by the highest G-R parameter values.

All seven recycling agents were also evaluated individually for their sensitivity to aging. Complex viscosity (η^*) was measured at 15°C and 10 rad/s by 50-mm DSR for all four aging levels (unaged, RTFO, RTFO and 20-hour PAV, RTFO and 40-h PAV) and then tabulated as shown in Appendix G, and an aging index was calculated by dividing the complex viscosity after RTFO and 40-h PAV by that of the unaged recycling agent. The chemically stable paraffinic oil P and the aromatic extract A1 had low aging indices of 1.09 and 1.15, respectively, indicating little oxidation. As expected, given many reactive double bonds that may oxidize or crosslink, the aging indices for the bio-based recycling agents were higher: 1.85 for V2, 2.60 for B2, and 2.88 for B1. The remaining two recycling agents (V3 and T1) had extremely high complex viscosities after RTFO and 40-h PAV, suggesting these recycling agents had almost completely crosslinked to form harder resin-like materials. Furthermore, as these two recycling agents aged in the PAV, FT-IR indicated strong growth in a broad spectral region between 900–1,250 cm^{-1}, with maximum changes noted near 1160 cm^{-1}. Such changes were minor to nonexistent for the other recycling agents.

Curiously, the corresponding binder blend with V3 showed no significant anomalies that would suggest similar crosslinking. Although the rejuvenated blend with T1 exhibited the highest G-R parameter value of the blends with the five bio-based rejuvenating agents, there was no indication of any gel formation or unusual behavior for the blend with V3 during aging. Other bio-based recycling agents, most particularly those that had been chemically modified, did not show this tendency to gel when aged alone. One possible explanation for the observed behavior is that the asphalt binder contains high concentrations of natural antioxidants, such as phenols (Branthaver et al. 1993). Although these antioxidants do not inhibit oxidation mechanisms known to create benzylic carbonyls in asphalt binder, they should help to protect simple olefinic double bonds in the bio-based recycling agents. Further work is needed to understand the functionality responsible for these high molecular weight products formed when some pure bio-based recycling agents are aged, but these results suggest that recycling agents should be evaluated in binder blends rather than by themselves.

After dose selection to match continuous PGH for the target climate and traffic conditions, the rejuvenated blend must be evaluated with respect to cracking resistance initially and with aging. A third experiment was completed to compare the conditioning sequence for rejuvenation and aging for the following two separate options in terms of Black space analysis and calculated G-R parameter:

- Conditioning sequence #1: The rejuvenated binder blend was prepared by combining DE base binder (PG 64–28), DE RAP at 0.5 RBR, and one of seven recycling agents at doses to match continuous PGH. Each blend was then subjected to 20-h PAV aging.
- Conditioning sequence #2: The recycled binder blend was prepared by combining DE base binder (PG 64–28) and DE RAP at 0.5 RBR. This blend was then subjected to 20-h PAV and then back-blended with one of the same seven unaged recycling agents at the same doses used in Conditioning sequence #1.

A Black space diagram for the blends from both conditioning sequences is shown in Figure 63, with calculated G-R parameters shown in Figure 64. In Figure 63, the lines on the bottom right represent Conditioning sequence #1, where the unaged recycled blend was combined with each recycling agent and then aged. The lines on the upper left represent Conditioning sequence #2, where the aged 0.50 RBR blend was then rejuvenated with the same dose of each of the seven unaged recycling agents. These results were surprising, with all binder blends in which the recycling agent was aged with the binder blend exhibiting lower stiffnesses and higher phase angles than corresponding blends with unaged recycling agent.

Figure 64 graphically shows the scale of this difference by comparing the G-R parameter values between the two conditioning sequences for all seven recycling agents. In spite of the fact that the recycling agents were not aged for binder blends subjected to Conditioning sequence #2,

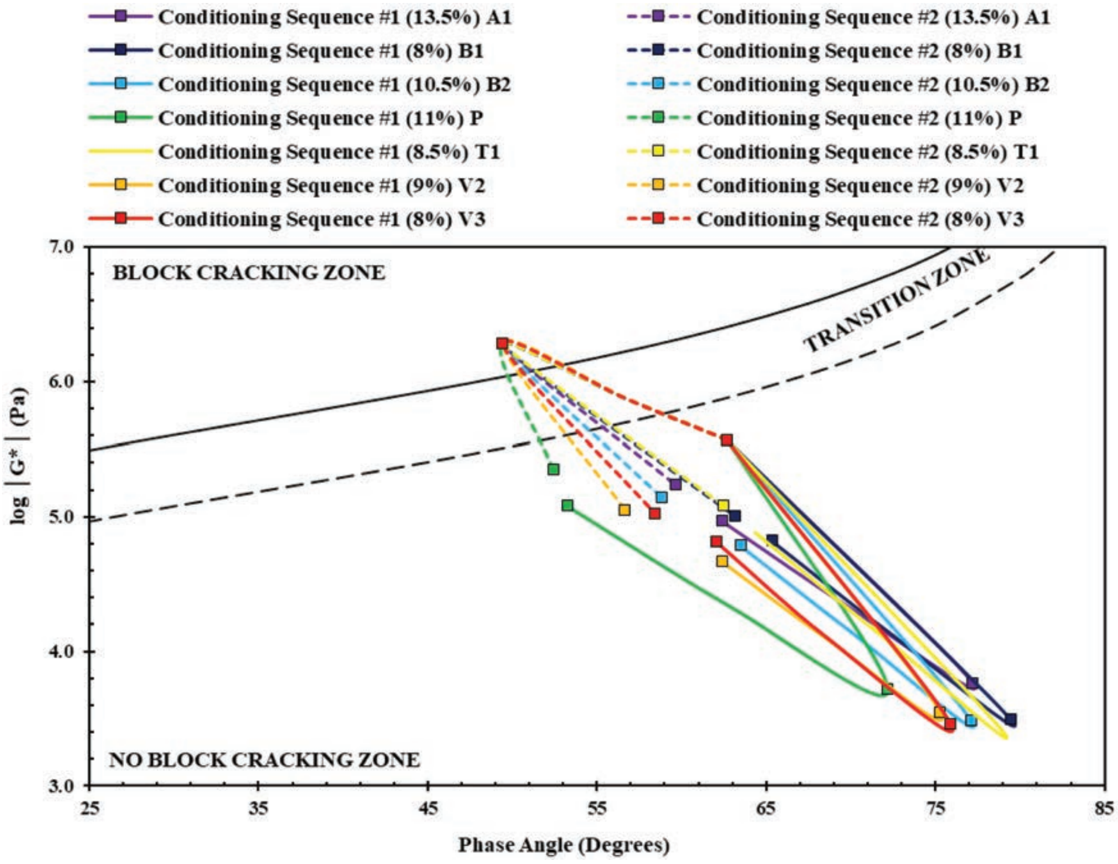


Figure 63. Black space diagram for different blends with different conditioning sequences.

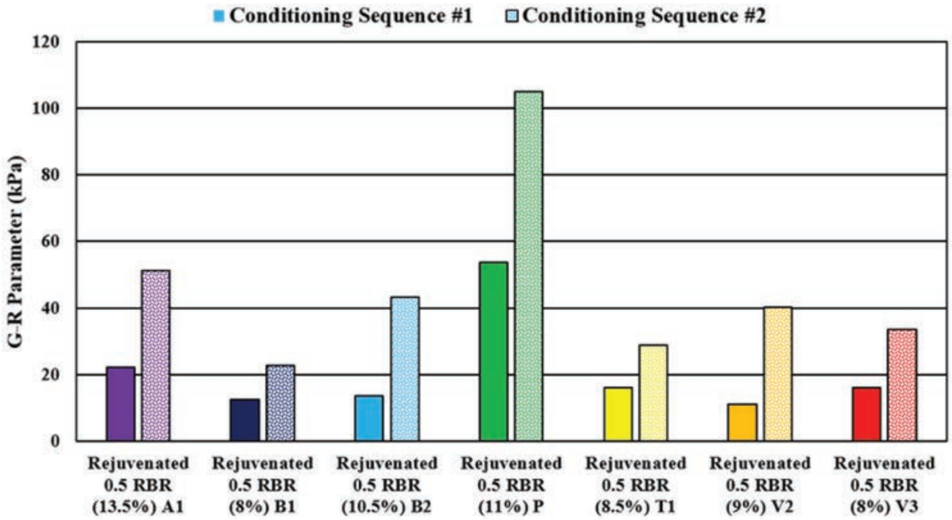


Figure 64. G-R parameter for different blends with different conditioning sequences.

their G-R parameter values were much higher (typically double) than the G-R parameter values of their counterpart blends in which the recycling agents were aged as part of the conditioning. One explanation for this unexpected behavior could be that the recycling agent is consuming some of the available oxygen during PAV aging, but the rheological consequences of these oxidation products were not as great as forming benzylic carbonyl on highly aromatic asphalt molecules, as discussed subsequently. The effectiveness of each recycling agent with aging is represented by low G-R parameter values after Conditioning sequence #1 with 20-h PAV, and these results are in agreement with the effectiveness rankings after 40-hour PAV discussed previously. After Conditioning sequence #1, binder blends with all five bio-based recycling agents had lower G-R parameter values within the range of 11 kPa–16 kPa, while the blend with aromatic extract A1 had a higher value (22 kPa), and the blend with paraffinic oil P exhibited an even higher value (53 kPa).

To better understand the unexpected reversal in G-R parameter values for the two conditioning sequences, CA_g was monitored for the rejuvenated binder blends subjected to the two different conditioning sequences, with results shown in Figure 65. These results contradicted those for the G-R parameter with CA_g indicating more oxygen uptake when the recycling agent was aged with the blend in Conditioning sequence #1 and the G-R parameter suggesting less embrittlement. This was true even for the aromatic extract A1, which should oxidize via mechanisms similar to those for asphalt binder, and the paraffinic oil P, which takes up almost no oxygen on its own. For this disparity to occur, the G-R/CA_g HS had to be much lower when the recycling agent was aged with the blend in Conditioning sequence #1 (more oxygen uptake, less damage) as opposed to when adding the recycling agent after the recycled blend was aged in Conditioning sequence #2. That is, when the recycling agent was present during aging, the damaging impact of each carbonyl-based oxygen atom on the G-R parameter was greatly reduced. In addition, rankings for carbonyl uptake in the rejuvenated blends were generally consistent with rankings for the recycling agents characterized by themselves. Some of the disparity in oxygen uptake might be attributed to the fact that the rejuvenated binder blend was much softer and less brittle before aging, so oxygen diffusion into the binder blend could be higher. However, oxygen diffusion during aging cannot explain the unexpected consequences on rheology.

Although CA_g is typically tied to increases in binder stiffness, results in this study suggest that the oxygen uptake versus binder embrittlement in terms of G-R/CA_g HS may change significantly

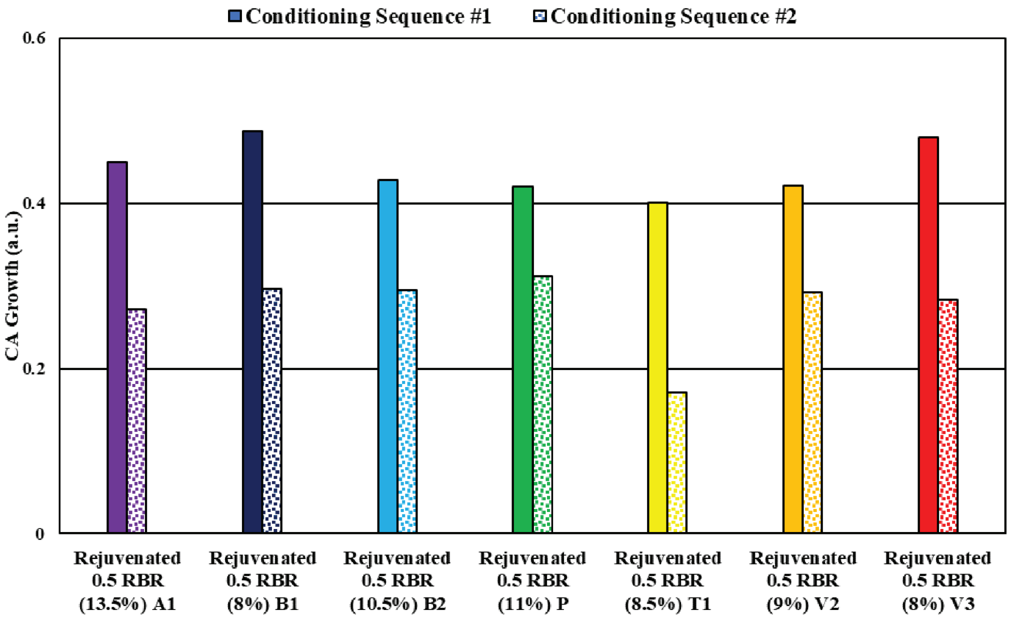


Figure 65. Carbonyl area growth in different blends with different conditioning sequences.

when a recycling agent is added to a recycled binder. If dissolved oxygen in the asphalt really can be diverted to other reactions, rather than forming the highly damaging benzylic carbonyl, there could be additional benefits from recycling agents beyond the initial impact on rheology.

The results presented in this section focused on providing a better understanding of concepts linking chemical changes during oxidation to resulting rheological response of binder blends with aging. Findings include the following:

- Because recycling agents may be rich in carbonyl content before oxidation, FT-IR analysis for aging must focus on growth in the carbonyl peak area (CA_g) between two aging conditions, not on CA at the final aging state.
- During PAV aging, recycling agents seem to change the pathway for at least some oxidation reactions within the recycled binder blend. That is, in the presence of a recycling agent, more carbonyls are formed in the aging blend, but the oxidative impact on key rheology indicators tied to cracking seem to be ameliorated. Such trends can be quantified by evaluating the change in G-R/CA_g HS when recycling agents are blended with high RBR binders before aging. Recycling agents that lower G-R/CA_g HS without significantly increasing total oxygen uptake should have better cracking resistance.
- The rejuvenation mechanism of recycling agents varies by recycling-agent type.

  The paraffinic oil P was included in this study as a presumed poor recycling agent. Blends with P had no problem satisfying target PG grades, but all evidence places this potential recycling agent in a category by itself as being the poorest performer that serves only as a softening agent, not a rejuvenator. Even though the paraffinic oil P showed almost no oxygen uptake on aging, a lack of compatibility with increasingly structured oxidized aromatics killed molecular motion, leading to extraordinarily low phase angles, high G-R parameter values, and marginal to failing performance predictions. These same problematic issues pervade industry concerns that high concentrations of REOB in binder blends lead to premature cracking. REOB is likewise a highly aliphatic oil that appears unable to stabilize asphaltenes in highly aged (40-h PAV) binders.

The aromatic extract A1 has historically been the gold standard for petroleum-based recycling agents. Often promoted as replacing the aromatics and resins lost to oxidation, these recycling agents can maintain compatibility with oxidized asphaltenes under much more rigorous aging conditions than their paraffinic counterparts. For this study, A1 served as a known control. Within appropriate limits for base binder quality and RAP quality and proportion, aromatic extracts can work well as recycling agents. However, based on the results from the TX field project, these recycling agents cannot restore cracking resistance when combined at high RBRs with low-quality binder blends and highly aged recycled materials including RAP and RAS. When viewed in the context of restoring binder rheology in Black space, A1 was much better than P. When used with appropriate constraints as proposed subsequently, A1 can be an effective recycling agent.

Nonvolatile vegetable oils and reacted bio-based oils offer a very different path to asphalt compatibilization and rejuvenation. There are no aromatics to compatibilize the asphaltenes in aged recycled binders. Instead, these recycling agents act almost like an emulsifier, with the highly polar carbonyl groups on the molecules interacting with polar sites on asphaltene agglomerates, while the less polar olefinic chain remains in the binder's mobile phase. The double bonds on the olefin chain increase molecular motion and lower the glass transition of the mobile phase. The result is an increased phase angle and better cracking resistance. With aging, the benefits of the double bond may be taken away through oxidative aging of the recycling agent itself. However, this oxidation does not always have the expected negative impact on rheological parameters tied to cracking. When vegetable or reacted bio-based oils are present during aging, much of the consumed oxygen goes to reducing the G-R/CA_g HS of the rejuvenated blend, rather than reducing the phase angle. That is, each oxygen atom reacting with a bio-based molecule has much less impact on G-R because these carbonyls do not lead to the type of asphaltene agglomerations that inhibit stress relaxation. Some oxidation of the double-bond sites on the recycling agent molecule could even be helpful by creating more compatibility with asphaltenes through polar interactions. Certain vegetable oil and reacted bio-based oil recycling agents have been chemically stabilized to further reduce the impact of long-term aging. Among the seven recycling agents included in this study, the modified vegetable oils V2 and V3 and the reacted bio-based oils B1 and B2 consistently showed the lowest G-R parameter values after PAV aging of rejuvenated blends. Even though each of these recycling agents elevates the carbonyl content as measured by FT-IR, the extra oxygen seems to have a positive impact on ultimate cracking resistance. Pure vegetable oils are usually edible, and flash points are high, so no safety concerns are reported. Although not included in this study, saturated fatty acid chains with no double bonds, such as steric or palmitic acid, have high melting points and behave like waxes. Even when substituted on larger triglyceride molecules, saturated fatty acids will crystallize and thereby damage rheological properties needed for cracking resistance. Thus, not all reacted bio-based oils should be used as recycling agents.

Tall oil T1 is a pine tree by-product from paper production. Given its moderate olefin content, the cracking resistance of aged blends with T1 was generally better than that for blends with the aromatic extract A1, but typically not as good as the vegetable oils and reacted bio-based oils. In addition, the molecular weight is lower, so T1 may also be slightly volatile.

- The current classification system for recycling agents is best described by ASTM D4552. This specification is based on kinematic viscosity at 60°C, flash point, saturates content, and viscosity ratio with short-term aging (TFO or RTFO). As discussed previously, the aging index based on complex viscosity for the recycling agent itself could be highly misleading, and this specification for recycling agents does not include critical aged rheological properties for the rejuvenated blend. Based on these results, evaluation tools are proposed for rejuvenated blends with long-term aging in Black space instead to capture the different rejuvenating mechanisms

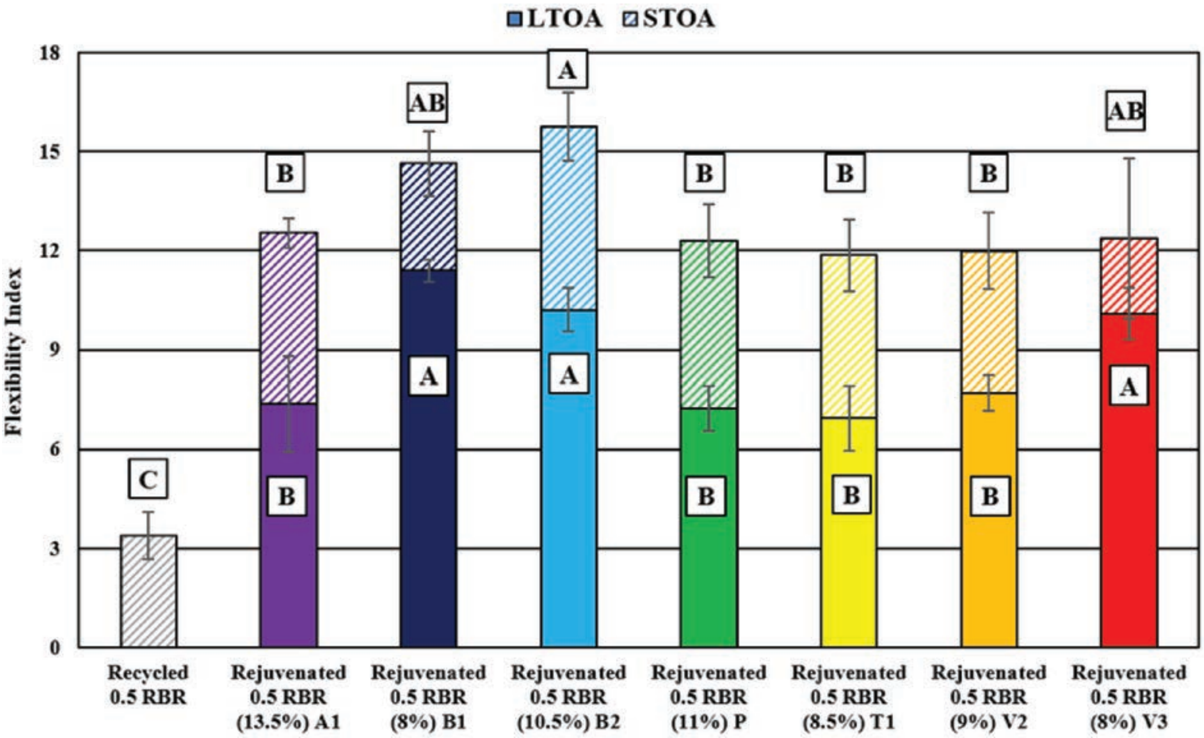


Figure 66. FI results for mixtures with different recycling agents.

used to restore rheology by different types of recycling agents that may be listed on a qualified products list.

Mixture characterization tests including I-FIT and HWTT were also conducted for comparison to the corresponding binder blends. Results shown in Figure 66 and Figure 67 illustrate similar rankings, with the reacted bio-based oils B1 and B2 and the modified vegetable oil V3 exhibiting superior performance in terms of FI, and the reacted bio-based oil B1 and the tall oil T1 exhibiting superior performance in terms of rutting resistance. For both mixture tests, the paraffinic oil P exhibited relatively poor performance, especially in terms of rutting resistance.

4.4 Mixture Performance

The effects of recycling, aging, and rejuvenation were evaluated on asphalt mixture performance in terms of stiffness/rheology by M_R and mixture Black space analysis with |E*| and G-R_m, intermediate-temperature cracking resistance by FI and CRI, low-temperature rheology and cracking resistance by BBR_m results and CRI_{Env}, and rutting resistance by $N_{12.5}$. Similar to binder blends, the selected recycling-agent doses to match continuous PGH for the target climate were evaluated using various base binders, recycled materials, RBRs, and recycling-agent types, taking into consideration different target climates: PG 70–22 (TX), PG 64–22 (IN), PG 64–28 (NV and DE), and PG 58–28 (WI). Table 26, Table 27, Table 28, Table 29, and Table 30 summarize the components and characteristics of the asphalt mixtures evaluated. Gray shading indicates field project combinations.

Similar to the evaluation of binder blends, the DOT control mixtures were regarded as the reference mixtures. Therefore, DOT control mixtures were compared to other mixtures of similar or higher RBR with recycling agent to evaluate the effectiveness of the recycling agents at the

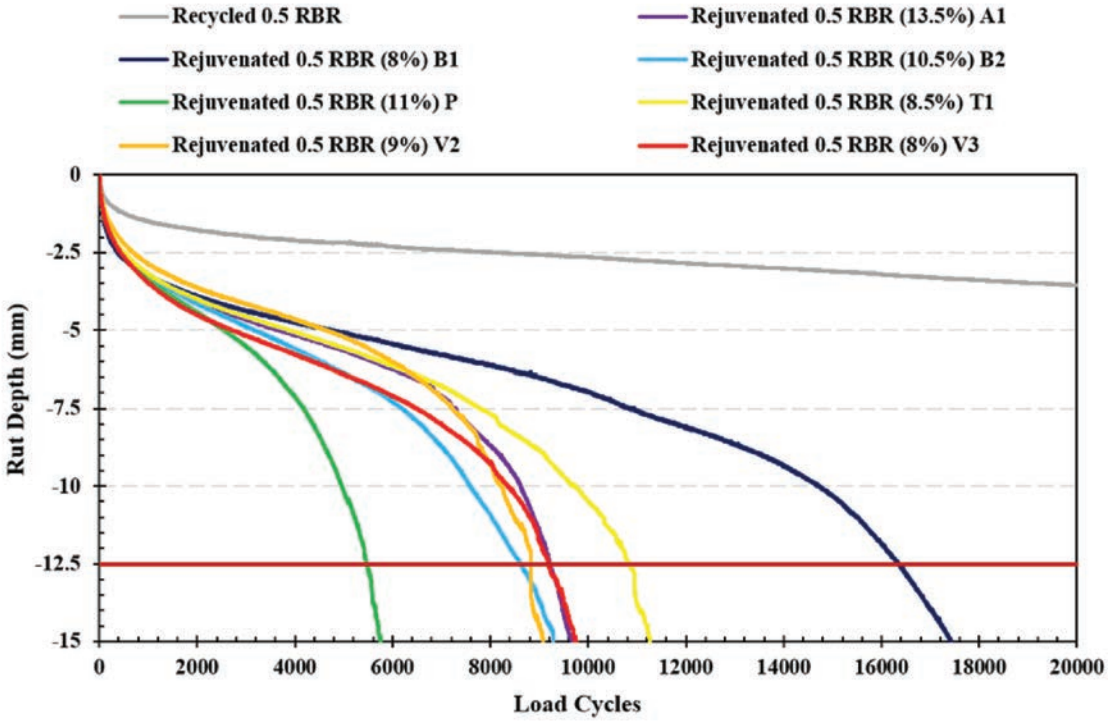


Figure 67. HWTT results for mixtures with different recycling agents.

selected doses in improving the performance of the DOT control mixtures, and in facilitating the use of higher RBR than currently allowed by the DOTs.

Results presented in this section are for LMLC specimens after STOA and LTOA. For M_R, FI, and CRI, the darker shade stacked column represents the results after STOA, and the hatched lighter-shade stacked column represents the results after LTOA. The error bars in each column represent ± one standard deviation from the average value based on the replicate measurements, and the letters inside each column represent Tukey's honestly significant difference (HSD), in which mixtures not connected with the same letter are considered significantly different. For the |E*| and BBR_m tests, Black space diagrams are presented, where the unfilled symbols represent the STOA specimens and the filled symbols represent the LTOA specimens.

4.4.1 Stiffness/Rheology (M_R, Intermediate-Temperature Mixture Black Space with |E*| and G-R_m)

As Figure 68 indicates, M_R results show that adding the selected dose of recycling agent to match continuous PGH for the target climate is more effective than adding the field dose in producing asphalt mixtures with statistically lower stiffness to that of the DOT control mixture with similar RBR (TX), or producing asphalt mixtures with statistically similar or lower stiffness to that of the DOT control mixtures with lower RBR (IN, NV, WI, and DE).

To explore beyond mixture stiffness, mixture Black space (log of |E*| versus phase angle) diagrams were used to qualitatively examine the relative location of mixtures with recycling, aging, and rejuvenation similar to the binder/binder blend analysis. In these diagrams, unfilled symbols represent the STOA condition, while filled symbols represent the LTOA condition. As for binders, with aging or the addition of recycled materials, the mixture rheological state moves from the lower right corner to the upper left corner of the plot, which indicates an increase in stiffness with a corresponding reduction in phase angle. With the addition of recycling agent for

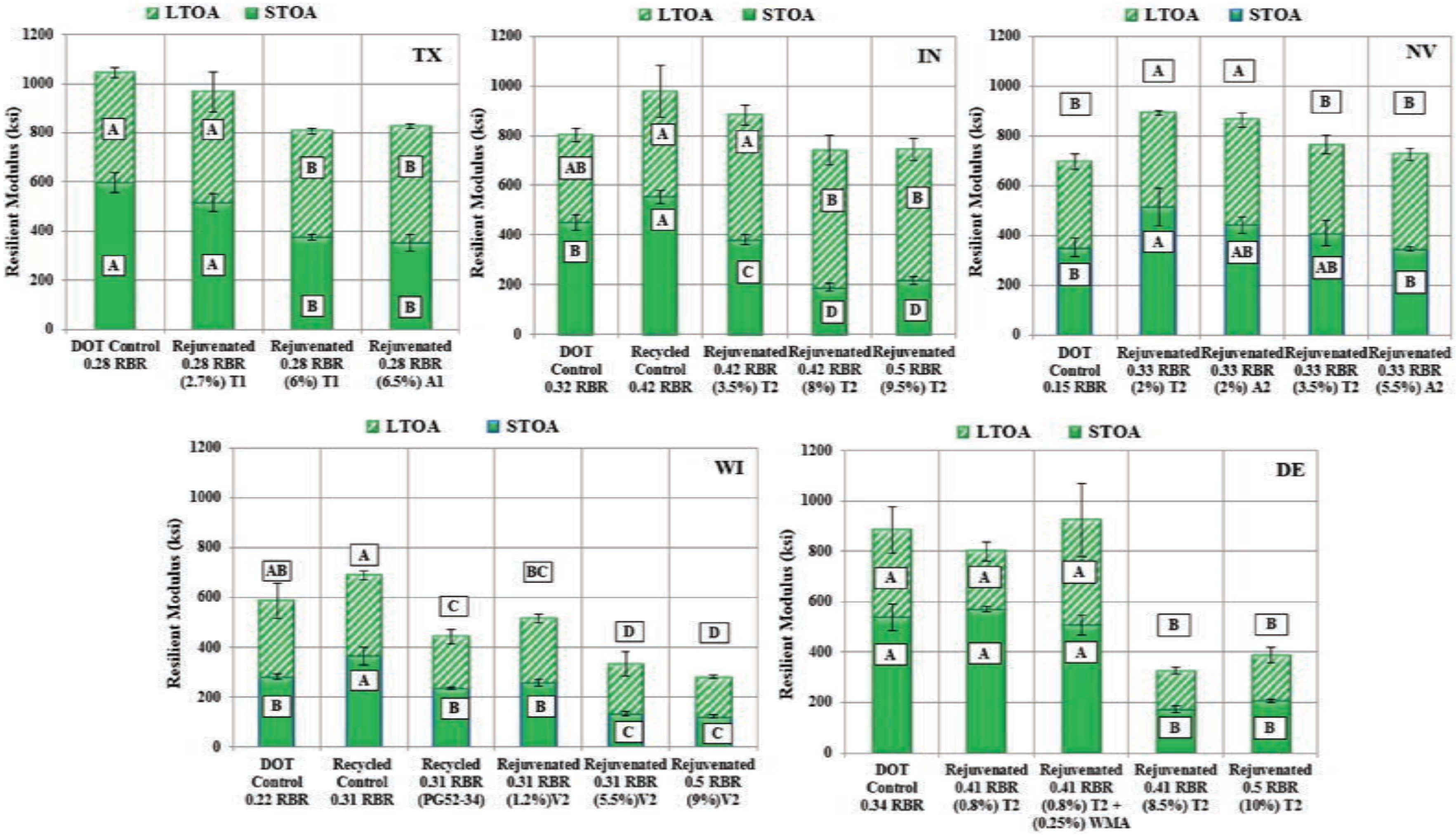


Figure 68. M_R *test results.*

rejuvenation, mixtures are expected to move toward the lower right corner, which indicates a reduction in stiffness with a corresponding increase in phase angle.

The magnitude and slope between two points in mixture Black space were also determined to quantitatively evaluate the change in rheological properties with aging, as defined in Equation 21 and Equation 22, respectively:

$$Magnitude = \sqrt{(\phi_{cond\,1} - \phi_{condo\,2})^2 + \left(Log\,|E*|_{cond\,1} - Log\,|E*|_{cond\,2}\right)^2} \qquad \text{[Equation 21]}$$

$$Slope = \left| \frac{Log\,|E*|_{cond\,1} - Log\,|E*|_{cond\,2}}{\delta_{cond\,1} - \delta_{cond\,2}} \right| \qquad \text{[Equation 22]}$$

where

$\phi_{cond\,1}$ = Condition 1 phase angle,
$\phi_{cond\,2}$ = Condition 2 phase angle,
$|E*|_{cond\,1}$ = Condition 1 dynamic modulus, and
$|E*|_{cond\,2}$ = Condition 2 dynamic modulus.

Generally, a smaller magnitude and steeper slope (less loss of phase angle) is desirable with aging.

G-R_m was also calculated and plotted in bar charts, with comparisons made against the reference DOT control mixture with a lower value desirable for better cracking resistance. In the bar charts, error bars represent + one standard deviation of average calculated values, and the letters inside each column represent Tukey's HSD statistical analysis results, with mixtures connected with the same letter statistically similar.

The Black space plot for the IN mixtures is shown in Figure 69, and the corresponding G-R_m results are shown in Figure 70. Both of these analyses indicate that the use of recycling agent at the dose to match continuous PGH for the target climate facilitates increasing RBR (to 0.4 or 0.5), even with LTOA, with statistically equivalent performance (and similar slope) to that of the DOT control mixture with lower RBR despite longer aging paths (larger magnitude). After STOA, a lower dose of recycling agent was also effective.

The Black space plot for the WI mixtures is shown in Figure 71, and the corresponding G-R_m results are presented in Figure 72. Both of these analyses show that for both aging conditions, the use of the lower field dose of recycling agent (1.2% V2) with higher 0.31 RBR resulted in rheological performance similar to that of the DOT control mixture at lower 0.22 RBR, but the use of the softer base binder (PG 52–34) resulted in improved performance with a shorter aging path (smaller magnitude) and steeper slope. At the recycling-agent doses to match continuous PGH for the target climate (5.5% for 0.31 RBR, 9% for 0.5 RBR), the resulting mixtures were even softer and less brittle (higher phase angle) with longer aging paths (larger magnitude) and steeper slopes compared to those of the DOT control mixture. Again, the use of recycling agents at the dose to match continuous PGH facilitated the use of higher RBRs.

The Black space plot for the DE mixtures shown in Figure 73 and the corresponding G-R_m results presented in Figure 74 concur with those from the other field projects. Both of these analyses show that for both aging conditions and with or without the WMA additive, the use of the lower field dose of recycling agent (0.8% T2) with higher 0.41 RBR resulted in rheological performance similar to that of the DOT control mixture at lower 0.33 RBR. At the recycling-agent doses to match continuous PGH for the target climate (8% for 0.41 RBR, 10% for 0.5 RBR), the resulting mixtures with similar slopes were significantly softer and less

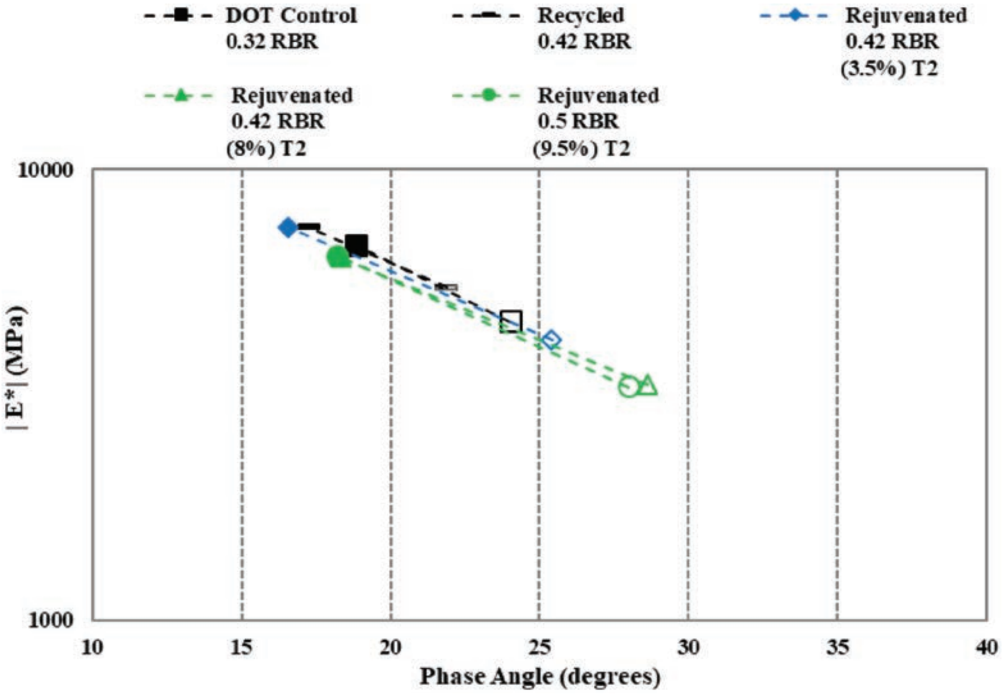


Figure 69. |E| test results in mixture Black space for IN mixtures.*

brittle (higher phase angle) with longer aging paths (larger magnitude) compared to those of the DOT control mixture.

4.4.2 Intermediate-Temperature Cracking Resistance (FI)

Figure 75 indicates that adding the selected dose of recycling agent is more effective than the field dose in producing asphalt mixtures with statistically higher FI than that of the DOT

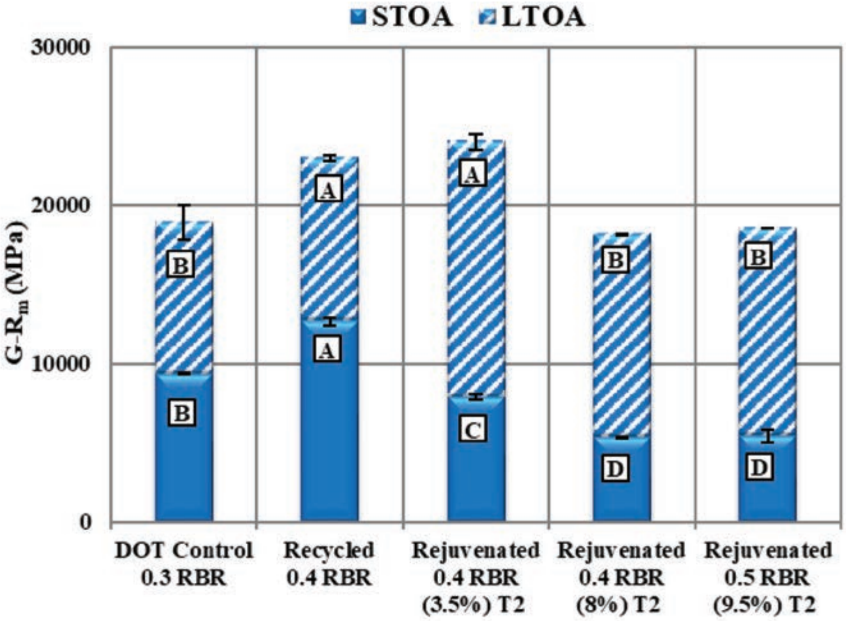


Figure 70. G-R_m results for IN mixtures.

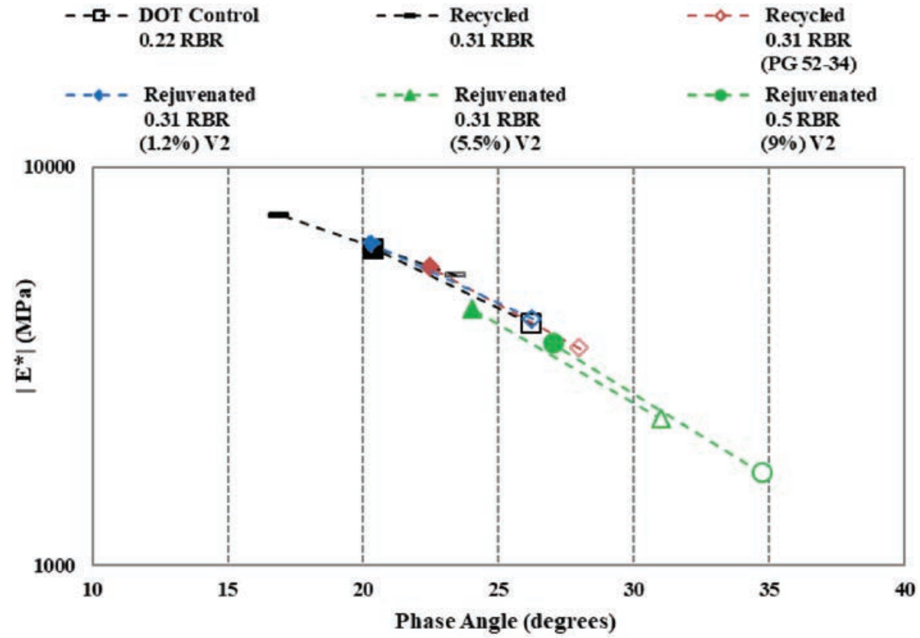


Figure 71. |E| test results in Black space for WI mixtures.*

control mixture with similar RBR (TX), or producing high RBR asphalt mixtures with statistically similar or higher FI to that of the DOT control mixtures with lower RBR (IN, NV, WI, and DE).

Similarly, Figure 76 for the CRI values demonstrates that adding the selected dose of recycling agent was adequate in producing asphalt mixtures with statistically higher CRI values than those of the DOT control mixture with similar RBR (TX), or producing asphalt mixtures with statistically similar or higher CRI values than those of the DOT control mixtures with lower RBR (IN, NV, WI, and DE).

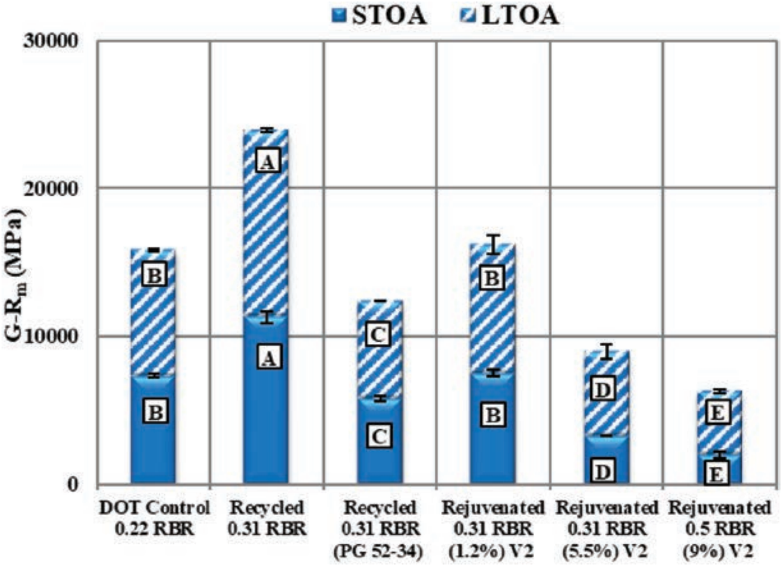


Figure 72. G-R$_m$ results for WI mixtures.

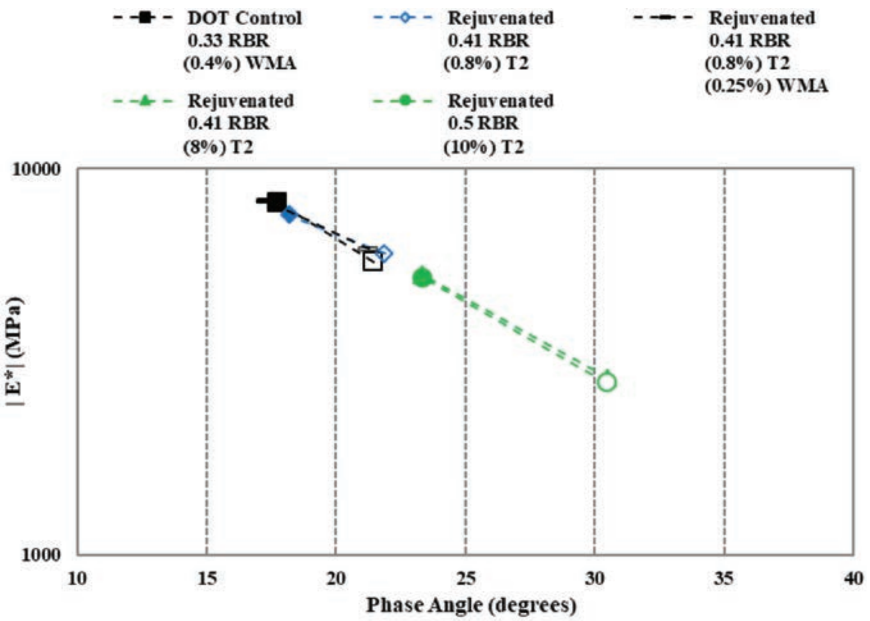


Figure 73. |E| test results in Black space for DE mixtures.*

4.4.3 Low-Temperature Cracking Resistance (Low-Temperature Mixture Black Space with S_m and m-value$_m$, CRI$_{Env}$)

The BBR$_m$ test and the UTSST were used to explore low-temperature mixture cracking resistance as data were available for different materials combinations from the five field projects. Low-temperature Black space is shown in Figure 77, along with the cracking thresholds developed by Romero (2016) based on field performance in Utah. These BBR$_m$ results consistently indicate that adding the selected dose of recycling agent was adequate in producing asphalt mixtures with similar or lower creep stiffness (S) and similar or higher relaxation (m-values) to the DOT control mixture with similar or lower RBR.

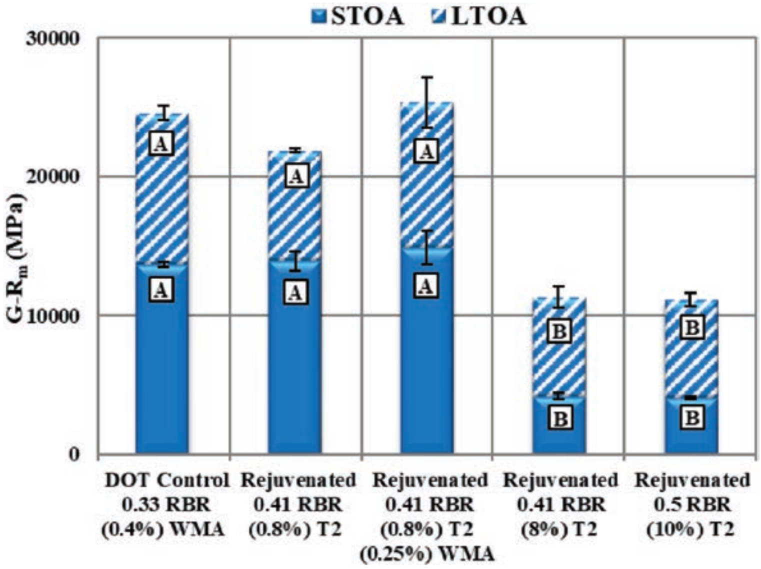


Figure 74. G-R$_m$ results for DE mixtures.

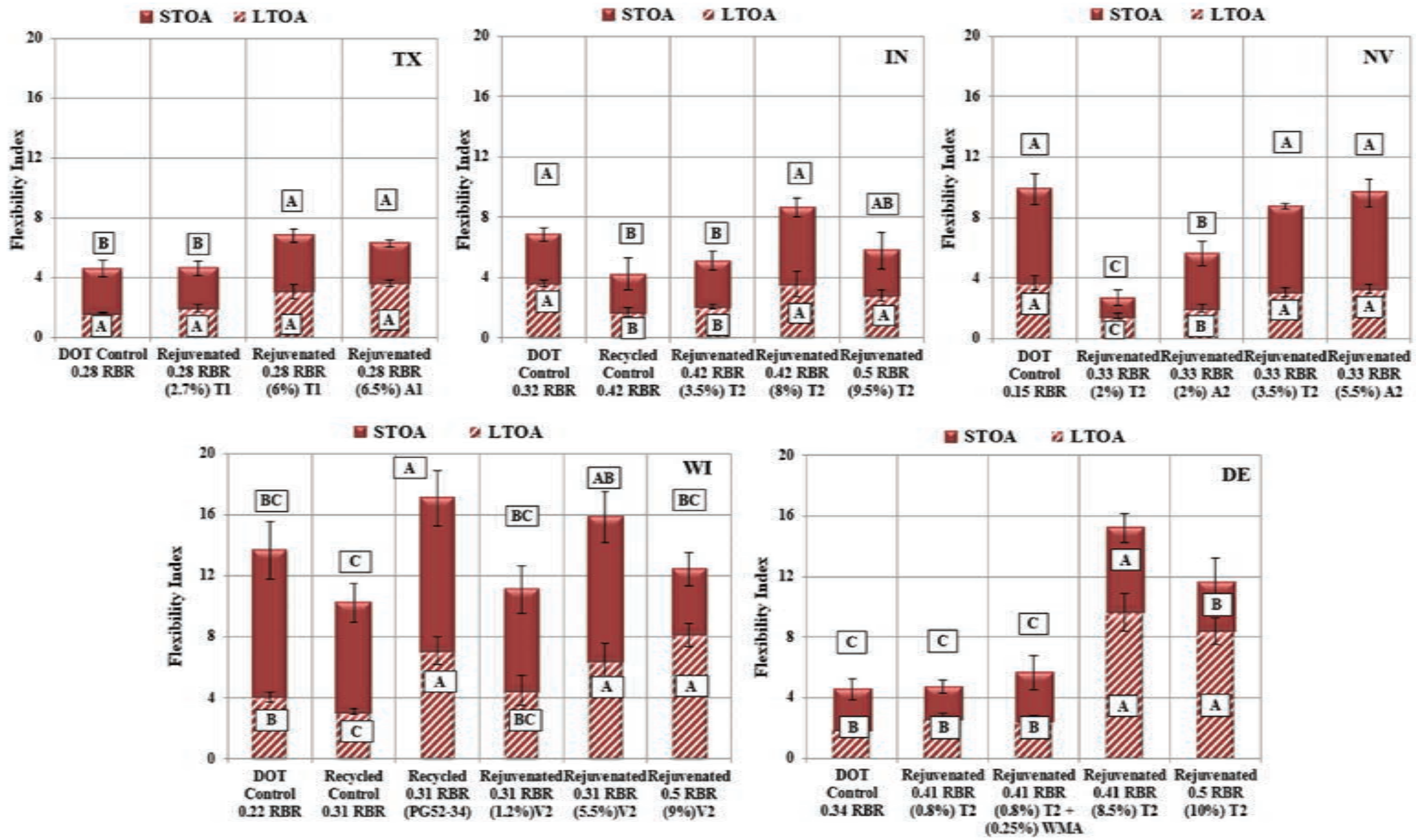


Figure 75. FI results.

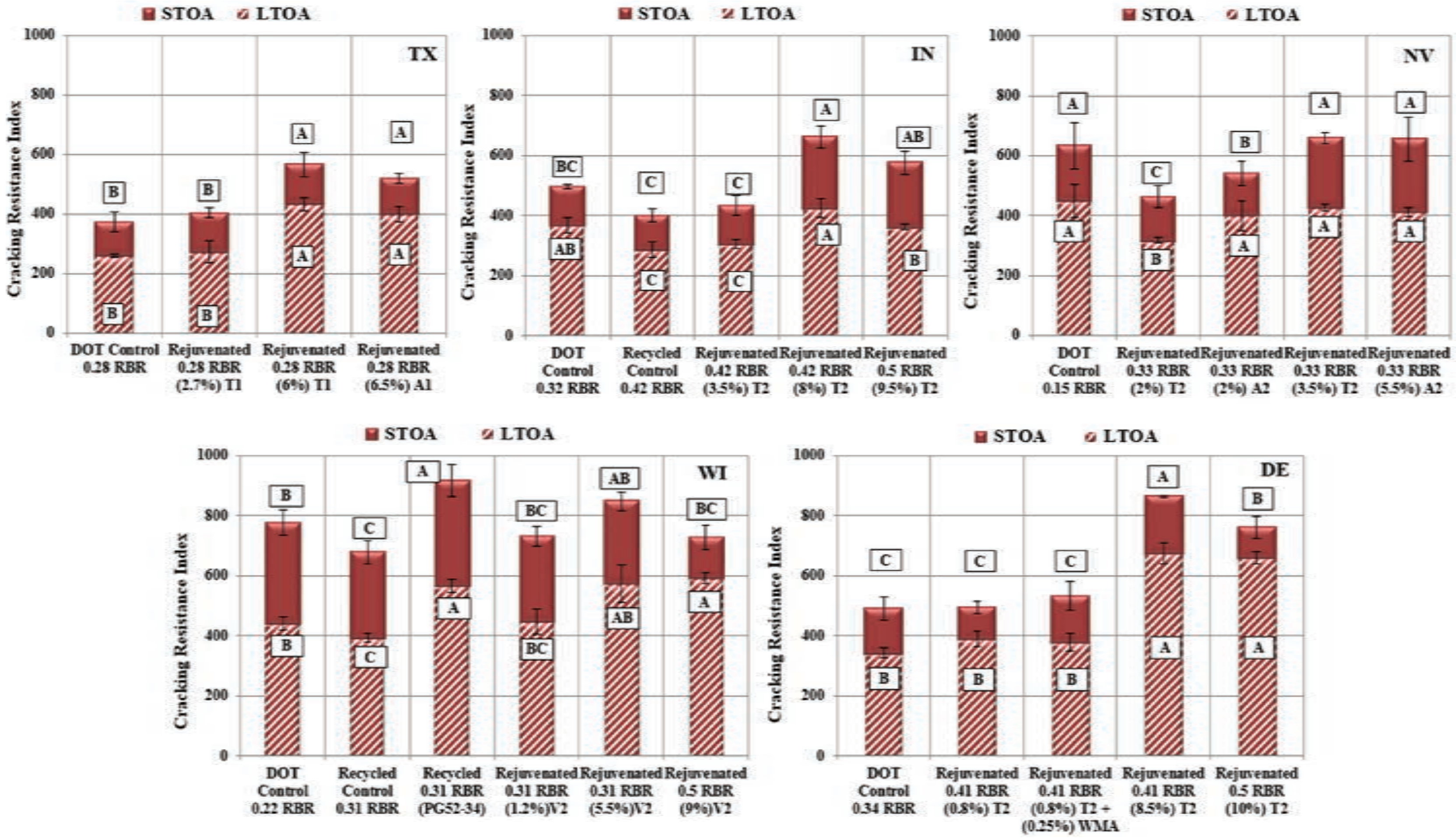


Figure 76. CRI results.

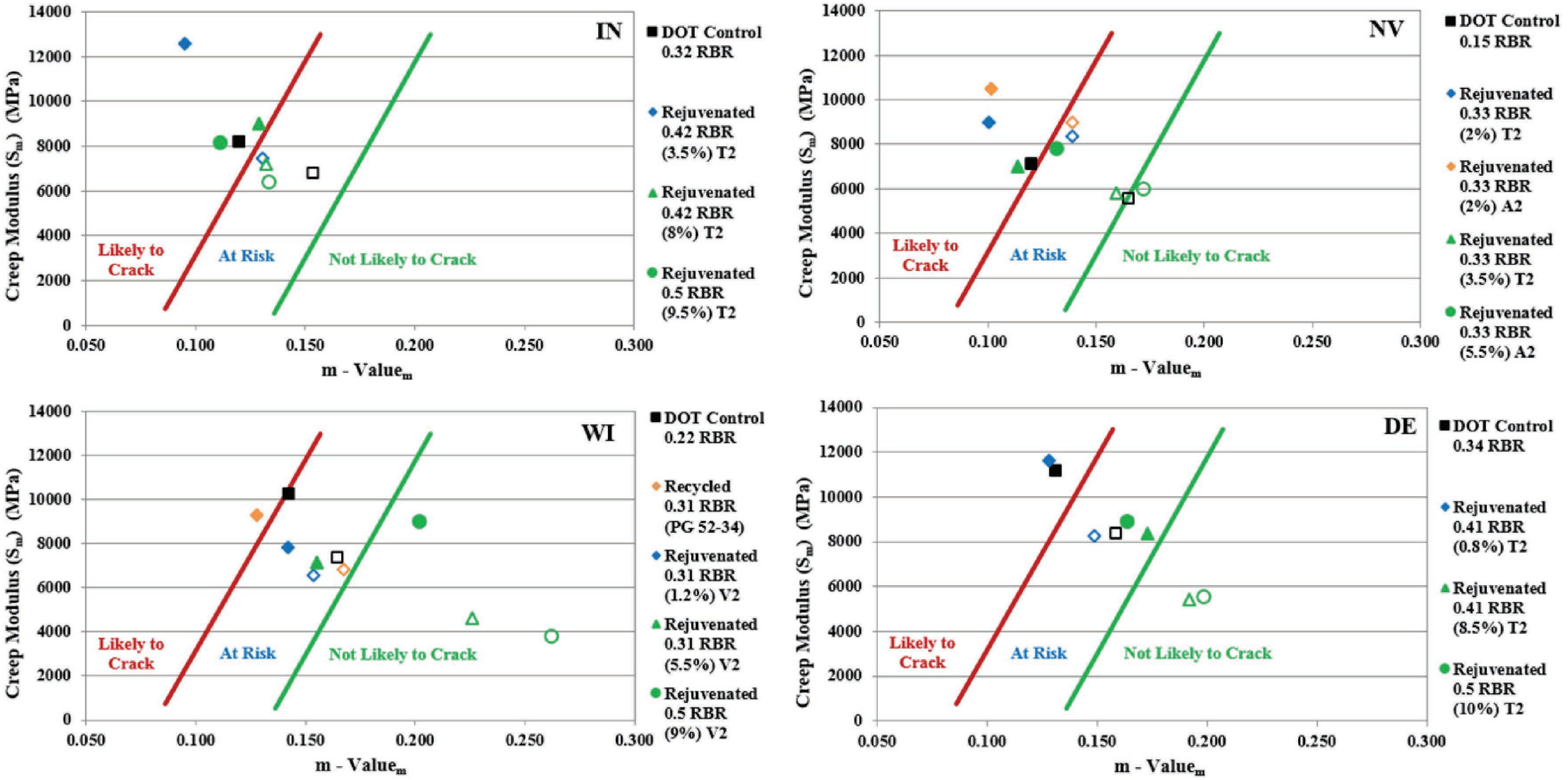


Figure 77. BBR$_m$ test results (unfilled symbols represent STOA specimens while filled symbols represent LTOA specimens).

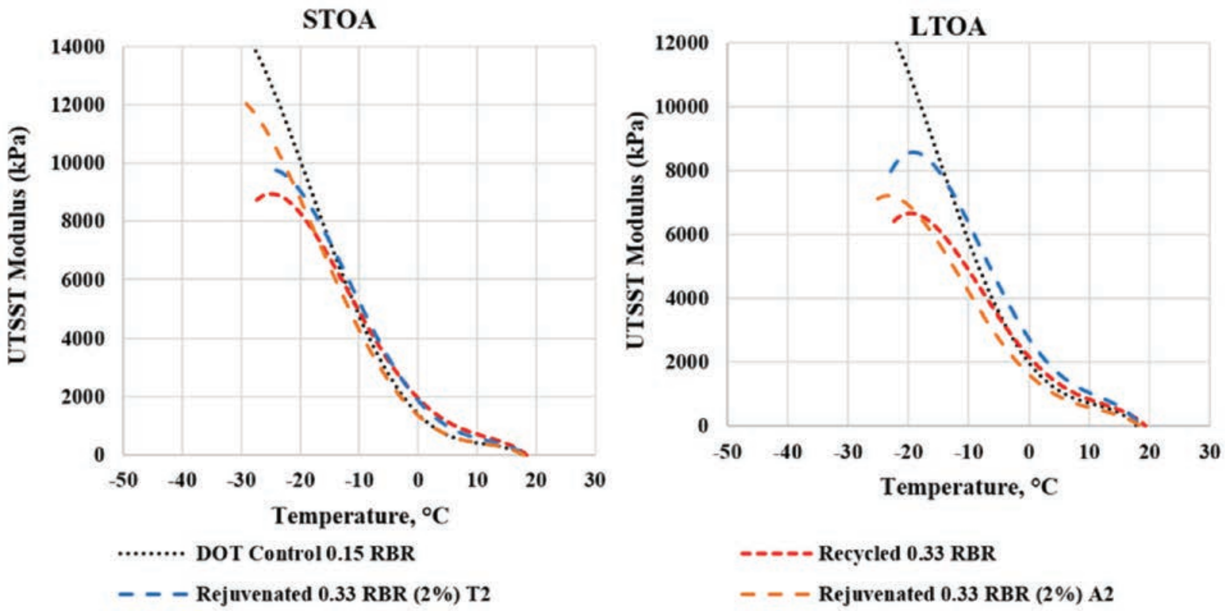


Figure 78. UTSST modulus curves for NV LMLC mixtures.

UTSST modulus and CRI_{Env} results for NV LMLC mixtures at different levels of aging are presented in Figure 78 and Figure 79, respectively. The moduli variation with decreasing temperature shows the low-temperature behavior of the mixture with a focus on viscous softening, crack initiation, and fracture for this study, while the CRI_{Env} provides an overall index that simultaneously takes these different aspects of behavior into account. For all mixtures at high 0.33 RBR, the effect of aging was seen by a shortening of the viscous softening plateau and a shift to warmer crack initiation and fracture temperatures. Similar effects of recycling were also shown when comparing the DOT control mixture to the recycled mixture at the higher 0.33 RBR at the same aging level. The effect of rejuvenation is opposite to that of aging, with a rotation counterclockwise and resulting decreased stiffness and colder crack initiation and fracture temperatures, and for both aging levels, this effect was illustrated for the mixture with A2 with a more pronounced

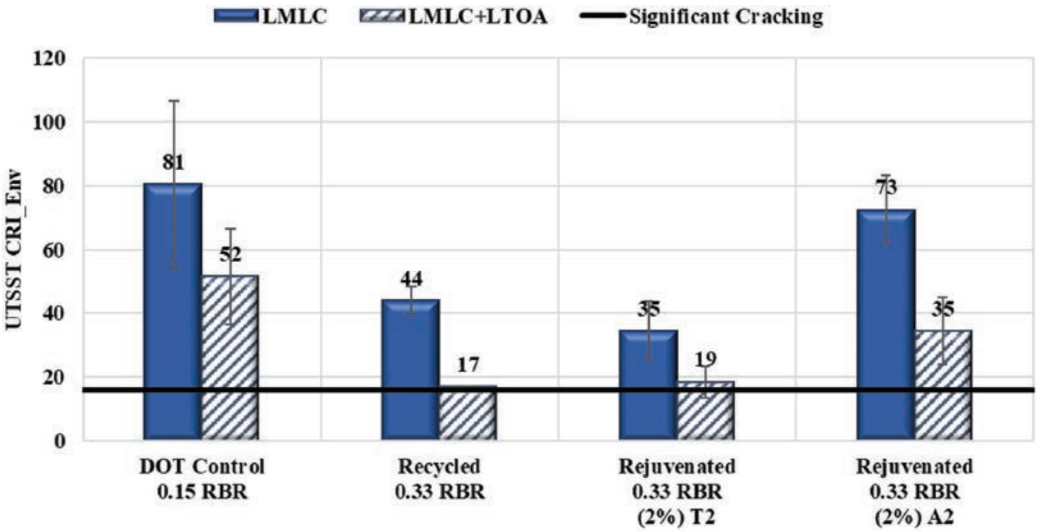


Figure 79. CRI_{Env} results for NV LMLC mixtures.

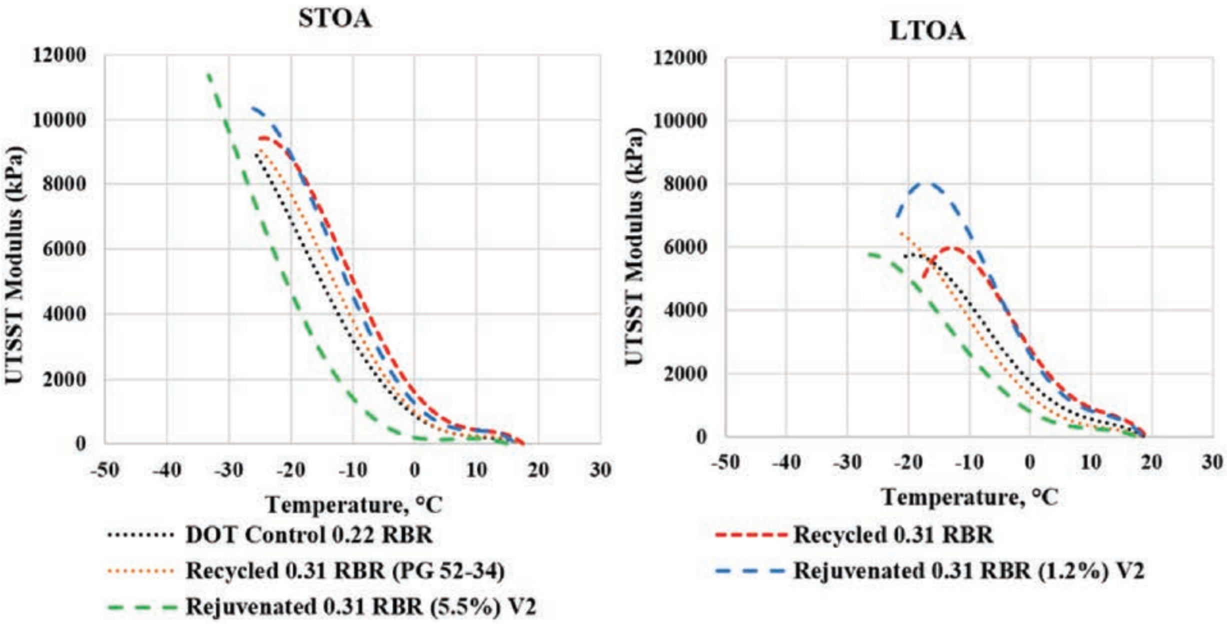


Figure 80. UTSST modulus curves for WI LMLC mixtures.

effect after LTOA. These results were confirmed by $\mathrm{CRI}_{\mathrm{Env}}$ values, although all three mixtures at high 0.3 RBR (both the recycled mixture and both rejuvenated mixtures) exhibited inadequate low-temperature cracking resistance based on the proposed threshold after LTOA.

UTSST modulus and $\mathrm{CRI}_{\mathrm{Env}}$ results for WI LMLC mixtures at different levels of aging are presented in Figure 80 and Figure 81, respectively. For all mixtures, the effect of aging was seen by a shortening of the viscous softening plateau and a shift to warmer crack initiation and fracture temperatures. Similar effects of recycling were also shown when comparing the DOT control mixture to the recycled mixture at higher 0.31 RBR at the same aging level. The effect of rejuvenation is opposite to that of aging, with a rotation counterclockwise and resulting decreased stiffness and colder crack initiation and fracture temperatures, and for both aging levels, this effect was illustrated for the rejuvenated mixtures and the mixture with a softer base binder with

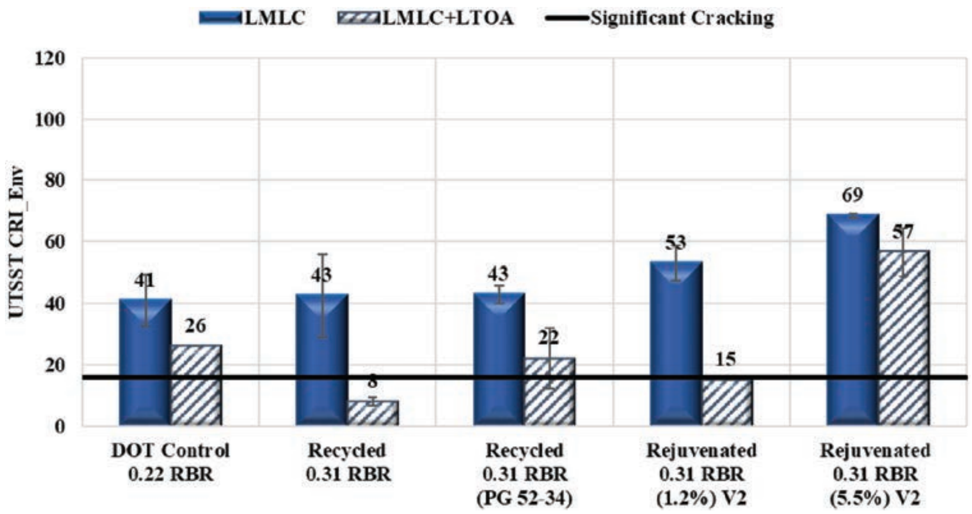


Figure 81. $\mathrm{CRI}_{\mathrm{Env}}$ results for WI LMLC mixtures.

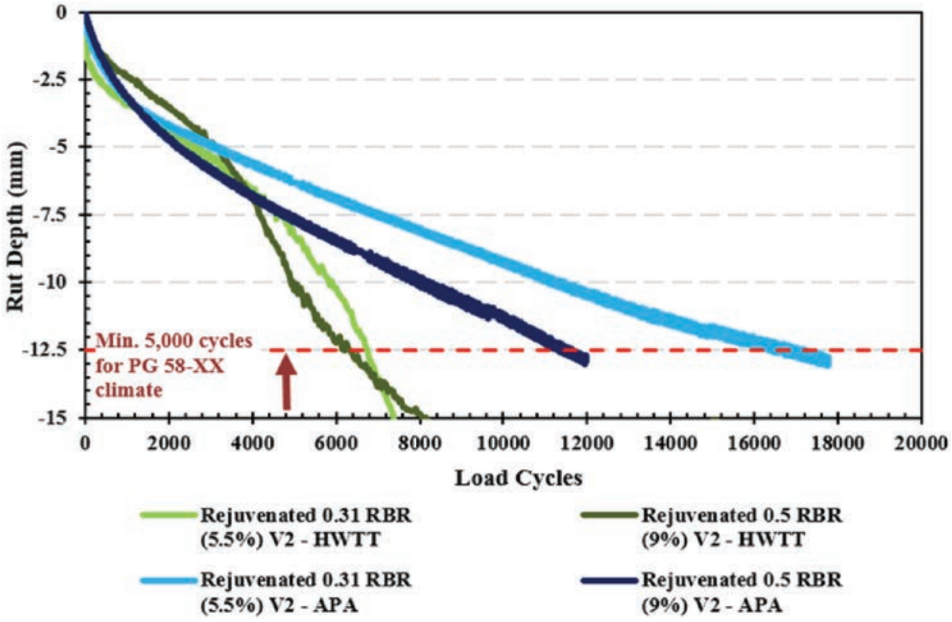


Figure 82. HWTT and APA test results for WI mixtures.

a more pronounced effect after LTOA. These results were confirmed by CRI_{Env} values, although the higher recycling-agent dose provided sufficient low-temperature cracking resistance even after LTOA.

4.4.4 Rutting Resistance

Figure 82 and Figure 83 show results for the HWTT tests (in wet condition), which demonstrated that WI asphalt mixtures (with the soft PG 58–28 base binder) and DE asphalt mixtures

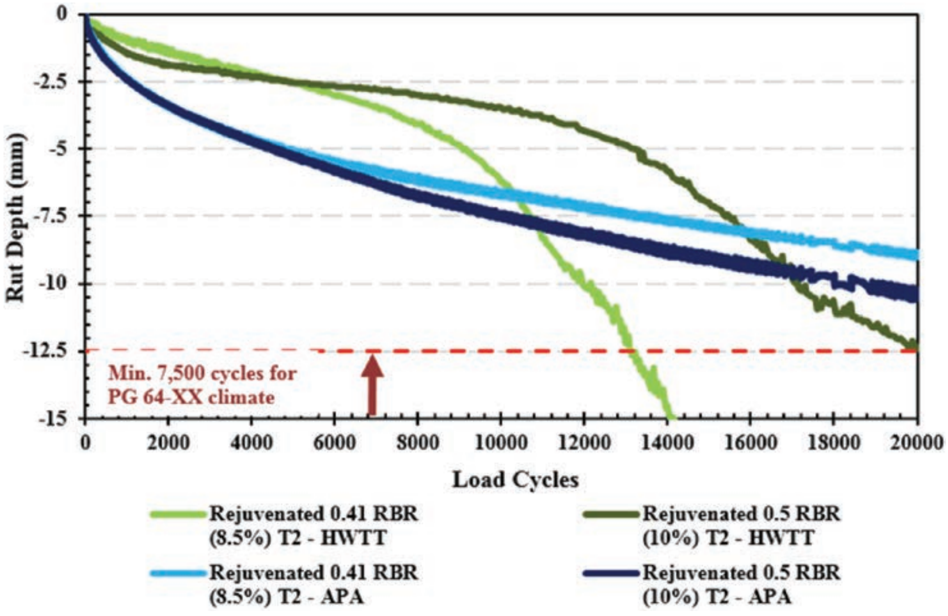


Figure 83. HWTT and APA test results for DE mixtures.

(with PG 64–28 base binder), all with the recycling agent at the selected dose, passed the minimum rutting requirements. In similar climates, mixtures with a target PG 58-XX and PG 64-XX climate are required to sustain at least 5,000 and 7,500 load cycles, respectively, before achieving 12.5 mm rut depth. As expected, APA results (in dry condition) demonstrated improved rutting resistance when water was not present. HWTT and APA test results confirmed that the doses to match continuous PGH of the target climate were not excessive in terms of being detrimental to the rutting performance of the asphalt mixtures.

4.5 Recycled Binder Availability

The amount of RAP binder in the mixture is typically represented as RBR. However, the quantity of effective RAP binder in the mixture is usually unknown, which raises concerns due to its ultimate effect on performance. The term *effective RAP binder* refers to the binder that is released from the RAP, becomes fluid, and blends with the base binder under typical mixing temperatures. Other terms used in the literature include RAP binder contribution, RAP binder activation, degree of RAP activation, RAP working binder, and RAP binder availability, as used in this report.

RAP binder availability is typically addressed through one of three assumptions:

- 0% availability, where the RAP acts as a black rock;
- 100% availability, where all the RAP binder becomes fluid and is available to blend with the base binder; and
- Partial availability, where a portion of the RAP binder becomes fluid and is available to blend with the base binder.

Although rarely measured, it is generally accepted that the third assumption is more realistic (McDaniel and Anderson 2001; D'Angelo et al. 2011). However, in a recent survey discussed in *NCHRP Synthesis 495: Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures* (Stroup-Gardiner 2016), 77% of the responding state highway agencies use the second assumption and consider 100% RAP binder availability; thus, they reduce the base binder content in the mixture by the RAP binder content. About 6% of the respondents in this same survey use the first assumption and consider 0% RAP binder availability, and approximately 17% use the third assumption and consider partial RAP binder availability, assuming around 75% of the RAP binder is available. Designing mixtures with the assumption of 100% availability could result in mixtures with less total binder content than the selected optimum from the mix design. In this case, coatability issues may arise, resulting in a dry mixture with a high AV content with increased potential for cracking, raveling, or moisture damage. Conversely, designing mixtures with the assumption of 0% availability could result in mixtures with potential rutting problems, due to possible excessive total binder content.

4.5.1 Methodology

D'Angelo et al. (2011) investigated the extent of RAP binder availability using the aggregate size exclusion method. In this method, the RAP occupies a designated size in the mixture different from that of the virgin aggregates. After mixing with the base binder, the RAP can be separated from the virgin aggregate, which facilitates evaluation of the binder contents for both materials. If the RAP has a higher binder content than the virgin aggregate, then the RAP binder is not fully available to blend with the base binder. In this case, most of the RAP acts like a black rock and the base binder coats the RAP as it does any other aggregate particle.

In a similar manner, the following methodology was developed and demonstrated in Phase 2 to estimate the RAP binder availability based on an evaluation of mixtures with specific sizes of virgin aggregate and RAP:

1. Prepare the virgin mixture using:
   a. Base binder.
   b. Virgin aggregate with three distinct fractions: a coarse size (passing the ½-in. sieve and retained on the ⅜-in. sieve), an intermediate size (passing the ⅜-in. sieve and retained on the No. 4 sieve), and fine sizes (a combination of material passing the No. 4 sieve and retained on the No. 8 sieve and passing the No. 8 and retained on the No. 30 sieve).
2. Condition the loose mixture in the oven for 2 h at 135°C to simulate short-term aging.
3. Sieve the loose mixture to separate the coated particles into the different sizes while both the mixture and the sieves are hot enough to allow separation.
4. Determine the binder content of each fraction using the ignition oven per AASHTO T 308 and label the binder content of the intermediate size fraction (passing the 3/8-inch sieve and retained on the No. 4 sieve) as *Reference* P_b.
5. Prepare the RAP mixture using:
   a. Base binder.
   b. Virgin aggregate with two distinct fractions: a coarse size (passing the ½-in. sieve and retained on the ⅜-in. sieve) and fine sizes (a combination of material passing the No. 4 sieve and retained on the No. 8 sieve and passing the No. 8 and retained on the No. 30 sieve).
   c. RAP of intermediate size (passing the ⅜-in. sieve and retained on the No. 4 sieve).
6. Repeat Steps 2 through 4 and label the binder content of the intermediate size fraction of RAP (passing the ⅜-inch sieve and retained on the No. 4 sieve) as *RAP′* P_b.

Figure 84 provides an illustration of the proposed methodology. The binder contents of the coated RAP (*RAP′* P_b) and coated virgin aggregate (*Reference* P_b) provide significant insight into the amount of RAP binder that is active and available.

To illustrate the methodology, consider an example of a virgin mixture consisting of base binder and virgin aggregate with distinct fractions with the percent retained for each fraction (by weight of total aggregate) of 28% (⅜ in.), 30% (No. 4), 28% (No. 8), and 14% (No. 30). The total binder content of this mixture is 4.5%. The measured binder contents for each sieve size by ignition oven are 2.7%, 4.0% (*Reference* P_b), and 6.1% for sieves ⅜ in., No. 4, and No. 8 + No. 30, respectively, with the coarse aggregate size absorbing less binder than the intermediate and fine aggregate sizes due to smaller surface area (Brown et al. 2009). The *Reference* P_b value is only valid for this particular mixture, with its specific total binder content and virgin aggregate type and gradation.

When using RAP (with a 4.5% binder content) to prepare a RAP mixture with 0.3 RBR (i.e., 30% RAP binder and 70% base binder) and a total binder content the same as in the virgin mixture (4.5%), the total binder content consists of 3.15% base binder (70%) plus 1.35% RAP binder (30%). Therefore, the base binder contents in each sieve size of aggregate should be close to 70% of the values measured in the virgin mixture with 100% base binder content (i.e., 1.9% [3/8 in.], 2.8% [No. 4], and 4.3% [No. 8 + No. 30]). These values were confirmed by preparing the same virgin mixture but with 3.15% binder content and determining the binder content for each sieve using the ignition oven. The addition of the RAP binder should bring the total binder content for each sieve size of aggregate to 2.7% (3/8 in.), 4.0% (No. 4), and 6.1% (No. 8 + No. 30).

In this RAP mixture, the *RAP′* P_b (binder content of RAP retained on the No. 4 sieve) is measured by ignition oven, and the following three outcomes are plausible depending on how much RAP binder is active or available:

<u>Scenario 1:</u> *RAP′* P_b = *Reference* P_b
= 4.0% in this example.

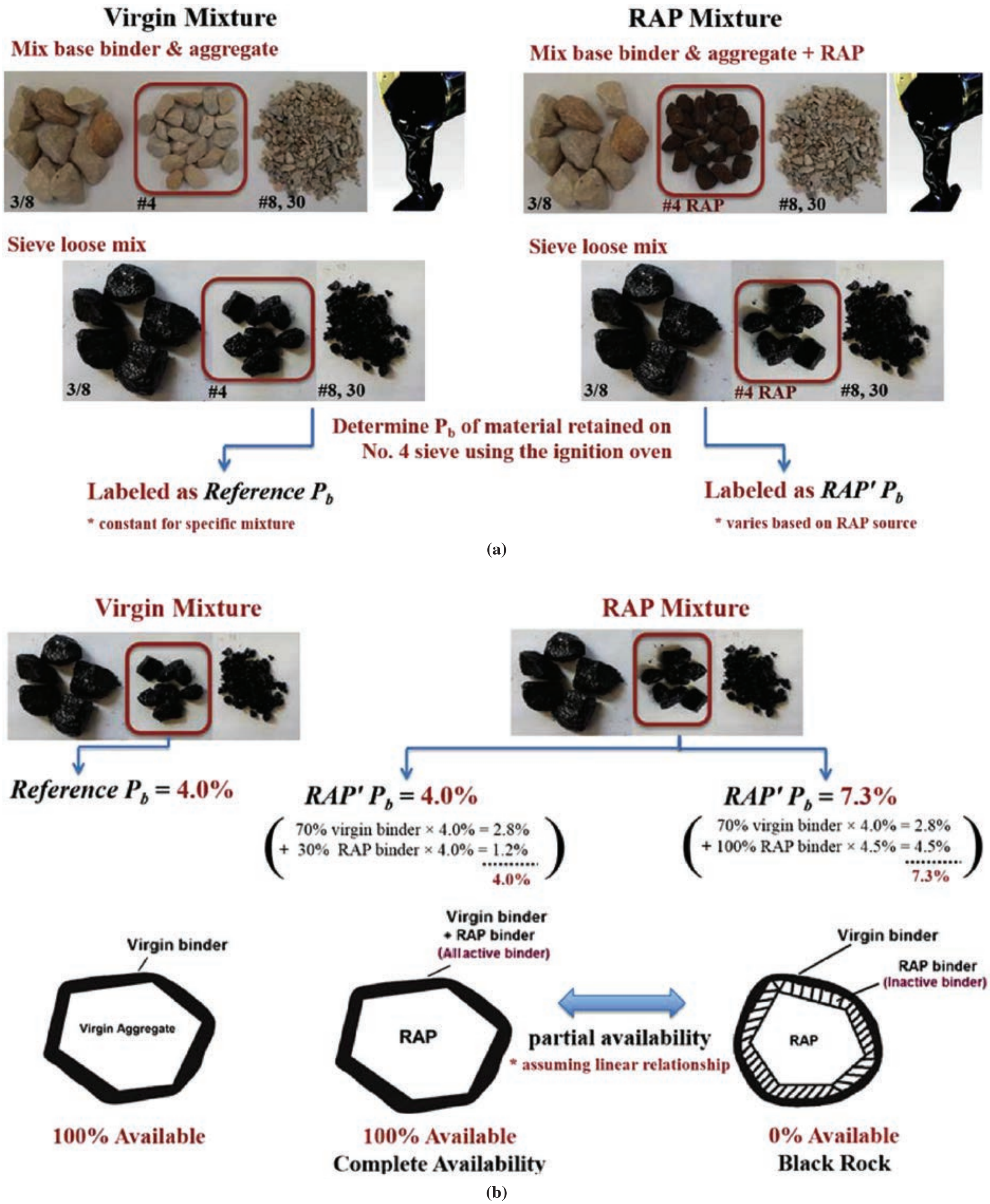


Figure 84. (a) Summary of the proposed method and (b) possible scenarios for RAP binder availability.

The coated RAP particles in the RAP mixture have the same binder content as the coated virgin aggregate particles on the No. 4 sieve in the virgin mixture. This would imply that the RAP binder is fully released, and completely active and available in the mixture, and the total binder blend (base and RAP binders) was evenly distributed within the mixture. This scenario would represent 100% RAP binder availability, as illustrated in Figure 84b.

<u>Scenario 2:</u> $RAP' \ P_b = [1\text{-RBR}] * Reference \ P_b + RAP \ binder \ content$
$= 7.3\%$ in this example.

The coated RAP particles in the RAP mixture have significantly more binder content than the coated virgin aggregate particles on the No. 4 sieve in the virgin mixture, and this difference is equal to the RAP binder content. This would imply that the RAP binder is acting as a black rock and the RAP binder is not available in the mixture. In other words, only the base binder was evenly distributed within the mixture (between the virgin aggregate and the RAP). This scenario would represent 0% RAP binder availability, as illustrated in Figure 84b. In this example, since the contribution from the base binder equals 2.8% (at 70% of the total binder, as calculated and verified previously when only the base binder is available), the $RAP' \ P_b$ will approach 7.3% (2.8% + 4.5%). Again, this value is only valid for these particular mixtures, with their specific virgin aggregate type and gradation, RAP binder content, and the total binder content in the mixture.

<u>Scenario 3:</u> $Reference \ P_b < RAP' \ P_b < ([1\text{-RBR}] * Reference \ P_b + RAP \ binder \ content)$

The coated RAP particles in the RAP mixture have more binder content than the coated virgin aggregate particles on the No. 4 sieve in the virgin mixture, but this difference is less than the RAP binder content. This represents partial binder availability, as illustrated in Figure 84b.

Therefore, the concept behind this methodology is that if there is no difference in binder contents between the coated RAP particles and the coated virgin aggregate particles (both retained on the No. 4 sieve), there is 100% RAP binder availability since the RAP binder is fully released and completely active and available in the mixture. However, if the coated RAP particles have a higher binder content than the coated virgin aggregate particles, then the binder in the RAP is not fully released and not fully active and available in the mixture. Depending on the difference between the binder contents of these particles, the RAP binder availability can be calculated.

To calculate the percent RAP binder availability, a linear relationship, as shown in Figure 85 and Equation 23, can be used between the following two extremes: Scenario 1 when $RAP' \ P_b$

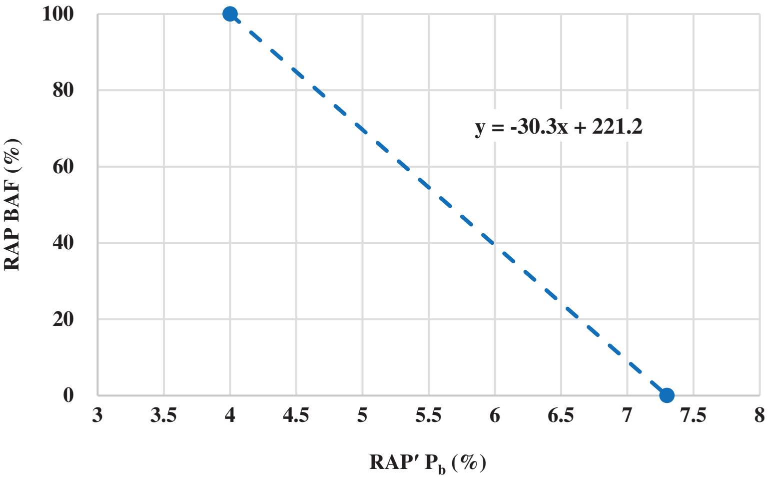


Figure 85. Example relationship between BAF and **RAP′ P_b.**

equals 4.0% in this example, which represents 100% availability, and Scenario 2 when $RAP'\ P_b$ equals 7.3% in this example, which represents 0% availability. From this relationship, a binder availability factor (BAF) for a given $Reference\ P_b$ and $RAP'\ P_b$ can be calculated. The RAP BAF is the percentage of available (effective) RAP binder in the mixture, and this factor can be used to adjust the base binder content in mixtures with RAP, to ensure that the total optimum (active) binder content as prescribed in the mix design is achieved.

$$RAP\ BAF(\%) = m \times RAP'\ Pb + b \qquad [\text{Equation } 23]$$

where

$RAP\ BAF\ (\%)$ = the RAP binder availability factor,
M = the slope (−30.3 in this example),
$RAP'\ P_b$ = the binder content of RAP particles retained on the No. 4 sieve, and
B = the intercept (221.2 in this example).

The slope and intercept values are dependent on both the virgin and the RAP asphalt mixtures (total binder content and aggregate type and gradation), while $RAP'\ P_b$ is dependent on the RAP binder availability. Therefore, as long as the virgin and RAP asphalt mixtures have the same total binder content and aggregate type and gradation, Equation 15 can be used to calculate the BAF. Notably, the value of the slope and intercept will proportionally change with the RAP binder content (i.e., using a different RAP source), but that will have no effect on the BAF. In the 0% availability case (Scenario 2 with $RAP'\ P_b$ equal to 7.3% in this example), $RAP'\ P_b$ will always equal $[1\text{-}RBR]*Reference\ P_b + RAP\ binder\ content$.

4.5.2 Verification

This methodology was initially verified in Phase 2 using artificial RAP (i.e., laboratory aged). The artificial RAP was produced by mixing a PG 64–22 base binder with virgin aggregate fractions retained on the No. 4 sieve at a binder content of 4.5% to simulate RAP particles retained on the No. 4 sieve. This artificial RAP was then aged in the laboratory according to the following protocols:

- No aging: labeled as RAP 1 and representing a soft RAP,
- 5 days at 110°C (230°F): labeled as RAP 2 and representing a stiff RAP,
- 10 days at 110°C (230°F): labeled as RAP 3 and representing a very stiff RAP, and
- 10 days at 110°C (230°F) plus 3 days at 150°C (302°F): labeled as RAP 4 and representing an extremely stiff RAP.

The BAF of each artificial RAP was calculated using the method described previously, by preparing virgin and RAP (artificial) mixtures with virgin aggregate from TX (limestone) with the percent retained for each fraction (by weight of total aggregate) of 28% (3/8 in.), 30% (No. 4), 28% (No. 8), and 14% (No. 30). The RBR in the RAP mixtures was 0.3, and the total binder content in both mixtures was 4.5%. In the virgin mixture, the $Reference\ P_b$ was 4.0% by ignition oven. In the artificial RAP mixtures, the $RAP'\ P_b$ values for each different artificial RAP were also determined by ignition oven.

Figure 86a shows the $RAP'\ P_b$ values for the artificial RAPs. As expected, the soft RAP (RAP 1) had a slightly higher binder content ($RAP'\ P_b$) than the $Reference\ P_b$ (4.27% versus 4.0%), while the extremely stiff RAP (RAP 4) had a much higher binder content ($RAP'\ P_b$) than the $Reference\ P_b$ (6.01% versus 4.0%). This resulted in higher BAF values for RAP 1 compared to RAP 4, as shown in Figure 86b. As expected, the BAF value has a negative correlation with RAP stiffness (or extent of aging): the softer the RAP binder, the higher the BAF.

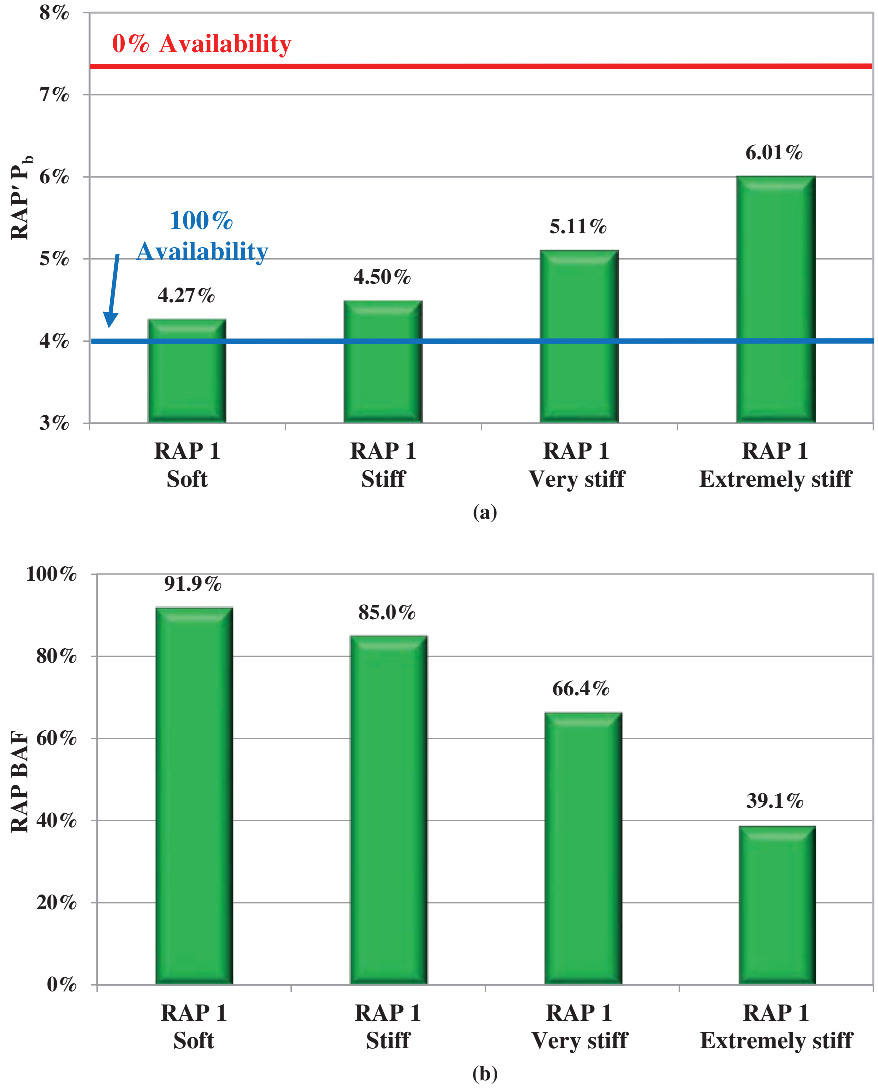


Figure 86. ***(a)*** **RAP' P_b** ***values, and (b) BAF values for asphalt mixtures with artificial RAPs.***

4.5.3 Factors Affecting RAP BAF

The proposed methodology was also used to estimate the RAP BAF of actual RAP materials from seven different sources in the United States: TX, Florida (FL), IN, New Hampshire (NH), NV, DE, and WI. These materials were used to evaluate the impact of the following variables on the RAP BAF:

- Mixing temperature and short-term conditioning period,
- RAP source and RAP binder PG,
- Recycling-agent addition and method of addition, and
- Base binder source (quality).

Mixtures were prepared at two mixing temperatures: 140°C and 150°C. Figure 87 a shows the results of RAP BAF versus mixing temperature. The error bars in each column represent ± one standard deviation from the average BAF value of the two replicates. It is clear that mixing temperature plays a dominant role in increasing the RAP BAF: the higher the mixing

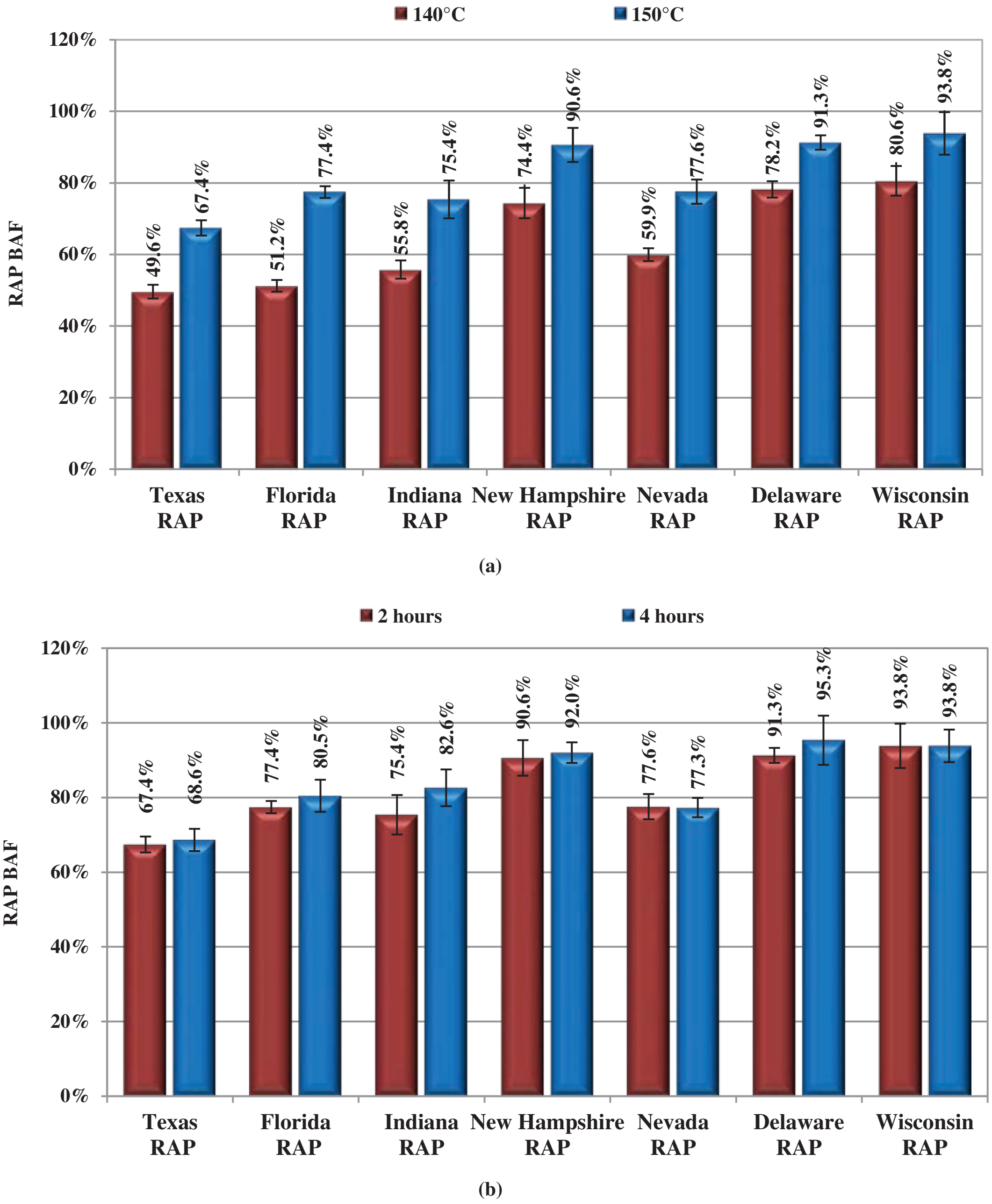


Figure 87. (a) Effect of mixing temperature on RAP BAF and (b) effect of short-term conditioning period on RAP BAF.

temperature, the higher the BAF. This is expected since higher mixing temperatures help soften the RAP binder, making it more fluid and facilitating its blending with the base binder.

Figure 87b shows the estimated RAP BAF of two different short-term conditioning periods (2 h versus 4 h); in both cases, mixing and conditioning temperatures were 150°C and 135°C, respectively. Extending the short-term conditioning to 4 h slightly increased the RAP BAF of FL, IN, and DE RAP sources, but statistically, there was no difference between 2 h versus 4 h of short-term conditioning time.

Figure 88 shows the results of RAP BAF versus RAP binder PGH at 140°C and 150°C mixing temperatures. A clear trend is observed in both cases: the lower the RAP binder PGH, the higher the BAF. Therefore, when mixing at 140°C, for instance, it is estimated that only 50% of the TX

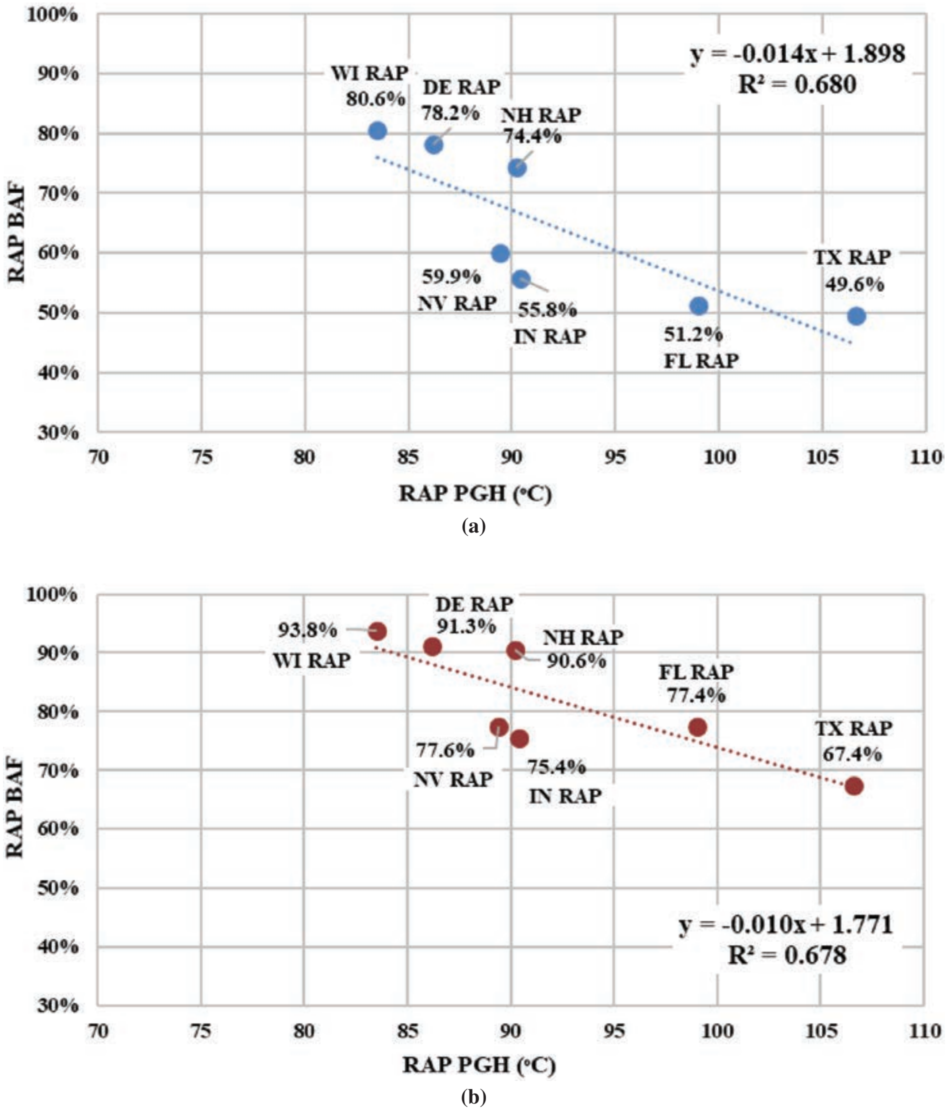
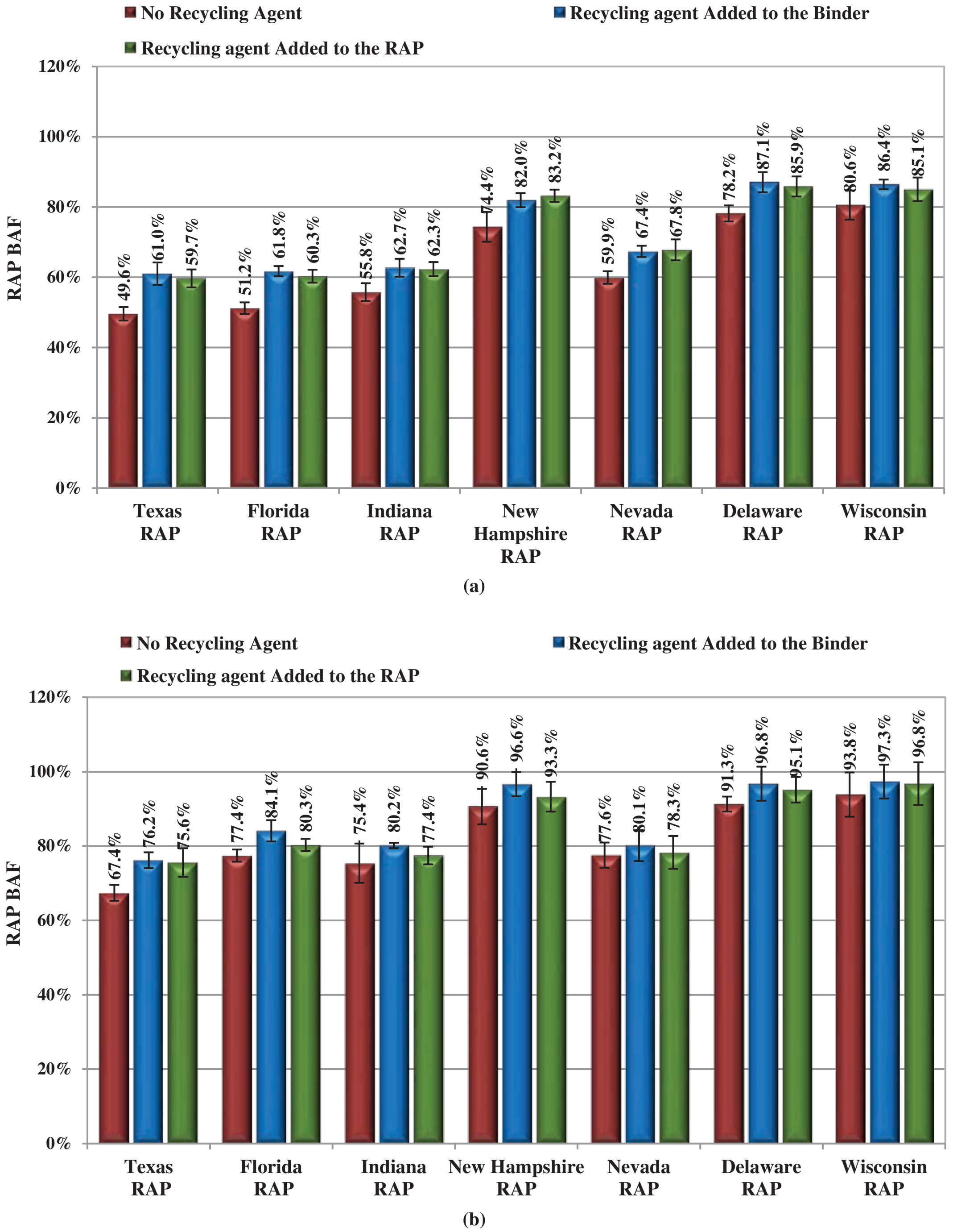


Figure 88. RAP BAF versus RAP PGH at (a) 140°C and (b) 150°C mixing temperature.

RAP binder will be active and available in the mixture, compared to 80% for the WI RAP. However, if the mixing temperature is increased to 150°C, the availability of the RAP binder from TX and WI will increase to about 70% and 95%, respectively.

To evaluate the effect of recycling-agent addition on the RAP BAF, a modified vegetable oil (V2) was added to the RAP mixtures at a dose of 5%. To evaluate the method of recycling-agent addition, the recycling agent was added to the base binder prior to mixing with the virgin aggregate and RAP in one set of RAP mixtures, while in another set, the recycling agent was added directly to the RAP (at room temperature for about 5 min) before mixing with the virgin aggregate and base binder.

Figure 89a shows that including the recycling agent in the mixture clearly increased the RAP BAF for most RAP sources at 140°C mixing temperature. However, the method of adding the recycling agent to the RAP directly, as opposed to mixing it with the base binder, did not show any significant effect on the RAP BAF. This could be due to the fact that the recycling agent was added to the RAP just 5 min before mixing and at room temperature, and thus, there was neither sufficient time nor an elevated temperature to aid the recycling agent in diffusing into the RAP binder.



(a)

(b)

Figure 89. Effect of recycling agent addition and method of addition on RAP BAF at (a) 140°C and (b) 150°C mixing temperature.

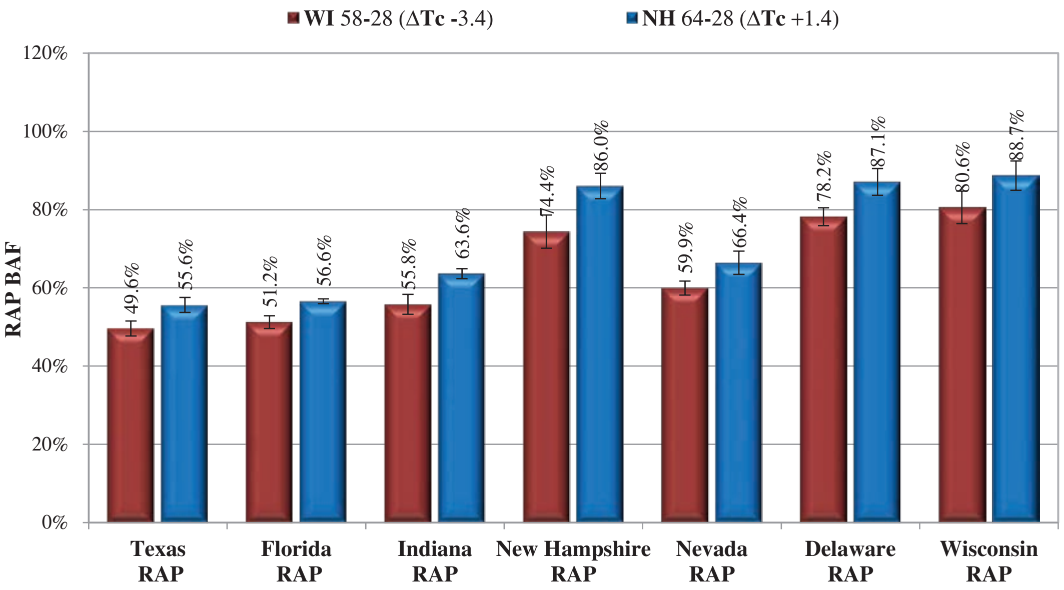


Figure 90. Effect of base binder source on RAP BAF.

Figure 89b shows, however, that adding the recycling agent slightly increased the RAP BAF at 150°C mixing temperature but did not show any statistical difference except for the TX and FL RAP sources. This would indicate that the recycling agent helps increase the RAP BAF only at low mixing temperatures and that increasing the mixing temperature has an equivalent effect to adding a recycling agent. The method of adding the recycling agent to the RAP directly, as opposed to mixing it with the base binder at 150°C mixing temperature, also did not show any significant effect on RAP BAF. Again, the limited time and room temperature conditions likely contributed to this result.

To evaluate the effect of base binder source, an additional set of virgin and RAP mixtures was prepared with a PG 64–28 base binder from NH, with the exact same composition as the mixtures with the PG 58–28 base binder from WI. The NH PG 64–28 base binder had a ΔT_c of +1.2, compared to the WI PG 58–28 with a ΔT_c of −3.4.

Figure 90 shows that using a high-quality base binder with a high (positive) ΔT_c value, such as the NH PG 64–28 binder, slightly increased the RAP BAF for all RAP sources compared to using the lower-quality WI PG 58–28 binder at the same 140°C mixing temperature. This is despite the fact that the WI PG 58–28 binder is softer on the high-temperature end but the same at the low-temperature end, compared to the NH PG 64–28 binder.

4.6 Key Findings

The key findings presented in this chapter are based on expanded laboratory performance results for both binder blends and mixtures with high RBRs to explore the impact of higher recycling agent doses than those used in the field projects and include the following:

- Recycling-agent effectiveness must be characterized in high RBR binder blends or mixtures initially and with long-term aging to capture initial compatibility and rheological response to oxidation.
- A recycling-agent dose to match continuous PGH for the target climate is required for high RBR binder blends and mixtures to maintain durability with long-term aging.

- Use of high-quality base binders improves performance of high RBR binder blends and mixtures with recycling agents.
- Rejuvenation mechanisms differ by recycling-agent type.
- Recycling agents are more effective in rejuvenating less-aged recycled materials (RAP more than RAS and MWAS more than TOAS) in balanced, limited proportions. RAS contents should be limited because at typical production temperatures, RAS likely acts as a filler with none of the stiff, brittle recycled binder available for blending.
- Adequate performance for high RBR binder blends with recycling agents can be evaluated by PGH, G-R parameter, and ΔT_c.
- Adequate performance for high RBR mixtures with recycling agents can be evaluated by $N_{12.5}$, $G\text{-}R_m$, FI, S_m and m-value_m, and CRI_{Env}.
- Some high RBR mixtures with recycling agent may be moisture susceptible.

CHAPTER 5

Practical Tools for Evaluation of High RBR Binder Blends and Mixtures

Chapter 5 presents the practical tools developed in this study to evaluate the effectiveness of a recycling agent initially and with aging for mixtures with high RBRs. These proposed tools are also included in the draft AASHTO standard practice in Appendix I.

5.1 Component Materials Selection Guidelines

Based on the results presented in Chapter 3 and Chapter 4 from Phase 2 and Phase 3, component materials selection and proportioning guidelines are proposed in Table 32. These guidelines are meant to be used as a system, with suggested thresholds to assist in selecting component materials for a high RBR mixture with a recycling agent. For comparison, ΔT_c and PGH values are provided in Table 33 for the base and recycled binders in this study.

The PGH thresholds after short-term aging by RTFO are based on the wide variety of materials (and climates) evaluated in this study, as shown in Table 1. The PGH limit for RAP precludes the use of TX RAP, and the PGH limit for RAS precludes the use of TOAS sources based on binder/binder blend and corresponding mixture results gathered throughout this study and highlighted in Chapter 4.

The ΔT_c thresholds after both short- and long-term aging by RTFO and 20-h PAV were selected to include the WI PG 58–28 base binder and WI RAP but preclude the TX PG 64–22 base binder and TX RAP due to consistent results across binder and mixture tests that highlighted good and poor performance from these materials, respectively. The NV PG 64–28P base binder was not considered since it is polymer modified and may require additional parameters to capture the corresponding adequate performance. Figure 91 provides further evidence of the relatively poor quality of the TX PG 64–22 base binder (ΔT_c of −4.6) compared to the IN PG 64–22 base binder (ΔT_c of −1.2) of the same PG grade. The DOT control binder blend (without recycling agent) was graded as a PG 82.3–13.3 and PG 77.9–21.3 for the TX and IN base binders, respectively. The selected doses in Figure 91 restored the PG of these blends to a target PG 64–22, and the blends with the IN PG 64–22 base binder required significantly lower recycling agent doses and exhibited much less negative ΔT_c values than the same blends with the TX PG 64–22 base binder.

Figure 92 again highlights the effect of a poor-quality base binder by comparing binder blends with these same two base binders (TX PG 64–22 and IN PG 64–22) in Black space, illustrating similar $|G^*|$ values but increased δ values (and thus lower G-R values) for the blends with IN PG 64–22 base binder even at lower recycling-agent doses.

Figure 93 illustrates the ultimate impact of a poor-quality base binder on mixture cracking performance, with the IN mixtures at lower recycling-agent doses exhibiting better performance (higher FI values) after LTOA, although similar FI values were realized for some recycling-agent types (V1) after STOA at the selected dose.

Table 32. Component materials selection and proportioning guidelines.

		Component Material			
Test	Parameter	Base (Virgin) Binder	Recycled Material (RAP)	Recycled Material (RAS)	Recycling Agent
***High-Temperature, Short-Term Aging*[a]**					
DSR	PGH	≤ 64°C	≤ 100°C	≤ 150°C	—
***Low-Temperature, Short- and Long-Term Aging*[b]**					
BBR	ΔT_c	≥ −3.5°C	≥ −7.5°C	—	—
Proportioning					
	RBR	—	≤ 0.5 RBR (RAPBR+RASBR)	≤ 0.15 RASBR	—
	Dose	—	—	—	≤ maximum[c] without sacrificing rutting resistance

NOTE: — = not applicable.

[a] Original binder and RTFO aged by AASHTO T 240.

[b] 20-h PAV aging at 100°C by AASHTO R 28.

[c] Percentage of total binder in the blend/mixture.

Table 33. Characteristics of the base binders and recycled binders.

Material		Source	PG	Continuous PGH (°C)	Continuous PGL (°C)	ΔT_c (°C)
Virgin/Base Binders		TX	64-22	68.2	−24.6	−4.6
		NH	64-28	66.9	−28.0	+1.2
		NV	64-28P[a]	65.6	−30.7	−3.6
		IN	64-22	66.2	−25.3	−1.2
		IN	58-28	59.9	−28.2	−8.0
		MN	58-28	58.6	−28.0	+0.1
		WI	58-28	59.4	−28.6	−3.4
		WI	52-34	52.3	−34.2	+0.4
		DE	64-28	66.5	−29.0	+0.1
Recycled Materials	RAP	TX	—	106.6	−2.4	−9.8
		IN	88-10	90.4	−13.7	−6.2
		NV	82-16	84.4	−20.4	−3.4
		NH	88-16	90.2	−20.6	−2.1
		WI	82-10	83.5	−10.9	−7.3
		DE	82-10	86.2	−13.8	−4.4
	MWAS	TX	—	130.7	—	—
		IN	—	123.3	—	—
		DE	—	146.0	—	—
	TOAS	TX	—	178.0	—	—
		CA	—	166.0	—	—

NOTE: — = not available because RAS binders were very stiff and did not meet the m-value criteria (>0.3), even at high testing temperatures.

[a] Polymer-modified binder.

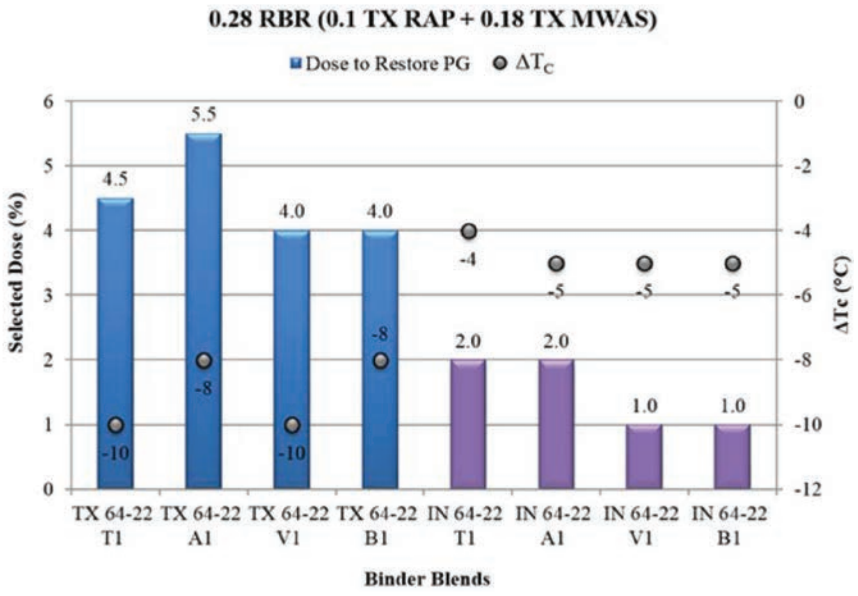


Figure 91. ΔT_c threshold: recycling-agent dose.

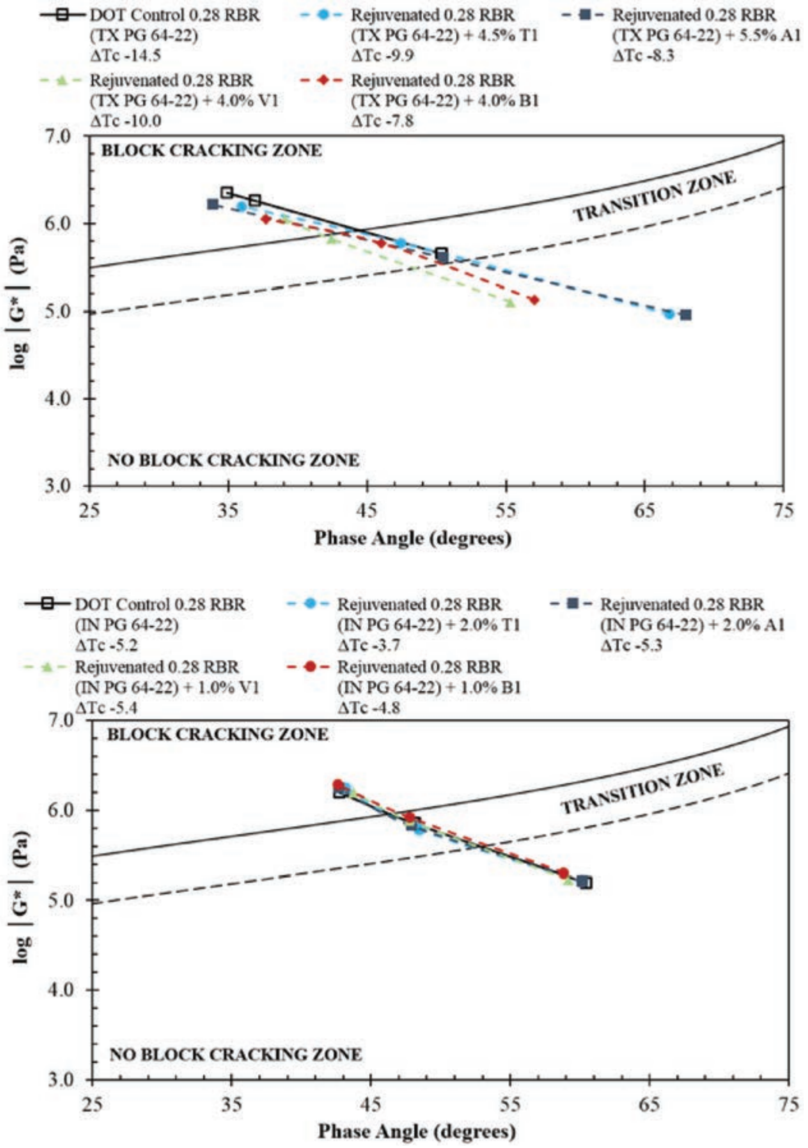


Figure 92. ΔT_c threshold: binder blend Black space.

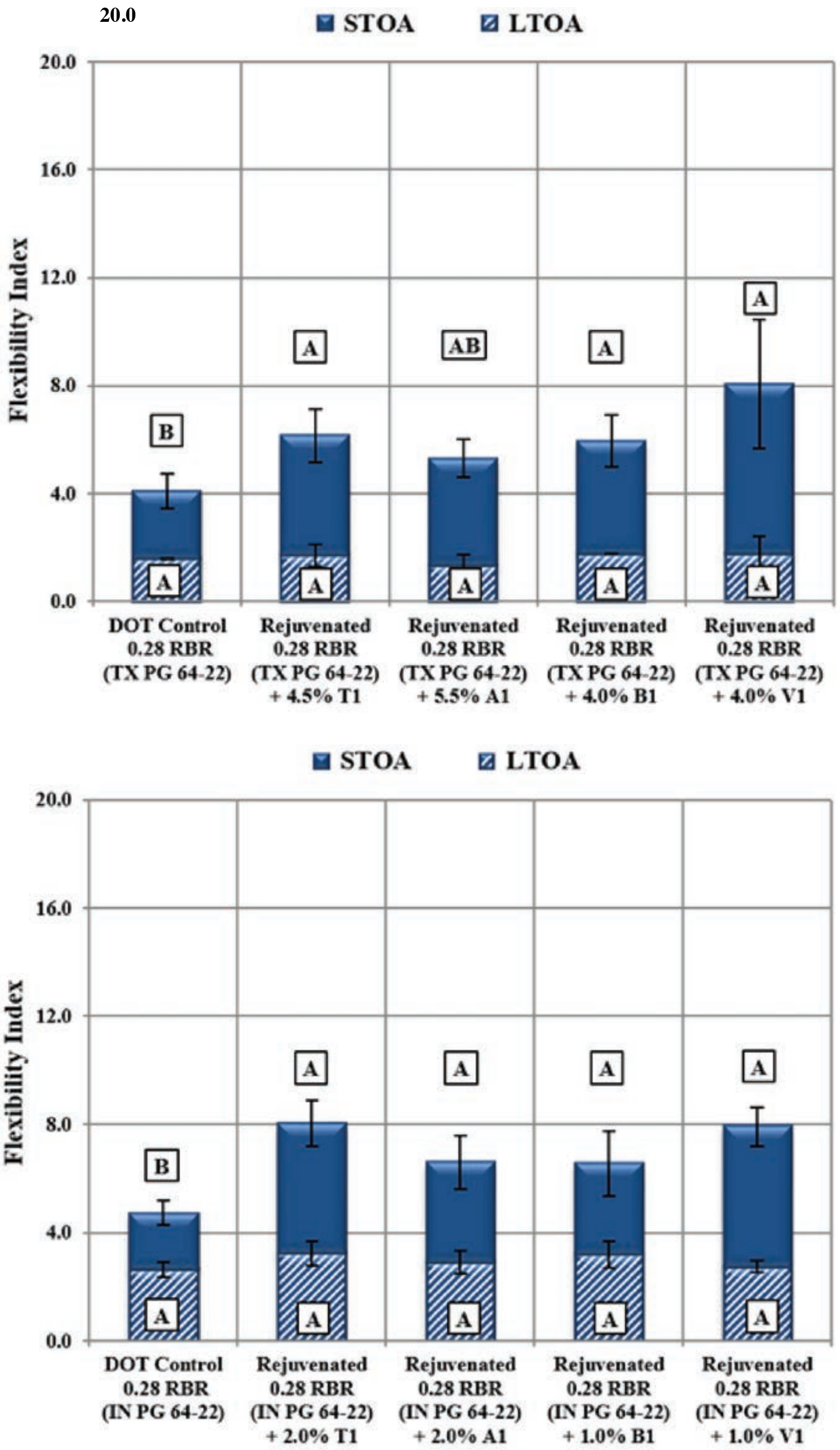


Figure 93. ***ΔT_c threshold: mixture cracking resistance.***

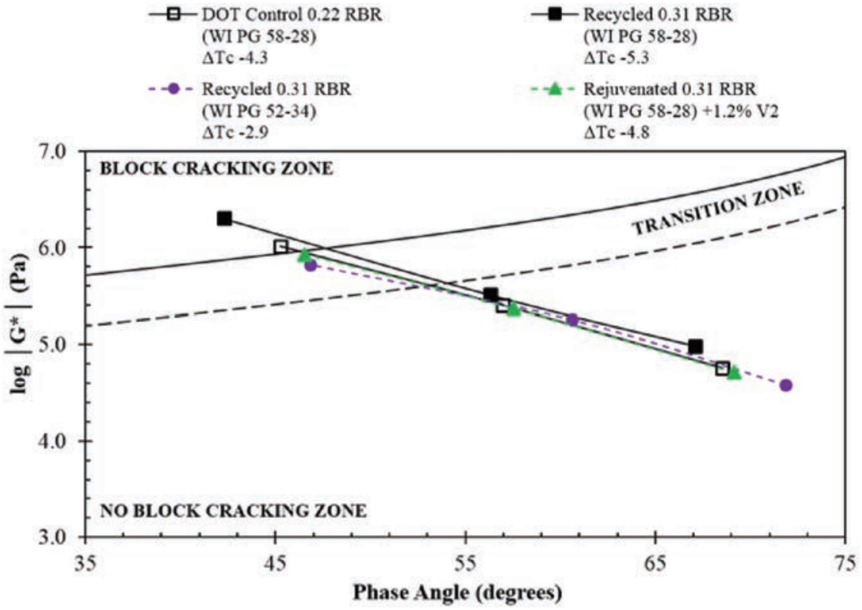


Figure 94. *ΔT_c threshold: binder blend Black space with lower PGH.*

Finally, Figure 94 and Figure 95 show the combined effect of using a softer base binder (WI PG 52–34 with a lower PGH) that is also of higher quality ($\Delta T_c = +0.4$) compared to the WI PG 58–28 ($\Delta T_c = -3.4$) used in the other binder blends and corresponding mixtures. This combination of a higher-quality and softer base binder effect facilitates the use of a relatively high RBR (0.31) without recycling agent with respect to the binder blend Black space diagram, ΔT_c of the binder blend, and mixture cracking resistance in terms of FI. The blend and mixture

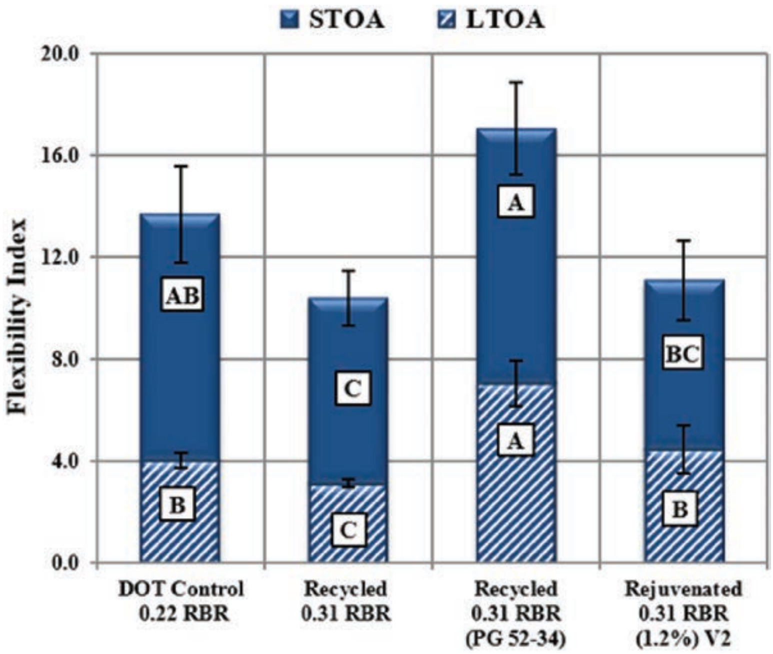


Figure 95. *ΔT_c threshold: mixture cracking resistance with lower PGH.*

with the softer base binder (WI PG 52–34) surpassed the rejuvenated binder blend and mixture with the WI PG 58–28 base binder and the field recycling agent dose of 1.2% with respect to these evaluation methods that include the effects of aging.

5.2 Recycling-Agent Dose Selection Method

As detailed in Chapter 2, the recycling-agent dose to restore the continuous PGH of the recycled binder blend to match PGH_{Target} yielded the best performance for rejuvenated binders and corresponding mixtures (Arámbula-Mercado et al. 2018b; Kaseer et al. 2017b; Garcia Cucalon et al. 2018) and also yielded blends that met the −22 and −28 PGL requirements. The simplified recycling-agent dose selection method based on DSR testing of unaged material can be summarized in the following three steps:

1. Determine PGH of the base and recycled binders per AASHTO M 320.
2. Select the base binder, RBR, and RAP/RAS combination and calculate PGH of the recycled binder blend as follows:

$$PGH_{Blend} = (RAP_{BR} \times PGH_{RAP}) + (RAS_{BR} \times PGH_{RAS}) + (B_{BR} \times PGH_{Base})$$

where

PGH_{Blend} = continuous PGH of the recycled binder blend (°C),
RAP_{BR} = RAP binder ratio (RAP binder percent by weight with respect to the total binder),
PGH_{RAP} = continuous PGH of the RAP binder (°C),
RAS_{BR} = RAS binder ratio (RAS binder percent by weight with respect to the total binder),
PGH_{RAS} = continuous PGH of the RAS binder (°C),
B_{BR} = base binder ratio (base binder percent by weight with respect to the total binder), and
PGH_{Base} = continuous PGH of the base binder (°C).

3. Estimate selected recycling agent dose as follows for a target PG climate:

$$Recycling\ Agent(\%) = (PGH_{Blend} - PGH_{Target})/Slope\ Rate$$

where

PGH_{Blend} = continuous PGH of the recycled binder blend (°C) calculated from previous equation and
PGH_{Target} = continuous PGH of target climate.

For tall oils (T), vegetable oils (V), or reacted bio-based oils (B), a recommended slope rate or rate of reduction in PGH of 1.82 can be used based on the materials included in this study as shown in Chapter 2. For aromatic extracts (A), a lower slope rate of 1.38 is recommended based on the materials evaluated in this study as shown in Chapter 2. Blending charts shown in Chapter 2 of recycling agent dose (0%, 2%, 5%, and 10%) versus PGH can also be utilized to determine slope rate.

These recycling agents are added to the binder blends or corresponding mixtures at the selected doses according to the following guidelines, as detailed in Chapter 1:

- For mixtures with only RAP and all binder blends, the recycling agent is added as 100% replacement for the base binder.

- For mixtures with RAP and RAS and doses greater than 5.0%, the recycling agent is added as 100% addition to the base binder with a mandatory requirement to ensure adequate mixture rutting resistance.

As detailed in Chapter 4, this recycling-agent dose selection method was verified in recycled and rejuvenated binder blends and mixtures using materials combinations from field projects in TX, NV, IN, WI, and DE.

5.3 Materials Proportioning Guidance

Recommended limits in Table 32 for RASBR of 0.15 (or approximately 3.5% by total weight of mixture) stem from current state DOT limits of 3–5% (Epps Martin et al. 2015) and comparisons of balanced (0.4 RAPBR + 0.1 RASBR) recycled materials combinations and equivalent but unbalanced (0.25 RASBR + 0.25 RAPBR) materials combinations as shown in Figure 96 and highlighted in Arámbula-Mercado et al. (2018a). While neither binder blend enters the block cracking zone with extended aging, the unbalanced mixture exhibited inadequate rutting resistance by HWTT with $N_{12.5}$ of 4,800 load cycles compared to the corresponding balanced mixture with $N_{12.5}$ of 16,500 load cycles. This poor mixture performance stems from the lack of RAS binder availability at normal mixing temperatures of 150°C–175°C (300°F–350°F), which likely results in the recycling agent oversoftening the base binder. A maximum limit for total RBR (RAPBR + RASBR) of 0.5 is also suggested based on the scope of materials combinations evaluated in this study, as shown in Table 1.

Finally, the proportioning threshold provided in Table 32 for recycling-agent dose is generic and based on the recycling-agent dose selection method proposed to restore the continuous PGH of the recycled binder blend to match PGH_{Target}. For the component materials and materials combinations evaluated in this study that followed the recommended component materials

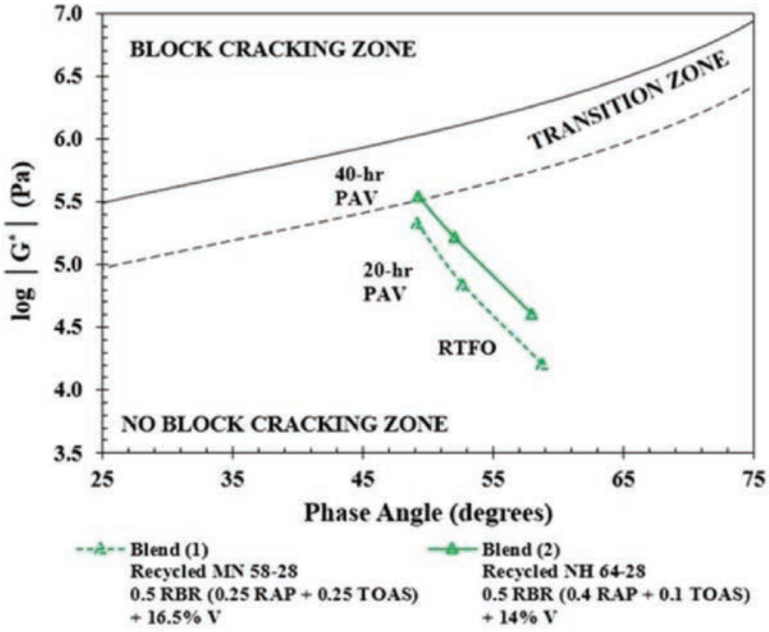


Figure 96. RBR thresholds: binder blend Black space and mixture rutting resistance.

guidelines in Table 32, this maximum was approximately 8%–10% to ensure adequate mixture rutting resistance. This suggested maximum range based on performance considerations was also similar to ranges provided by the following two efforts that examined current economic considerations for the recycling agents evaluated in this study:

- Discussions with recycling-agent manufacturers that recommended 6%–8% based on economics.
- An economic analysis that indicated that using recycling agents at doses of 10%–15% is reasonable to double the RAP content from 20% to 40% and save from $6 to $8 per ton of mixture when virgin material costs are relatively high (Epps Martin et al. 2017).

Ultimately, the recycling-agent dose should be selected to satisfy binder blend and corresponding mixture performance requirements and be feasible economically.

By utilizing the suggested maximum recycling-agent dose range based on performance considerations and Equation 2 to estimate recycling-agent dose, materials combinations can also be screened to determine reasonable and balanced recycled materials content (RAPBR, RASBR) for specific base binders. Table 34 provides a series of examples for 0.5 RBR combinations formulated to a PGH_{Target} of 70. The first materials combination has unbalanced RAPBR/RASBR with a relatively poor-quality TX PG 64–22 base binder ($\Delta T_c = -4.6$), highly aged TX RAP (PGH = 106.6°C), and TX TOAS (PGH = 178.0°C) that results in a very high recycling-agent dose that is likely uneconomical and would likely result in inadequate rutting resistance in a corresponding mixture. This unbalanced RAPBR/RASBR combination stems from the lack of binder availability from highly aged recycled materials at normal mixing temperatures of 150°C –175°C (300°F –350°F) and likely oversoftening of the base binder by the recycling agent. These highly aged TX recycled materials may be useful at lower RBRs, with a more balanced RAPBR/RASBR, or with a different base binder. The second materials combination uses the same materials but balances the RAPBR/RASBR to 0.4/0.1 with a significant reduction in recycling agent dose. However, its absolute value remains beyond the suggested range. By changing the RAS type to the less-aged TX MWAS (PGH = 130.7°C) in the third materials combination, the recycling agent dose can be further reduced, but it is still beyond the suggested range. By changing the RAP type to the less-aged NH RAP (PGH = 90.2°C) in the fourth materials combination, the recycling agent dose is again reduced, but this combination is not effective unless RAP with a lower PGH is available locally. Finally, the fifth materials combination illustrates that changing the base (virgin) binder to a softer PG grade (both PGH and PGL) of higher quality ($\Delta T_c = 0.0$) can further reduce the recycling-agent dose to an acceptable and likely economical value.

Table 34. Materials proportioning examples at 0.5 RBR and PGH_{Target} of 70.

Base (Virgin) Binder	RAP	RAS	Recycling-Agent Dose (%)	Comments
TX PG 64-22 $\Delta T_c = -4.6$	0.25 TX RAP	0.25 TX TOAS	19.4	Unbalanced, Very High Dose
	0.4 TX RAP	0.1 TX TOAS	13.5	Δ RAP/RAS, High Dose
	0.4 TX RAP	0.1 TX MWAS	10.9	Δ RAS Type, High Dose
	0.4 NH RAP	0.1 TX MWAS	7.3	Δ RAP Type, Marginal Dose
MN PG 58-28 $\Delta T_c = 0.0$	0.4 NH RAP	0.1 TX MWAS	5.0	Δ Base Binder, Acceptable Dose

5.4 Binder Blend Rheological Evaluation Tools

Table 35 provides binder blend evaluation tools for use with high RBRs and recycling agents. These tools are meant to be used as a system, with requirements recommended for at least one high-temperature and one intermediate- or low-temperature test where data are available for a specific combination of materials in a high RBR blend with a recycling agent.

For recycled or rejuvenated binder blends with high RBRs, the continuous PGH of the target climate should be matched using either a softer base binder or a recycling agent with a recycling-agent dose selected based on the method detailed in Chapter 2 and summarized previously. Some of the other recommended thresholds are adopted from existing research, including the intermediate-temperature G-R parameter criteria (Glover et al. 2015; Rowe 2011) and the low-temperature ΔT_c criteria (Anderson et al. 2011), with the recommended aging conditions developed based on this extensive study and the materials combinations in Table 1 and laboratory tests in Table 13. In this study, ΔT_c values after 20-h PAV aging were utilized for practicality, but extended aging after 40-h PAV is recommended for the G-R parameter because the standard 20-h PAV aging by AASHTO R 28 is not always sufficient to evaluate the evolution of recycling agent effectiveness. The $T_{\delta = 45°}$ thresholds are provided as an alternate intermediate-temperature parameter based on their correlation to the G-R parameter (Garcia Cucalon et al. 2018). A comparison of binder blends in Black space in Chapter 4 that includes the G-R parameter thresholds illustrates the effects of increased recycling agent doses to ensure long-term durability with high RBRs.

5.5 Mixture Performance Evaluation Tools

Table 36 provides comprehensive mixture evaluation tools for use with high RBRs and recycling agents that balance mixture cracking resistance at both intermediate and low temperatures and rutting resistance at high temperatures. Evaluation of rejuvenated mixtures is imperative since these mixture properties control performance and allow for consideration of incomplete blending between base and recycled binders and recycling agent. These tools are meant to be utilized as a system, with requirements recommended for at least one high-temperature and one intermediate- or low-temperature test where data are available for a specific materials combination in a high RBR mixture with a recycling agent.

Some of these recommended thresholds are adopted from existing specifications, including the low-temperature BBR_m criteria and the high-temperature $N_{12.5}$ rutting criteria. Thresholds

Table 35. Binder blend evaluation tools for use with High RBRs and recycling agents.

Test	Parameter	Suggested Performance Threshold
High-Temperature, Original and Short-Term Aging		
DSR	PGH	Target Climate
Intermediate-Temperature, Track with Aging		
DSR	G-R	$\leq$ 180 kPa after 20-h PAV $\leq$ 600 kPa after 40-h PAV
DSR	$T_{\delta = 45°}$	$\leq$ 32°C after 20-h PAV $\leq$ 45°C after 40-h PAV
Low-Temperature, Short- and Long-Term Aging		
BBR	ΔT_c	$\geq$ −5.0 after 20-h PAV

Table 36. Mixture evaluation tools for use with High RBRs and recycling agents.

Test	Parameter	Suggested Performance Threshold
High-Temperature, Short-Term Aging		
HWTT or APA	$N_{12.5}$	≥ 5,000 for PG 58-XX ≥ 7,500 for PG 64-XX in cold climate ≥ 10,000 for PG 64-XX in warm climate ≥ 15,000 for PG 70-XX
Intermediate-Temperature, Track with Aging		
|E*|	$G\text{-}R_m$	≤ 8,000 MPa after STOA ≤ 19,000 MPa after LTOA
Intermediate-Temperature, Short-Term Aging		
I-FIT	FI	≥ 7 after STOA
Low-Temperature, Short- and Long-Term Aging		
BBR_m	S_m and m-value$_m$	≤ Utah threshold on m-value$_m$ vs. S_m after STOA (Figure 77)
UTSST	CRI_{Env}	≥ 17 after LTOA

for S_m and m-value$_m$ parameters in low-temperature mixture Black space as shown in Chapter 4 are proposed as developed by Romero (2016) based on field performance of seven field projects in Utah. Thresholds for $N_{12.5}$ from HWTT specifications from IL for PG 58-XX and PG 64-XX target climates and from TX for PG 64-XX and PG 70-XX climates are also suggested. These two states (IL and TX) provide examples of cold and warm climates, respectively, based on recommended separation at 40° north latitude, as suggested in NCHRP 09–52. These cold and warm climates are specified in Table 36 for mixture rutting resistance with different thresholds depending on climate for the results of HWTT or APA tests conducted at a single temperature (50°C). This effect of climate was illustrated throughout this study and requires further research to tie laboratory and field aging, which is especially critical for high RBR mixtures.

Results from this study were utilized to set thresholds for intermediate- and low-temperature cracking resistance and a combined intermediate-temperature rheological property for mixtures. For intermediate-temperature mixture cracking resistance, the comparison in Chapter 3 of laboratory and field performance led to the proposed threshold of 7 for FI for available data from LMLC specimens after STOA (Figure 46). For low-temperature mixture cracking resistance, however, the comparison in Chapter 3 led to the proposed threshold of 38 for CRI_{Env} for RPMLC specimens after LTOA (Figure 45), so $G\text{-}R_m$ was utilized as a limiting combined rheological property for both RPMLC and LMLC specimens to transform the CRI_{Env} threshold to an adjusted value for LMLC specimens after LTOA, as shown in Figure 97 and Figure 98. The threshold of 38 developed in Chapter 3 for RPMLC specimens was utilized with the relationship in Figure 97 to find a limiting combined rheological property of 19,000 MPa. This value was then used with the relationship in Figure 98 to determine a threshold of 17 for CRI_{Env} for LMLC specimens after LTOA.

Finally, correlations between cracking resistance parameters (FI and CRI_{Env}) and $G\text{-}R_m$ for LMLC specimens, as shown in Figure 98 and Figure 99, provided evidence that a maximum threshold of 19,000 MPa appears reasonable after LTOA, with cracking likely for mixtures with $G\text{-}R_m$ values of 8,000 MPa after STOA based on proposed thresholds for CRI_{Env} and FI, respectively.

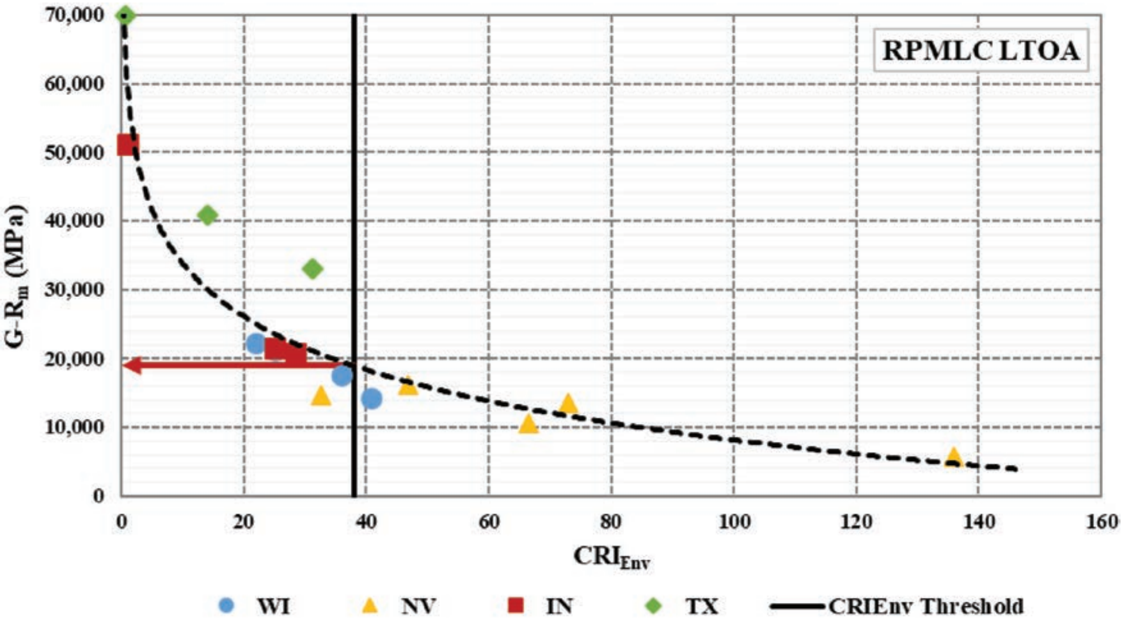


Figure 97. G-R_m versus CRI_{Env} for RPMLC specimens after LTOA to find limiting combined rheological property.

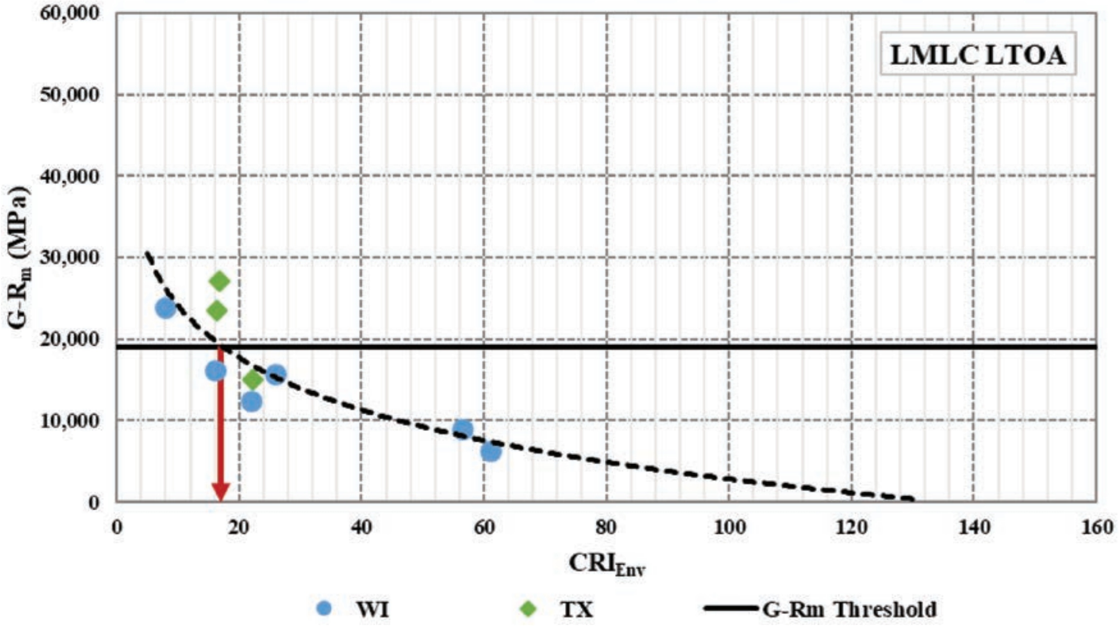


Figure 98. G-R_m versus CRI_{Env} for LMLC specimens after LTOA to develop CRI_{Env} threshold.

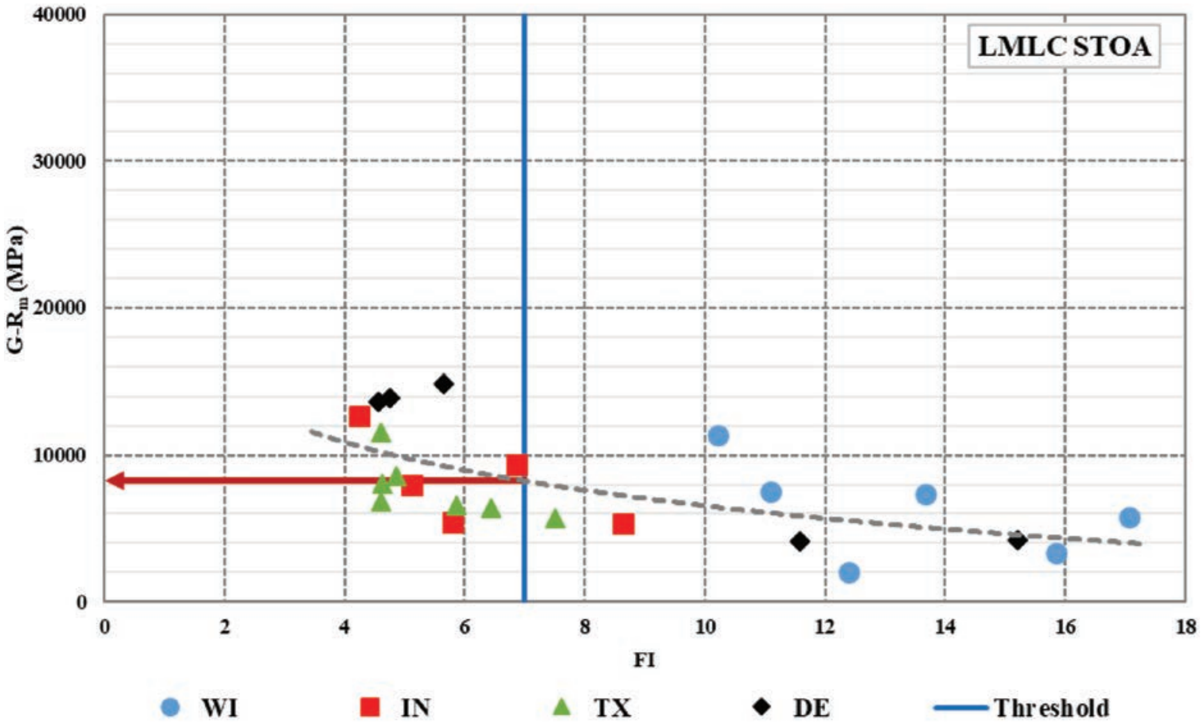


Figure 99. G-R$_m$ versus CRI$_{Env}$ for LMLC specimens after STOA to develop G-R$_m$ threshold.

5.6 RAP Recycled Binder Availability Factor

Based on the strong correlation between RAP BAF and RAP PGH shown in Figure 88, the RAP BAF can be estimated using Equation 24 and Equation 25 for mixing temperatures of 140°C and 150°C, respectively:

$$RAP\ BAF = -0.014(RAP\ PGH) + 1.898\ for\ 140°C \qquad [\text{Equation 24}]$$

$$RAP\ BAF = -0.010(RAP\ PGH) + 1.771\ for\ 150°C \qquad [\text{Equation 25}]$$

This value is suggested for use in reducing the recycled binder from the RAP to the RBR in a mixture to ensure that sufficient base binder is included in a mix design.

5.7 Laboratory Aging and Climate Effects

Results from this study repeatedly illustrate that initial rheological quality and how rheology changes due to aging are important, and both depend somewhat on field project location, with the first based on component material availability and economics and the second based on climate. This section presents evaluations of standard laboratory aging protocols that are independent of location and the effects on predicted binder performance in terms of the G-R parameter and measured mixture performance in terms of M_R and FI.

5.7.1 Binder Climate Effects

A preliminary comparison between laboratory and predicted field oxidative aging of select base binders was conducted using the following two analyses:

- Analysis A—Different Climate: prediction of the evolution of CA for one base binder (NH PG 64–28) in three different climates—Durham, NH; Reno, NV; and Tyler, TX.

Table 37. Predicted field in-service times and equivalent PAV durations to reach cracking onset for different base binders and climates.

Base Binder	Climate	Predicted In-Service Time to Reach G-R = 180 kPa (years)	Equivalent PAV Duration to Reach G-R = 180 kPa (h)
TX PG 64-22	Reno, NV	5.0	13
NH PG 64-28	Durham, NH	6.1	52
	Reno, NV	4.6	55
	Tyler, TX	4.1	58
NV 64-28P	Reno, NV	11.9	59

- Analysis B—Different Base Binder: prediction of the evolution of CA for each of three base binders (TX PG 64–22, NH PG 64–28, and NV PG 64–28P) in one climate in Reno, NV.

TEMPS was used to predict hourly pavement temperatures at selected depths in the HMA layer for each of the three climates. The G-R/CA_g HS for the evaluated binders was used in conjunction with the predicted evolution of CA (and calculated CA_g) to estimate the in-service time to reach the cracking onset threshold (i.e., G-R = 180 kPa). Table 37 summarizes the predicted number of years for Analysis A and Analysis B with the following observations provided based on these results:

- Analysis A: The NH PG 64–28 base binder had the highest predicted number of in-service years to reach cracking onset when used in the NH climate. The lowest number of years to reach cracking onset was observed in the TX climate, as demonstrated by a 50% reduction in the predicted in-service time compared to the NH climate. The results indicated that the NH PG 64–28 base binder will age much faster in the TX climate when compared to NV and NH climates and thus reach cracking onset earlier in the pavement service life.
- Analysis B: The NV PG 64–28P base binder had a predicted in-service time to reach cracking onset that was more than twice the number of years predicted for the other two base binders in the same NV climate. The results indicated that the NV PG 64–28P base binder outperforms the other two base binders in the NV climate, which both showed similar performance.

These three base binders were also long-term aged for 20-, 40-, and 60-h PAV aging. The PAV-aged binders were tested to determine the G-R parameter, and the results are summarized in Table 38.

The equivalent PAV duration to reach a G-R parameter value of 180 kPa was then estimated based on the evolution of the G-R parameter as a function of predicted in-service time as summarized in Table 37. Consequently, the following observations were made:

- Analysis A: The NH PG 64–28 base binder required 52, 55, and 58 hours in the PAV to reach the same level of G-R parameter (180 kPa) in the three different climates of NH, NV, and TX, respectively. Thus, a longer PAV duration is needed for the NH PG 64–28 base binder when used in the TX climate to reach cracking onset.
- Analysis B: An equivalent PAV duration to reach cracking onset in the NV climate of 13, 55, and 59 hours was estimated for the TX PG 64–22, NH PG 64–28, and NV PG 64–28P base

Table 38. Measured G-R parameter after PAV aging for different base binders.

PAV Aging Duration (hours)	G-R at 15°C and 0.005 rad/s (kPa) TX PG 64-22 Base Binder	NH 64-28 Base Binder	NV 64-28P Base Binder
20	218.4	22.7	17.8
40	523.5	85.4	50.2
60	772.5	249.6	218.4

binders, respectively. Thus, the TX PG 64–22 base binder exhibited a large G-R value and required a much shorter PAV duration to reach cracking onset.

Figure 100 shows the measured G-R parameter for all three base binders after PAV aging as a function of PAV aging duration. The data clearly show that the TX PG 64–22 base binder had a significantly higher G-R parameter (> 180 kPa) when compared to the other two base binders, both having comparable G-R parameter values. However, the TX PG 64–22 base binder had a lower susceptibility to PAV aging, as demonstrated with a lower slope compared to the NH PG 64–28 and NV PG 64–28P base binders. Thus, for a given location and associated climate, a mixture with the TX PG 64–22 base binder will likely exhibit cracking early in the pavement's life, while mixtures with the NH PG 64–28 and NV PG 64–28P base binders are expected to perform similarly and not exhibit cracking until much later.

Figure 101 shows the measured G-R parameter for all three base binders after PAV aging as a function of the predicted in-service years in the NV climate. The data in Figure 101 show a different behavior for each of the three base binders. While NH PG 64–28 and NV PG 64–28P had similar G-R parameter values, they exhibited different in-service times to reach the measured G-R threshold. This is due to the fact that both binders have different chemical properties in terms of binder kinetics that led to a difference in the predictions of binder oxidative aging as a function of time. The rate of change in G-R parameter as a function of in-service time was higher for the TX PG 64–22 when compared to the NH PG 64–28 and the NV PG 64–28P base binders, both having relatively comparable rates. These results contradict the observed behavior of the base binders as a function of PAV aging duration (Figure 100).

Overall, the data in Figure 101 show that the NV PG 64–28P outperformed both the TX PG 64–22 and NH PG 64–28 base binders in the NV climate, as demonstrated with lower G-R parameter values and longer in-service time to reach cracking onset (i.e., G-R = 180 kPa). These results suggest the need for a threshold value for both the magnitude of the G-R parameter and the rate of change in the G-R parameter as a function of in-service time. This requires testing of binders at multiple PAV aging durations (preferably three). However, a reliable use

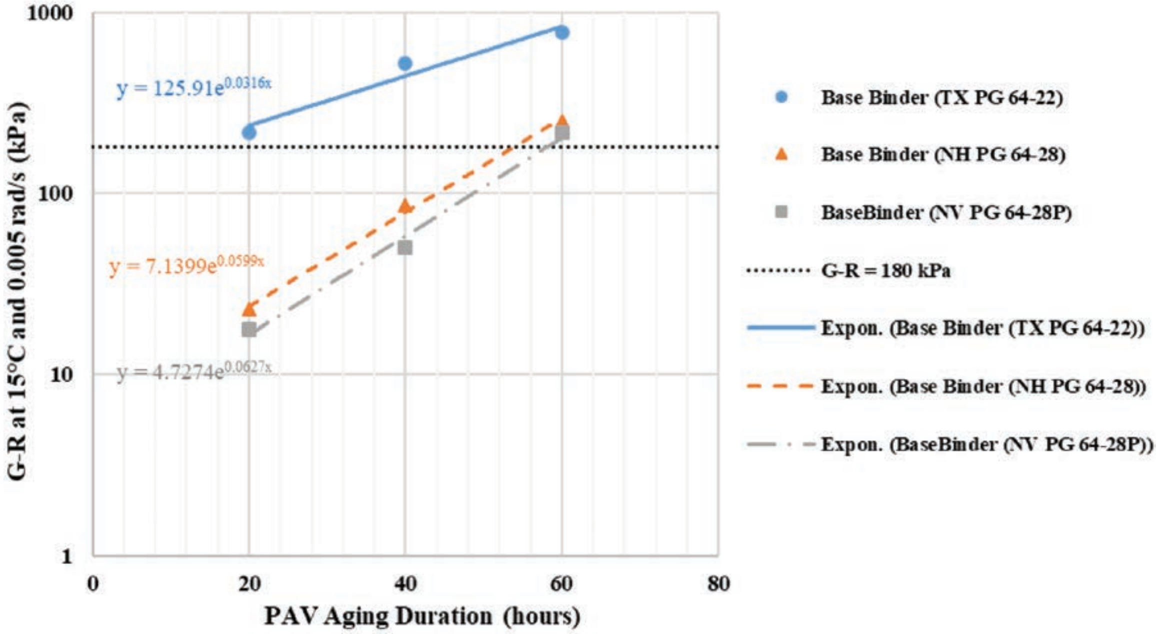


Figure 100. PAV-based G-R parameter versus PAV aging duration for TX PG 64–22, NH PG 64–28, and NV PG 64–28P base binders.

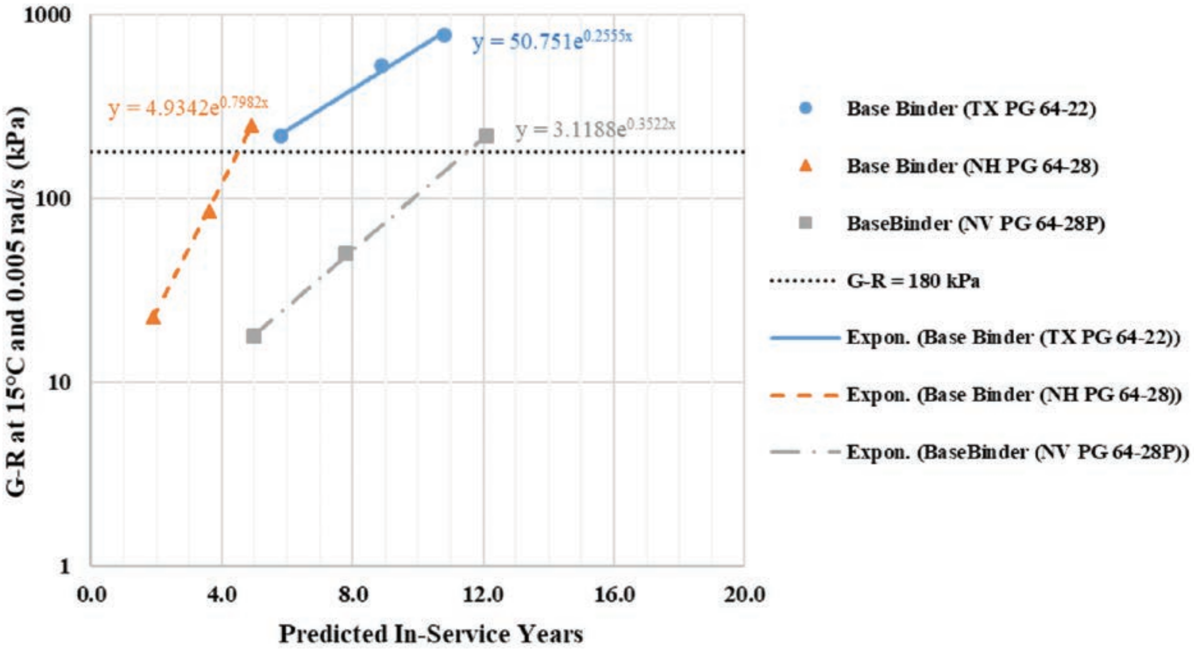


Figure 101. PAV-based G-R parameter versus predicted in-service time for TX PG 64–22, NH PG 64–28, and NV PG 64–28P base binders.

of the threshold value on the rate of change in the G-R parameter necessitates the adjustment of the PAV aging durations to properly simulate in-service oxidative aging. This will be a challenge since the representative PAV aging durations are not only climate specific but also binder specific (i.e., function of binder chemical properties and kinetics). A possible solution is direct measurement of CA on PAV-aged binders after multiple durations using FT-IR and development of a threshold value for G-R/CA_g HS.

5.7.2 Mixture Climate Effects

Cumulative degree days (CDDs; 32°F base) based on daily average temperatures since construction were gathered for each field project location (TX, IN, NV, WI, and DE) to provide a quantitative basis for field aging that accounts for differences in construction dates and environments at different field project locations, as utilized previously in NCHRP 09–52 (Newcomb et al. 2015a).

CDD curves for the field projects in this study are presented in Figure 102 with coring dates indicated by a black point. Similar to the field projects from NCHRP 09–52, the TX field project (in a warmer climate) showed a constant steeper CDD slope. For the WI and DE field projects, which were constructed in the fall and are located in milder climates, flat initial CDD slopes were evident. The IN and NV field projects also demonstrated a flat CDD slope during the fall/winter seasons.

Figure 103 shows the CDD values for postconstruction cores of 18 mixtures over a wide range of mixture components and production parameters versus their associated average M_R ratios (aged/unaged) and a power trendline with a high coefficient of determination (R^2). Figure 103 also shows the corresponding average M_R ratio of 1.88 for all LMLC specimens with an STOA protocol of 2 h at 135°C (275°F) plus LTOA of 5 days at 85°C (185°F) plotted as a circle where the value crosses the power trendline for the M_R ratio versus CDD relationship. The vertical and horizontal error bars represent one standard deviation from the average M_R

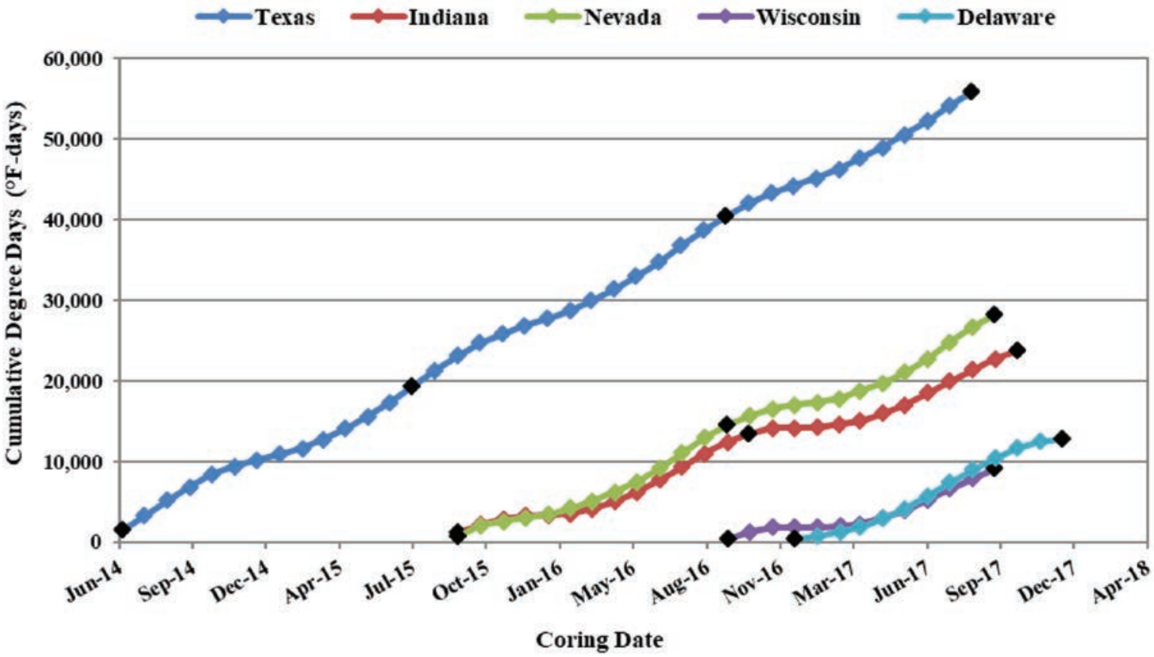


Figure 102. Cumulative degree days for NCHRP 09–58 field projects.

ratio value and corresponding CDD values, respectively. A laboratory STOA protocol of 2 h at 135°C (275°F) plus LTOA of 5 days at 85°C (185°F) was able to produce mixture aging equivalent to an average of 17,000 CDDs in the field, which is close to the 16,000 CDDs reported in NCHRP 09–52. Based on the CDD curves shown in Figure 102, the in-service time for each field project corresponding to 17,000 CDDs was determined and is summarized in Table 39. As shown, the laboratory STOA protocol of 2 h at 135°C (275°F) plus LTOA of 5 days at 85°C

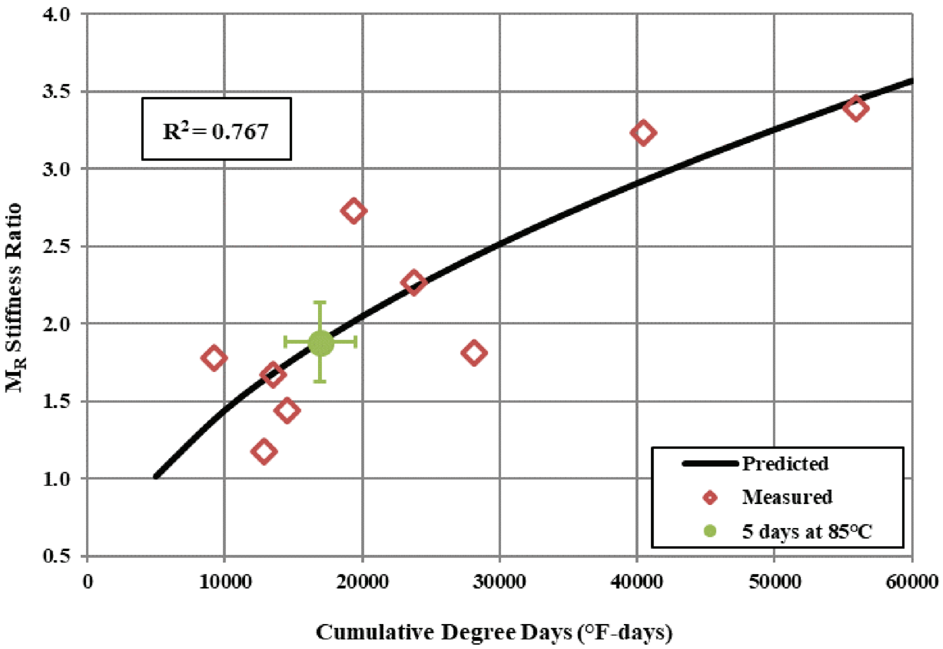


Figure 103. M_R *ratio versus CDD for postconstruction cores and correlation of LTOA with field aging.*

Table 39. Correlation of field aging in terms of in-service time for M_R ratio and laboratory LTOA of 5 days at 85°C (185°F).

Field Project	In-Service Time for M_R Ratio after 2 h at 135°C (275 °F) + 5 days at 85°C (185°F)
TX	12 months
NV	15 months
DE	17 months
IN	20 months
WI	24 months

(185°F) was equivalent to approximately 12 months in service in warmer climates such as TX and 24 months in service in colder climates such as WI. These results are again in agreement with those from NCHRP 09–52.

Similar to the M_R ratio versus CDD relationship and the correlation of laboratory LTOA to field aging for the M_R ratio, Figure 104 shows the CDD values for the postconstruction cores of 18 mixtures versus their associated average FI ratios (aged/unaged) and a power trendline with a high coefficient of determination (R^2). Figure 104 also shows the corresponding average FI ratio of 0.4 for all LMLC specimens with an STOA protocol of 2 h at 135°C (275°F) plus LTOA of 5 days at 85°C (185°F) plotted as a circle where the value crosses the power trendline for the FI ratio versus CDD relationship. The vertical and horizontal error bars represent one standard deviation from the average FI ratio value and corresponding CDD values, respectively. A laboratory STOA protocol of 2 h at 135°C (275°F) plus LTOA of 5 days at 85°C (185°F) was able to produce mixture aging equivalent to an average of 12,000 CDDs in the field. Based on the CDD curves shown in Figure 102, the in-service time for each field project corresponding to 12,000 CDDs was determined and is summarized in Table 40. As shown, the laboratory STOA protocol of 2 hours at 135°C (275°F) plus LTOA of 5 days at 85°C (185°F) was equivalent to approximately 8 months in service in warmer climates such as TX and 20 months in service in colder climates such as WI.

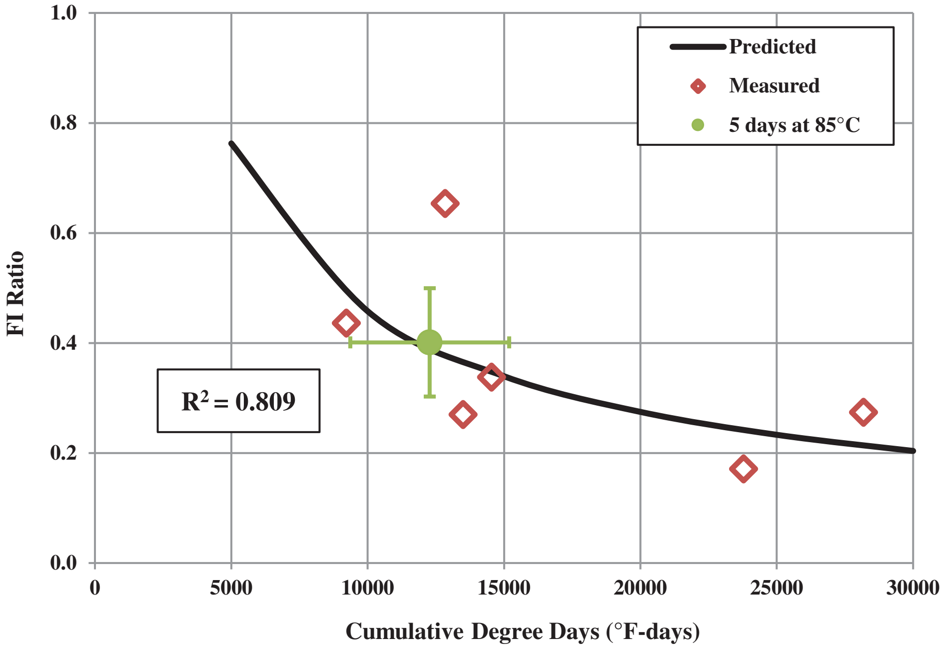


Figure 104. FI ratio versus CDD for postconstruction cores and correlation of LTOA protocols with field aging.

Table 40. Correlation of field aging in terms of in-service time for FI ratio and laboratory LTOA of 5 days at 85°C (185°F).

Field Project	In-Service Time for FI Ratio after 2 h at 135°C (275 °F) + 5 days at 85°C (185°F)
TX	8 months
NV	10 months
DE	11 months
IN	12 months
WI	20 months

5.8 Key Findings

Key findings from this study presented in this chapter based on the practical tools developed to evaluate the effectiveness of a recycling agent initially and with aging for mixtures with high RBRs include the following:

- Recycling-agent effectiveness must be characterized in high RBR binder blends or mixtures initially and with long-term aging to capture initial compatibility and rheological response to oxidation.
- Recycling-agent dose to match continuous PGH for the target climate is required for high RBR binder blends and mixtures to maintain durability with long-term aging.
- Use of high-quality base binders ($\Delta T_c \geq -3.5$) improves performance of high RBR binder blends and mixtures with recycling agents.
- Recycling agents are more effective in rejuvenating less-aged recycled materials (RAP more than RAS and MWAS more than TOAS) in balanced, limited proportions (< 0.5 RAPBR + RASBR and ≤ 0.15 RASBR). RAS contents should be limited because at typical production temperatures, RAS likely acts as a filler with none of the stiff, brittle recycled binder available for blending.
- Adequate performance for high RBR binder blends with recycling agents can be controlled with proposed thresholds for PGH, G-R parameter, and ΔT_c.
- Adequate performance for high RBR mixtures with recycling agents can be controlled with proposed thresholds for $N_{12.5}$, G-R_m, FI, S_m and m-value$_m$, and CRI_{Env}.
- Recycled binder in RAP and RAS is not 100% available in mixtures, with binder availability dependent on age and climate and proposed maximum limits on PGH of 100°C and 150°C, respectively.
- A binder oxidative aging model can be used to evaluate different binders in different climates and explore the tie between field and laboratory aging.
- Based on CDD, laboratory STOA of 2 h at 135°C (275°F) plus LTOA of 5 days at 85°C (185°F) was equivalent to approximately 8 or 12 months in service in warmer climates and 20 or 24 months in service in colder climates for mixture cracking resistance and stiffness, respectively.

CHAPTER 6

Summary and Path Forward

Chapter 6 presents a summary of the key findings from this study and suggests further research and implementation activities.

6.1 Summary

The results from this study are presented in this report and organized with key results from Phase 1 and Phase 2 highlighted in Chapter 1 and Chapter 2, respectively. Field performance of the test sections in the five field projects is provided in Chapter 3 and compared to corresponding laboratory performance at low recycling-agent doses, and expanded laboratory performance results at higher recycling agent-doses are shown in Chapter 4. Chapter 5 summarizes the evaluation tools developed as a result of the extensive data generated and analyses conducted in all three phases of this study and included in a draft AASHTO standard practice provided in Appendix I.

The comprehensive results presented in this report and documented in multiple publications and presentations indicated that the following factors are not distinct but instead contribute concurrently to determine the performance of mixtures with high RBRs and recycling agents initially and with aging:

- Base binder PG and quality (ΔT_c);
- Binder modification by polymers or WMA or other additives;
- Proportions of recycled materials (RAPBR and RASBR);
- Recycling-agent type;
- Recycling-agent dose; and
- Recycled binder availability, which is a function of its aging state and production temperature.

These overlapping factors and their interplay highlighted the need to evaluate mixture performance and necessitated the development of the following tools that are included in the draft AASHTO standard practice (Appendix I) to facilitate the evaluation of the effectiveness of recycling agents in high RBR binder blends and corresponding mixtures initially and with aging:

- Component materials selection guidelines based on PGH and ΔT_c and limiting RAS content and total RBR.
- Recycling-agent dose selection method and materials proportioning based on PGH.
- Binder blend rheological evaluation tools with thresholds for PGH and the G-R parameter or $T_{\delta = 45°}$ from DSR testing and ΔT_c from BBR testing.
- Mixture performance evaluation tools with thresholds for $N_{12.5}$ from HWTT or APA testing, G-R_m parameter from $|E^*|$ testing, FI from I-FIT testing, S_m and m-value_m from BBR_m testing, and CRI_{Env} from UTSST testing.
- Recycled binder availability factor for RAP that correlates with PGH.

The evaluation tools for binder blends and mixtures include aging protocols, recycling-agent blending methods, and laboratory tests and corresponding thresholds for adequate performance. Additional investigations of chemical compatibility of recycling agents with base and recycled binders and representative binder blending were also completed in Phase 2, and laboratory aging and climate effects were explored for both binder blends and mixtures.

Table 41 provides a summary of the key findings from this study that were highlighted at the end of each chapter, and cross-references all of the laboratory and field experiments that justify these findings (Epps Martin et al. 2015, 2017).

6.2 Path Forward

Based on results presented in this final report, challenges remain for evaluating recycling-agent effectiveness initially and with aging for mixtures with high RBRs and recycling agents. This section provides suggested areas of future research and implementation activities.

6.2.1 Suggested Future Research

Ideas for suggested future research generated during this study include the following:

- Moisture Susceptibility: In the process of determining the selected recycling-agent dose to match continuous PGH for the target climate and verifying the rutting resistance of rejuvenated mixtures, limited HWTT testing was performed. Some mixtures failed HWTT criteria; however, additional dry HWTT testing conducted in the APA Junior indicated these same mixtures had adequate rutting resistance. These results suggest that adequate rutting resistance can be achieved, but moisture susceptibility may be an issue when recycling agents are used. Further research outside the scope of this study is needed.
- Long-Term Aging: Based on the data from NCHRP 09–52, a more significant laboratory LTOA protocol compared to the 5 days at 85°C (185°F) is needed to simulate approximately 7 to 10 years of field aging, when asphalt pavements are most vulnerable to cracking. Recently, several studies including NCHRP Project 09–54 "Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction" (Kim et al. 2017) have evaluated additional laboratory LTOA protocols, and the findings from these studies are summarized as follows:
  - Reinke (2015): LTOA protocol of 12 h to 24 h of loose mix aging at 135°C (275°F) was representative of approximately 8 years in Minnesota.
  - Blankenship and Zeinali (2016): LTOA protocol of 24 h of loose mix aging at 135°C (275°F) was equivalent to 5 to 7 years of field aging.
  - Elwardany et al. (2016): Oven aging of loose mix was more promising than aging compacted specimens; LTOA protocol of 13 to 21 days of loose mix aging at 95°C (203°F) was equivalent to approximately 8 years in Virginia.
  - Hanz et al. (2016): LTOA protocol of 12 h of loose mix aging at 135°C (275°F) was equivalent to that of 5 days at 85°C (185°F) for compacted specimens.
  - Kim et al. (2017): Loose mix aging at 95°C for predefined durations (9–21 days) based on climatic data can approximately represent 4 to 16 years of service.

  Therefore, in future research, LTOA protocols of loose mix aging at 95°C (203°F) or 135°C (275°F) prior to compaction need to be explored.
- Rheological Evaluation of Modified Binders:
  - Historical data from evaluation of unmodified base binders indicate that fracture properties are related to stiffness and linear viscoelastic (LVE) characteristics (Heukelom 1966) and that the embrittlement of binders with aging correlates to the observed reduction in phase angle (Ruan et al. 2003). Furthermore, other frequency- and temperature-dependent

Table 41. NCHRP 09–58 key findings.

Key Findings	Binder Blend Results						Mortar Results	Mixture Results								
	PG & ΔT_c	G-R Parameter	$T_{\delta = 45°}$	SAR-AD, T_g, T_g End	CA_g	Aging Prediction	PG & ΔT_c	CI	Binder Content P_b	M_R	$\lvert E^*\rvert$ & $G\text{-}R_m$	FI	S_m, m-value$_m$	$N_{12.5}$	CRI_{Env}	D^R, G^R vs N_f
Recycling-agent effectiveness must be characterized in high RBR binder blends or mixtures initially and with long-term aging to capture initial compatibility and rheological response to oxidation.	—	✓	—	—	✓	✓	—	—	—	✓	✓	✓	✓	✓	✓	—
Recycling-agent dose to match continuous PGH for target climate is required for high RBR binder blends and mixtures to maintain durability with long-term aging, with lower dose to restore PGL only sufficient with short-term aging. Recycling agent doses used in the field projects in this study were insufficient with aging.	✓	✓	✓	—	—	—	—	—	—	✓	✓	✓	✓	✓	✓	—
Recycling agents are more effective in rejuvenating less-aged recycled materials (RAP more than RAS and MWAS more than TOAS) in balanced, limited proportions ($\leq$ 0.5 RAPBR + RASBR and $\leq$ 0.15 RASBR). RAS contents should be limited because at typical production temperatures, RAS likely acts as a filler with none of the stiff, brittle recycled binder available for blending.	✓	✓	—	—	—	—	✓	—	—	✓	✓	✓	✓	—	—	—
Rejuvenation mechanisms differ by recycling-agent type.	✓	✓	—	—	✓	✓	✓	—	—	—	—	—	—	—	—	—
Chemical analysis of high RBR binder blends with recycling agents is challenging, and additional evaluation tools are needed.	—	—	—	✓	✓	—	—	—	—	—	—	—	—	—	—	—
Use of high-quality base binders ($\Delta T_c \geq -3.5$) improves performance of high RBR binder blends and mixtures with recycling agents.	✓	✓	✓	—	—	✓	✓	—	—	✓	✓	✓	✓	—	—	—
Recycled binder in RAP and RAS is not 100% available in mixtures, with binder availability dependent on age and climate and proposed maximum limits on PGH of 100°C and 150°C, respectively.	—	—	—	—	—	—	—	—	✓	—	—	—	—	—	—	—
Adequate performance for high RBR binder blends with recycling agents can be controlled with proposed thresholds for PGH, G-R parameter, and ΔT_c. Crossover temperature ($T_{\delta = 45°}$) can be used as an alternative approach to the G-R parameter.	✓	✓	✓	—	—	—	—	—	—	—	—	—	—	—	—	—
Mortar procedures provide realistic assessment of binder blending and narrow the PG UTI as compared to that of a corresponding binder blend.	✓	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—

(continued on next page)

Table 41. (Continued).

Key Findings	Binder Blend Results						Mortar Results	Mixture Results								
	PG & ΔT_c	G-R Parameter	$T_{\delta=45}$	SAR-AD, T_g, T_g End	CA_g	Aging Prediction	PG & ΔT_c	CI	Binder Content P_b	M_R	$\lvert E^* \rvert$ & G-R_m	FI	S_m, m-value$_m$	$N_{12.5}$	CRI_{Env}	D^R, G^R vs N_f
Adequate performance for high RBR mixtures with recycling agents can be controlled with proposed thresholds for $N_{12.5}$, G-R_m, FI, S_m and m-value$_m$, and CRI_{Env}. Field performance can be used to establish or verify thresholds for adequate mixture cracking performance or performance of recycled asphalt mixtures with high RBR, and recycling agents can be compared to that of DOT control mixtures.	—	—	—	—	—	—	—	—	—	—	✓	✓	✓	✓	✓	—
Some high RBR mixtures with recycling agent may be moisture susceptible.	—	—	—	—	—	—	—	—	—	—	—	—	—	✓	—	—
A binder oxidative aging model can be used to evaluate different binders in different climates and explore the tie between field and laboratory aging.	—	—	—	—	—	✓	—	—	—	—	—	—	—	—	—	—
Based on CDD, laboratory STOA of 2 h at 135°C (275°F) plus LTOA of 5 days at 85°C (185°F) was equivalent to approximately 8 or 12 months in service in warmer climates and 20 or 24 months in service in colder climates for mixture cracking resistance and stiffness, respectively.	—	—	—	—	—	—	—	—	—	✓	—	✓	—	—	—	—
Standard laboratory fabrication protocols with STOA produce specimens that represent cores for high RBR mixtures with and without recycling agent.	—	—	—	—	—	—	—	—	—	✓	—	✓	—	—	—	—
100% addition with a mandatory requirement to ensure adequate mixture rutting resistance is recommended to add recycling agents at doses > 5.0% in mixtures with RAS.	—	—	—	—	—	—	—	✓	—		—	—	—	—	—	—
Modifications are needed for testing high RBR mixtures after long-term aging.	—	—	—	—	—	—	—	—	—		—	✓	—	—	—	✓
Reheating to produce RPMLC specimens is especially detrimental to high RBR mixtures with recycling agents.	—	—	—	—	—	—	—	—	—	✓	—	✓			✓	✓

NOTE: — = not applicable.

properties of viscoelastic materials (such as fracture properties) can be shifted by the LVE time–temperature superposition principles provided that the same molecular motions govern both LVE and fracture properties (Tabatabaee et al. 2013; Roland 2011). A relationship between LVE and fracture properties is commonly accepted for neat asphalt binders and mixtures (not polymer-modified); nevertheless, characterization of polymer-modified binders in the LVE range is arguably effective in capturing the benefit of polymer modification in improving binder cracking resistance. The current PGI specifications, G-R parameter, and $T_{\delta = 45°}$ commonly rank polymer-modified materials in the same range or with poorer performance compared to unmodified binders with respect to cracking, while field experience supports the benefit of polymer modification (Von Quintus et al. 2007).

  - Considering the $T_{\delta = 45°}$ approach developed in this study, at a given frequency, the polymer-modified materials may exhibit the transition from solid- to fluid-like behavior at a higher temperature compared to unmodified binders. A higher $T_{\delta = 45°}$ implies that there is a wider temperature range in which the material is predominantly storing (G') stress instead of dissipating (G") stress due to viscous flow. However, if the failure strength of the polymer-modified material is significantly higher than the accumulated thermal and/or load induced stresses, the material may exhibit satisfactory performance with respect to low- or intermediate-temperature cracking. It is important to highlight that in the parallel aging process of the asphalt binder and the polymer modifier, the first can increase while the second can reduce $T_{\delta = 45°}$, while both mechanisms are expected to contribute to an overall loss in fracture/fatigue resistance. Therefore, an overall increase in $T_{\delta = 45°}$ with aging is more than likely an indicator of reduced fracture/fatigue resistance in a polymer-modified binder.
  - Further research is needed for improved characterization/ranking of the cracking resistance of polymer-modified binders. DSR-based experimental methods such as the linear amplitude sweep (LAS) test, the multiple stress creep and recovery (MSCR) test, or the bitumen yield energy test (BYET) are available to characterize polymer-modified binders with respect to rutting and cracking resistance. The BYET approach was developed as a DSR surrogate for the ASTM D113 ductility test as a performance index for specification of polymer-modified binders to measure fracture properties (Tabatabaee et al. 2013).
  - For fatigue evaluation of binders, test temperature selection becomes critical since different temperatures may result in different rankings. To overcome this issue, test temperatures could be normalized to $T_{\delta = 45°}$, similar to the normalization to glass transition temperature previously presented for evaluating low-temperature time-dependent fracture mechanics properties of asphalt binders (Gauthier and Anderson 2006).
  - Climate-based adjustment of $T_{\delta = 45°}$ thresholds should also be considered in future research to possibly determine an intermediate-temperature PG grade analogous to PGH and PGL.

- Chemical Assessment of Recycling Agents: Differences other than carbonyl need to be explored in FT-IR spectra. Although CA_g is typically tied to increases in binder stiffness, results in this study suggest that the oxygen uptake versus binder embrittlement in terms of G-R/CA_g HS may change significantly when a recycling agent is added to a recycled binder, resulting in additional benefits from recycling agents beyond the initial impact on rheology.
- Climate Effects: More research is needed, with additional field projects, to develop more refined mixture cracking resistance thresholds at both intermediate and low temperatures for different climates across the United States.
- Specimen Fabrication: Additional validation of the recommended specimen fabrication aging protocols and guidelines for recycling-agent blending by addition, replacement, or a combination of both methods should be completed for mixtures with various optimum binder contents since the amount of total binder in the mixture and other factors, such as binder availability/contribution of the recycled materials and RBR, will likely have an effect on coatability.

6.2.2 Suggested Implementation Activities

Ideas for suggested implementation activities generated to apply the results of this study include the following:

- Field Demonstration Project: Unfortunately, the majority of the field projects in this study used significantly lower recycling-agent doses than those selected to match continuous PGH for the target climate. Thus, a field demonstration project with a recycling-agent dose selected by the method developed in this study is needed for validation of the evaluation tools also developed in this study. This demonstration project requires a minimum of the following two test sections: one with recycled materials at the maximum proportion allowed by current specifications and one with recycled materials at a higher RBR than that allowed by current specifications and a recycling agent at the dose selected by the method developed in this study.
- Review of State Specifications: The tools developed in this study can be utilized to review state specifications limiting recycled materials (RAP and RAS) and propose revisions as necessary based on characterization of commonly used base binders and recycled materials sources and application of these tools.
- Field Performance Monitoring: Additional data gathered through continued field performance monitoring of the field projects in this study could be invaluable in adjusting proposed mixture performance thresholds.

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Abbreviations and Symbols

A	pre-exponential factor
A_i	area of crack initiation
A_p	area of crack propagation
A_v	area of viscous behavior
$A_{vgt\text{–}crit}$	area under the thermal stress–strain plot between the viscous–glassy transition temperature and the required environmental temperature at a given location
$A_{vgt\text{–}F}$	area under the thermal stress–strain plot between the viscous–glassy transition temperature and the fracture temperature of the restrained UTSST specimen
AASHTO	American Association of State Highway and Transportation Officials
AMPT	asphalt mixture performance tester
ANOVA	analysis of variance
APA	asphalt pavement analyzer
ASTM	American Society for Testing and Materials
AV	air void
BAF	binder availability factor
$BaseBR$	base binder ratio
BBR	bending beam rheometer
BBR*m*	BBR for mixtures
BYET	bitumen yield energy test
C	pseudo stiffness
CA	carbonyl area
CA_g	carbonyl area growth
CA_0	original or tank CA measurement
CA$_{\text{tank}}$	carbonyl area tank condition
CDD	cumulative degree day
CI	coatability index
CII	colloidal stability index
CRI	cracking resistance index
CRI_{ENV}	UTSST cracking resistance index including the environmental adjustment factor
D^R	average reduction in pseudo stiffness up to failure
DCC	damage characteristic curve
DE	Delaware
DOB	degree of blending
DOT	department of transportation
DSR	dynamic shear rheometer
E_a	activation energy
EBM	energy-based mechanistic

$\|E^*\|$	dynamic complex modulus
FHWA	Federal Highway Administration
FI	flexibility index
ELS	evaporative light scattering
FT-IR	Fourier-transform infrared
$\|G^*\|$	shear complex modulus
G'	shear storage modulus
G''	shear loss modulus
G-R	Glover-Rowe parameter
G^R	rate of pseudo strain energy release
HMA	hot-mix asphalt
HS	hardening susceptibility
HSD	honestly significant difference
HWTD	Hamburg wheel-tracking device
HWTT	Hamburg wheel-tracking test
I-FIT	Illinois Flexibility Index Test
IDT	indirect tensile strength
IN	Indiana
k_c	slow or constant rate of CA_g
k_f	fast rate of CA_g
LAS	linear amplitude sweep
LMLC	laboratory-mixed, laboratory-compacted
LSV	low shear viscosity
LTOA	long-term oven aging
LTPP	Long-Term Pavement Performance Program
LVDT	linear variable differential transformer
LVE	linear viscoelastic
M	magnitude of fast rate reaction in terms of CA_g
M_R	resilient modulus
MDSC	modulated differential scanning calorimeter
MSCR	multiple stress creep and recovery
MWAS	manufacturer waste asphalt shingles
N	number of load cycles
Nf	number of cycles to failure
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
NH	New Hampshire
NMAS	nominal maximum aggregate size
NV	Nevada
OT	overlay test
P	absolute oxygen pressure during oxidation, atm
Pb_{RAP}	binder content of the RAP
Pb_{RAS}	binder content of the RAS
P_{max}	peak load
P_{RAP}	percentage of RAP by weight of mixture
P_{RAS}	percentage of RAS by weight of mixture
Pb_{total}	binder content of the combined mixture
PAV	pressure aging vessel
PG	performance grade

PGH	high-temperature PG
PGI	intermediate-temperature PG
PGL	low-temperature PG
r_{Cag}	rate of CA_g
R	ideal gas constant
RAP	reclaimed asphalt pavement
RAPBR	RAP binder ratio
RAS	recycled asphalt shingles
RASBR	RAS binder ratio
RBR	recycled binder ratio
RDT	repeated uniaxial direct tension
RE	rejuvenating effectiveness
REOB	recycled engine oil bottom
RI	rheological indices
RPMLC	reheated plant mix laboratory compacted
RTFO	rolling thin film oven
SAR-AD	saturates, aromatics, resins–asphaltene determinator
SCB	semicircular bending
SHRP	Strategic Highway Research Program
SSD	saturated surface dry
STOA	short-term oven aging
S-VECD	simplified viscoelastic continuum damage
t	time, days
T	temperature
$T_{\delta = 45°}$	crossover temperature
T_g	glass transition temperature
TEMPS	Temperature Estimate Model for Pavement Structure
TOAS	tear-off asphalt shingles
TPA	total pericondensed aromatics
TSR	tensile strength ratio
TSRST	thermal stress restrained specimen test
TX	Texas
TxDOT	Texas Department of Transportation
U	load-line displacement
UTI	useful temperature interval
UTSST	uniaxial thermal stress and strain test
W_f	work of fracture
WI	Wisconsin
WMA	warm-mix asphalt
α	reaction order with respect to oxidation pressure
δ	binder phase angle
σ_f	thermal stress at fracture
σ_{vgt}	thermal stress at viscous–glassy transition
ϕ	mixture phase angle
ω_c	crossover frequency

APPENDIX A

Texas Construction Report

The Texas Department of Transportation (TxDOT) executed the Texas State Highway 31 (SH 31) reconstruction project (Project ID CSJ 064-01-068) in the summer of 2014. This reconstruction project, located in northeast Texas, included an approximately 1.4-mi-long asphalt overlay placement. This project used five test sections to study and evaluate the effects of different rejuvenators on the performance of asphalt mixtures with high RAP and RAS content. Originally, this project was initiated under a research study sponsored by TxDOT. The overlay was constructed in the first week of June 2014. The general contractor provided the materials and paved the overlay.

SH 31, at this project site, is a divided rural highway with two lanes in each direction. Typical roadbed width, in each direction, was 30 ft including two 12-ft travel lanes and a 3-ft shoulder on each side. The contractor placed five test sections on the eastbound outside travel lane and right shoulder. These test sections were located between the east side of the city of Murchison and the west side of the city of Brownsboro, Texas (Figure A.1). The new construction of these test sections included 1-inch crack attenuating mix (CAM) followed by one layer of hot rubber seal coat and 2-inch dense-grade Type C mix as a surface course. The inner part of the existing pavement structure before this reconstruction included a 4-inch HMA layer and 6-inch cement concrete layer. The outside (6 ft) of the existing pavement structure included a 4-inch HMA layer, then another 6-inch HMA layer, and 4 inches of iron core base at the bottom. Figure A.2 shows the typical existing pavement structure. Pavement widening at some point in the past attributed to this unusual pavement structure. Annual average daily traffic in each direction measured in 2013 was approximately 5000 with 18 percent truck traffic.

Each of the five test sections had a different surface mix design for the Type C mixture, as shown in Table A.1.

Table A.1: Test Sections with Five Different Mixtures.

Section No.	Section Name	Description	Additive/Rejuvenator Dosage
1	Virgin Mix	Only virgin aggregate with PG 70-22 binder	N/A
2	Control Mix	10% RAP and 5% MWAS with PG 64-22 + WMA additive	WMA additive: 0.5% of total AC by weight
3	T1	10% RAP and 5% MWAS with PG 64-22 + T1	T1: 0.2% of total mix by weight (0.75% weight of RAP + 1.0% weight of RAS)
4	T2	10% RAP and 5% MWAS with PG 64-22 + T2 + WMA additive	T2: 3.7% of total AC by weight WMA additive: 0.3% of total AC by weight
5	E1	10% RAP and 5% MWAS with PG 64-22 + E1	E1: 1.3% of total AC by weight

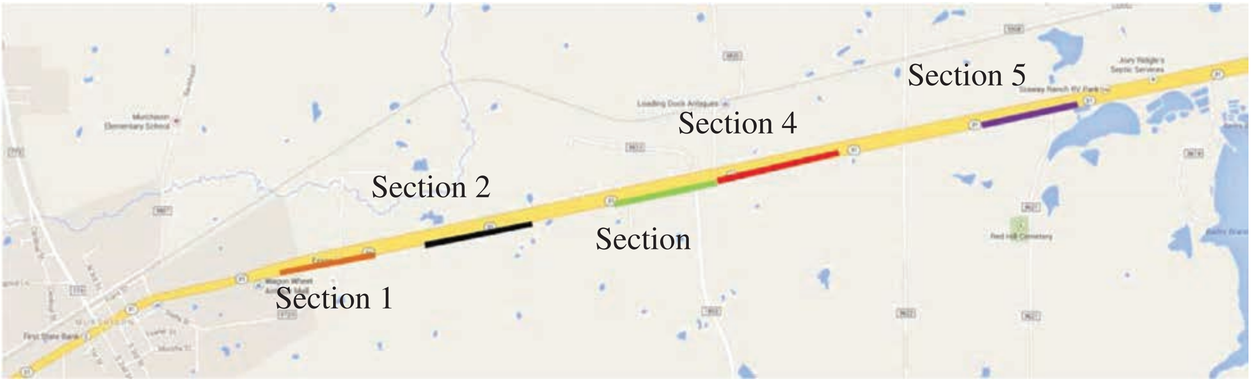


Figure A.1: Layout of Five Test Sections on SH 31.

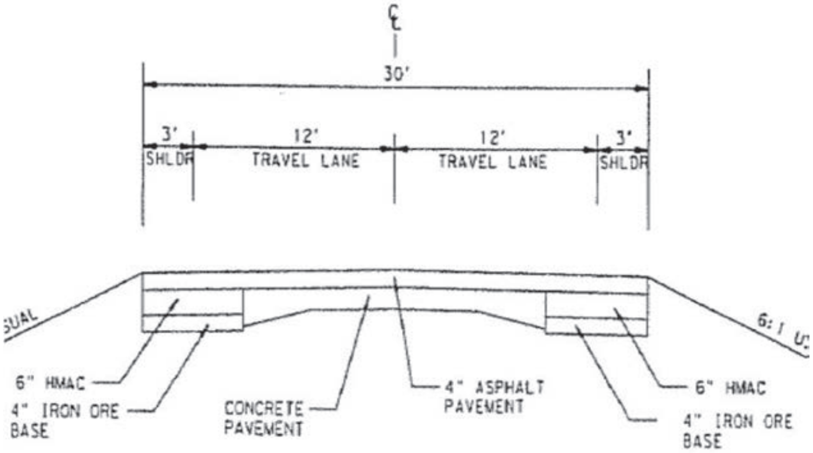


Figure A.2: Typical Existing Section.

A.1. MATERIALS AND MIXTURES

Figure A.3 and A.4 present the mixture designs used for this construction project. Two types of binders were used: an unmodified PG 64-22 and an SBS modified PG 70-22. The specific source of the RAP is unknown, since it came from several highway sections. RAS was produced by shredding and grinding manufacturer waste shingles. The TxDOT Class A (granite) aggregate came from a quarry in Oklahoma, while the TxDOT Class B (limestone) aggregate came from a quarry located in Bridgeport, Texas. All mixtures for this project were produced at the contractor's hot-mix plant located just west of Tyler, Texas. Table A.2 summarizes the production, placement, and ambient temperatures during laydown for different mixes.

A.2. PRODUCTION OF MIX AND PAVING

For each test section, 350 tons of mix was produced and placed. Sections 1, 2, and 3 were constructed on June 3, 2014. All the area was paved with the control mix except sections 1, 3, 4, and 5; each section was approximately was 1800 ft long. Note that Section 2 was established between Sections 1 and 3. Sections 4 and 5 were paved on June 4, 2014. Section 4 mix was placed right next to the Section 3. Besides the test sections, other areas of the roadbed were paved with the control mix. Production began with the mixture used in Section 1 (virgin aggregate with PG 70-22 binder) at 7:15 a.m. on June 03, 2014, at a rate of 200 tons/hr. Table A.2 presents the mixture production schedule with temperature.

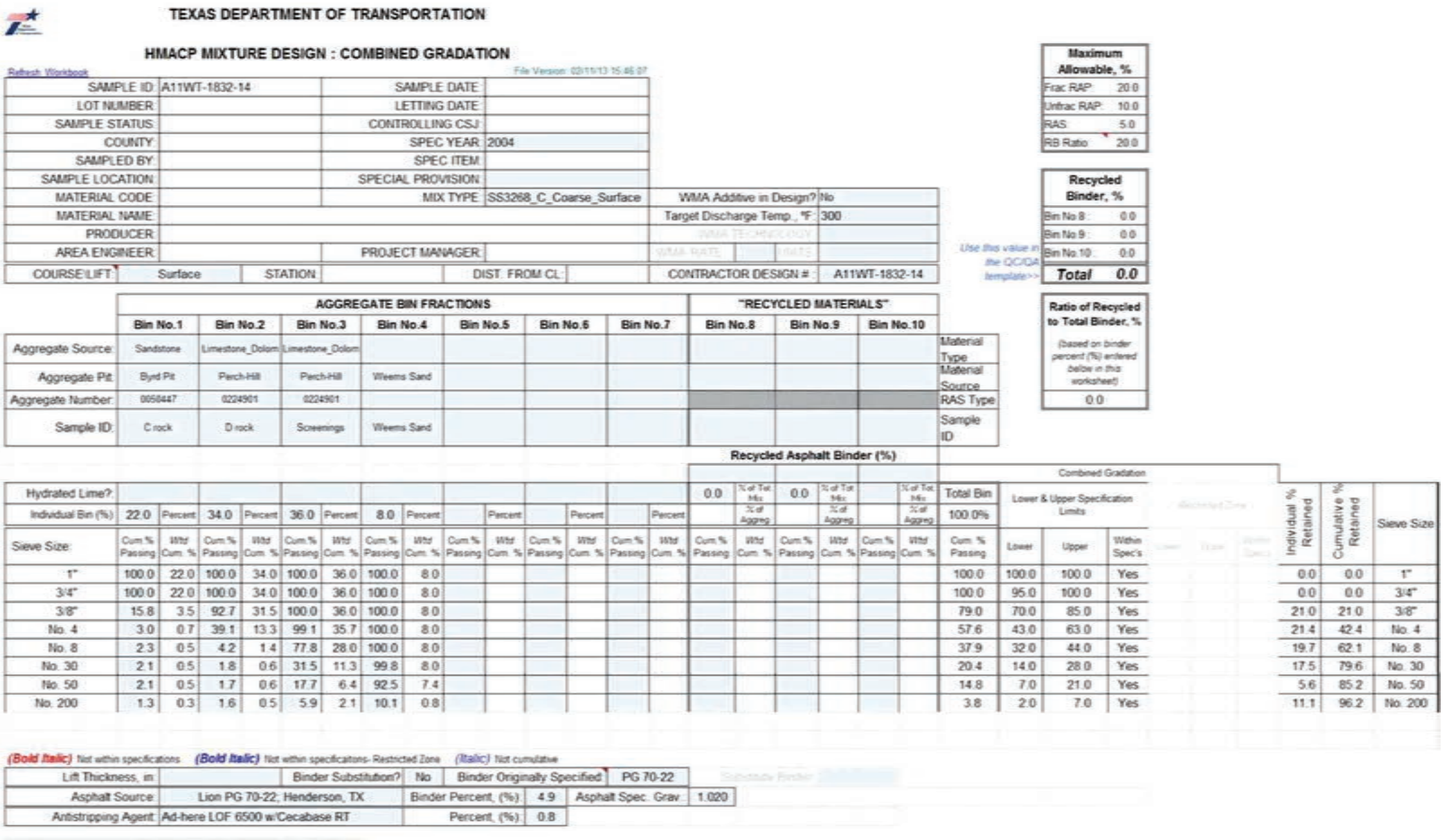
Table A.2: Production, Paving, and Ambient Temperatures

Section	Mixture	Date of Production	Plant Mix Temp, °F	Paving Temp, °F	Ambient Temp, °F
1	Virgin Mix	06/03/2014	325–327	285–290	75–80
2	Control Mix	06/03/2014	275–280	255–260	80–84
3	T1	06/03/2014	280–290	265–270	86–88
4	T2	06/04/2014	275–285	240–250	74–78
5	E1	06/04/2014	280–287	260–265	81–84

A.2.1. Section 1: Virgin Mix

Section 1 was paved on the morning of June 3, 2014. It started at Station 472+37 and ended at Station 490+00 (global positioning system [GPS] coordinate N 32.28094/W 095.73956 to N 32.28194/W 095.73400). The ambient temperature was 75°F during the paving of this section. The virgin mix was produced at around 310°F and then hauled to the paving side in 30 min. The hauling truck (a “flow boy”) directly dumped the mix into the shuttle buggy (material transfer device), and then the mix was transferred to the paver (Figure A.5). The temperature behind the paver was around 290ºF, measured using infrared temperature gun. In addition, an infrared Pave-IR bar was used to measure the asphalt mat temperature behind the paver.

A steel-wheel vibratory (breakdown) roller closely followed the paver. The compaction was achieved by two passes at vibrating mode and two passes at static mode (Figure A.5 a), followed by four passes of a pneumatic roller (Figure A.6 b) and then two passes of a static steel finish roller (Figure A.6 c). Figure A.7 shows the compacted mat.



TEXAS DEPARTMENT OF TRANSPORTATION

HMACP MIXTURE DESIGN : COMBINED GRADATION

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LOT NUMBER:		LETTING DATE:	
SAMPLE STATUS:		CONTROLLING CSJ:	
COUNTY:		SPEC YEAR:	2004
SAMPLED BY:		SPEC ITEM:	
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	SS3268_C_Coarse_Surface
MATERIAL NAME:			
PRODUCER:			
AREA ENGINEER:		PROJECT MANAGER:	

WMA Additive in Design?	No
Target Discharge Temp., °F:	300
WMA TECHNOLOGY	
WMA RATE	

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:		CONTRACTOR DESIGN #:	A11WT-1832-14

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	20.0

Recycled Binder, %	
Bin No.8:	0.0
Bin No.9:	0.0
Bin No.10:	0.0
Total	***0.0***

Use this value in the QC/QA template>>

Ratio of Recycled to Total Binder, %

(based on binder percent (%) entered below in this worksheet)

0.0

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8	Bin No.9	Bin No.10	
Aggregate Source:	Sandstone	Limestone_Dolom	Limestone_Dolom								Material Type
Aggregate Pit:	Byrd Pit	Perch-Hill	Perch-Hill	Weems Sand							Material Source
Aggregate Number:	0058447	0224901	0224901								RAS Type
Sample ID:	C rock	D rock	Screenings	Weems Sand							Sample ID

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7	
Hydrated Lime?:														
Individual Bin (%):	22.0	Percent	34.0	Percent	36.0	Percent	8.0	Percent		Percent		Percent		Percent
Sieve Size:	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %
1"	100.0	22.0	100.0	34.0	100.0	36.0	100.0	8.0						
3/4"	100.0	22.0	100.0	34.0	100.0	36.0	100.0	8.0						
3/8"	15.8	3.5	92.7	31.5	100.0	36.0	100.0	8.0						
No. 4	3.0	0.7	39.1	13.3	99.1	35.7	100.0	8.0						
No. 8	2.3	0.5	4.2	1.4	77.8	28.0	100.0	8.0						
No. 30	2.1	0.5	1.8	0.6	31.5	11.3	99.8	8.0						
No. 50	2.1	0.5	1.7	0.6	17.7	6.4	92.5	7.4						
No. 200	1.3	0.3	1.6	0.5	5.9	2.1	10.1	0.8						

Recycled Asphalt Binder (%)

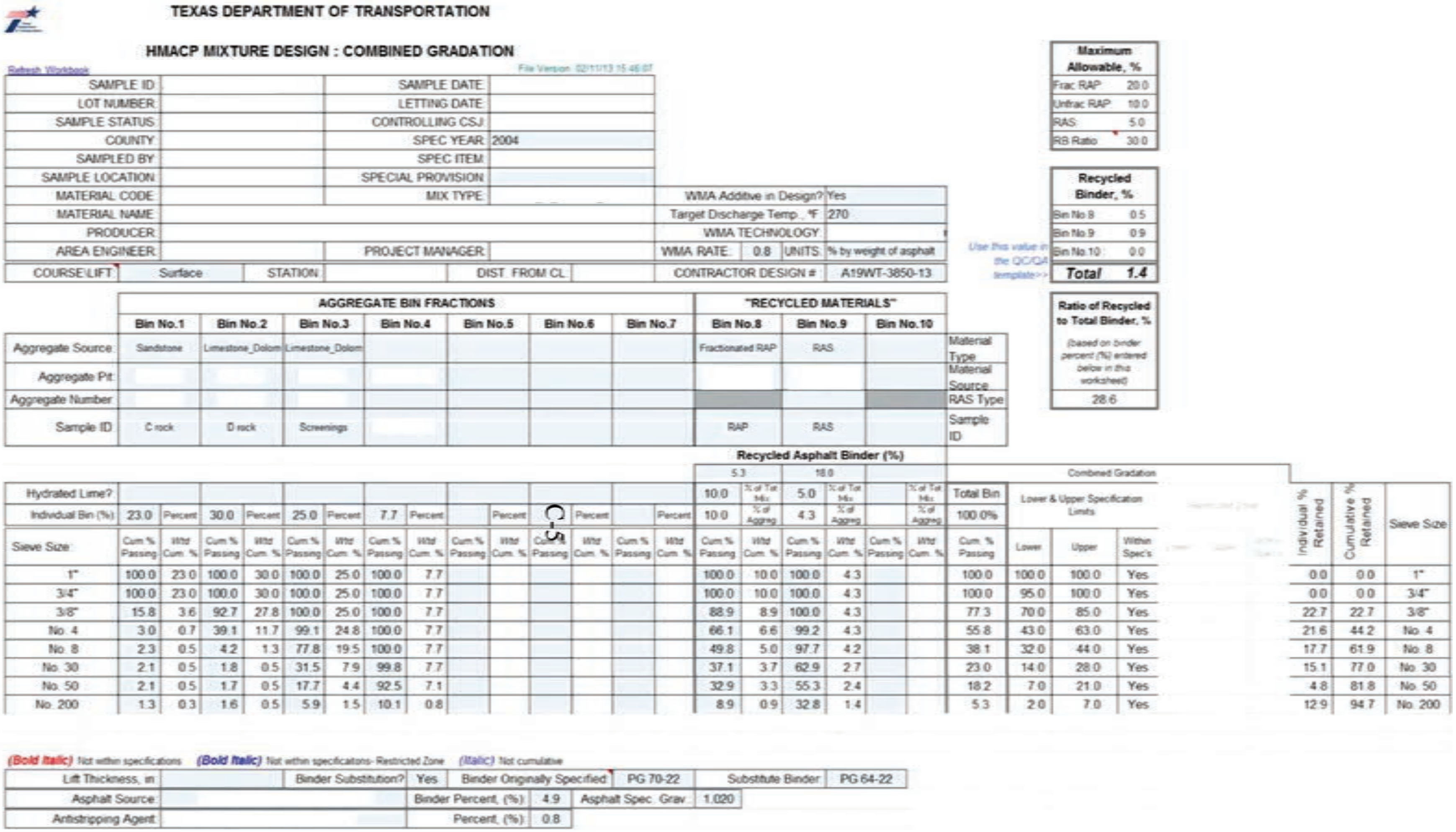
Combined Gradation

	Bin No.8		Bin No.9		Bin No.10			Lower & Upper Specification Limits			Restricted Zone					
Hydrated Lime?:	0.0	% of Tot Mix	0.0	% of Tot Mix		% of Tot Mix	Total Bin									
Individual Bin (%):		% of Aggreg		% of Aggreg		% of Aggreg	100.0%									
Sieve Size:	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's	Lower	Upper	Within Spec's	Individual % Retained	Cumulative % Retained	Sieve Size
1"							100.0	100.0	100.0	Yes				0.0	0.0	1"
3/4"							100.0	95.0	100.0	Yes				0.0	0.0	3/4"
3/8"							79.0	70.0	85.0	Yes				21.0	21.0	3/8"
No. 4							57.6	43.0	63.0	Yes				21.4	42.4	No. 4
No. 8							37.9	32.0	44.0	Yes				19.7	62.1	No. 8
No. 30							20.4	14.0	28.0	Yes				17.5	79.6	No. 30
No. 50							14.8	7.0	21.0	Yes				5.6	85.2	No. 50
No. 200							3.8	2.0	7.0	Yes				11.1	96.2	No. 200

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specificaitons- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:		Binder Substitution?	No	Binder Originally Specified:	PG 70-22	Substitute Binder:	
Asphalt Source:	Lion PG 70-22; Henderson, TX	Binder Percent, (%):	4.9	Asphalt Spec. Grav.:	1.020		
Antistripping Agent:	Ad-here LOF 6500 w/Cecabase RT	Percent, (%):	0.8				

Figure A.3: Mixture Design of Virgin Mix Placed on Section 1 (Virgin Mix).



TEXAS DEPARTMENT OF TRANSPORTATION

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SAMPLED BY:		SPEC ITEM:	
SAMPLE LOCATION:		SPECIAL PROVISION:	
MATERIAL CODE:		MIX TYPE:	
MATERIAL NAME:			
PRODUCER:			
AREA ENGINEER:		PROJECT MANAGER:	

COURSE\LIFT:	Surface	STATION:		DIST. FROM CL:	

WMA Additive in Design?:	Yes		
Target Discharge Temp., °F:	270		
WMA TECHNOLOGY:			
WMA RATE:	0.8	UNITS:	% by weight of asphalt
CONTRACTOR DESIGN #:	A19WT-3850-13		

Maximum Allowable, %	
Frac RAP:	20.0
Unfrac RAP:	10.0
RAS:	5.0
RB Ratio:	30.0

Recycled Binder, %	
Bin No.8:	0.5
Bin No.9:	0.9
Bin No.10:	0.0
Total	**1.4**

Use this value in the QC/QA template>>

Ratio of Recycled to Total Binder, %
(based on binder percent (%) entered below in this worksheet)
28.6

	AGGREGATE BIN FRACTIONS							"RECYCLED MATERIALS"			
	Bin No.1	**Bin No.2**	**Bin No.3**	**Bin No.4**	**Bin No.5**	**Bin No.6**	**Bin No.7**	**Bin No.8**	**Bin No.9**	**Bin No.10**	
Aggregate Source:	Sandstone	Limestone_Dolom	Limestone_Dolom					Fractionated RAP	RAS		Material Type
Aggregate Pit:											Material Source
Aggregate Number:											RAS Type
Sample ID:	C rock	D rock	Screenings					RAP	RAS		Sample ID

	Bin No.1		Bin No.2		Bin No.3		Bin No.4		Bin No.5		Bin No.6		Bin No.7		Bin No.8		Bin No.9		Bin No.10		Combined Gradation						
Recycled Asphalt Binder (%)															5.3		18.0										
Hydrated Lime?															10.0	% of Tot Mix	5.0	% of Tot Mix		% of Tot Mix	Total Bin	Lower & Upper Specification Limits			Individual % Retained	Cumulative % Retained	Sieve Size
Individual Bin (%):	23.0	Percent	30.0	Percent	25.0	Percent	7.7	Percent		Percent		Percent		Percent	10.0	% of Aggreg	4.3	% of Aggreg		% of Aggreg	100.0%						
Sieve Size:	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum % Passing	Wtd Cum. %	Cum. % Passing	Lower	Upper	Within Spec's			
1"	100.0	23.0	100.0	30.0	100.0	25.0	100.0	7.7							100.0	10.0	100.0	4.3			100.0	100.0	100.0	Yes	0.0	0.0	1"
3/4"	100.0	23.0	100.0	30.0	100.0	25.0	100.0	7.7							100.0	10.0	100.0	4.3			100.0	95.0	100.0	Yes	0.0	0.0	3/4"
3/8"	15.8	3.6	92.7	27.8	100.0	25.0	100.0	7.7							88.9	8.9	100.0	4.3			77.3	70.0	85.0	Yes	22.7	22.7	3/8"
No. 4	3.0	0.7	39.1	11.7	99.1	24.8	100.0	7.7							66.1	6.6	99.2	4.3			55.8	43.0	63.0	Yes	21.6	44.2	No. 4
No. 8	2.3	0.5	4.2	1.3	77.8	19.5	100.0	7.7							49.8	5.0	97.7	4.2			38.1	32.0	44.0	Yes	17.7	61.9	No. 8
No. 30	2.1	0.5	1.8	0.5	31.5	7.9	99.8	7.7							37.1	3.7	62.9	2.7			23.0	14.0	28.0	Yes	15.1	77.0	No. 30
No. 50	2.1	0.5	1.7	0.5	17.7	4.4	92.5	7.1							32.9	3.3	55.3	2.4			18.2	7.0	21.0	Yes	4.8	81.8	No. 50
No. 200	1.3	0.3	1.6	0.5	5.9	1.5	10.1	0.8							8.9	0.9	32.8	1.4			5.3	2.0	7.0	Yes	12.9	94.7	No. 200

(Bold Italic) Not within specifications ***(Bold Italic)*** Not within specifications- Restricted Zone *(Italic)* Not cumulative

Lift Thickness, in:		Binder Substitution?:	Yes	Binder Originally Specified:	PG 70-22	Substitute Binder:	PG 64-22
Asphalt Source:		Binder Percent, (%):	4.9	Asphalt Spec. Grav.:	1.020		
Antistripping Agent:		Percent, (%):	0.8				

Figure A.4: Mixture Design of Control Mix Placed on Section 2 (Control Mix).

Figure A.5: Shuttle Buggy and Paver.

(a) Vibratory Roller (b) Pneumatic Roller (c) Steel Finish Roller

Figure A.6: Rollers Used for Compaction.

Figure A.7: Finished Test Section 1: Virgin Mix.

A.2.2. Section 2: Control Mix

Section 2 was the control mix section with 10 percent RAP and 5 percent RAS. This section was a warm-mix asphalt section. It started at Station 501+50 and ended at Station 520+00 (GPS coordinate N 32.28265/W 095.73025 to N 32.28371/W 095.72421). The mix temperature measured at the dump truck at the project site was around 275–280°F, and the mat surface temperature behind the paver was around 260°F. The rolling pattern was similar to that of Section 1 except that the breakdown roller had three passes in vibratory mode and one pass in static mode followed by four passes with the pneumatic roller and then two passes with the static steel finish roller. Some minor segregation was observed after the laydown at the center of the mat (Figure A.8 a), but they were not noticeable on the compacted mat (Figure A.8 b).

(a) (b)

Figure A.8: Section 2; (a) Observed Segregation on Loose Mat, and (b) Finished Surface.

A.2.3 Section 3: Control Mix with Rejuvenator T1

Section 3 started at Station 536+00 and ended at Station 557+00 (GPS coordinate N 32.28460/W 095.71922 to N 32.28585/W 095.72226). The mix temperature measured at the dumping truck was around 290°F, although it was supposed to be a warm-mix temperature of 275°F or below according to the experimental design. The mat temperature behind the paver was around 270°F. Section 3 employed the same rolling pattern as Section 2. Again, some segregation was observed on the loose mat (Figure A.9 a), but the finished surface did not show any sign of segregation (Figure A.9 b).

(a) (b)

Figure A.9: Section 3; (a) Observed Segregation on Loose Mat of Section 3, and (b) Finished Surface.

A.2.4. Section 4: Control Mix with Rejuvenator T2

Section 4 started at Station 557+00 and ended at Station 580+00, (GPS coordinate N 32.28585/W 095.72226 to N 32.287081/W 095.70523). Note that the end of Section 3 was the beginning of Section 4. Section 4 and Section 2 had the same rolling pattern. Section 4 was paved in the early morning at around 8:30 a.m. In the beginning, the mix temperature measured at the dumping truck was around 270°F. The mat temperature behind the paver was around 230–240°F. However, obvious segregation was observed on the loose mat (Figure A.10). The paving crew asked to increase the production temperature. After the speed limit sign (Figure A.11), the mix dumping temperature measured from the truck was 285°F. However, segregation issue was not resolved (Figure A.12).

Figure A.10: Segregation behind the Paver—Section 4.

Figure A.11: Mix with Higher Production Temperature Placed beyond Speed Limit Sign.

Figure A.12: Observed Segregation Even after Increasing the Production Temperature.

A.2.5. Section 5: Control Mix with Rejuvenator-ERA-1

Section 5 started at Station 607+00 and ended at Station 527+00, (GPS N 32.28858/W 095.69669 to N 32.28970/W 095.69034). Section 5 was paved on the afternoon of June 4 starting at around 1:00 p.m. The mix temperature measured at the dumping truck was around 287°F, although it was supposed to be a WMA temperature of 275 F or below. The mat temperature behind the paver was around 265ºF. A rolling pattern similar to Section 2 was used to compact the mat. No obvious segregation (Figure A.13) was observed in Section 5.

Figure A.13: No Obvious Segregation in Section 5.

A.3. DESCRIPTION OF ASPHALT MIX PLANT

All the mixtures were produced at an asphalt mix plant located on the west side of Tyler, Texas. The average distance between the plant and the test sections was about 20 mi, or a 25-min drive. This plant was unique in the sense that it had two drums: one for drying the aggregates and the other for mixing. Figure A.14 shows the overview of this hot-mix plant. RAP and RAS were added with hot aggregate just outside the drying drum before they entered into the mixing drum. The binder was directly injected into the mixing drum. The admixtures and rejuvenators were injected into the AC line. This plant, manufactured in 1997, has a capacity of 400 tons of mixture per hour. The parallel mixing drum has a dimension of 18 ft long by 6 ft diameter with a 15-ft-long mixing zone. The counterflow drying drum has a dimension of 38 ft long by 9 ft diameter. This natural-gas-fueled plant has a conventional baghouse emission system where part of the fines is returned to the drum. The plant has six bins for virgin aggregates and three bins for RAP and RAS. There are also three insulated silos with a storage capacity of 200 tons of mix each. The plant has three horizontal binder storage tanks. The plant produced typically 200 tons per hour of mix during the construction of the test sections. The storage temperatures at the tanks were 304°F and 294°F for the PG 70-22 and PG 64-22 binders, respectively. The additives and recycling agents were kept at an ambient temperature.

Figure A.14: Overview of the Asphalt Mix Plant.

A.4. SAMPLE COLLECTION

Plant mix was collected from the trucks at the plant by climbing on scaffolding. Figure A.15 shows the sample collection at the plant. Due to the demand from multiple research projects and universities involved, a large amount of plant mix was collected in 5-gal buckets from multiple trucks. Small amounts of the plant mix were brought back to the onsite laboratory for immediate compaction. The plant mix samples were collected usually after 200 tons of production for any given section. The material sampling scheme is presented in Table A.3. With the help of the contractor, the research team also collected forty 6-inch-diameter cores from the test sections. These cores were obtained from the outside shoulder. The team also collected quality-control cores at random locations.

Table A.3: Material Sampling Scheme.

Sample Type	Material	Point of Sampling
Lab Mixed, Lab Compacted	Fine Aggregate	Stockpile
	Coarse Aggregate	Stockpile
	RAP	Stockpile
	RAS	Stockpile
	Admixture/Rejuvenators	Storage Tank (plastic tote in metal cage) at Plant
	PG 64-22 Asphalt	Terminal
	PG 76 -22 Asphalt	Terminal
Plant Mixed, Lab Compacted	Loose Mix	Truck at Plant
Plant Mixed, Field Compacted	Cores	Shoulder

Figure A.15: Collection of Loose Mix from Truck at Asphalt Mix Plant.

A.5. ONSITE SPECIMEN COMPACTION

Twenty specimens 6.0 inches diameter by 2.4 inches height were compacted onsite at the laboratory located within the plant premises. Loose plant mix collected from the trucks was quickly brought to the laboratory and placed in the oven between 1 to 2 hr to achieve its compaction temperature. The researchers compacted these specimens using a Superpave gyratory compactor to 7 ± 1 percent air voids. Specimens were compacted at 270°F and 250°F for mixtures with PG 70-22 (Section 1) and PG 64-22 binders, respectively.

A.6 STOCKPILES AND PLANT DETAILS

Figure A.16 shows the separate conveyor belts carrying virgin aggregates and RAP/RAS to the different parts of the asphalt plant. Figure A.17 depicts the entry point of admixture/rejuvenator into the AC line. Figure A.18 through A.20 depict RAS, RAP, and aggregate stockpiles. None of the stockpiles was covered. Moisture content of RAP, RAS, screenings, and sand was 5.5 percent, 6.4 percent, 5.4 percent, and 8.1 percent, respectively. Average moisture content of 5.0 percent was input during the production. The RAP was screened over a 2-inch sieve before mixing with the aggregate. RAS was produced by shredding the manufactured waste shingles using a shredder located on site.

Figure A.16: Aggregate and RAP/RAS on Separate Conveyor Belts.

Figure A.17: Admixture/Rejuvenator Injected Directly into the AC Line.

Figure A.18: RAS Stockpile.

Figure A.19: RAP Stockpile.

Figure A.20: Aggregate (One of Several) Stockpile

APPENDIX B

Nevada Construction Report

In a collaborative effort with University of Nevada, Reno and its NCHRP 9-58 research team, the Washoe County of Northern Nevada implemented a major rehabilitation project on Matterhorn Blvd (PWP-WA-2015-179) to study the influence of rejuvenators on hot mix asphalt (HMA) with high recycled asphalt pavement (RAP) materials. The Matterhorn Blvd is a low volume road with a single lane in each direction located 17 miles north of Reno, Nevada. The existing pavement before rehabilitation had 3.5 to 5.0 inches of HMA on top of the aggregate base and it was severely damaged by thermal cracking. The old asphalt pavement layer was constructed using lightweight Allite aggregates with a water absorption of the aggregate being around 5.3%. The rehabilitation project consisted of pulverization and compaction of the existing asphalt pavement and base to the depth of 6 inches and placing a new 3 inch thick overlay on top.

Five test sections were constructed in September 2015 and the description of each section is given in Table B.1. The test sections were laid out on Matterhorn Blvd as shown in Figure B.1. Each section spreads to about 24 ft wide and 2000 ft long.

Table B.1: Description of Nevada test sections

Sections	Description
Section 1 (Virgin section)	PG64-28NV/ No RAP / No Recycling Agent
Section 2 (Control section with 0.3RBR)	PG64-28NV/ 0.30 RAP Binder Ratio (RBR)/ No Recycling Agent
Section 3 (T2 section)	PG64-28NV/ 0.30 RBR / T2
Section 4 (A2 section)	PG64-28NV/ 0.30 RBR / A2
Section 5 (Control section with 0.15RBR)	PG64-28NV/ 0.15 RBR / No Recycling Agent

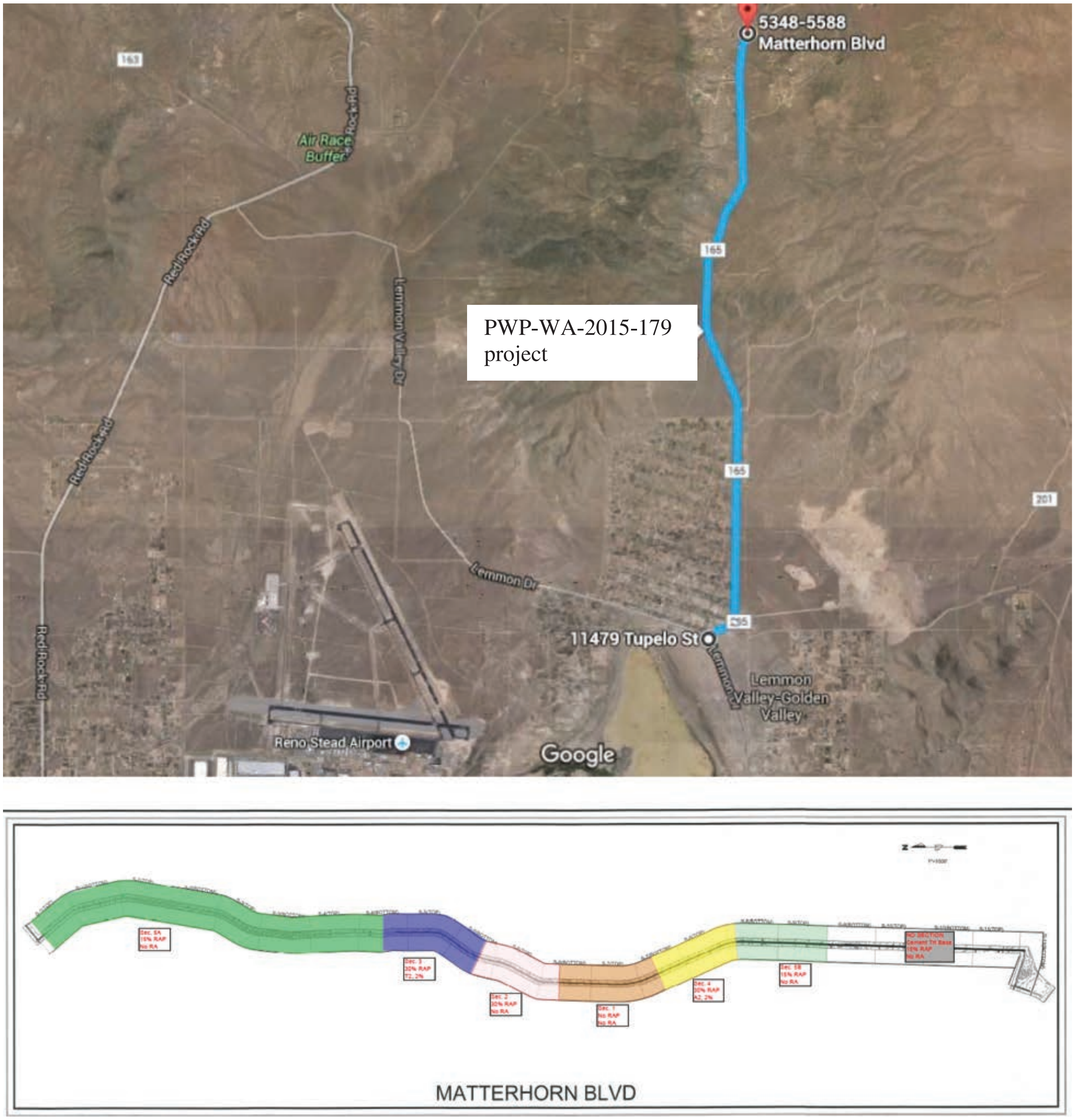


Figure B.1: Nevada test sections layout.

B.1. MATERIALS AND HMA PRODUCTION

The aggregates and RAP materials were obtained from a pit in Lockwood and the asphalt binder was a PG64-28NV polymer-modified. The RAP material was a mixture of plant rejects and locally obtained old pavement materials processed to meet the ½" RAP specification of the Orange Book Standard Specifications for Public Work Construction (SSPWC) from Washoe County. The job mix formula (JMF) was obtained by combining five aggregate stockpiles: ¾" crushed aggregates (17%), ½" crushed aggregates (10%), 3/8" crushed aggregates (15%), #4 crusher fines (14%), and #4 Natural fines (10%); all the percentages are by total weight of mixture. The contractor conducted the Marshall Mix designs (50 blows) for Type 2 HMA mixes according to the Orange Book (SSPWC). The volumetric properties of the designed mixes are summarized in Table B.2. Figure B.2 shows the pictures of raw materials at the mixing plant. The coarse and fine aggregates were marinated with 1% hydrated lime and stored in separate stockpiles prior to mixing.

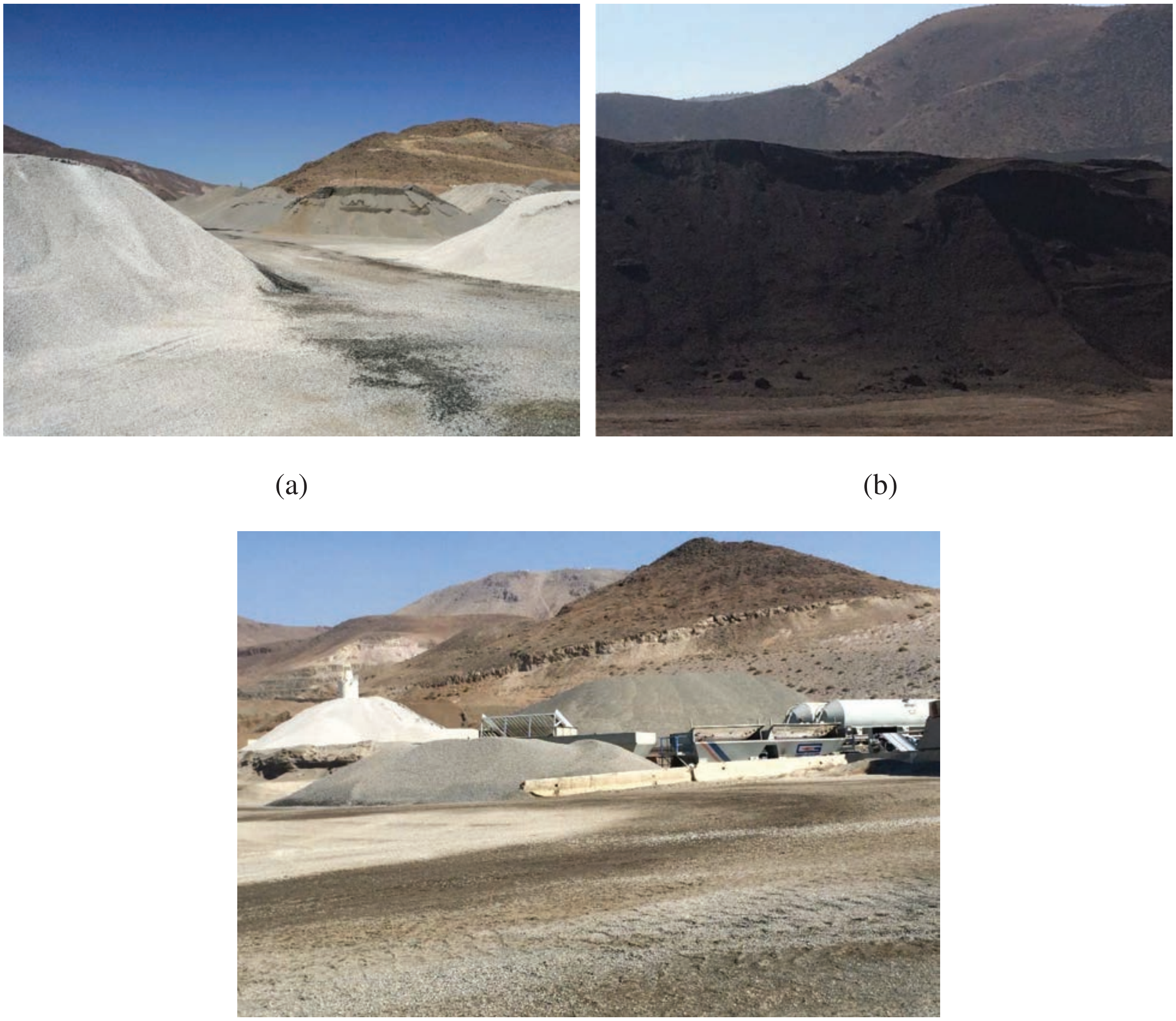
The marinated aggregates were mixed with asphalt in a continuous mixing drum (Figure B.3 b) at 335°F. The recycling agents were heated at 120°F and injected to the asphalt line during mixing as recommended by the manufacturer. Mixed HMA mixtures were transferred to the silos for storage. The silo time (storage time) varied between 30 minutes and 3 hours throughout the production. The average temperature of HMA when discharged from the silo into the hauling truck was 320°F. The construction site was located at about 23 miles from the mixing plant and the average hauling time was around 30 minutes. Figure B.3 shows the pictures of the asphalt mixing plant at Lockwood.

Table B.2: Summary of the Nevada Test Sections Mix Designs

	Section 1	**Section 2**	**Section 3**	**Section 4**	**Section 5**
RAP, %	0	33	33	33	15
RA type, %	-	-	T2[1], 2.0%	A2[1], 2.0%	-
RAP Binder Ratio (RBR)	0	0.324	0.332	0.324	0.144
Optimum total binder content, %TWM[2]	5.37	4.60	4.50	4.60	5.04
Virgin binder content, %TWM[2]	5.37	3.11	3.01	3.11	4.32
VMA, %	13.3	13.7	13.9	14.0	13.3
VFA, %	69.8	71.1	71.2	71.8	69.8

[1] T2-Evoflex, A2-Reclamite

[2] TWM denotes "Total Weight of Mix"



(a)

(b)

(c)

Figure B.2: Picture of (a) Aggregate stockpiles; (b) Processed RAP stockpile; and (c) Marinated aggregate stockpile along with asphalt binder tanks at the asphalt plant.

(a) (b)

(c)

Figure B.3: Picture of (a) Array of aggregate bins; (b) Continuous mixing drum; and (c) Storage silos at the asphalt plant.

B.2. CONSTRUCTION

The pulverization and compaction of the existing asphalt pavement and base was completed few days prior to the construction of the new asphalt pavement layer. The pulverized and compacted base layer was wetted and levelled by a motor grader before placing the HMA. The air temperature varied between 77 and 84°F and the wind speed varied between 5 and 15 mph during construction. The HMA was transported to the construction site using belly dump trucks with the capacity of 40 ton. The HMA was placed in a window on top of the compacted base.

Figure B.4 shows the belly dump truck and the HMA material placed in a windrow. A windrow elevator picked up the HMA and transferred it into the paver hopper. A paver (Figure B.5) laid down the HMA on top of the base. The HMA layer was placed in one lift since the target thickness of the layer was 3 inches. One lane (12 ft) was paved at a time and the other lane was kept open to the traffic. The paved HMA mixtures were compacted using three types of rollers; CAT CB64 vibratory roller, Volvo DD38 vibratory roller, and CAT CC34 pneumatic rollers. The breakdown roller (CAT CB64) did four vibratory passes and one static pass followed by two static passes by the pneumatic roller. The Volvo DD38 was used to compact the joints properly and finish the compaction with two static passes. A pass here is defined as both wheels of the compactor rolling over a specific point on the mat. Figure B.6 shows the fleet of compactors and the break down compactor behind the paver. A summary of the windrow temperature and beginning and end station marks of each test section are given in Table B.3. Physical or functional differences were not observed between mixtures with recycling agents and regular HMA mixes during the mixing and compaction process in the field. Figure B.7 shows the pictures of pavement surfaces of the test sections. The mat densities were measured after the completion of compaction using nuclear density gauges by both contractor and consultant.

(a) (b)

Figure B.4: Picture of (a) Belly dump truck; and (b) HMA placed in a windrow.

Figure B.5: Picture of the windrow lifter and paver.

(a) (b)

Figure B.6: Picture of (a) Fleet of compactors; and (b) Breakdown roller behind the paver.

Table B.3: Summary of the windrow temperature and station locations

Construction Date	Section number	RBR	Recycling agent	Lane	Start station	Stop station	Windrow HMA Temp. (°F)
10-Sept. 2015	4	0.30	A2	SB	279	304	305
				NB	279	304	290-310
	1	0.00	None	SB	252+70	279	295-305
				NB	252+70	279	295-305
11-Sept. 2015	3	0.30	T2	SB	226	252+70	310-320
				NB	232+50	252+70	302
	2	0.30	None	SB	198+50	226	290-305
				NB	197+55	232+50	310-320
16 and 17-Sept. 2015	5	0.15	None	SB	102	198+50	300-310
				NB	102	197+55	300-310

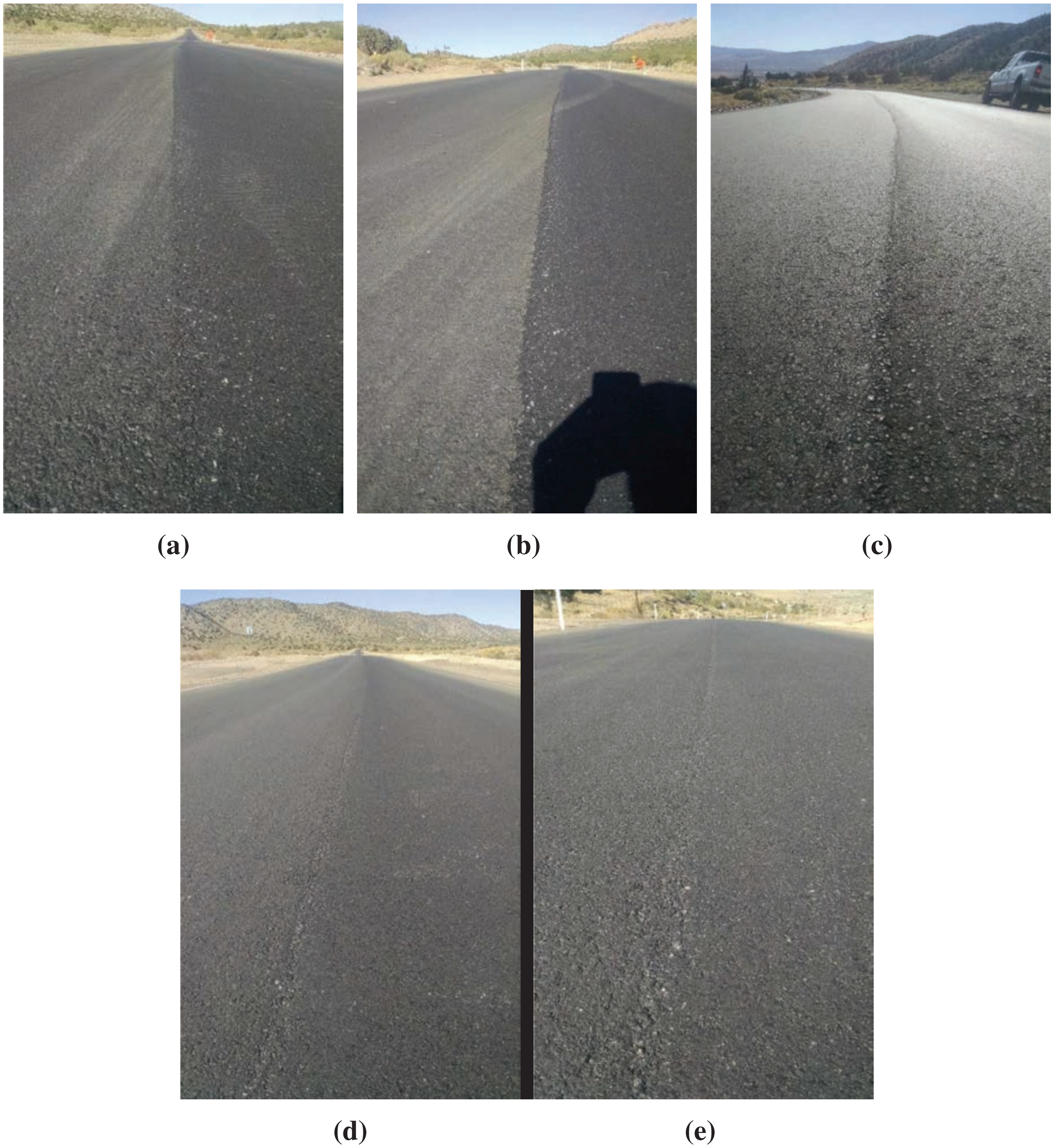


Figure B.7: Picture of compacted pavement surface of (a) Section 1-virgin; (b) Section 2-control with 0.3 RBR; (c) Section 3-0.3 RBR with T2; (d) Section 4-0.3 RBR with A2; and (e) Section 5-control with 0.15 RBR.

APPENDIX C

Indiana Construction Report

La Porte County executed the reconstruction of CO Road W2100 South in the fall of 2015. This field project, located in north-central part of Indiana, consisted of a 2.8 mile-long binder course and asphalt overlay placement. Three sections were placed on the eastbound lane between County Road South 875W and County Road South 600W near the town of La Crosse, IN to evaluate the effect of a softer virgin binder and a recycling agent on the performance of an asphalt mixture with high RAP and RAS content. Details of sections included in the field project are listed in Table C.1. Figure C.1 shows the layout of the sections. Note that the remaining surface course was paved with the control mix. The overlay and binder course were paved in the first week of September 2015.

Table C.1: Indiana Field Project Sections

Section No.	Section Name	Description	Additive/Rejuvenator Dosage
1	Virgin	PG 64-22 binder	N/A
2	Evoflex	16% RAP + 8% MWAS + PG 58-28 binder	3% Evoflex rejuvenator by weight of total asphalt content
3	Control	28% RAP + 2% MWAS + PG 58-28 binder	N/A

CO Road W2100 South is a two-way undivided rural road located in the south side of La Porte County in Indiana. La Porte County itself is located in the north-central part of Indiana bordering Lake Michigan. The typical roadbed width was 26 ft., including two 11-ft. travel lanes (paved) and 2-ft. unpaved shoulder on each side. The portion of the road where the field project is located is straight without intersections and with few driveways. The traffic is low and consists of occasional farm equipment. The reconstruction of this field project included a 1.5 in. binder course (19mm Superpave mix), followed by a 1.5 in. surface course (9.5 mm Superpave mix).

The existing pavement, which consisted of a seal coat on top of a gravel/dirt road, was in poor condition. Figure C.2 shows a portion of the field project where the left lane was paved with the binder course and the right lane had the original pavement surface. Figure C.3 also depicts the existing pavement surface on another portion of the field project. As can be seen in Figure C.2 and Figure C.3, the entire pavement had numerous potholes and large areas where the seal coat was missing.

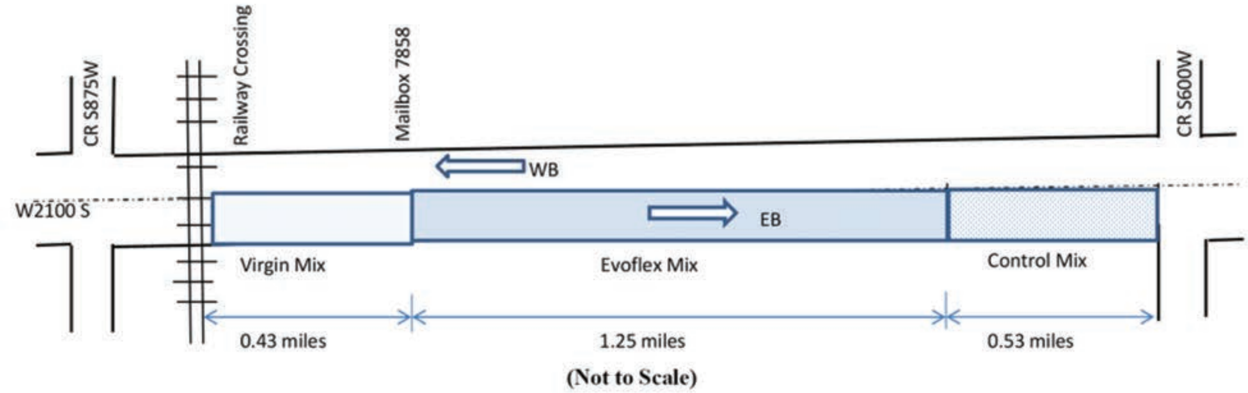


Figure C.1: Sections Layout for the Indiana field project.

Figure C.2: Binder course and existing pavement surface at the Indiana field project.

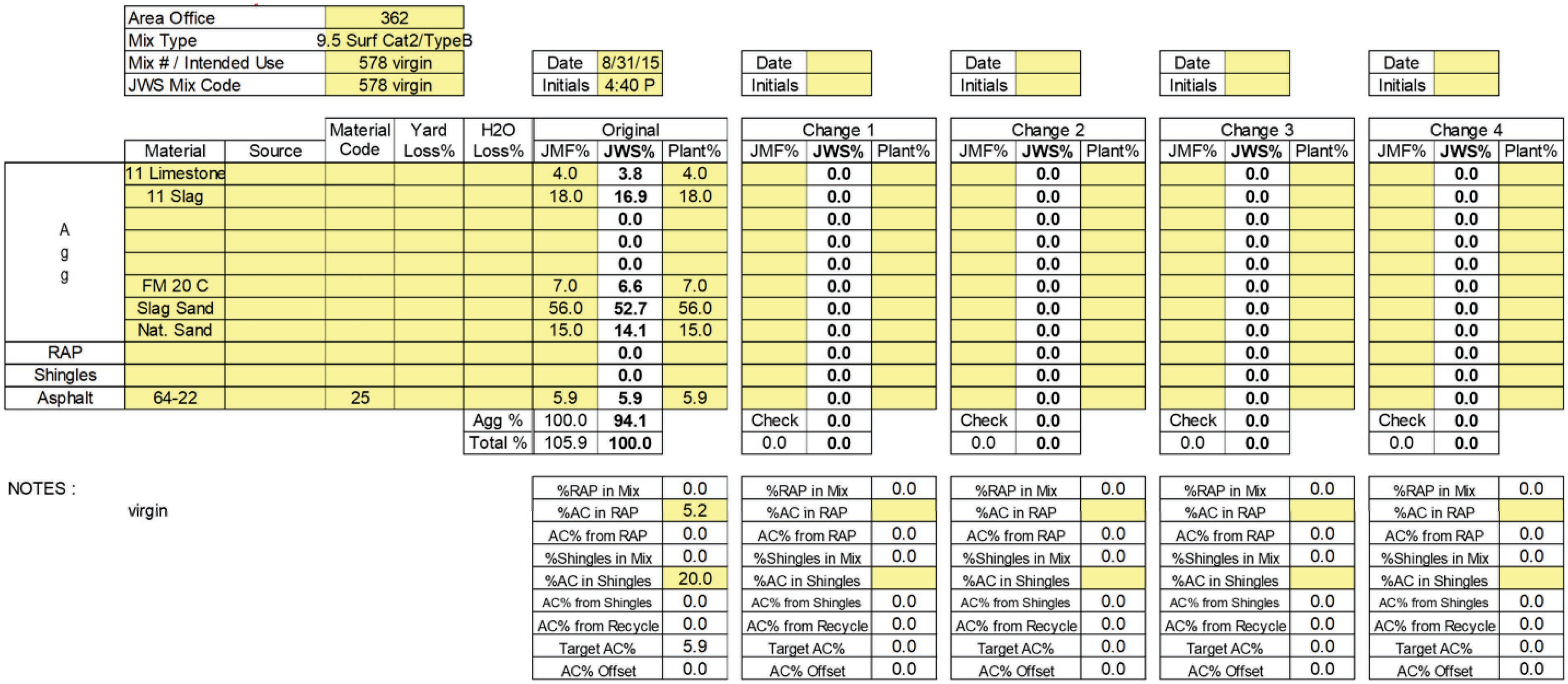
Figure C.3: Existing pavement surface at the Indiana field project.

C.1 MATERIALS AND MIXTURES

All three mixes were designed using the 9.5 mm Superpave Mix Cat 2/ Type B surface mix with 75 Superpave gyrations following the Indiana Department of Transportation specifications. Two virgin binders (i.e., PG 64-22 and PG 58-28) were used. Aggregates including limestone and slug from blast furnace from multiple sources were also employed. The source of RAP is unknown. RAS was produced by shredding and grinding manufacturer's waste shingles. Shingles were shredded on-site at the asphalt mix plant. The shingles were 100% passing the 3/8-in. sieve. Samples of the stockpiles of aggregate and RAS materials available at the asphalt mix plant are illustrated in Figure C.4 and Figure C.5. Figure C.6, Figure C.7, and Figure C.8 present the mix designs used in this field project.

Figure C.4: One of several aggregate stockpiles.

Figure C.5: RAP stockpile.



Area Office	362
Mix Type	9.5 Surf Cat2/TypeB
Mix # / Intended Use	578 virgin
JWS Mix Code	578 virgin

	Original	Change 1	Change 2	Change 3	Change 4
Date	8/31/15				
Initials	4:40 P				

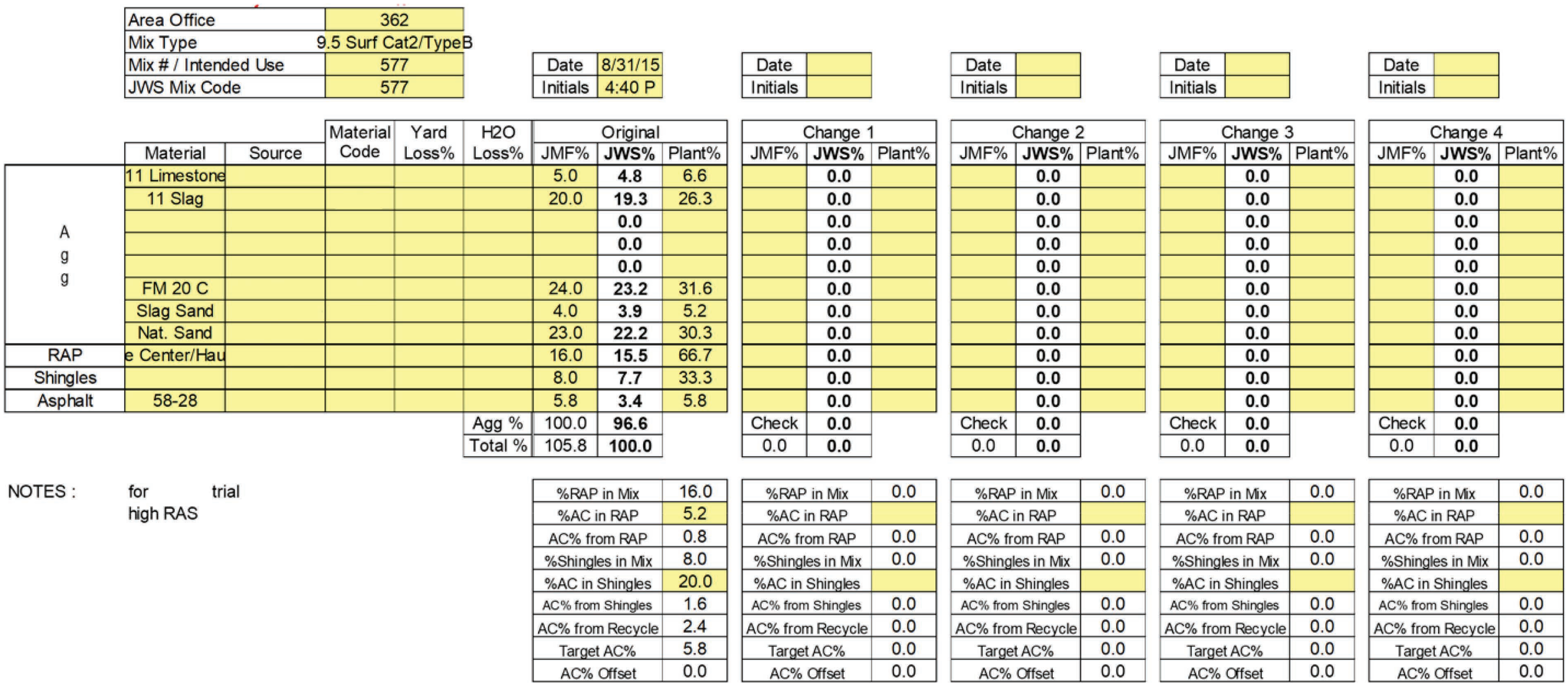
						Original			Change 1			Change 2			Change 3			Change 4		
	Material	Source	Material Code	Yard Loss%	H2O Loss%	JMF%	**JWS%**	Plant%	JMF%	**JWS%**	Plant%	JMF%	**JWS%**	Plant%	JMF%	**JWS%**	Plant%	JMF%	**JWS%**	Plant%
Agg	11 Limestone					4.0	**3.8**	4.0		**0.0**			**0.0**			**0.0**			**0.0**	
	11 Slag					18.0	**16.9**	18.0		**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
	FM 20 C					7.0	**6.6**	7.0		**0.0**			**0.0**			**0.0**			**0.0**	
	Slag Sand					56.0	**52.7**	56.0		**0.0**			**0.0**			**0.0**			**0.0**	
	Nat. Sand					15.0	**14.1**	15.0		**0.0**			**0.0**			**0.0**			**0.0**	
RAP							**0.0**			**0.0**			**0.0**			**0.0**			**0.0**	
Shingles							**0.0**			**0.0**			**0.0**			**0.0**			**0.0**	
Asphalt	64-22		25			5.9	**5.9**	5.9		**0.0**			**0.0**			**0.0**			**0.0**	
					Agg %	100.0	**94.1**		Check	**0.0**		Check	**0.0**		Check	**0.0**		Check	**0.0**	
					Total %	105.9	**100.0**		0.0	**0.0**		0.0	**0.0**		0.0	**0.0**		0.0	**0.0**	

NOTES :

virgin

	Original	Change 1	Change 2	Change 3	Change 4
%RAP in Mix	0.0	0.0	0.0	0.0	0.0
%AC in RAP	5.2				
AC% from RAP	0.0	0.0	0.0	0.0	0.0
%Shingles in Mix	0.0	0.0	0.0	0.0	0.0
%AC in Shingles	20.0				
AC% from Shingles	0.0	0.0	0.0	0.0	0.0
AC% from Recycle	0.0	0.0	0.0	0.0	0.0
Target AC%	5.9	0.0	0.0	0.0	0.0
AC% Offset	0.0	0.0	0.0	0.0	0.0

Figure C.6: Summary of virgin mix design.



Area Office	362
Mix Type	9.5 Surf Cat2/TypeB
Mix # / Intended Use	577
JWS Mix Code	577

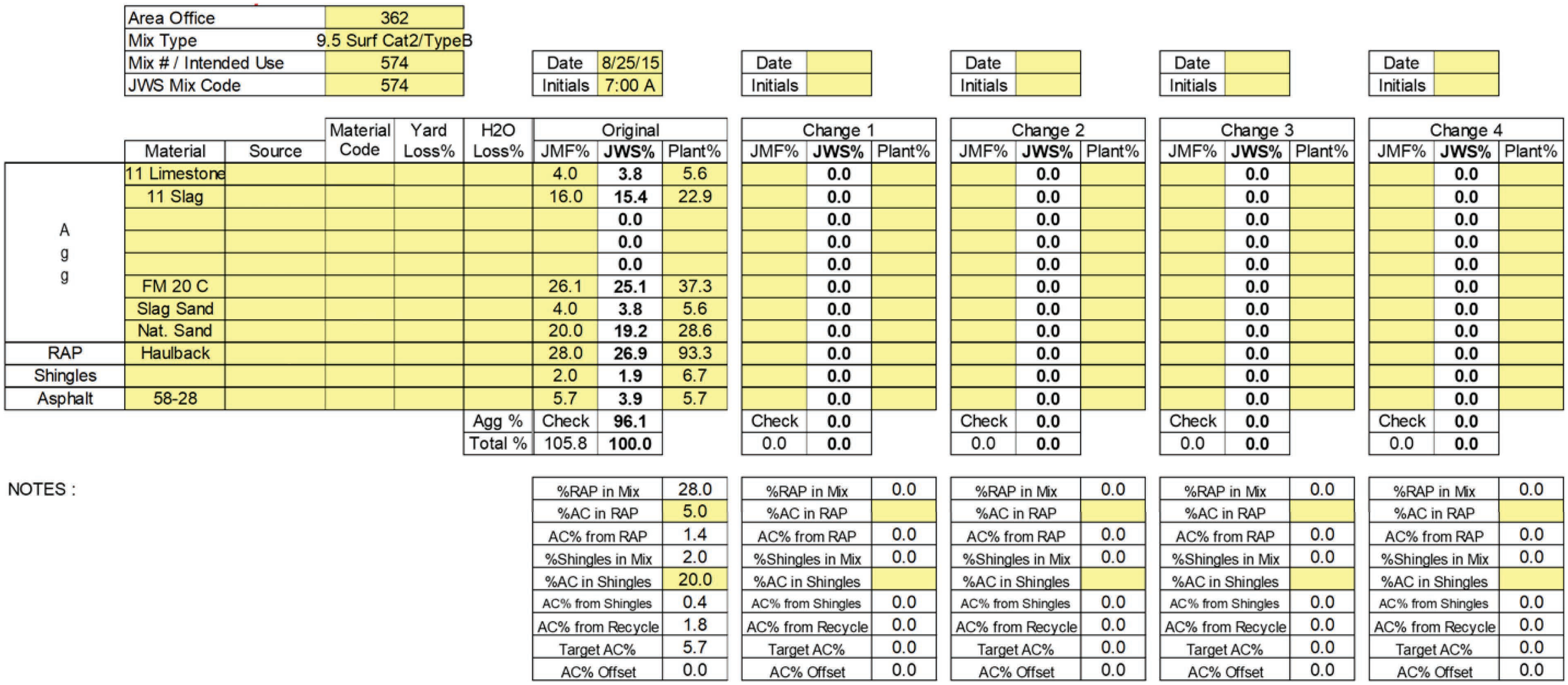
	Original	Change 1	Change 2	Change 3	Change 4
Date	8/31/15				
Initials	4:40 P				

	Material	Source	Material Code	Yard Loss%	H2O Loss%	Original JMF%	Original JWS%	Original Plant%	Change 1 JMF%	Change 1 JWS%	Change 1 Plant%	Change 2 JMF%	Change 2 JWS%	Change 2 Plant%	Change 3 JMF%	Change 3 JWS%	Change 3 Plant%	Change 4 JMF%	Change 4 JWS%	Change 4 Plant%
Agg	11 Limestone					5.0	**4.8**	6.6		**0.0**			**0.0**			**0.0**			**0.0**	
	11 Slag					20.0	**19.3**	26.3		**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
	FM 20 C					24.0	**23.2**	31.6		**0.0**			**0.0**			**0.0**			**0.0**	
	Slag Sand					4.0	**3.9**	5.2		**0.0**			**0.0**			**0.0**			**0.0**	
	Nat. Sand					23.0	**22.2**	30.3		**0.0**			**0.0**			**0.0**			**0.0**	
RAP	e Center/Hau					16.0	**15.5**	66.7		**0.0**			**0.0**			**0.0**			**0.0**	
Shingles						8.0	**7.7**	33.3		**0.0**			**0.0**			**0.0**			**0.0**	
Asphalt	58-28					5.8	**3.4**	5.8		**0.0**			**0.0**			**0.0**			**0.0**	
					Agg %	100.0	**96.6**		Check	**0.0**		Check	**0.0**		Check	**0.0**		Check	**0.0**	
					Total %	105.8	**100.0**		0.0	**0.0**		0.0	**0.0**		0.0	**0.0**		0.0	**0.0**	

NOTES : for trial
high RAS

	Original	Change 1	Change 2	Change 3	Change 4
%RAP in Mix	16.0	0.0	0.0	0.0	0.0
%AC in RAP	5.2				
AC% from RAP	0.8	0.0	0.0	0.0	0.0
%Shingles in Mix	8.0	0.0	0.0	0.0	0.0
%AC in Shingles	20.0				
AC% from Shingles	1.6	0.0	0.0	0.0	0.0
AC% from Recycle	2.4	0.0	0.0	0.0	0.0
Target AC%	5.8	0.0	0.0	0.0	0.0
AC% Offset	0.0	0.0	0.0	0.0	0.0

Figure C.7: Summary of T2 mix design.



Area Office	362
Mix Type	9.5 Surf Cat2/TypeB
Mix # / Intended Use	574
JWS Mix Code	574

	Original		Change 1		Change 2		Change 3		Change 4	
Date	8/25/15	Date		Date		Date		Date		
Initials	7:00 A	Initials		Initials		Initials		Initials		

			Material Code	Yard Loss%	H2O Loss%	Original			Change 1			Change 2			Change 3			Change 4		
	Material	Source				JMF%	**JWS%**	Plant%	JMF%	**JWS%**	Plant%	JMF%	**JWS%**	Plant%	JMF%	**JWS%**	Plant%	JMF%	**JWS%**	Plant%
Agg	11 Limestone					4.0	**3.8**	5.6		**0.0**			**0.0**			**0.0**			**0.0**	
	11 Slag					16.0	**15.4**	22.9		**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
							0.0			**0.0**			**0.0**			**0.0**			**0.0**	
	FM 20 C					26.1	**25.1**	37.3		**0.0**			**0.0**			**0.0**			**0.0**	
	Slag Sand					4.0	**3.8**	5.6		**0.0**			**0.0**			**0.0**			**0.0**	
	Nat. Sand					20.0	**19.2**	28.6		**0.0**			**0.0**			**0.0**			**0.0**	
RAP	Haulback					28.0	**26.9**	93.3		**0.0**			**0.0**			**0.0**			**0.0**	
Shingles						2.0	**1.9**	6.7		**0.0**			**0.0**			**0.0**			**0.0**	
Asphalt	58-28					5.7	**3.9**	5.7		**0.0**			**0.0**			**0.0**			**0.0**	
					Agg %	Check	**96.1**		Check	**0.0**		Check	**0.0**		Check	**0.0**		Check	**0.0**	
					Total %	105.8	**100.0**		0.0	**0.0**		0.0	**0.0**		0.0	**0.0**		0.0	**0.0**	

NOTES :

%RAP in Mix	28.0	%RAP in Mix	0.0	%RAP in Mix	0.0	%RAP in Mix	0.0	%RAP in Mix	0.0
%AC in RAP	5.0	%AC in RAP		%AC in RAP		%AC in RAP		%AC in RAP	
AC% from RAP	1.4	AC% from RAP	0.0	AC% from RAP	0.0	AC% from RAP	0.0	AC% from RAP	0.0
%Shingles in Mix	2.0	%Shingles in Mix	0.0	%Shingles in Mix	0.0	%Shingles in Mix	0.0	%Shingles in Mix	0.0
%AC in Shingles	20.0	%AC in Shingles		%AC in Shingles		%AC in Shingles		%AC in Shingles	
AC% from Shingles	0.4	AC% from Shingles	0.0	AC% from Shingles	0.0	AC% from Shingles	0.0	AC% from Shingles	0.0
AC% from Recycle	1.8	AC% from Recycle	0.0	AC% from Recycle	0.0	AC% from Recycle	0.0	AC% from Recycle	0.0
Target AC%	5.7	Target AC%	0.0	Target AC%	0.0	Target AC%	0.0	Target AC%	0.0
AC% Offset	0.0	AC% Offset	0.0	AC% Offset	0.0	AC% Offset	0.0	AC% Offset	0.0

Figure C.8: Summary of control mix design.

Figure C.9: Overview of asphalt mix plant at La Porte, Indiana.

During production, the RAP and RAS materials were added along with the heated aggregate just outside the drying drum, before entering the mixing drum. The binder was directly injected into the mixing drum. The recycling agent was injected via pump and regulator to the binder line (Figure C.10). The plant produced at a typical rate of 200 to 250 tons per hour during the construction of the field project. Table C.2 summarizes the production, placement, and ambient temperatures during laydown.

Table C.2: Production, Paving and Ambient Temperatures for the Indiana Field Project

Section	Mix	Date of Production	Plant Mix Temp, °F	Paving Temp, °F	Ambient Temp, °F
1	Virgin	09/04/2015	310-315	260 - 270	70 - 75
2	T2	09/04/2015	295-300	260 - 272	75 - 80
3	Control	09/04/2015	295-300	265 - 280	80 - 82

Figure C.10: Recycling agent injected to the binder line (left) and pump used to regulate the recycling agent dosage (right).

C.2 MIX PRODUCTION

All mixes were produced and paved on the same day. Production of the virgin mix began at 6 am local time on September 4, 2015. Approximately 200 tons of virgin mix was produced at 200 tons/hour capacity. The virgin mix was produced at 315°F. Ambient temperature was in lower 70s in the early morning and in lower 80s in the afternoon. There was little or no wind until late in the afternoon.

Sample collection began after production of 85 tons of virgin mix. The virgin mix was produced first, followed by the T2 mix. Approximately 630 tons of the T2 mix was produced, although the first 30 to 35 tons did not include the recycling agent. T2 was added at 3 percent by weight of total asphalt content. Sample collection began after production of 143 tons of the T2 mix. The T2 mix was produced at 300°F. Three representatives from the recycling agent supplier were present during the production of this mix to assure proper application of the T2.

Soon after finishing the production of the T2 mix, the asphalt mix plant started producing the control mix. Until the end of the day, approximately 600 tons of control mix was produced. Note that the remainder of the CO Road W2100 was paved with the control mix.

C.3 PAVING OPERATIONS

Before placement of binder course and surface course, the contractor applied a rapid set tack coat with shot rate of 0.08 gal/yd^2 and 0.06 gal/yd^2, respectively. All mixes were hauled to the job site using end-dump truck with tarp covers. The virgin mix was placed on the eastbound lane starting just 200 ft. east of railway crossing to Mailbox 7858; the length of the virgin section was approximately 0.43 miles. The trucks dumped the loose mix directly into the paver chute as shown in Figure C.11. A shuttle buggy or any other material transfer device was not employed during construction. An infrared temperature gun was used to measure the temperature behind the paver.

Figure C.11: Paving of the surface layer at the Indiana field project.

Placement of the T2 mix started near the Mailbox 7858 and continued for approximately 1.25 miles. The first 300 ft. of this section did not include the recycling agent in the mix. The control mix test section began at the end of T2 mix section, approximately 0.53 miles from County Road S600W.

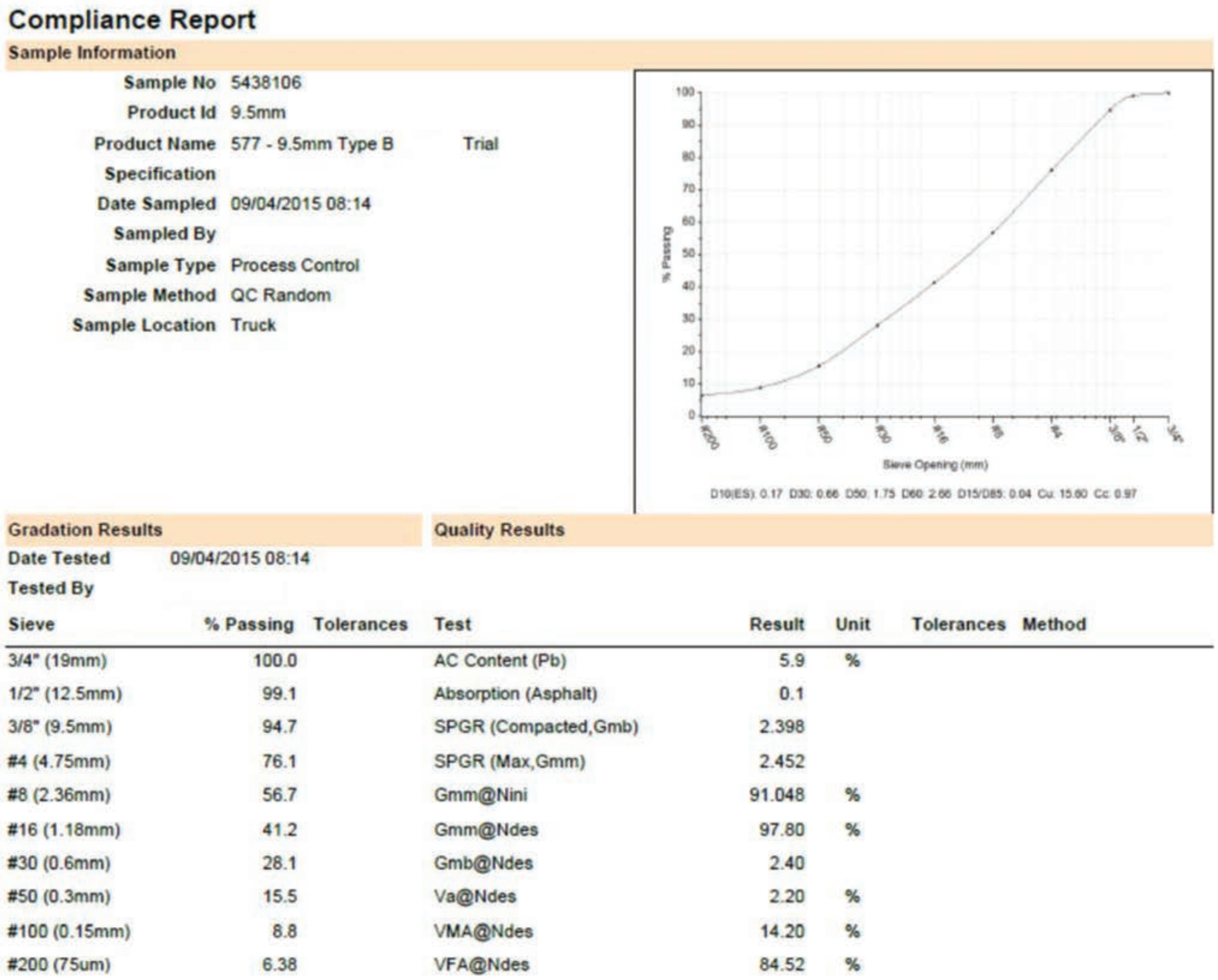
A steel-wheel vibratory (breakdown) roller followed closely the paver shown in Figure C.12. The compaction was achieved by four passes on vibrating mode, and two passes on static mode (Figure C.13 a), followed by three passes at vibrating mode and two passes at static mode by a separate roller (Figure C.13 b), and then several passes of static steel finish roller (Figure C.13 c). All mixes were placed and compacted in the same way. No visible sign of segregation was noticed on the sections.

Figure C.12: Paver used for laydown at the Indiana field project.

(a) Vibratory Roller 1 (b) Vibratory Roller 2 (c) Finish Roller

Figure C.13: Rollers used for compaction at the Indiana field project.

Quality control reports noted 90 percent density achievement in the field. Figure C.14 and Figure C.15 present the quality control results from the T2 and Control test sections mixes, respectively. The contractor could not provide the quality control results corresponding to the virgin mix.



Compliance Report

Sample Information

Sample No 5438106
Product Id 9.5mm
Product Name 577 - 9.5mm Type B Trial
Specification
Date Sampled 09/04/2015 08:14
Sampled By
Sample Type Process Control
Sample Method QC Random
Sample Location Truck

D10(ES): 0.17 D30: 0.66 D50: 1.75 D60: 2.66 D15/D85: 0.04 Cu: 15.60 Cc: 0.97

Gradation Results

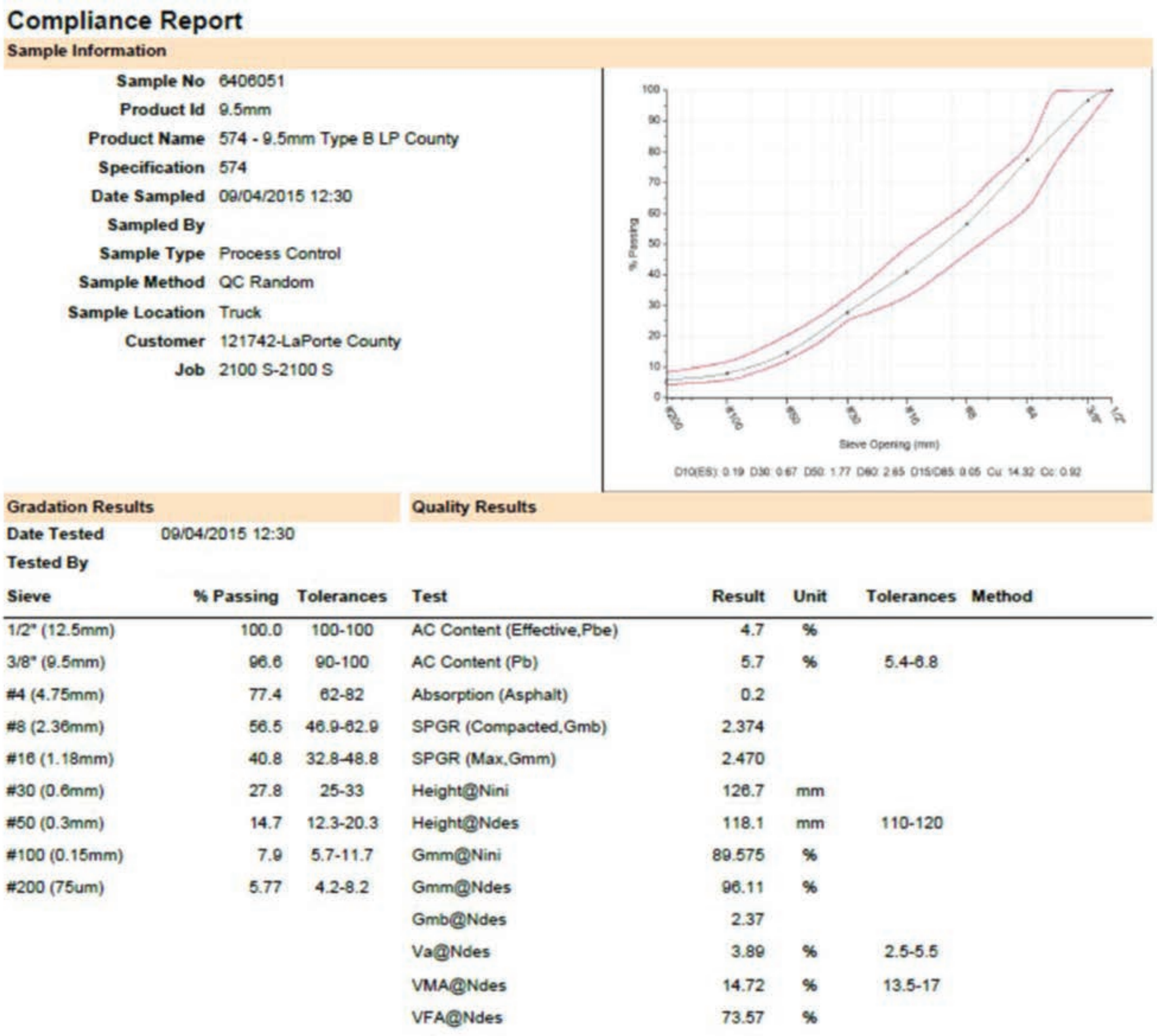
Date Tested 09/04/2015 08:14
Tested By

Sieve	% Passing	Tolerances
3/4" (19mm)	100.0	
1/2" (12.5mm)	99.1	
3/8" (9.5mm)	94.7	
#4 (4.75mm)	76.1	
#8 (2.36mm)	56.7	
#16 (1.18mm)	41.2	
#30 (0.6mm)	28.1	
#50 (0.3mm)	15.5	
#100 (0.15mm)	8.8	
#200 (75um)	6.38	

Quality Results

Test	Result	Unit	Tolerances	Method
AC Content (Pb)	5.9	%		
Absorption (Asphalt)	0.1			
SPGR (Compacted,Gmb)	2.398			
SPGR (Max,Gmm)	2.452			
Gmm@Nini	91.048	%		
Gmm@Ndes	97.80	%		
Gmb@Ndes	2.40			
Va@Ndes	2.20	%		
VMA@Ndes	14.20	%		
VFA@Ndes	84.52	%		

Figure C.14: Quality control results for the T2 mix.



Compliance Report

Sample Information

Sample No	6406051
Product Id	9.5mm
Product Name	574 - 9.5mm Type B LP County
Specification	574
Date Sampled	09/04/2015 12:30
Sampled By	
Sample Type	Process Control
Sample Method	QC Random
Sample Location	Truck
Customer	121742-LaPorte County
Job	2100 S-2100 S

Gradation Results

Date Tested 09/04/2015 12:30

Tested By

Sieve	% Passing	Tolerances
1/2" (12.5mm)	100.0	100-100
3/8" (9.5mm)	96.6	90-100
#4 (4.75mm)	77.4	62-82
#8 (2.36mm)	56.5	46.9-62.9
#16 (1.18mm)	40.8	32.8-48.8
#30 (0.6mm)	27.8	25-33
#50 (0.3mm)	14.7	12.3-20.3
#100 (0.15mm)	7.9	5.7-11.7
#200 (75um)	5.77	4.2-8.2

Quality Results

Test	Result	Unit	Tolerances	Method
AC Content (Effective,Pbe)	4.7	%		
AC Content (Pb)	5.7	%	5.4-6.8	
Absorption (Asphalt)	0.2			
SPGR (Compacted,Gmb)	2.374			
SPGR (Max,Gmm)	2.470			
Height@Nini	126.7	mm		
Height@Ndes	118.1	mm	110-120	
Gmm@Nini	89.575	%		
Gmm@Ndes	96.11	%		
Gmb@Ndes	2.37			
Va@Ndes	3.89	%	2.5-5.5	
VMA@Ndes	14.72	%	13.5-17	
VFA@Ndes	73.57	%		

Figure C.15: Quality control results for the control mix.

C.4 SAMPLE COLLECTION

Plant mix was collected from the dump trucks at the asphalt mix plant by climbing on scaffolding. Due to the large quantities of plant mix needed for research purposes, multiple dump trucks were sampled. The samples were collected after about 100 tons of production for each section. The material sampling scheme is listed in Table C.4. With the help of the paving contractor, the research team also collected 27 six-in. diameter field cores (Figure C.16) from the sections. The cores were obtained from the center of the eastbound travel lane.

Table C.4: Materials Sampling Scheme

Sample Type	Material	Point of Sampling
Lab-Mixed, Lab-Compacted	Fine aggregate	Stockpile
	Coarse aggregate	Stockpile
	RAP	Stockpile
	RAS	Stockpile
	Recycling agent	Storage tank (plastic tote in metal cage) at plant
	PG 64-22 binder	Storage tank
	PG 58-28 binder	Storage tank
Plant-Mixed, Lab-Compacted	Loose Mix	Dump truck at plant
Plant-Mixed, Field-Compacted	Field Cores	EB Travel Lane (Center)

Figure C.16: Core with surface and binder layers

APPENDIX D

Wisconsin Construction Report

The rehabilitation of the pavement surface for Wisconsin State Highway 36 (SH36) was done in the fall of 2016. SH36 is a two-way divided road located near Muskego, Wisconsin. Muskego itself is located in the southeastern portion of Wisconsin, about 20 miles west from Lake Michigan (Milwaukee area). The south bound (SB) is surfaced with concrete pavement while the north bound (NB) is surfaced with asphalt concrete (AC). The typical road bed for the NB was 38-feet including two 12-feet travel lanes with a structure that consists primarily of Portland cement concrete (PCC) with asphalt overlays of variable thickness constructed over the years. In addition, the 8-feet asphalt paved shoulder sits over a granular base.

The SH36 rehabilitation project included localized repairs on jointed Portland cement concrete (JPCC) pavement in the SB and milling 2” of existing AC pavement and replacement with a 2” overlay in the north bound (NB). The contractor’s rehabilitation activities relevant to this project included approximately 3 miles of AC pavement on the NB outer lane and shoulder of SH36. The project overview is presented in Figure D.1 with details of the test section locations provided in Table D.1.

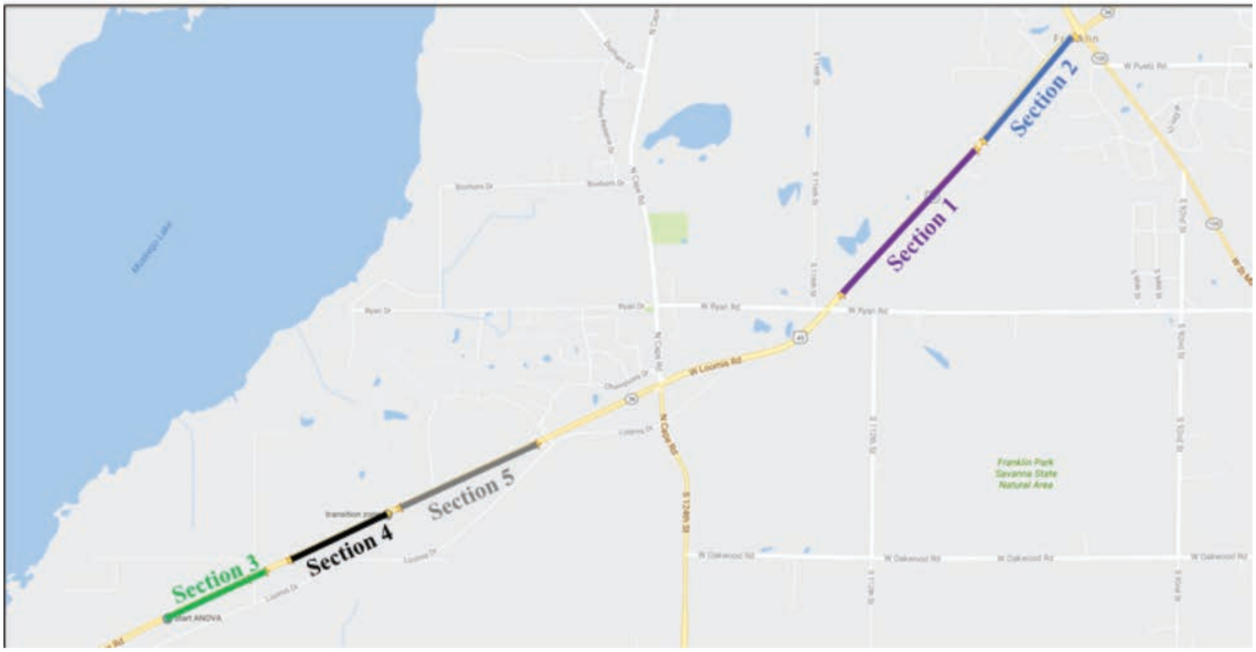


Figure D.1: Project Overview.

Current Wisconsin DOT (WisDOT) specifications allow up to 25% binder replacement for upper AC layers (Section 460 Hot Mix Asphalt Pavement). Binder replacement can be achieved by incorporation of reclaimed asphalt pavement (RAP), fractionated RAP (FRAP), or recycled asphalt shingles (RAS) that cannot exceed 5% by weight of the aggregate blend. The contractor's approved RAP inclusive mix design (Design 250-0052-2016) consists of a 12.5mm Nominal Maximum Aggregate Size (NMAS) E-3 (WisDOT specifications) that considers 22.8% binder replacement. The contractor demonstrated that an alternative design with higher percentage of RAP (31% binder replacement) satisfied all WisDOT mixture requirements (Design HR_250-0316-2016) including volumetrics and Tensile Strength Ratio (TSR). Project sections 1 through 4 specified in Table D.1 are considered plausible alternatives to the contractor's design 250-0052-2016 (Section 5). In this project sections 1, 3, 4, and 5 were evaluated.

Table D.1: Description of Experimental Sections Constructed in SH36

	Section 1	**Section 2**	**Section 3**	**Section 4**	**Section 5**
Label	HR 52-34	HR 58-28 3%	HR 58-28 V2	HR 58-28 Control	58-28 DOT Control
Description	36% RAP Binder PG 52-34	36% RAP Binder PG 58-28 Regressed AV 3%	36% RAP Binder PG 58-28 + 1.2% V2	36% RAP Binder PG 58-28 - Control	27% RAP Binder PG 58-28 – DOT Control
Design	HR_250-0316-2016	50-0316-2016_3.0	HR_250-0316-2016	HR_250-0316-2016	WisDOT #250-0052-2016
Additive	NA	NA	1.2% V2 1815	NA	NA
Paving Date	9-19-2016	9-19-2016	9-26-2016	9-26-2016	9-26-2016
Coord. Start	42.882070, -88.046489	42.882534, -88.045854	42.854431, -88.111383	42.857861, -88.101445	42.860935, -88.092682
Coord. End	42.873548, -88.057185	42.888704, -88.038507	42.857178, -88.103563	42.860563, -88.093735	42.864691, -88.081787
Cores	NB Outer lane	NB Outer lane	NB Outer lane	NB Outer lane	NB Outer lane

The existing pavement (outer lane and shoulder as shown in Figure D.2) exhibited severe transverse cracking throughout. Cracks were mostly evenly spaced, and the 2 inch milling operation did not remove the entire cracked pavement. During the coring process described subsequently, a core was found cracked all through the old layers. The pavement cracking is attributed to joint reflection and/or thermal cracking. The paving operation proceeded as a 2" overlay without full depth structural repair. The pavement structure on the NB lanes of SH36 consisted of AC over JPCC constructed on top of a granular base as indicated in the project plans. During the coring process, the thickness of AC layers was found to be variable across the project. Sections 1 and 2 had AC layers adding up to around 8 to 10 inches (including the 2 inch overlay) while AC layers in sections 3, 4, and 5 added up to about 4 to 6 inches.

Figure D.2: Existing Pavement Condition.

The asphalt mixtures were produced at an asphalt plant in Muskego (Figure D.3). Most of the area was paved, including the location of the aggregate stockpiles. The stockpiles were not covered (except for the RAS, which was not used in this field project). The paved surface helped control the moisture content in the stockpiles. The aggregates were extracted and crushed locally. The natural sand was extracted from the same quarry.

Figure D.3: Asphalt Plant Overview.

A drum plant was used to produce the hot mix asphalt (HMA), and production details are given in Figure D.4, Figure D.5, and Figure D.6. The plant had nine bins for aggregate inclusion, and four were used in this field project. The aggregate bins, point of aggregate inclusion, and point of inclusion of DEG (baghouse filler) are shown in Figure D.4. Two bins were used for RAP inclusion (Figure D.5), one with crushed RAP passing the ½-inch sieve while the second RAP fraction had up to 3 inch RAP agglomerates. The total 36% RAP was achieved by adding 20% of passing 3-inch RAP and 16% passing ½-inch RAP. The combined RAP passed through an in-line ¾-inch screening system. All the RAP agglomerates larger than the screening size were transferred to an in-line crushing system, thus the entire RAP added to the mixtures passed the required ¾-inch screening. Both fractionated RAP sources were reported to have 4.65% asphalt content.

The inclusion of asphalt binder is shown in Figure D.6. Section 3 included a recycling agent (V2) which was blended in-line with the PG 58-28 asphalt binder at a dosage of 1.2% by weight of binder. The "Green Machine", a system commonly used for warm-mix additive and inclusion of anti-stripping agents, was used for dosing the recycling agent. V2 is a modified vegetable oil.

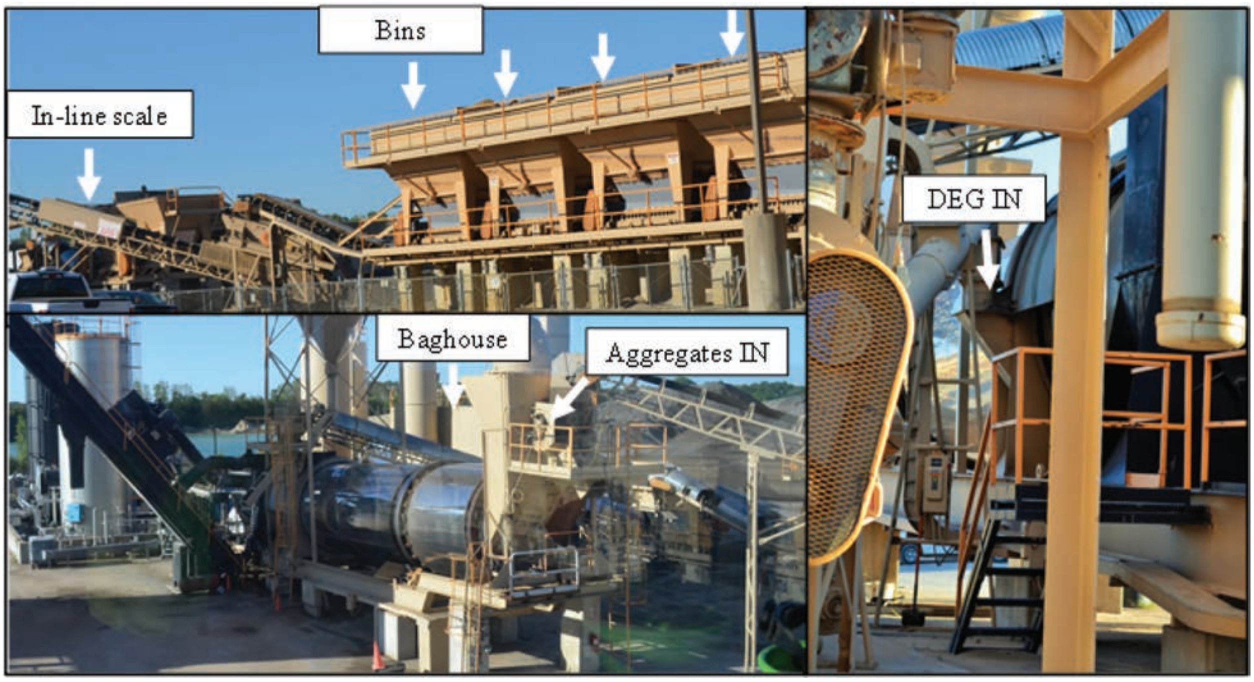


Figure D.4: Production Details – Aggregates.

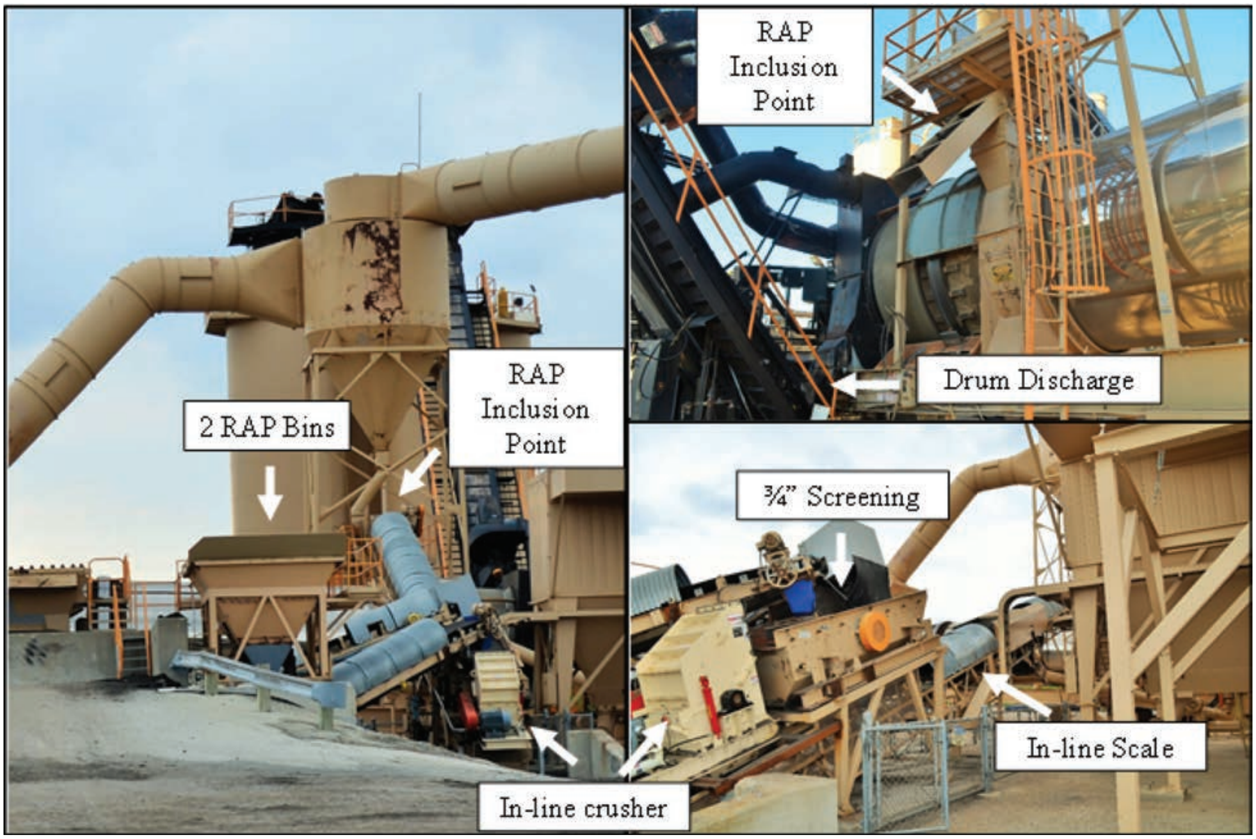


Figure D.5: Production Details - Recycled Materials.

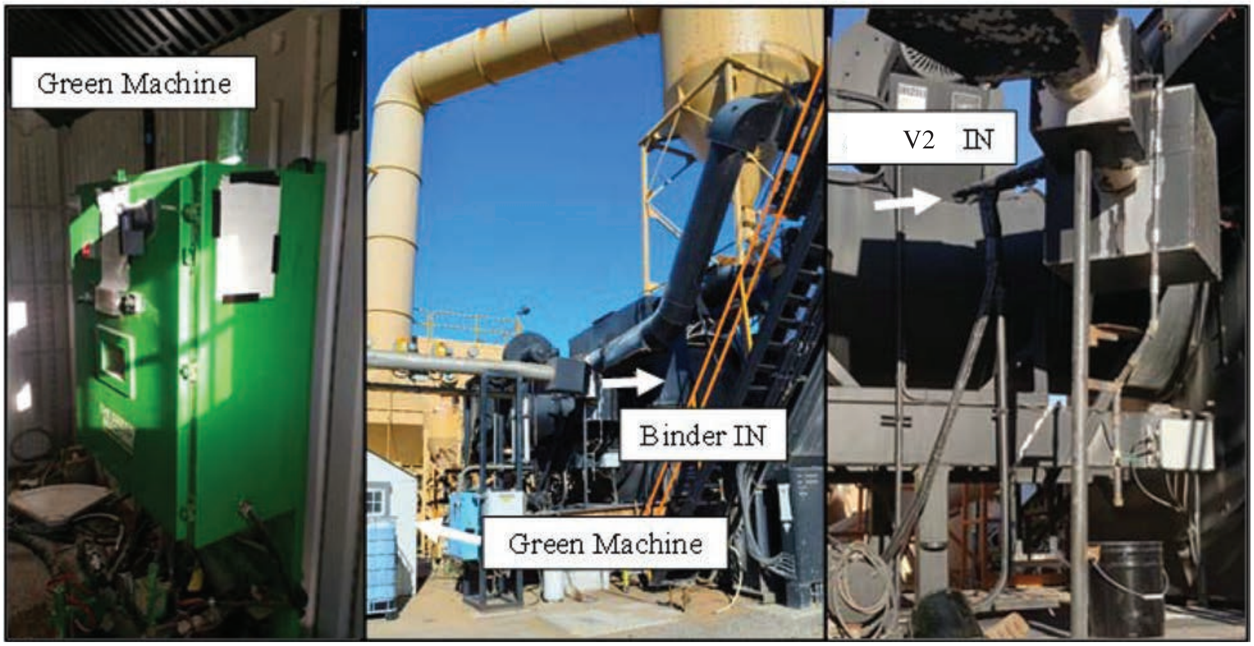


Figure D.6: Production Details – Binder and Recycling Agent (V2).

The construction process is shown in Figure D.7. A tack coat was applied over the milled pavement surface prior to placement of the overlay. Two pavers were operating simultaneously, one paving the traffic lane (operating with a material transfer device) and the second paving the shoulder (without a material transfer device). The rolling pattern included first a steel roller with vibration (hot), followed by a pneumatic roller (intermediate), and finally a steel roller with no vibration (cold). The time between production and placement was estimated to be about one hour for sections 1, 2, and 5. The silo storage time was about 20 to 30 min and hauling time was 30 min. The trucks had a minimum waiting time before transferring the asphalt mixture to the paver (or material transfer device for the traffic lane). The paving process was significantly slowed down during the last 400ft of section 3 (HR 58-28 + V2) due to the work required at the intersection with Thode Dr. The waiting time for the trucks at the paving site was about one hour for that last portion of section 3 and the starting of section 4 (HR 58-28 control). By the time section 5 was being paved, the process resumed normal pace.

Figure D.7: Construction Process.

Production and placement temperatures were monitored at the plant drum discharge, in the truck before leaving the asphalt plant, and during placement between the paver and roller 1 as shown in Figure D.8. The plant supervisor reported that production temperature was 320°F for all the mixtures throughout the project. The temperature readings and weather information are summarized in Table D.2. Measurements were primarily taken with a heat gun at the surface.

Figure D.8: Temperature Readings.

Table D.2: Production and Placement Temperatures (°F).

	Section 1	Section 2	Section 3	Section 4	Section 5
High temperature (Weather.com)	84	84	65	65	65
Ground temperature (Heat gun)	100	100	74	74	74
Pavement temperature (Heat gun)	108-110	108-110	92	92	92
Truck (QC/QA)	313	316	313	308	313
Paver to roller 1 (Heat gun)	270-280	255-260	270-275	255-280	260-280

Raw materials (i.e. aggregates, RAP, binders, recycling agent) and plant mix were collected as described in Figure D.1. All aggregates and RAP were in outdoor stockpiles, and a front loader assisted in preparing sampling piles from which materials were collected as shown in Figure D.1 a. Binders were sampled in line, right before injection into the plant drum (Figure D.1 b). Plant mixtures were sampled by dumping a small sampling pile on a clean paved surface as shown in Figure D.1 c. Mixture samples were taken for the contractor, WisDOT, and TTI simultaneously.

(a) Aggregates

(b) Binder

(c) Mixtures

Figure D.9: Sampling Materials.

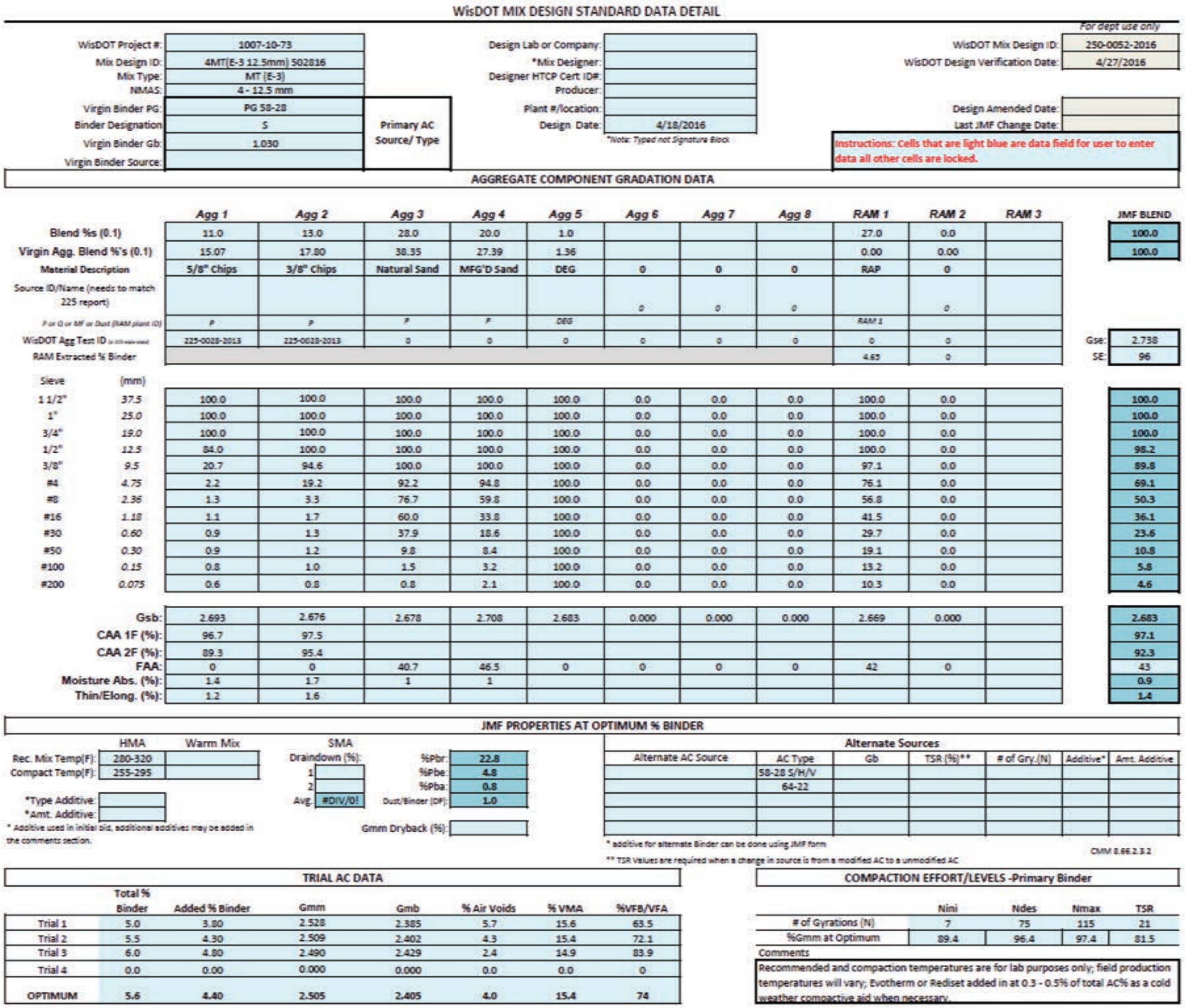
Coring was performed during the same day of paving, and density gauge readings were taken a priori. Six cores were obtained per pavement section, all from the outer traffic lane of SH36. The coring process is illustrated in Figure D.10 with a bag of ice placed for about 15 min to ensure the asphalt mixture had cooled down. Cores were taken along the length of the entire asphalt pavement thickness, until the mixtures detached from the underlying Portland cement concrete (PCC) or granular base. Detailed locations, approximate core thickness, density gauge readings, and notes taken during the coring process are presented in Table D.3.

Figure D.10: Coring.

Table D.3: Cores Description

Section	Core #	Density (%Gmm)	Reference	Thickness (in)	Notes
1	1	94.3		9.25	8-10" AC, probably on top of base. Rough aggregate surface observed
1	2	94.2		8.5	8-10" AC on top of PCC
1	3	NA	996+00	9.25	8-10" AC, probably on top of base. Rough aggregate surface observed
1	4	94.8	999+00	9.75	8-10" AC on top of PCC
1	5	94.4	1004+00	9.75	8-10" AC on top of PCC
1	6	95.3	1009+00	8	8-10" AC, probably on top of base. Rough aggregate surface observed
2	1	94.5	1019+00	NA	8-10" AC, probably on top of base. Rough aggregate surface observed
2	2	92.2	1021+00	NA	8-10" AC, probably on top of base. Rough aggregate surface observed
2	3	94.4	1026+00	NA	8-10" AC, probably on top of base. Rough aggregate surface observed
2	4	94	1030+00	NA	8-10" AC on top of PCC
2	5	95.5	1034+00	NA	8-10" AC on top of PCC
2	6	95.9	1038+00	NA	Specimen broke during coring.
3	1	93	811+30	4.5	4" AC on top of PCC (10")
3	2	92.2	817+00	Broke	4" AC on top of PCC
3	3	95.5	819+00	4.5	5" AC on top of PCC
3	4	95.9	823+00	4.75	5" AC on top of PCC
3	5	93.2	827+00	4.75	5" AC on top of PCC
3	6	94.5	830+00	4	4" AC on top of PCC
4	1	93	839+00	5.25	6" AC on top of PCC
4	2	93.9	841+00	5	6" AC on top of PCC
4	3	96.3	844+00	4.5	5" AC on top of PCC
4	4	94.1	847+00	4.75	5" AC on top of PCC
4	5	93.8	mailbox 14650	4.75	5" AC on top of PCC
4	6	96	859+00	5.75	6" AC on top of PCC
5	1	96.1	865+00	5	6" AC on top of PCC
5	2	94.9	871+00	9	8+" AC on top of base
5	3	94.5	country club	5.75	6" AC on top of PCC
5	4	95.9	880+00	4.5	5" AC on top of PCC
5	5	95.7	885+00	4.5	5" AC on top of PCC
5	6	95.2	893+00	5	5" AC on top of PCC

Mix design and quality control reports provided by the contractor are shown next.



WisDOT MIX DESIGN STANDARD DATA DETAIL

WisDOT Project #:	1007-10-73	Design Lab or Company:		WisDOT Mix Design ID:	250-0052-2016
Mix Design ID:	4MT(E-3 12.5mm) 502816	*Mix Designer:		WisDOT Design Verification Date:	4/27/2016
Mix Type:	MT (E-3)	Designer HTCP Cert ID#:			
NMAS:	4 - 12.5 mm	Producer:			
Virgin Binder PG:	PG 58-28	Plant #/location:		Design Amended Date:	
Binder Designation	S	Design Date:	4/18/2016	Last JMF Change Date:	
Virgin Binder Gb:	1.030				
Virgin Binder Source:					

For dept use only

Primary AC Source/ Type

*Note: Typed not Signature Block

Instructions: Cells that are light blue are data field for user to enter data all other cells are locked.

AGGREGATE COMPONENT GRADATION DATA

		Agg 1	Agg 2	Agg 3	Agg 4	Agg 5	Agg 6	Agg 7	Agg 8	RAM 1	RAM 2	RAM 3	JMF BLEND
Blend %s (0.1)		11.0	13.0	28.0	20.0	1.0				27.0	0.0		100.0
Virgin Agg. Blend %'s (0.1)		15.07	17.80	38.35	27.39	1.36				0.00	0.00		100.0
Material Description		5/8" Chips	3/8" Chips	Natural Sand	MFG'D Sand	DEG	0	0	0	RAP	0		
Source ID/Name (needs to match 225 report)							0	0	0		0		
P or Q or MF or Dust (RAM plant ID)		P	P	P	P	DEG				RAM 1			
WisDOT Agg Test ID		225-0028-2013	225-0028-2013	0	0	0	0	0	0	0	0		Gse: 2.738
RAM Extracted % Binder										4.65	0		SE: 96
Sieve	(mm)												
1 1/2"	37.5	100.0	100.0	100.0	100.0	100.0	0.0	0.0	0.0	100.0	0.0		100.0
1"	25.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0	0.0	100.0	0.0		100.0
3/4"	19.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0	0.0	100.0	0.0		100.0
1/2"	12.5	84.0	100.0	100.0	100.0	100.0	0.0	0.0	0.0	100.0	0.0		98.2
3/8"	9.5	20.7	94.6	100.0	100.0	100.0	0.0	0.0	0.0	97.1	0.0		89.8
#4	4.75	2.2	19.2	92.2	94.8	100.0	0.0	0.0	0.0	76.1	0.0		69.1
#8	2.36	1.3	3.3	76.7	59.8	100.0	0.0	0.0	0.0	56.8	0.0		50.3
#16	1.18	1.1	1.7	60.0	33.8	100.0	0.0	0.0	0.0	41.5	0.0		36.1
#30	0.60	0.9	1.3	37.9	18.6	100.0	0.0	0.0	0.0	29.7	0.0		23.6
#50	0.30	0.9	1.2	9.8	8.4	100.0	0.0	0.0	0.0	19.1	0.0		10.8
#100	0.15	0.8	1.0	1.5	3.2	100.0	0.0	0.0	0.0	13.2	0.0		5.8
#200	0.075	0.6	0.8	0.8	2.1	100.0	0.0	0.0	0.0	10.3	0.0		4.6
Gsb:		2.693	2.676	2.678	2.708	2.683	0.000	0.000	0.000	2.669	0.000		2.683
CAA 1F (%):		96.7	97.5										97.1
CAA 2F (%):		89.3	95.4										92.3
FAA:		0	0	40.7	46.5	0	0	0	0	42	0		43
Moisture Abs. (%):		1.4	1.7	1	1								0.9
Thin/Elong. (%):		1.2	1.6										1.4

JMF PROPERTIES AT OPTIMUM % BINDER

	HMA	Warm Mix
Rec. Mix Temp(F):	280-320	
Compact Temp(F):	255-295	

*Type Additive:

*Amt. Additive:

* Additive used in initial bid, additional additives may be added in the comments section.

SMA

Draindown (%):	
1	
2	
Avg.	#DIV/0!

%Pbr:	22.8
%Pbe:	4.8
%Pba:	0.8
Dust/Binder (DP):	1.0

Gmm Dryback (%):

Alternate Sources

Alternate AC Source	AC Type	Gb	TSR (%)**	# of Gry.(N)	Additive*	Amt. Additive
	58-28 S/H/V					
	64-22					

* additive for alternate Binder can be done using JMF form

** TSR Values are required when a change in source is from a modified AC to a unmodified AC

CMM 8.66.2.3.2

TRIAL AC DATA

	Total % Binder	Added % Binder	Gmm	Gmb	% Air Voids	% VMA	%VFB/VFA
Trial 1	5.0	3.80	2.528	2.385	5.7	15.6	63.5
Trial 2	5.5	4.30	2.509	2.402	4.3	15.4	72.1
Trial 3	6.0	4.80	2.490	2.429	2.4	14.9	83.9
Trial 4	0.0	0.00	0.000	0.000	0.0	0.0	0
OPTIMUM	5.6	4.40	2.505	2.405	4.0	15.4	74

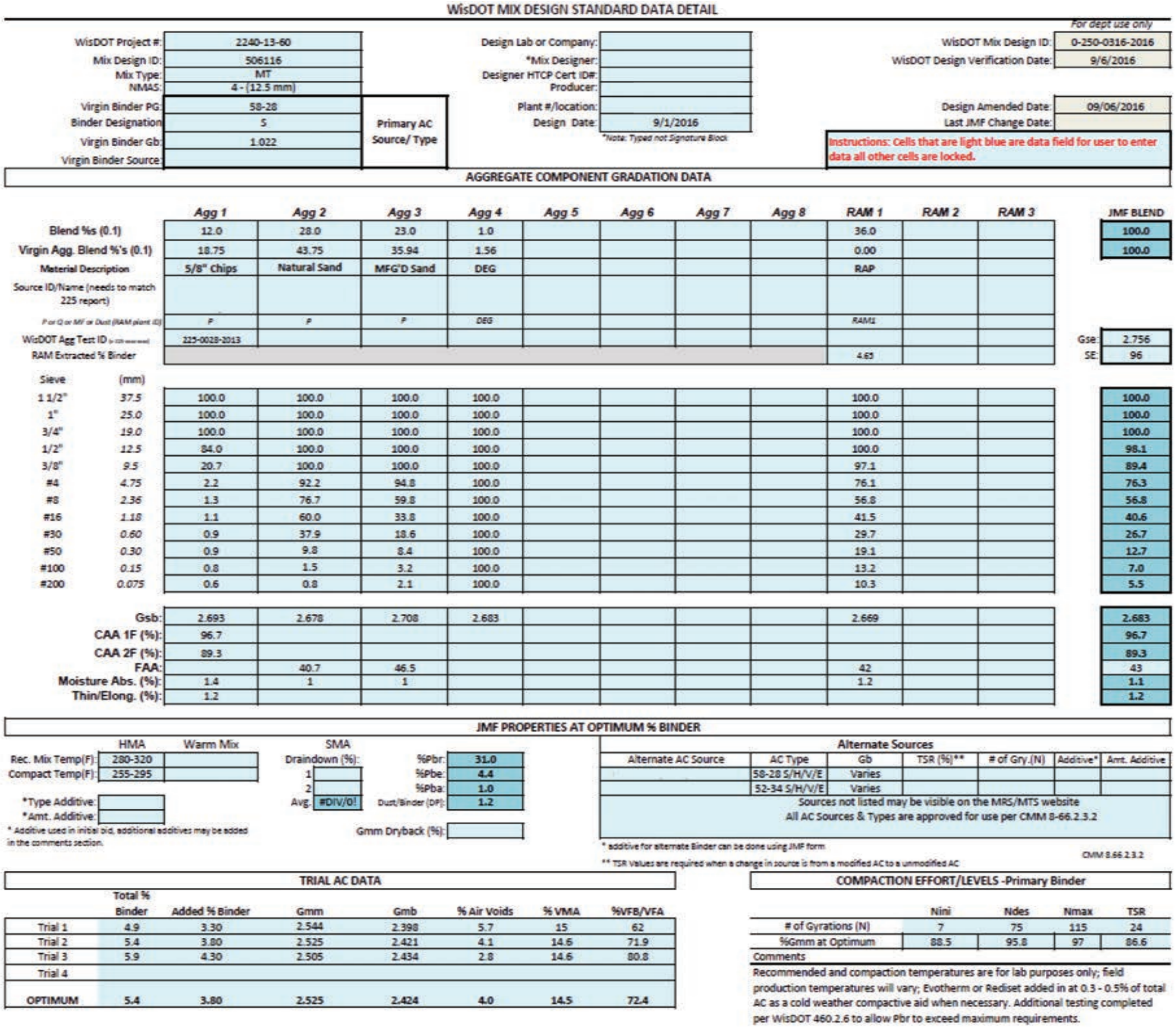
COMPACTION EFFORT/LEVELS -Primary Binder

	Nini	Ndes	Nmax	TSR
# of Gyrations (N)	7	75	115	21
%Gmm at Optimum	89.4	96.4	97.4	81.5

Comments

Recommended and compaction temperatures are for lab purposes only; field production temperatures will vary; Evotherm or Rediset added in at 0.3 - 0.5% of total AC% as a cold weather compactive aid when necessary.

Figure D.11: Mix Design – DOT Control (0-250-0052-2016)



WisDOT MIX DESIGN STANDARD DATA DETAIL

WisDOT Project #:	2240-13-60	Design Lab or Company:		
Mix Design ID:	506116	*Mix Designer:		
Mix Type:	MT	Designer HTCP Cert ID#:		
NMAS:	4 - (12.5 mm)	Producer:		
Virgin Binder PG:	58-28	Plant #/location:		
Binder Designation	5	Design Date:	9/1/2016	
Virgin Binder Gb:	1.022			
Virgin Binder Source:				

Primary AC Source/ Type

*Note: Typed not Signature Block

For dept use only

WisDOT Mix Design ID:	0-250-0316-2016
WisDOT Design Verification Date:	9/6/2016
Design Amended Date:	09/06/2016
Last JMF Change Date:	

Instructions: Cells that are light blue are data field for user to enter data all other cells are locked.

AGGREGATE COMPONENT GRADATION DATA

		Agg 1	Agg 2	Agg 3	Agg 4	Agg 5	Agg 6	Agg 7	Agg 8	RAM 1	RAM 2	RAM 3	JMF BLEND
Blend %s (0.1)		12.0	28.0	23.0	1.0					36.0			100.0
Virgin Agg. Blend %'s (0.1)		18.75	43.75	35.94	1.56					0.00			100.0
Material Description		5/8" Chips	Natural Sand	MFG'D Sand	DEG					RAP			
Source ID/Name (needs to match 225 report)													
P or Q or MF or Dust (RAM plant ID)		P	P	P	DEG					RAM1			
WisDOT Agg Test ID		225-0028-2013											Gse: 2.756
RAM Extracted % Binder										4.65			SE: 96
Sieve	(mm)												
1 1/2"	37.5	100.0	100.0	100.0	100.0					100.0			100.0
1"	25.0	100.0	100.0	100.0	100.0					100.0			100.0
3/4"	19.0	100.0	100.0	100.0	100.0					100.0			100.0
1/2"	12.5	84.0	100.0	100.0	100.0					100.0			98.1
3/8"	9.5	20.7	100.0	100.0	100.0					97.1			89.4
#4	4.75	2.2	92.2	94.8	100.0					76.1			76.3
#8	2.36	1.3	76.7	59.8	100.0					56.8			56.8
#16	1.18	1.1	60.0	33.8	100.0					41.5			40.6
#30	0.60	0.9	37.9	18.6	100.0					29.7			26.7
#50	0.30	0.9	9.8	8.4	100.0					19.1			12.7
#100	0.15	0.8	1.5	3.2	100.0					13.2			7.0
#200	0.075	0.6	0.8	2.1	100.0					10.3			5.5
Gsb:		2.693	2.678	2.708	2.683					2.669			2.683
CAA 1F (%):		96.7											96.7
CAA 2F (%):		89.3											89.3
FAA:			40.7	46.5						42			43
Moisture Abs. (%):		1.4	1	1						1.2			1.1
Thin/Elong. (%):		1.2											1.2

JMF PROPERTIES AT OPTIMUM % BINDER

	HMA	Warm Mix
Rec. Mix Temp(F):	280-320	
Compact Temp(F):	255-295	

*Type Additive:	
*Amt. Additive:	

* Additive used in initial bid, additional additives may be added in the comments section.

SMA	
Draindown (%):	
1	
2	
Avg.	#DIV/0!

%Pbr:	31.0
%Pbe:	4.4
%Pba:	1.0
Dust/Binder (DP):	1.2
Gmm Dryback (%):	

Alternate Sources

Alternate AC Source	AC Type	Gb	TSR (%)**	# of Gry.(N)	Additive*	Amt. Additive
	58-28 S/H/V/E	Varies				
	52-34 S/H/V/E	Varies				

Sources not listed may be visible on the MRS/MTS website

All AC Sources & Types are approved for use per CMM 8-66.2.3.2

* additive for alternate Binder can be done using JMF form

** TSR Values are required when a change in source is from a modified AC to a unmodified AC

CMM 8.66.2.3.2

TRIAL AC DATA

	Total % Binder	Added % Binder	Gmm	Gmb	% Air Voids	% VMA	%VFB/VFA
Trial 1	4.9	3.30	2.544	2.398	5.7	15	62
Trial 2	5.4	3.80	2.525	2.421	4.1	14.6	71.9
Trial 3	5.9	4.30	2.505	2.434	2.8	14.6	80.8
Trial 4							
OPTIMUM	5.4	3.80	2.525	2.424	4.0	14.5	72.4

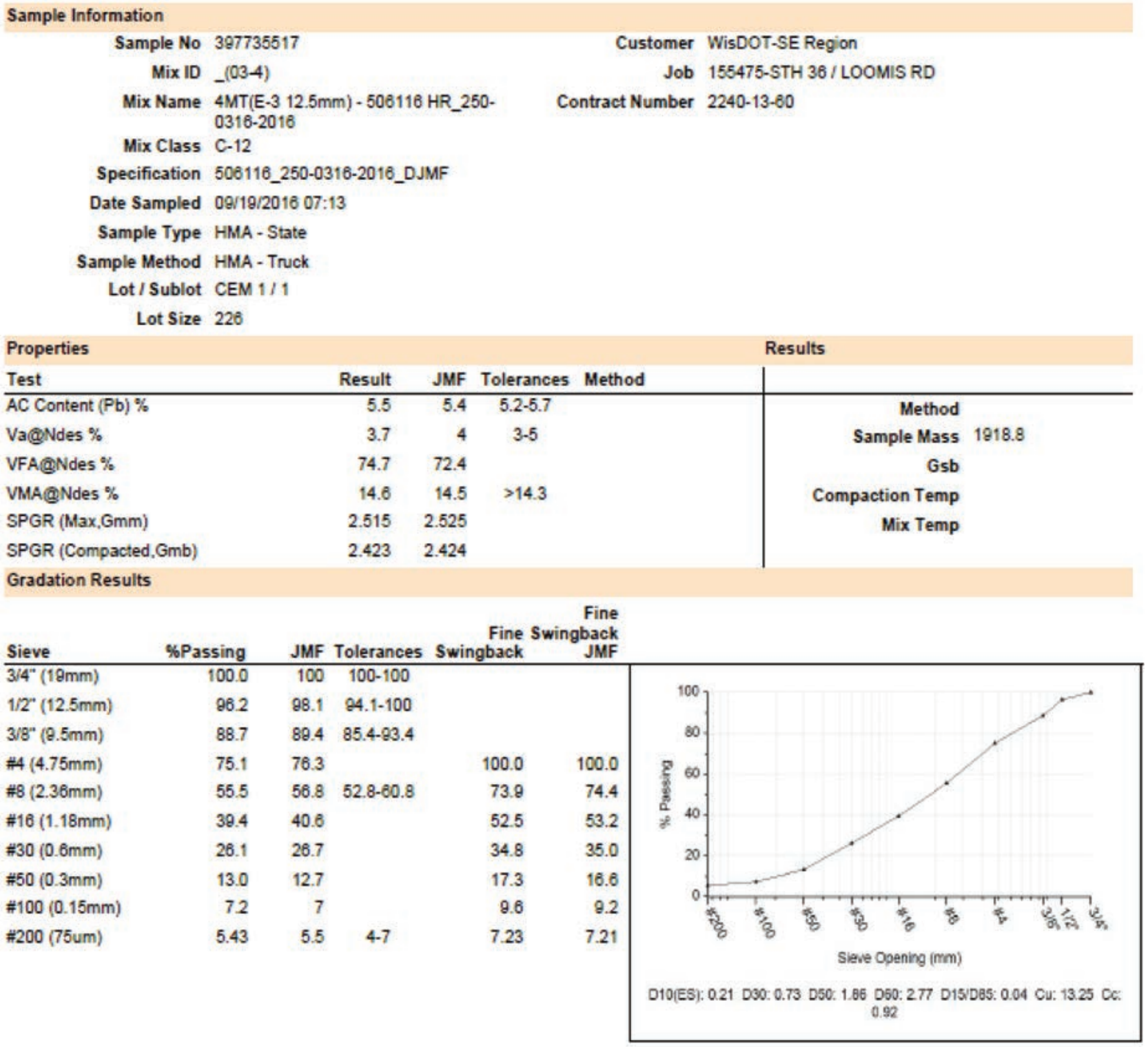
COMPACTION EFFORT/LEVELS -Primary Binder

	Nini	Ndes	Nmax	TSR
# of Gyrations (N)	7	75	115	24
%Gmm at Optimum	88.5	95.8	97	86.6

Comments

Recommended and compaction temperatures are for lab purposes only; field production temperatures will vary; Evotherm or Rediset added in at 0.3 - 0.5% of total AC as a cold weather compactive aid when necessary. Additional testing completed per WisDOT 460.2.6 to allow Pbr to exceed maximum requirements.

Figure D.11: Mix Design – High RAP (0-250-0316-2016)



Sample Information

Sample No	397735517	**Customer**	WisDOT-SE Region
Mix ID	_(03-4)	**Job**	155475-STH 36 / LOOMIS RD
Mix Name	4MT(E-3 12.5mm) - 506116 HR_250-0316-2016	**Contract Number**	2240-13-60
Mix Class	C-12		
Specification	506116_250-0316-2016_DJMF		
Date Sampled	09/19/2016 07:13		
Sample Type	HMA - State		
Sample Method	HMA - Truck		
Lot / Sublot	CEM 1 / 1		
Lot Size	226		

Properties

Test	Result	JMF	Tolerances	Method
AC Content (Pb) %	5.5	5.4	5.2-5.7	
Va@Ndes %	3.7	4	3-5	
VFA@Ndes %	74.7	72.4		
VMA@Ndes %	14.6	14.5	>14.3	
SPGR (Max,Gmm)	2.515	2.525		
SPGR (Compacted,Gmb)	2.423	2.424		

Results

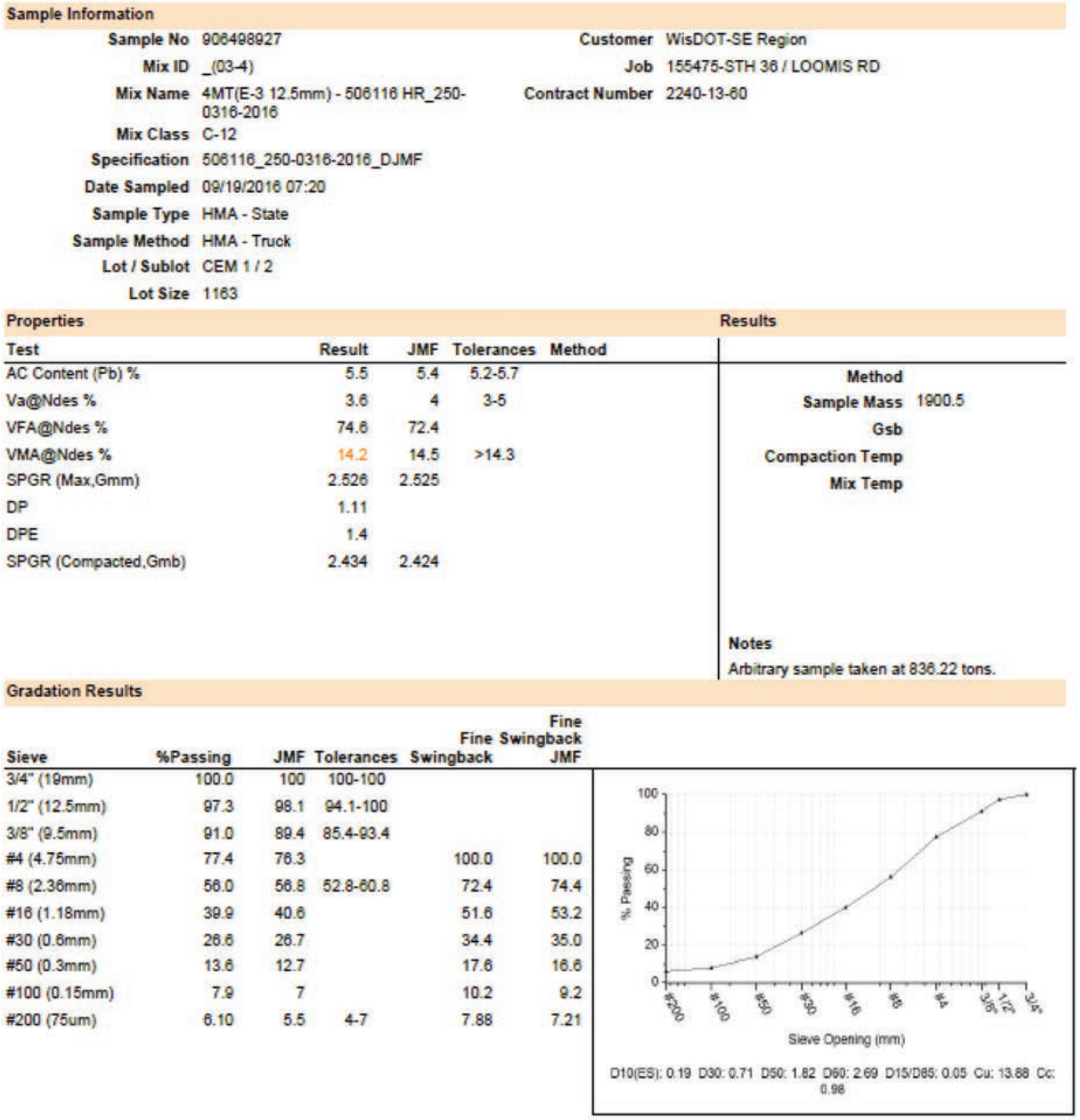
Method	
Sample Mass	1918.8
Gsb	
Compaction Temp	
Mix Temp	

Gradation Results

Sieve	%Passing	JMF	Tolerances	Fine Swingback	Fine Swingback JMF
3/4" (19mm)	100.0	100	100-100		
1/2" (12.5mm)	96.2	98.1	94.1-100		
3/8" (9.5mm)	88.7	89.4	85.4-93.4		
#4 (4.75mm)	75.1	76.3		100.0	100.0
#8 (2.36mm)	55.5	56.8	52.8-60.8	73.9	74.4
#16 (1.18mm)	39.4	40.6		52.5	53.2
#30 (0.6mm)	26.1	26.7		34.8	35.0
#50 (0.3mm)	13.0	12.7		17.3	16.6
#100 (0.15mm)	7.2	7		9.6	9.2
#200 (75um)	5.43	5.5	4-7	7.23	7.21

D10(ES): 0.21 D30: 0.73 D50: 1.86 D60: 2.77 D15/D85: 0.04 Cu: 13.25 Cc: 0.92

Figure D.12: Section 1 – High RAP PG 52-34



Sample Information

Sample No	906498927	**Customer**	WisDOT-SE Region
Mix ID	_(03-4)	**Job**	155475-STH 36 / LOOMIS RD
Mix Name	4MT(E-3 12.5mm) - 506116 HR_250-0316-2016	**Contract Number**	2240-13-60
Mix Class	C-12		
Specification	506116_250-0316-2016_DJMF		
Date Sampled	09/19/2016 07:20		
Sample Type	HMA - State		
Sample Method	HMA - Truck		
Lot / Sublot	CEM 1 / 2		
Lot Size	1163		

Properties

Test	Result	JMF	Tolerances	Method
AC Content (Pb) %	5.5	5.4	5.2-5.7	
Va@Ndes %	3.6	4	3-5	
VFA@Ndes %	74.6	72.4		
VMA@Ndes %	14.2	14.5	>14.3	
SPGR (Max,Gmm)	2.526	2.525		
DP	1.11			
DPE	1.4			
SPGR (Compacted,Gmb)	2.434	2.424		

Results

Method	
Sample Mass	1900.5
Gsb	
Compaction Temp	
Mix Temp	

Notes

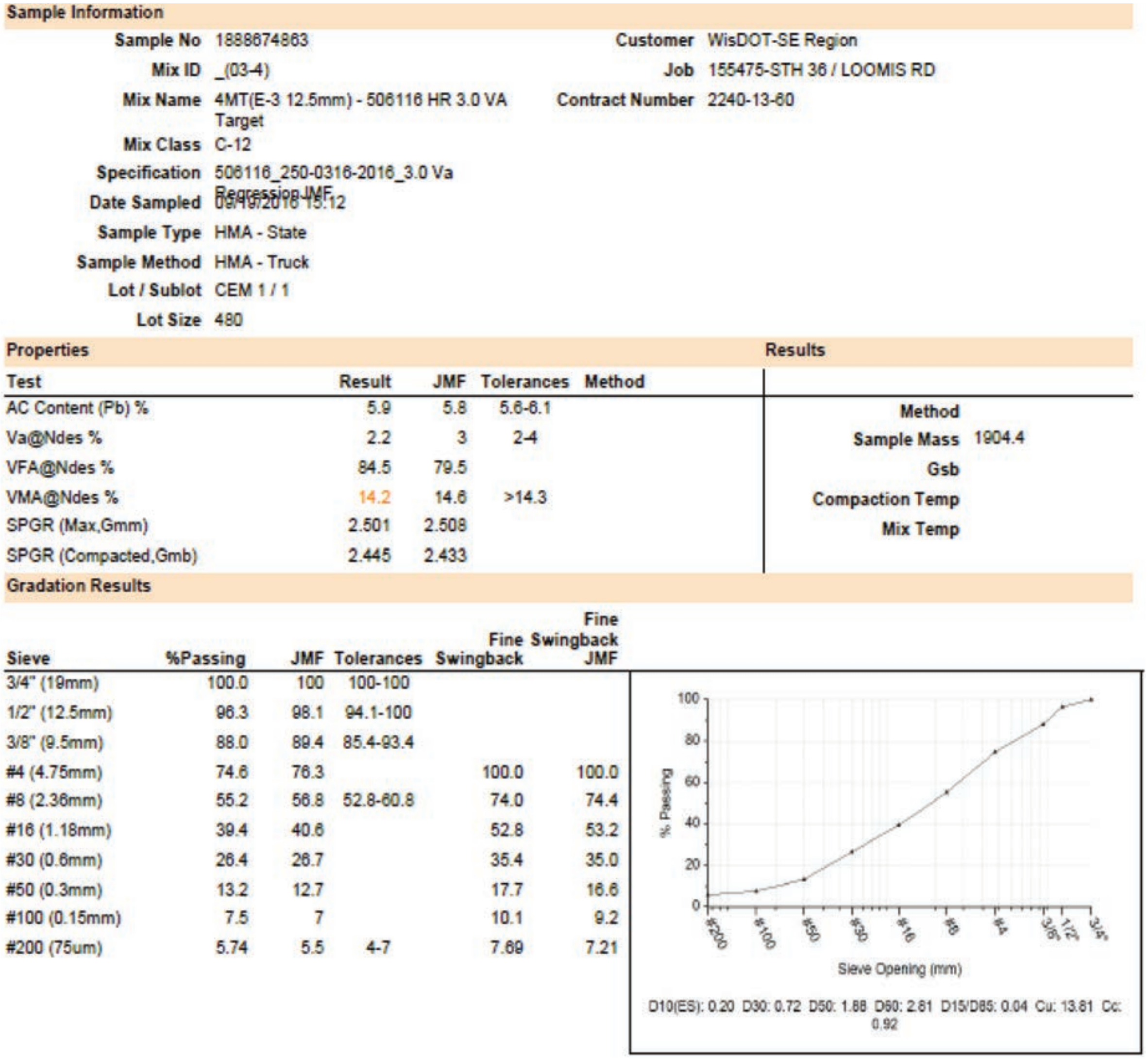
Arbitrary sample taken at 836.22 tons.

Gradation Results

Sieve	%Passing	JMF	Tolerances	Fine Swingback	Fine Swingback JMF
3/4" (19mm)	100.0	100	100-100		
1/2" (12.5mm)	97.3	98.1	94.1-100		
3/8" (9.5mm)	91.0	89.4	85.4-93.4		
#4 (4.75mm)	77.4	76.3		100.0	100.0
#8 (2.36mm)	56.0	56.8	52.8-60.8	72.4	74.4
#16 (1.18mm)	39.9	40.6		51.6	53.2
#30 (0.6mm)	26.6	26.7		34.4	35.0
#50 (0.3mm)	13.6	12.7		17.6	16.6
#100 (0.15mm)	7.9	7		10.2	9.2
#200 (75um)	6.10	5.5	4-7	7.88	7.21

D10(ES): 0.19 D30: 0.71 D50: 1.82 D60: 2.69 D15/D85: 0.05 Cu: 13.88 Cc: 0.98

Figure D.13: Section 1 – High RAP PG 52-34



Sample Information

Sample No	1888674863	**Customer**	WisDOT-SE Region
Mix ID	_(03-4)	**Job**	155475-STH 36 / LOOMIS RD
Mix Name	4MT(E-3 12.5mm) - 506116 HR 3.0 VA Target	**Contract Number**	2240-13-60
Mix Class	C-12		
Specification	506116_250-0316-2016_3.0 Va Regression JMF		
Date Sampled	09/16/2016 15:12		
Sample Type	HMA - State		
Sample Method	HMA - Truck		
Lot / Sublot	CEM 1 / 1		
Lot Size	480		

Properties

Test	Result	JMF	Tolerances	Method
AC Content (Pb) %	5.9	5.8	5.6-6.1	
Va@Ndes %	2.2	3	2-4	
VFA@Ndes %	84.5	79.5		
VMA@Ndes %	14.2	14.6	>14.3	
SPGR (Max,Gmm)	2.501	2.508		
SPGR (Compacted,Gmb)	2.445	2.433		

Results

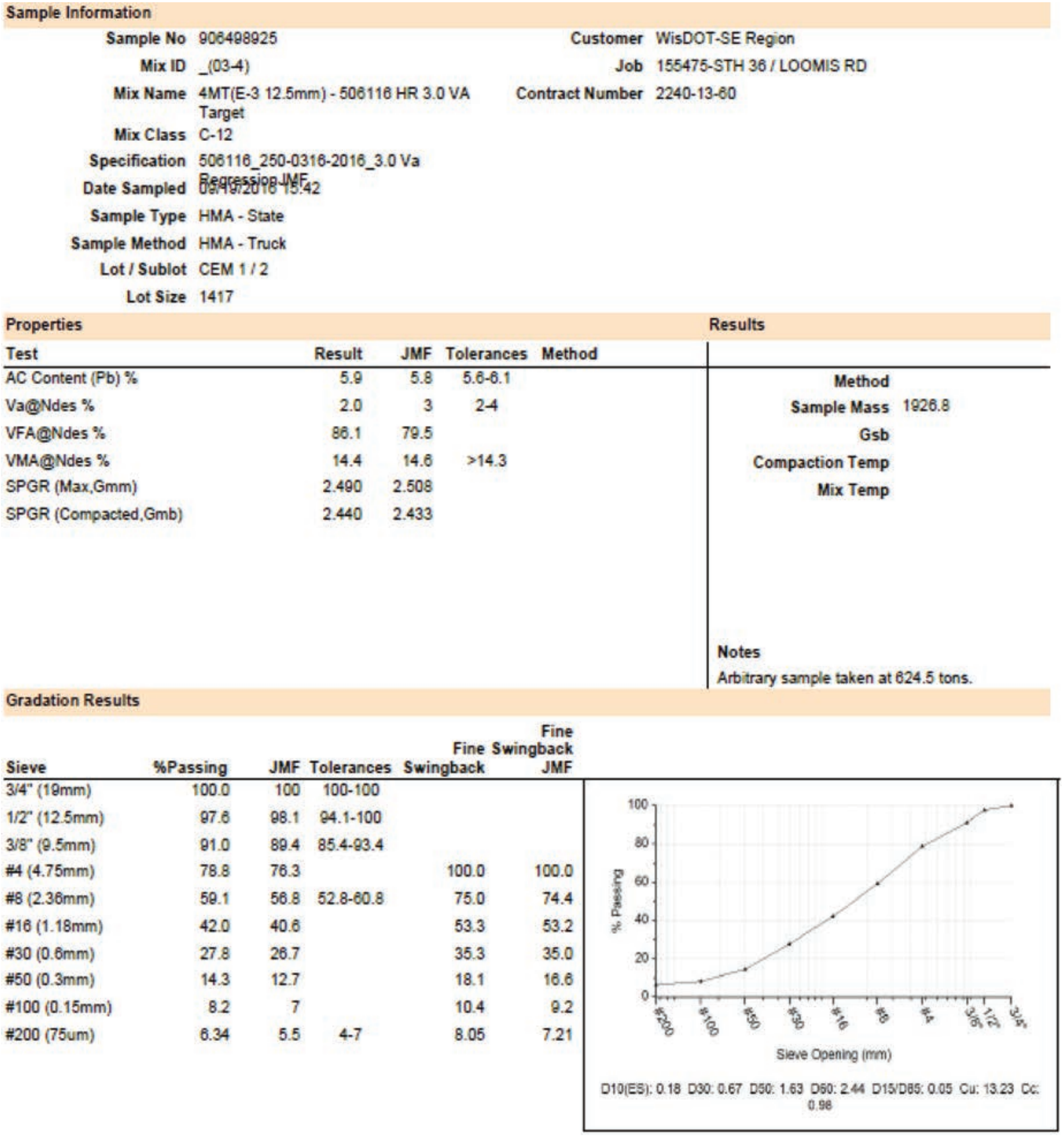
Method	
Sample Mass	1904.4
Gsb	
Compaction Temp	
Mix Temp	

Gradation Results

Sieve	%Passing	JMF	Tolerances	Fine Swingback	Fine Swingback JMF
3/4" (19mm)	100.0	100	100-100		
1/2" (12.5mm)	96.3	98.1	94.1-100		
3/8" (9.5mm)	88.0	89.4	85.4-93.4		
#4 (4.75mm)	74.6	76.3		100.0	100.0
#8 (2.36mm)	55.2	56.8	52.8-60.8	74.0	74.4
#16 (1.18mm)	39.4	40.6		52.8	53.2
#30 (0.6mm)	26.4	26.7		35.4	35.0
#50 (0.3mm)	13.2	12.7		17.7	16.6
#100 (0.15mm)	7.5	7		10.1	9.2
#200 (75um)	5.74	5.5	4-7	7.69	7.21

D10(ES): 0.20 D30: 0.72 D50: 1.88 D60: 2.61 D15/D85: 0.04 Cu: 13.61 Cc: 0.92

Figure D.14: Section 2 - HR PG 58-28 Regressed AV 3%



Sample Information

Sample No	906498925	**Customer**	WisDOT-SE Region
Mix ID	_(03-4)	**Job**	155475-STH 36 / LOOMIS RD
Mix Name	4MT(E-3 12.5mm) - 506116 HR 3.0 VA Target	**Contract Number**	2240-13-60
Mix Class	C-12		
Specification	506116_250-0316-2016_3.0 Va Regression JMF		
Date Sampled	09/19/2016 15:42		
Sample Type	HMA - State		
Sample Method	HMA - Truck		
Lot / Sublot	CEM 1 / 2		
Lot Size	1417		

Properties

Test	Result	JMF	Tolerances	Method
AC Content (Pb) %	5.9	5.8	5.6-6.1	
Va@Ndes %	2.0	3	2-4	
VFA@Ndes %	86.1	79.5		
VMA@Ndes %	14.4	14.6	>14.3	
SPGR (Max,Gmm)	2.490	2.508		
SPGR (Compacted,Gmb)	2.440	2.433		

Results

Method

Sample Mass 1926.8

Gsb

Compaction Temp

Mix Temp

Notes

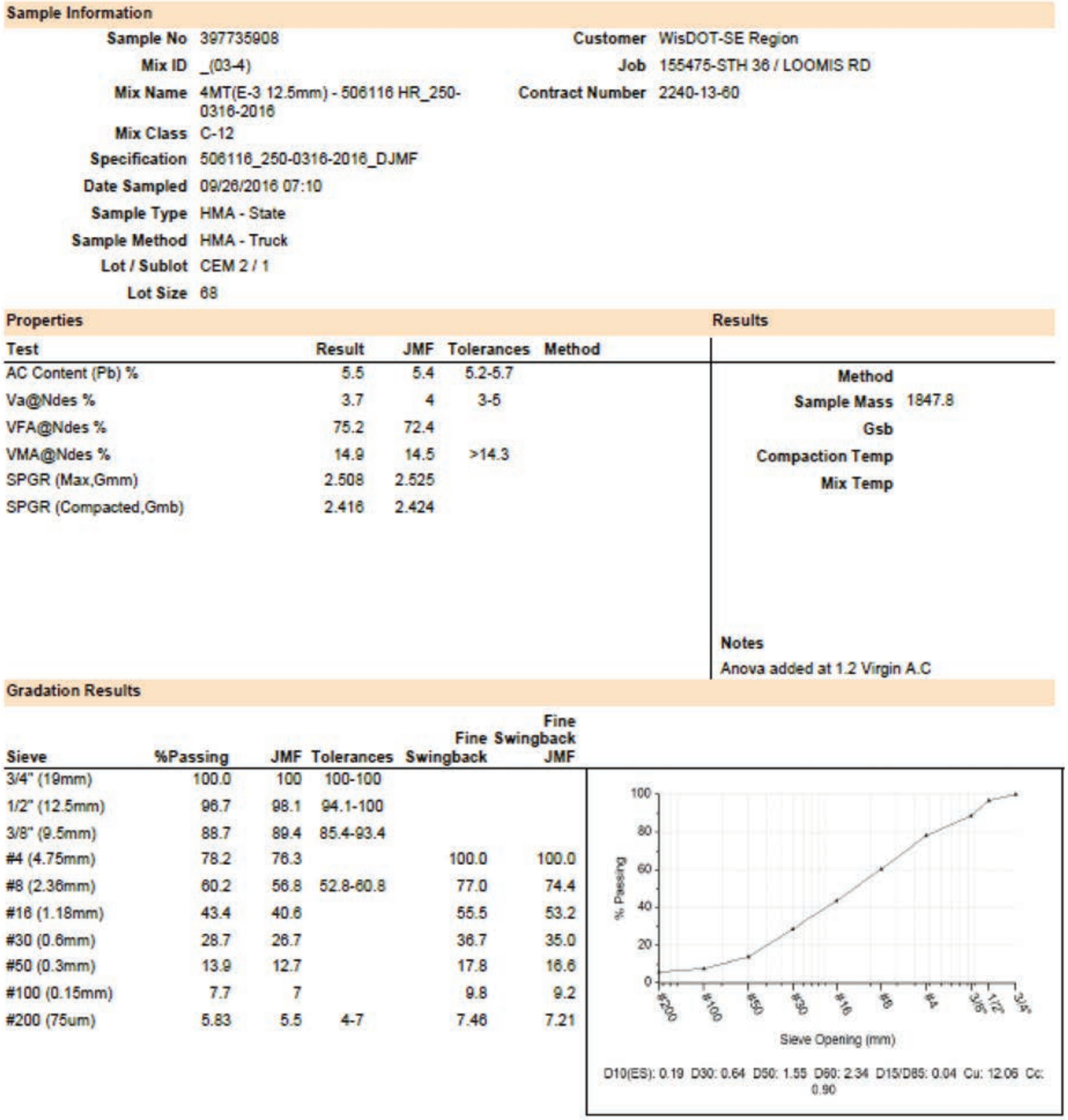
Arbitrary sample taken at 624.5 tons.

Gradation Results

Sieve	%Passing	JMF	Tolerances	Fine Swingback	Fine Swingback JMF
3/4" (19mm)	100.0	100	100-100		
1/2" (12.5mm)	97.6	98.1	94.1-100		
3/8" (9.5mm)	91.0	89.4	85.4-93.4		
#4 (4.75mm)	78.8	76.3		100.0	100.0
#8 (2.36mm)	59.1	56.8	52.8-60.8	75.0	74.4
#16 (1.18mm)	42.0	40.6		53.3	53.2
#30 (0.6mm)	27.8	26.7		35.3	35.0
#50 (0.3mm)	14.3	12.7		18.1	16.6
#100 (0.15mm)	8.2	7		10.4	9.2
#200 (75um)	6.34	5.5	4-7	8.05	7.21

D10(ES): 0.18 D30: 0.67 D50: 1.63 D60: 2.44 D15/D85: 0.05 Cu: 13.23 Cc: 0.98

Figure D.14: Section 2 - HR PG 58-28 Regressed AV 3%



Sample Information

Sample No	397735908	**Customer**	WisDOT-SE Region
Mix ID	_(03-4)	**Job**	155475-STH 36 / LOOMIS RD
Mix Name	4MT(E-3 12.5mm) - 506116 HR_250-0316-2016	**Contract Number**	2240-13-60
Mix Class	C-12		
Specification	506116_250-0316-2016_DJMF		
Date Sampled	09/26/2016 07:10		
Sample Type	HMA - State		
Sample Method	HMA - Truck		
Lot / Sublot	CEM 2 / 1		
Lot Size	68		

Properties

Test	Result	JMF	Tolerances	Method
AC Content (Pb) %	5.5	5.4	5.2-5.7	
Va@Ndes %	3.7	4	3-5	
VFA@Ndes %	75.2	72.4		
VMA@Ndes %	14.9	14.5	>14.3	
SPGR (Max,Gmm)	2.508	2.525		
SPGR (Compacted,Gmb)	2.416	2.424		

Results

Method	
Sample Mass	1847.8
Gsb	
Compaction Temp	
Mix Temp	

Notes

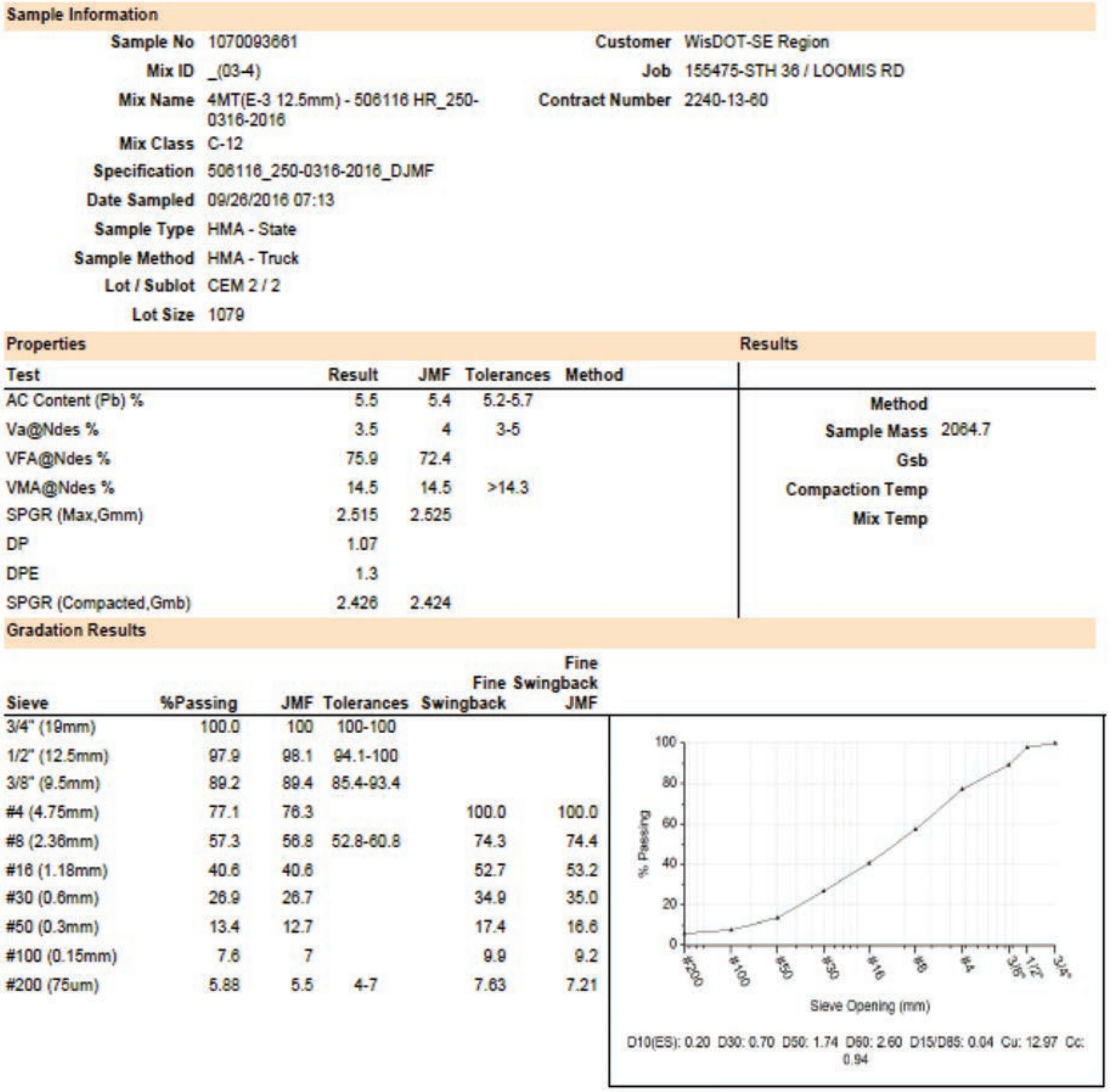
Anova added at 1.2 Virgin A.C

Gradation Results

Sieve	%Passing	JMF	Tolerances	Fine Swingback	Fine Swingback JMF
3/4" (19mm)	100.0	100	100-100		
1/2" (12.5mm)	96.7	98.1	94.1-100		
3/8" (9.5mm)	88.7	89.4	85.4-93.4		
#4 (4.75mm)	78.2	76.3		100.0	100.0
#8 (2.36mm)	60.2	56.8	52.8-60.8	77.0	74.4
#16 (1.18mm)	43.4	40.6		55.5	53.2
#30 (0.6mm)	28.7	26.7		36.7	35.0
#50 (0.3mm)	13.9	12.7		17.8	16.6
#100 (0.15mm)	7.7	7		9.8	9.2
#200 (75um)	5.83	5.5	4-7	7.46	7.21

D10(ES): 0.19 D30: 0.64 D50: 1.55 D60: 2.34 D15/D85: 0.04 Cu: 12.06 Cc: 0.90

Figure D.15: Section 3 – HR PG 58-28 with 1.2% V2



Sample Information

Sample No	1070093661	**Customer**	WisDOT-SE Region
Mix ID	_(03-4)	**Job**	155475-STH 36 / LOOMIS RD
Mix Name	4MT(E-3 12.5mm) - 506116 HR_250-0316-2016	**Contract Number**	2240-13-60
Mix Class	C-12		
Specification	506116_250-0316-2016_DJMF		
Date Sampled	09/26/2016 07:13		
Sample Type	HMA - State		
Sample Method	HMA - Truck		
Lot / Sublot	CEM 2 / 2		
Lot Size	1079		

Properties

Test	Result	JMF	Tolerances	Method
AC Content (Pb) %	5.5	5.4	5.2-5.7	
Va@Ndes %	3.5	4	3-5	
VFA@Ndes %	75.9	72.4		
VMA@Ndes %	14.5	14.5	>14.3	
SPGR (Max,Gmm)	2.515	2.525		
DP	1.07			
DPE	1.3			
SPGR (Compacted,Gmb)	2.426	2.424		

Results

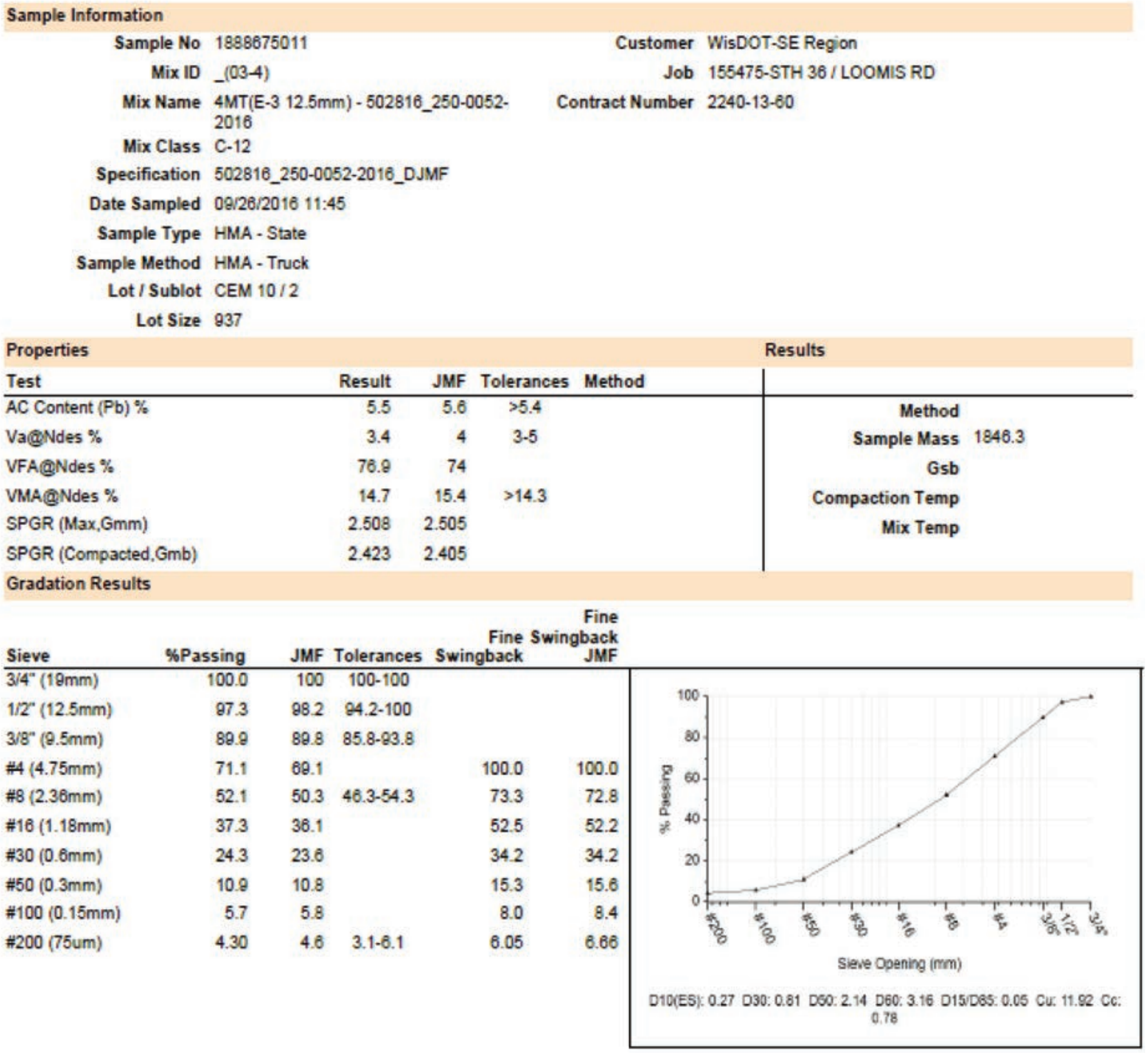
Method
Sample Mass 2064.7
Gsb
Compaction Temp
Mix Temp

Gradation Results

Sieve	%Passing	JMF	Tolerances	Fine Swingback	Fine Swingback JMF
3/4" (19mm)	100.0	100	100-100		
1/2" (12.5mm)	97.9	98.1	94.1-100		
3/8" (9.5mm)	89.2	89.4	85.4-93.4		
#4 (4.75mm)	77.1	76.3		100.0	100.0
#8 (2.36mm)	57.3	56.8	52.8-60.8	74.3	74.4
#16 (1.18mm)	40.6	40.6		52.7	53.2
#30 (0.6mm)	26.9	26.7		34.9	35.0
#50 (0.3mm)	13.4	12.7		17.4	16.6
#100 (0.15mm)	7.6	7		9.9	9.2
#200 (75um)	5.88	5.5	4-7	7.63	7.21

D10(ES): 0.20 D30: 0.70 D50: 1.74 D60: 2.60 D15/D85: 0.04 Cu: 12.97 Cc: 0.94

Figure D.16: Section 4 – HR PG 58-28 Control



Sample Information

Sample No	1888675011	**Customer**	WisDOT-SE Region
Mix ID	_(03-4)	**Job**	155475-STH 36 / LOOMIS RD
Mix Name	4MT(E-3 12.5mm) - 502816_250-0052-2016	**Contract Number**	2240-13-60
Mix Class	C-12		
Specification	502816_250-0052-2016_DJMF		
Date Sampled	09/26/2016 11:45		
Sample Type	HMA - State		
Sample Method	HMA - Truck		
Lot / Sublot	CEM 10 / 2		
Lot Size	937		

Properties

Test	Result	JMF	Tolerances	Method
AC Content (Pb) %	5.5	5.6	>5.4	
Va@Ndes %	3.4	4	3-5	
VFA@Ndes %	76.9	74		
VMA@Ndes %	14.7	15.4	>14.3	
SPGR (Max,Gmm)	2.508	2.505		
SPGR (Compacted,Gmb)	2.423	2.405		

Results

Method	
Sample Mass	1846.3
Gsb	
Compaction Temp	
Mix Temp	

Gradation Results

Sieve	%Passing	JMF	Tolerances	Fine Swingback	Fine Swingback JMF
3/4" (19mm)	100.0	100	100-100		
1/2" (12.5mm)	97.3	98.2	94.2-100		
3/8" (9.5mm)	89.9	89.8	85.8-93.8		
#4 (4.75mm)	71.1	69.1		100.0	100.0
#8 (2.36mm)	52.1	50.3	46.3-54.3	73.3	72.8
#16 (1.18mm)	37.3	36.1		52.5	52.2
#30 (0.6mm)	24.3	23.6		34.2	34.2
#50 (0.3mm)	10.9	10.8		15.3	15.6
#100 (0.15mm)	5.7	5.8		8.0	8.4
#200 (75um)	4.30	4.6	3.1-6.1	6.05	6.66

D10(ES): 0.27 D30: 0.81 D50: 2.14 D60: 3.16 D15/D85: 0.05 Cu: 11.92 Cc: 0.78

Figure D.17: Section 5 – DOT Control PG 58-28

APPENDIX E

Delaware Construction Report

Delaware Department of Transportation (DelDOT) executed the Port Penn/Pole Bridge Road overlay project in late fall of 2016. The approximately 2.2-mile overlay project was paved on December 02, 2016 and located near Middletown in north-central part of Delaware. The project started on Port Penn Road at the intersection with Route 9 (east end) and extended to partially on Pole Bridge Road (west end). The project included one-inch milling of existing surface layer and placement of two-inches overlay. Typical paving width was 11 feet. The project had three test sections to evaluate the effects of recycling agents (rejuvenators) on the performance of asphalt mixtures with high RAP and RAS content. Diamond Materials was the general contractor for this project.

Figure E.1 shows the general project location and a typical section where left side was already paved with surface course and right side shows the milled surface before overlay placement. Three test sections were placed along the entire length of the project limits (Figure E.2). Both Port Penn/Pole Bridge Roads are two-way undivided rural road located in the north central side New Castle County in Delaware. Typical roadbed width was 26 feet including two 11-feet travel lanes (paved) and 2-feet unpaved grassy shoulder on each side. This section of roadway relatively horizontal with numerous intersections and driveways. The traffic on this road is moderate to light and consists of occasional truck traffic to/from the port.

Figure E.1: Project Site showing Surface Course and Milled Surface.

Before milling, the existing surface had some longitudinal cracks. When the researcher was present during the construction, the existing surface was already been milled. But the milled surface did not show any cracking which indicates that the longitudinal cracking on the existing surface was top down superficial cracking. Figure E.3 shows a typical full depth core extracted after the paving. The existing structure was found to be about six inches asphalt layer constructed at different times. The subbase below the HMA appeared as mix of crushed concrete and millings with unknown thickness. Under this study, three test sections were placed as surface course. Each of the three test sections had different surface mix design using 9.5 mm Superpave mixture as shown in Table E.1.

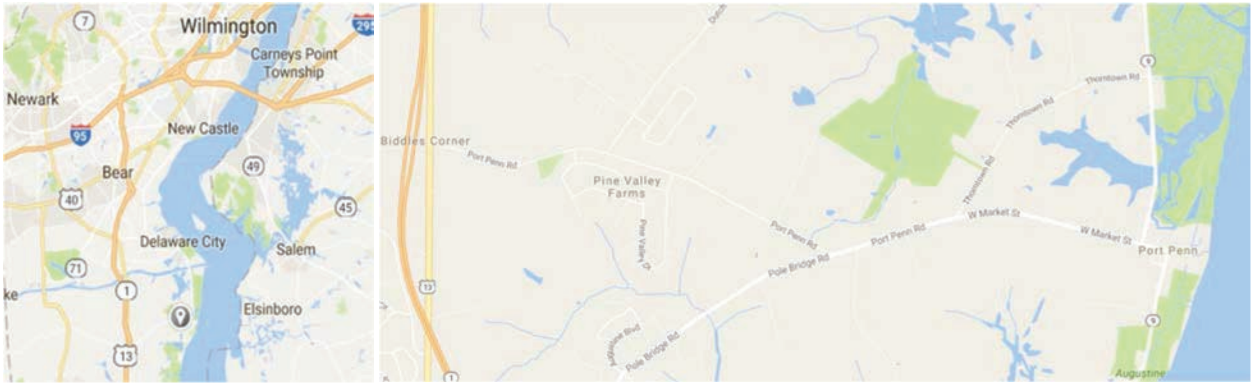


Figure E.2: Project Location.

Figure E.3: Typical Full Depth Field Core.

Table E.1: Test Sections Mixture Description.

Section No.	Section Name	Description	Additive/Rejuvenator Dosage
1	Control Mix	20% RAP + 4% RAS with 3.6% PG 64-28 virgin binder	0.4 % warm mix additive by weight of total asphalt content
2	T2	29% RAP + 4% RAS with 3.2% PG 64-28 virgin binder	0.8 % T2 by weight of total asphalt content
3	T2 plus warm mix additive	29% RAP + 4% RAS with 3.2% PG 64-28 virgin binder	0.25 % warm mix additive + 0.8 % T2 by weight of total asphalt content

E.1 MATERIALS AND MIXTURES

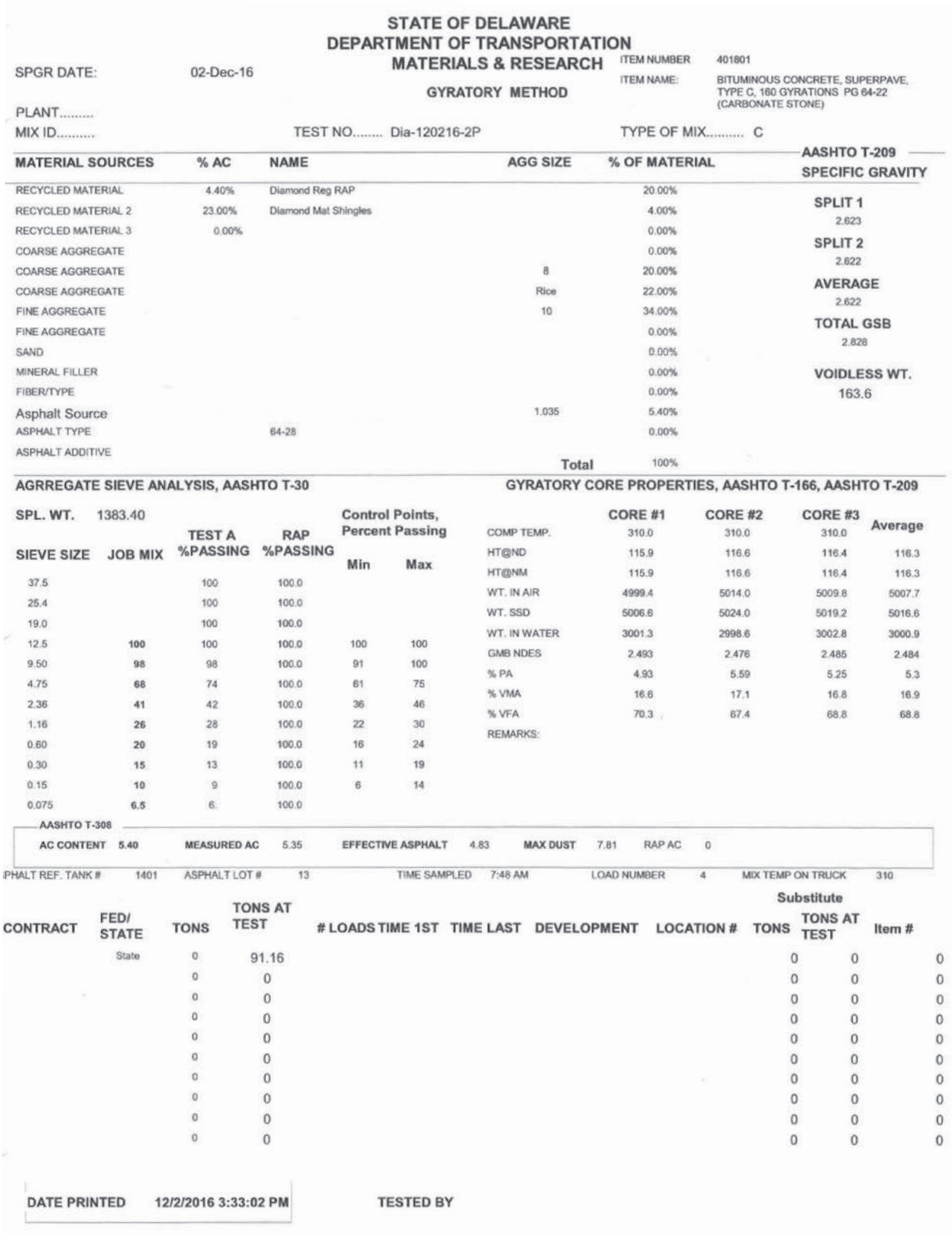
All three test sections used DelDOT's standard Type C (12.5 mm) Superpave mixture designed with 160 gyrations. A PG 64-28 neat binder was used in all mixtures. The source of RAP was unknown; it came from several different highway sections. RAS was produced by shredding and grinding post consumers' waste shingles from multiple sources. Shingles were shredded on-site at the plant. The shingles were 100% passing the #3/8 inch sieve.

The Control Mix (Test Section 1) had virgin aggregate from three different stockpiles along with 20% RAP and 4% RAS. The virgin aggregate came from several sources. The control mix had 0.4% warm mix additive by weight of total asphalt content. During design it was considered that the combined contribution of RAP and RAS was 2.2 percent recycled binder in the control mixture resulting in 5.8 percent total asphalt content.

The T2 Mix (Test Section 2) had a PG 64-28 virgin binder, and virgin aggregate from three different stockpiles along with 29% RAP and 4% RAS. As previously mentioned, the virgin aggregate came from several sources. The T2 mix had 0.8% recycling agent by the weight of total asphalt content.

The T2 plus warm mix additive mix (Test Section 3) had similar components as the T2 Mix (Test Section 2), except that it had additional 0.25% warm mix additive by weight of total mixture.

Figure E.4 through Figure E.6 present the quality control data for the mixtures. Job mix formulas are also included in the quality control report.



STATE OF DELAWARE
DEPARTMENT OF TRANSPORTATION
MATERIALS & RESEARCH

GYRATORY METHOD

SPGR DATE: 02-Dec-16

ITEM NUMBER 401801

ITEM NAME: BITUMINOUS CONCRETE, SUPERPAVE, TYPE C, 160 GYRATIONS PG 64-22 (CARBONATE STONE)

PLANT.........

MIX ID..........

TEST NO........ Dia-120216-2P

TYPE OF MIX.......... C

MATERIAL SOURCES	% AC	NAME	AGG SIZE	% OF MATERIAL
RECYCLED MATERIAL	4.40%	Diamond Reg RAP		20.00%
RECYCLED MATERIAL 2	23.00%	Diamond Mat Shingles		4.00%
RECYCLED MATERIAL 3	0.00%			0.00%
COARSE AGGREGATE				0.00%
COARSE AGGREGATE			8	20.00%
COARSE AGGREGATE			Rice	22.00%
FINE AGGREGATE			10	34.00%
FINE AGGREGATE				0.00%
SAND				0.00%
MINERAL FILLER				0.00%
FIBER/TYPE				0.00%
Asphalt Source			1.035	5.40%
ASPHALT TYPE		64-28		0.00%
ASPHALT ADDITIVE				
			Total	100%

AASHTO T-209 SPECIFIC GRAVITY

SPLIT 1 2.623

SPLIT 2 2.622

AVERAGE 2.622

TOTAL GSB 2.828

VOIDLESS WT. 163.6

AGRREGATE SIEVE ANALYSIS, AASHTO T-30

SPL. WT. 1383.40

SIEVE SIZE	JOB MIX	TEST A %PASSING	RAP %PASSING	Control Points, Percent Passing Min	Control Points, Percent Passing Max
37.5		100	100.0		
25.4		100	100.0		
19.0		100	100.0		
12.5	**100**	100	100.0	100	100
9.50	**98**	98	100.0	91	100
4.75	**68**	74	100.0	61	75
2.36	**41**	42	100.0	36	46
1.16	**26**	28	100.0	22	30
0.60	**20**	19	100.0	16	24
0.30	**15**	13	100.0	11	19
0.15	**10**	9	100.0	6	14
0.075	**6.5**	6.	100.0		

GYRATORY CORE PROPERTIES, AASHTO T-166, AASHTO T-209

	CORE #1	CORE #2	CORE #3	Average
COMP TEMP.	310.0	310.0	310.0	
HT@ND	115.9	116.6	116.4	116.3
HT@NM	115.9	116.6	116.4	116.3
WT. IN AIR	4999.4	5014.0	5009.8	5007.7
WT. SSD	5006.6	5024.0	5019.2	5016.6
WT. IN WATER	3001.3	2998.6	3002.8	3000.9
GMB NDES	2.493	2.476	2.485	2.484
% PA	4.93	5.59	5.25	5.3
% VMA	16.6	17.1	16.8	16.9
% VFA	70.3	67.4	68.8	68.8
REMARKS:				

AASHTO T-308

AC CONTENT 5.40 **MEASURED AC** 5.35 **EFFECTIVE ASPHALT** 4.83 **MAX DUST** 7.81 RAP AC 0

PHALT REF. TANK # 1401 ASPHALT LOT # 13 TIME SAMPLED 7:48 AM LOAD NUMBER 4 MIX TEMP ON TRUCK 310

CONTRACT	FED/STATE	TONS	TONS AT TEST	# LOADS	TIME 1ST	TIME LAST	DEVELOPMENT	LOCATION #	Substitute TONS	Substitute TONS AT TEST	Item #
	State	0	91.16						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0

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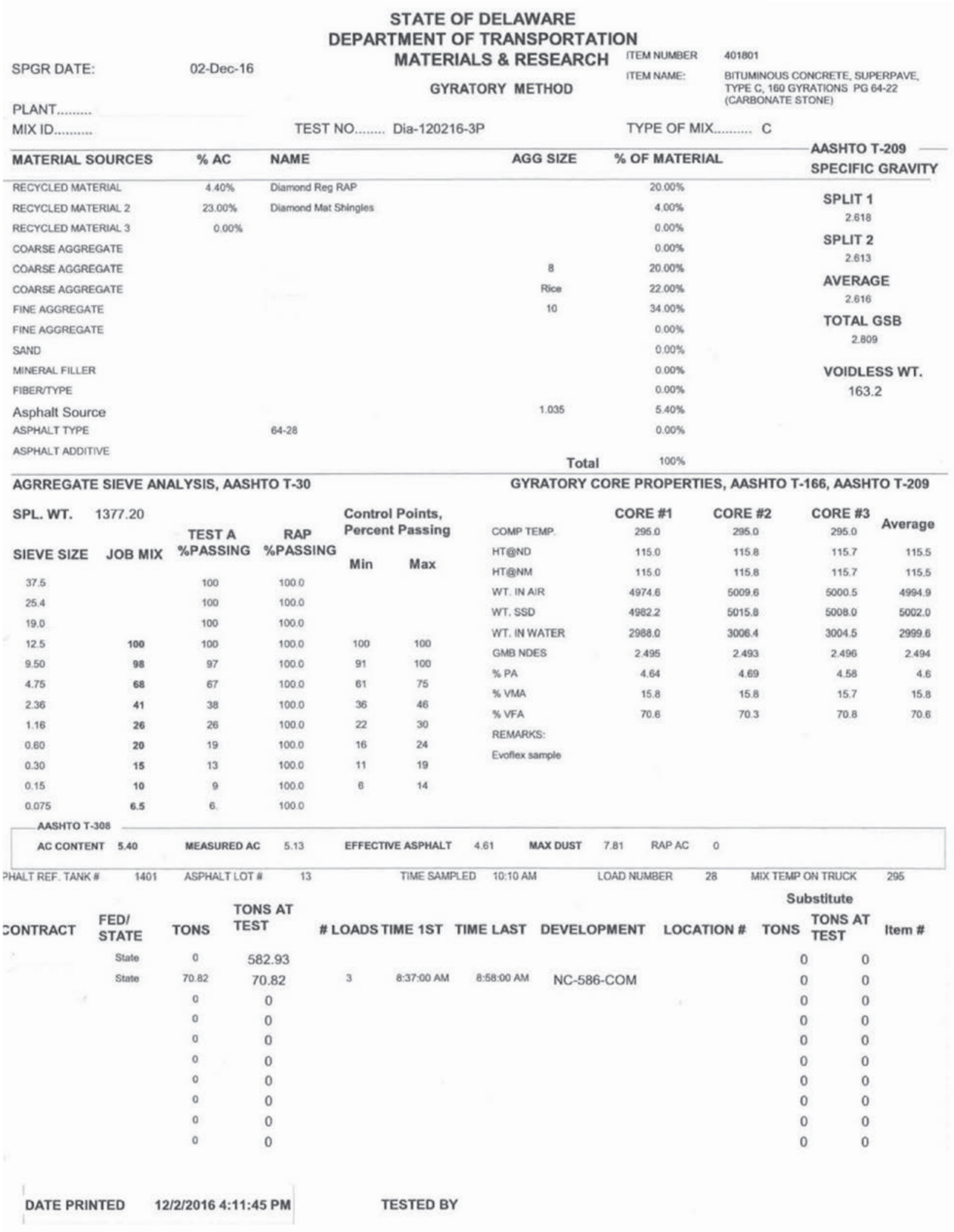
Figure E.4: Mixture Design for Test Section 1.



STATE OF DELAWARE
DEPARTMENT OF TRANSPORTATION
MATERIALS & RESEARCH

GYRATORY METHOD

SPGR DATE: 02-Dec-16

ITEM NUMBER 401801

ITEM NAME: BITUMINOUS CONCRETE, SUPERPAVE, TYPE C, 160 GYRATIONS PG 64-22 (CARBONATE STONE)

PLANT.........

MIX ID..........

TEST NO........ Dia-120216-3P

TYPE OF MIX.......... C

MATERIAL SOURCES	% AC	NAME	AGG SIZE	% OF MATERIAL
RECYCLED MATERIAL	4.40%	Diamond Reg RAP		20.00%
RECYCLED MATERIAL 2	23.00%	Diamond Mat Shingles		4.00%
RECYCLED MATERIAL 3	0.00%			0.00%
COARSE AGGREGATE				0.00%
COARSE AGGREGATE			8	20.00%
COARSE AGGREGATE			Rice	22.00%
FINE AGGREGATE			10	34.00%
FINE AGGREGATE				0.00%
SAND				0.00%
MINERAL FILLER				0.00%
FIBER/TYPE				0.00%
Asphalt Source			1.035	5.40%
ASPHALT TYPE		64-28		0.00%
ASPHALT ADDITIVE				
			Total	100%

AASHTO T-209
SPECIFIC GRAVITY

SPLIT 1
2.618

SPLIT 2
2.613

AVERAGE
2.616

TOTAL GSB
2.809

VOIDLESS WT.
163.2

AGRREGATE SIEVE ANALYSIS, AASHTO T-30

SPL. WT. 1377.20

SIEVE SIZE	JOB MIX	TEST A %PASSING	RAP %PASSING	Control Points, Percent Passing Min	Control Points, Percent Passing Max
37.5		100	100.0		
25.4		100	100.0		
19.0		100	100.0		
12.5	**100**	100	100.0	100	100
9.50	**98**	97	100.0	91	100
4.75	**68**	67	100.0	61	75
2.36	**41**	38	100.0	36	46
1.16	**26**	26	100.0	22	30
0.60	**20**	19	100.0	16	24
0.30	**15**	13	100.0	11	19
0.15	**10**	9	100.0	6	14
0.075	**6.5**	6.	100.0		

GYRATORY CORE PROPERTIES, AASHTO T-166, AASHTO T-209

	CORE #1	CORE #2	CORE #3	Average
COMP TEMP.	295.0	295.0	295.0	
HT@ND	115.0	115.8	115.7	115.5
HT@NM	115.0	115.8	115.7	115.5
WT. IN AIR	4974.6	5009.6	5000.5	4994.9
WT. SSD	4982.2	5015.8	5008.0	5002.0
WT. IN WATER	2988.0	3006.4	3004.5	2999.6
GMB NDES	2.495	2.493	2.496	2.494
% PA	4.64	4.69	4.58	4.6
% VMA	15.8	15.8	15.7	15.8
% VFA	70.6	70.3	70.8	70.6

REMARKS:
Evoflex sample

AASHTO T-308

AC CONTENT 5.40 **MEASURED AC** 5.13 **EFFECTIVE ASPHALT** 4.61 **MAX DUST** 7.81 RAP AC 0

PHALT REF. TANK # 1401 ASPHALT LOT # 13 TIME SAMPLED 10:10 AM LOAD NUMBER 28 MIX TEMP ON TRUCK 295

CONTRACT	FED/ STATE	TONS	TONS AT TEST	# LOADS	TIME 1ST	TIME LAST	DEVELOPMENT	LOCATION #	Substitute TONS	Substitute TONS AT TEST	Item #
	State	0	582.93						0	0	
	State	70.82	70.82	3	8:37:00 AM	8:58:00 AM	NC-586-COM		0	0	
		0	0						0	0	
		0	0						0	0	
		0	0						0	0	
		0	0						0	0	
		0	0						0	0	
		0	0						0	0	
		0	0						0	0	
		0	0						0	0	

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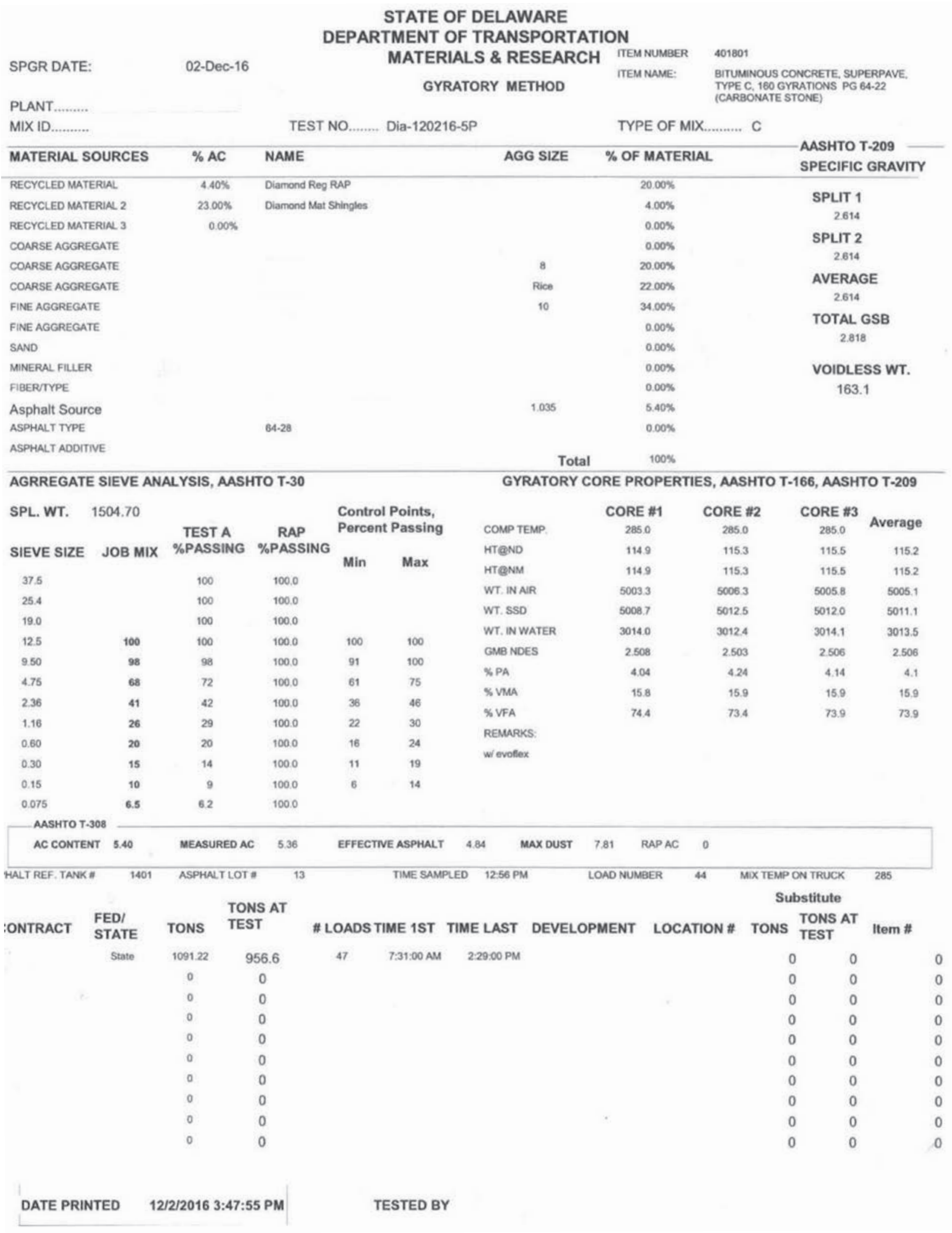
Figure E.5: Mixture Design for Test Section 2.



STATE OF DELAWARE
DEPARTMENT OF TRANSPORTATION
MATERIALS & RESEARCH
GYRATORY METHOD

SPGR DATE: 02-Dec-16

ITEM NUMBER 401801

ITEM NAME: BITUMINOUS CONCRETE, SUPERPAVE, TYPE C, 160 GYRATIONS PG 64-22 (CARBONATE STONE)

PLANT.........

MIX ID..........

TEST NO........ Dia-120216-5P

TYPE OF MIX.......... C

MATERIAL SOURCES	% AC	NAME	AGG SIZE	% OF MATERIAL
RECYCLED MATERIAL	4.40%	Diamond Reg RAP		20.00%
RECYCLED MATERIAL 2	23.00%	Diamond Mat Shingles		4.00%
RECYCLED MATERIAL 3	0.00%			0.00%
COARSE AGGREGATE				0.00%
COARSE AGGREGATE			8	20.00%
COARSE AGGREGATE			Rice	22.00%
FINE AGGREGATE			10	34.00%
FINE AGGREGATE				0.00%
SAND				0.00%
MINERAL FILLER				0.00%
FIBER/TYPE				0.00%
Asphalt Source			1.035	5.40%
ASPHALT TYPE		64-28		0.00%
ASPHALT ADDITIVE				
			Total	100%

AASHTO T-209 SPECIFIC GRAVITY

SPLIT 1	2.614
SPLIT 2	2.614
AVERAGE	2.614
TOTAL GSB	2.818
VOIDLESS WT.	163.1

AGRREGATE SIEVE ANALYSIS, AASHTO T-30

SPL. WT. 1504.70

SIEVE SIZE	JOB MIX	TEST A %PASSING	RAP %PASSING	Control Points, Percent Passing Min	Control Points, Percent Passing Max
37.5		100	100.0		
25.4		100	100.0		
19.0		100	100.0		
12.5	**100**	100	100.0	100	100
9.50	**98**	98	100.0	91	100
4.75	**68**	72	100.0	61	75
2.36	**41**	42	100.0	36	46
1.16	**26**	29	100.0	22	30
0.60	**20**	20	100.0	16	24
0.30	**15**	14	100.0	11	19
0.15	**10**	9	100.0	6	14
0.075	**6.5**	6.2	100.0		

GYRATORY CORE PROPERTIES, AASHTO T-166, AASHTO T-209

	CORE #1	CORE #2	CORE #3	Average
COMP TEMP.	285.0	285.0	285.0	
HT@ND	114.9	115.3	115.5	115.2
HT@NM	114.9	115.3	115.5	115.2
WT. IN AIR	5003.3	5006.3	5005.8	5005.1
WT. SSD	5008.7	5012.5	5012.0	5011.1
WT. IN WATER	3014.0	3012.4	3014.1	3013.5
GMB NDES	2.508	2.503	2.506	2.506
% PA	4.04	4.24	4.14	4.1
% VMA	15.8	15.9	15.9	15.9
% VFA	74.4	73.4	73.9	73.9

REMARKS:
w/ evoflex

AASHTO T-308

AC CONTENT 5.40 **MEASURED AC** 5.36 **EFFECTIVE ASPHALT** 4.84 **MAX DUST** 7.81 RAP AC 0

HALT REF. TANK # 1401 ASPHALT LOT # 13 TIME SAMPLED 12:56 PM LOAD NUMBER 44 MIX TEMP ON TRUCK 285

ONTRACT	FED/ STATE	TONS	TONS AT TEST	# LOADS	TIME 1ST	TIME LAST	DEVELOPMENT	LOCATION #	Substitute TONS	Substitute TONS AT TEST	Item #
	State	1091.22	956.6	47	7:31:00 AM	2:29:00 PM			0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0
		0	0						0	0	0

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Figure E.6: Mixture Design for Test Section 3.

E.2 DESCRIPTION OF ASPHALT PLANT

All three mixtures were produced at an asphalt mix plant located on the Southeast side of Wilmington, Delaware. Figure E.7 shows an overview of the hot mix plant. The average distance between the plant and the test sections was about 25 miles or approximately 35 minutes away by vehicle. The counter flow drum plant had a capacity of 400 tons per hour. In addition, a conventional baghouse emission system where part of the fines was returned to the drum was part of the operation. The plant had five bins for virgin aggregates and three bins for RAP and RAS. The plant had three insulated silos with a capacity of 250 tons each and three others with capacity of 200 tons each. The capacity of the binder storage tank at the asphalt plant was 25,000 gallons.

The RAP and RAS were added with the hot aggregate just outside the drying drum before they entered into the mixing drum. The recycling agent (T2) and the warm mix additive were injected to the asphalt binder line, and blend was directly injected to the mixing drum. Figure E.8 shows the pump and regulator to inject the recycling agent and warm mix into asphalt binder line. Two representatives from the recycling agent and warm mix additive suppliers were on-site during the production of the mixtures.

The temperature of the binder in the storage tanks was maintained at 300°F. Both the warm mix additive and the recycling agent were stored and pumped into the binder line at ambient temperature.

Figure E.7: Overview of the Asphalt Plant at Wilmington, Delaware.

Figure E.8: Injection System of the Warm Mix Additive and Recycling Agent to the Binder Line and Pump to Regulate Rate.

E.3 MIX PRODUCTION AND PAVING

All three mixtures were produced and paved on the same day. All three mixtures were produced at 310°F. Ambient temperature was in the lower 40°F in the early morning and in the lower 50°F in the afternoon. Wind was flowing at 15 to 20 mph. The average duration of the mixture storage in the silo was approximately one hour. Sample collection began after production of 100 tons of mix for each test section.

Production of control began at 7 am local time on December 02, 2016. Approximately 400 tons of control mix was produced at 350 tons/hour capacity. After the control mix, the T2 mix was produced with approximately 400 tons. Finally, the plant produced the T2 plus warm mix additive mix with approximately 700 tons. Table E.2 summarizes the mixture production schedule, placement, and ambient temperatures during laydown for different mixes.

Table E.2: Production, Paving and Ambient Temperatures.

Section	Mixture	Date of Production	Plant Mix Temp, °F	Paving Temp, °F	Ambient Temp, °F
1	Control Mix	12/02/2016	310	270 – 275	41 – 45
2	T2	12/02/2016	310	275 – 280	48 – 50
3	T2 plus warm mix additive	12/02/2016	310	275 – 283	50 – 51

This project was not set up with station number or mile markers. The research team used the mail box and electric pole to identify the limits of each test section. The Control mix (Section 1) was placed on the west bound lane starting just 70 feet west of Electric Pole TP DPRC 113 or 175 feet west of Mailbox 1065 (west end) and extended to 160 feet west of intersection with Liberty Street (east end). The T2 mix (Section 2) was placed on both westbound and eastbound lanes. This mix on westbound lane was only 160 feet long starting at the end of control section and ending at the project limit at east end (Liberty Street). This mix on eastbound lane started from 100 feet west of Mailbox 988 (east end) and ended at 80 feet west of Mail box 892 (or 140 feet east of Mailbox 893). The T2 plus warm mix additive mix (Section 3) was placed on westbound lane starting where the T2 mix (Section 2) ended and extended to some part of Pole Bridge Road. Although this mix was placed on Pole Bridge, only the part on Port Penn Rd. is included in this project.

Before laydown, the contractor applied a CSS1-h tack coat at rate of 0.045 gal/sq yd. Figure E.9 shows the application using a distributor truck. The tack coat application did not appear uniform or sufficient. The tack coat was applied at a temperature of 130°F.

Figure E.9: Application of Tack Coat on Milled Surface.

Figure E.10 through Figure E.12 show the laydown of mixture, compaction of material, and finished surface, respectively.

The mixes were hauled to the job site using end-dump truck. The trucks had tarp to cover the mixes during transit. The trucks dumped the loose mix directly into the paver chute (Figure E.10). A shuttle buggy or other material transfer device was not used this project. The temperature behind the paver was measured using infrared temperature gun.

The steel-wheel vibratory (breakdown) roller closely followed the paver. The compaction was achieved by three passes at vibrating mode by a roller, (Figure E.11 a), followed by three passes at static mode another roller (Figure E.11 b) of same size and weight. All 3 test mixtures were placed and compacted in a similar way.

Figure E.10: Paving of the Surface Layer.

(a) Vibratory Roller

(b) Static Roller

Figure E.11: Rollers Used During Compaction.

Figure E.12: Finished Pavement Surface.

E.4 SAMPLE COLLECTION

Plant mix was collected from the trucks at plants by climbing on scaffolding (Figure E.13). Due to the demand from multiple research projects and universities involved, large amount of plant mix was collected in five-gallon buckets from multiple trucks. The plant mix samples were collected usually after 100 tons of production for any given section. The materials sampling scheme is listed in Table E.3.

With the help of the paving contractor, the research team also collected 24 six-inch diameter road cores from three test sections. Road cores were obtained from the center of the travel lane. Among these 24 cores, three of them (one from each of the test sections) were obtained at full depth asphalt layer to determine the existing pavement structure. All three full-depth cores showed similar pavement structure (Figure E.3). Figure E.14 through Figure E.17 show pictures of the RAP, RAS, and aggregate stockpiles.

Table E.3: Materials Sampling Scheme.

Sample Type	Material	Point of Sampling
Lab-Mixed, Lab-Compacted	Fine Aggregate	Stockpile
	Coarse Aggregate	Stockpile
	RAP	Stockpile
	RAS	Stockpile
	Rejuvenator	Storage tank (plastic tote in metal cage) at plant
	PG 64-28 Asphalt	Storage Tank
Plant-Mixed, Lab-Compacted	Loose Mix	Truck at Plant
	Compacted Specimens	Onsite Lab and DelDOT lab at Dover, DE.
Plant-Mixed, Field-Compacted	Road Cores	Travel Lane (Center)

Figure E.13: Collection of Loose Plant Mix.

Figure E.14: Primary RAP Stockpile.

Figure E.15: RAS Stockpile.

Figure E.16: Aggregate (one of several) Stockpile.

Figure E.17: Aggregate (one of several) Stockpile.

APPENDIX F

Binder Blend Aging Prediction Data

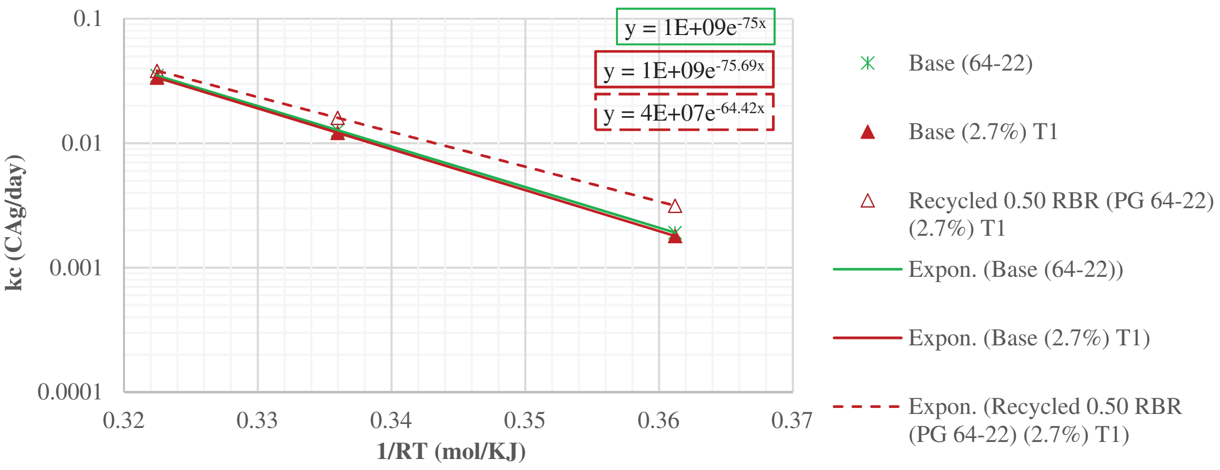

Figure F.1. Constant Rate Oxidation Kinetics for PG 64-22 Base Binder Blends

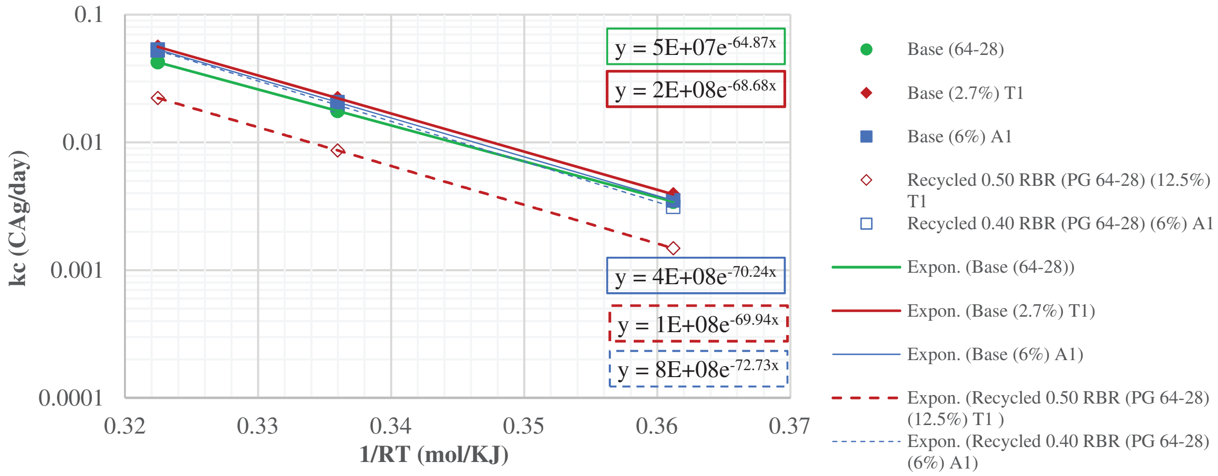

Figure F.2. Constant Rate Oxidation Kinetics for PG 64-28 Base Binder Blends

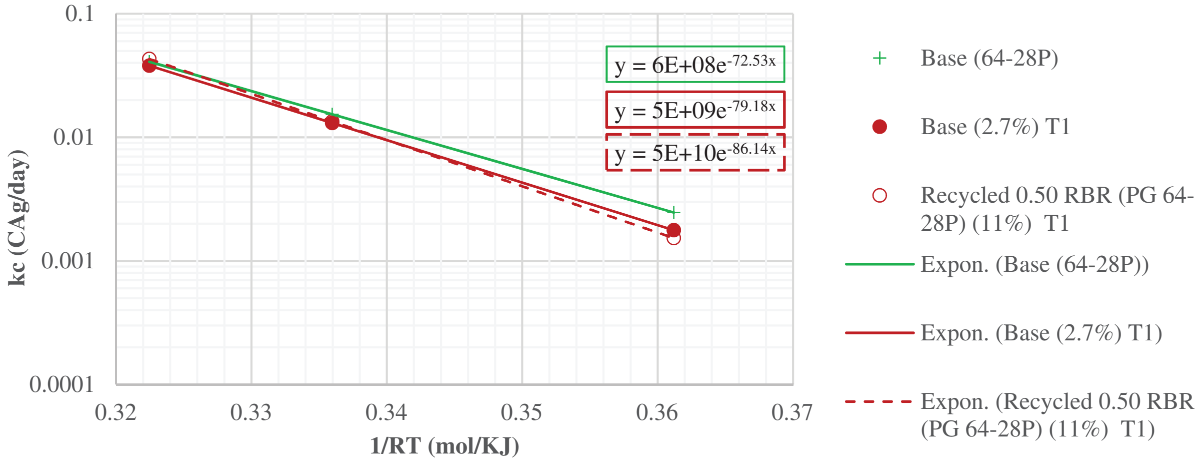

Figure F.3. Constant Rate Oxidation Kinetics for PG 64-28P Base Binder Blends

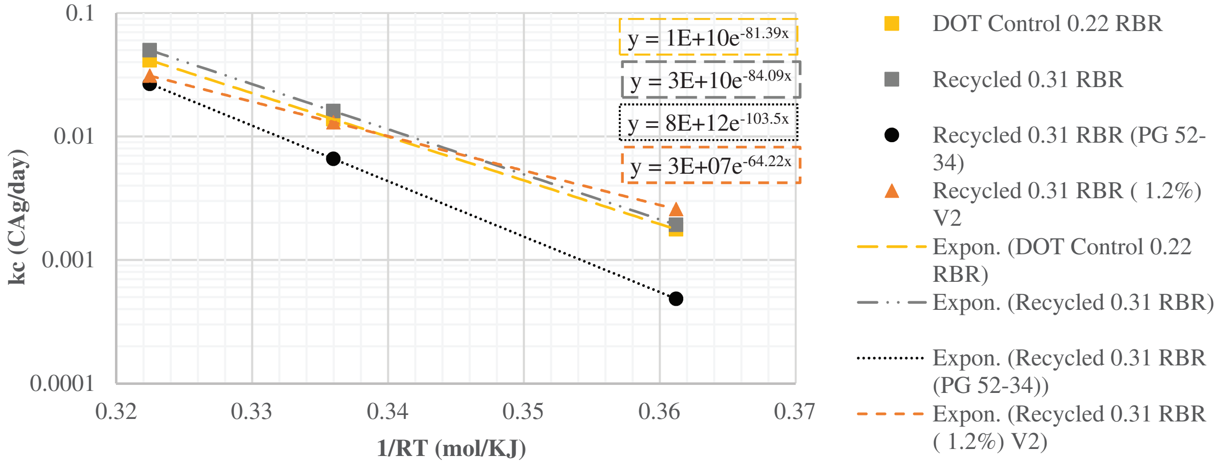

Figure F.4. Constant Rate Oxidation Kinetics for PG 58-28 Base Binder Blends

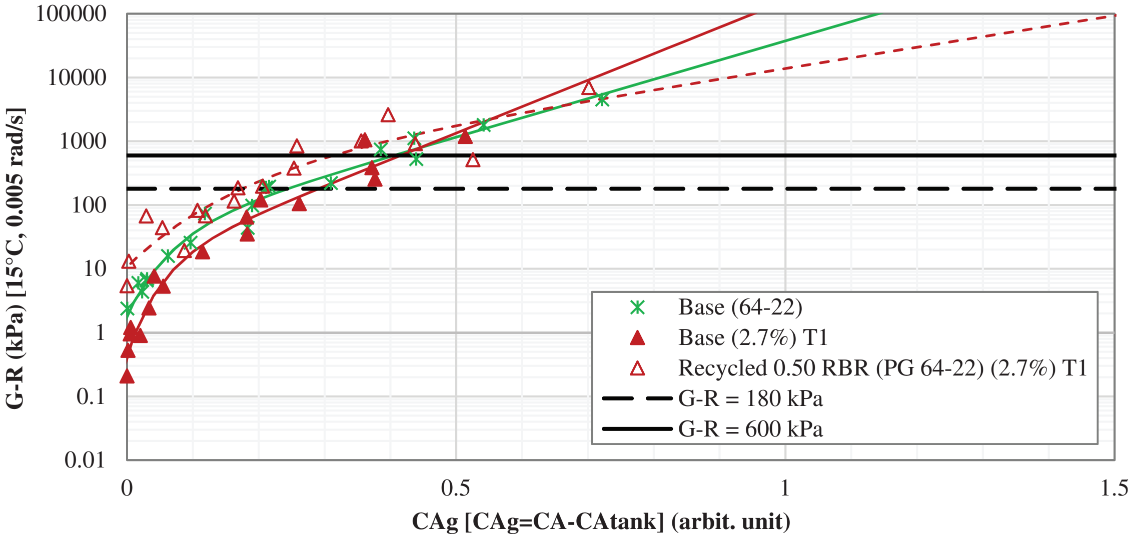

Figure F.5. Glover-Rowe Parameter at 15°C for PG 64-22 Base Binder (TX (Expanded) Material Cluster).

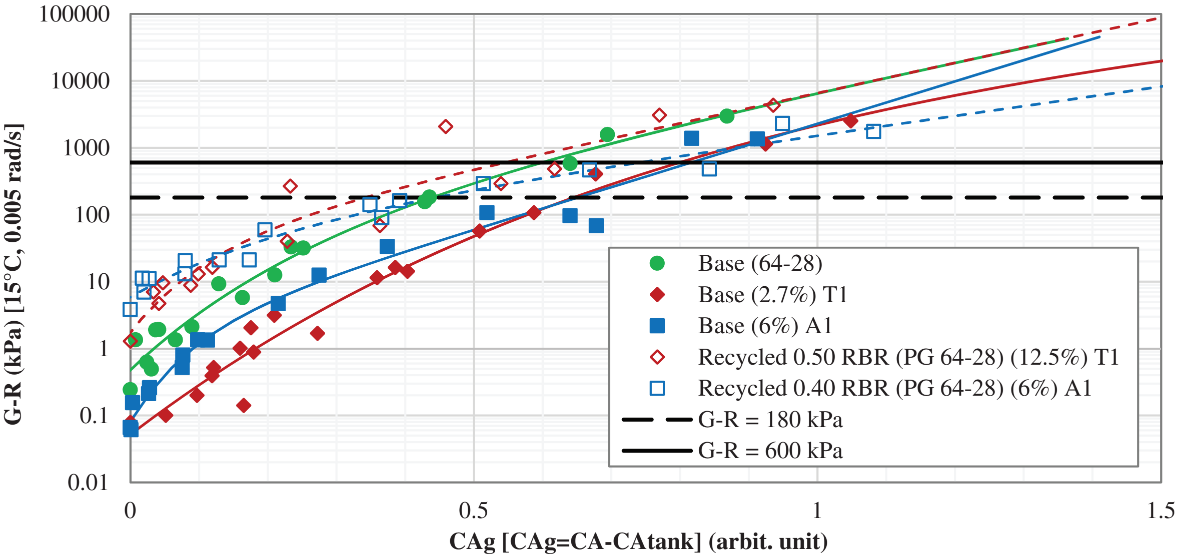

Figure F.6. Glover-Rowe Parameter at 15°C for PG 64-28 Base Binder (NH (Expanded) Material Cluster).

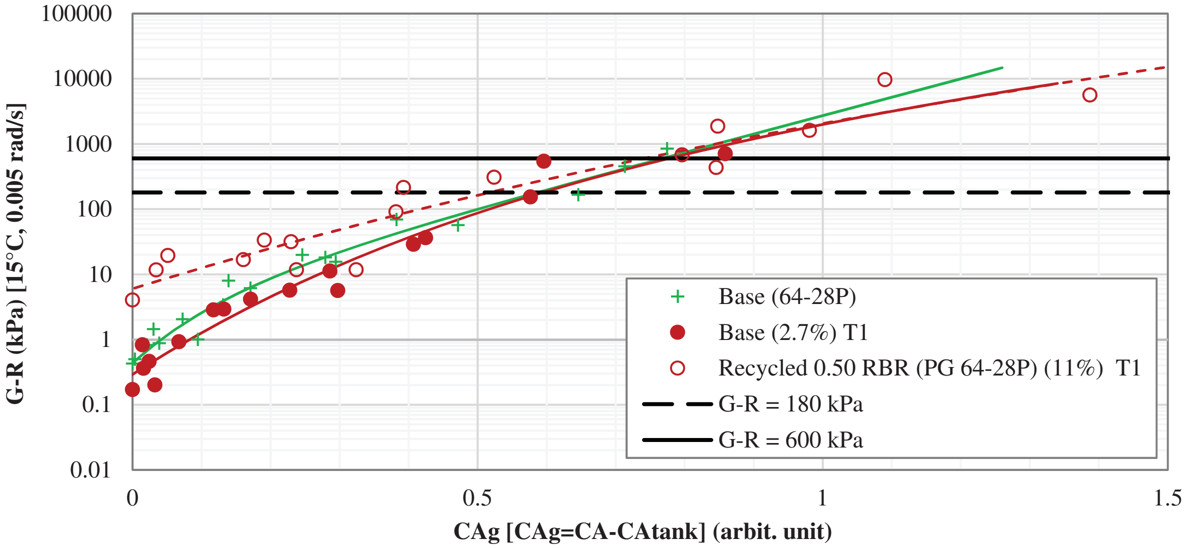

Figure F.7. Glover-Rowe Parameter at 15°C for PG 64-28P Base Binder (NV (Expanded) Material Cluster).

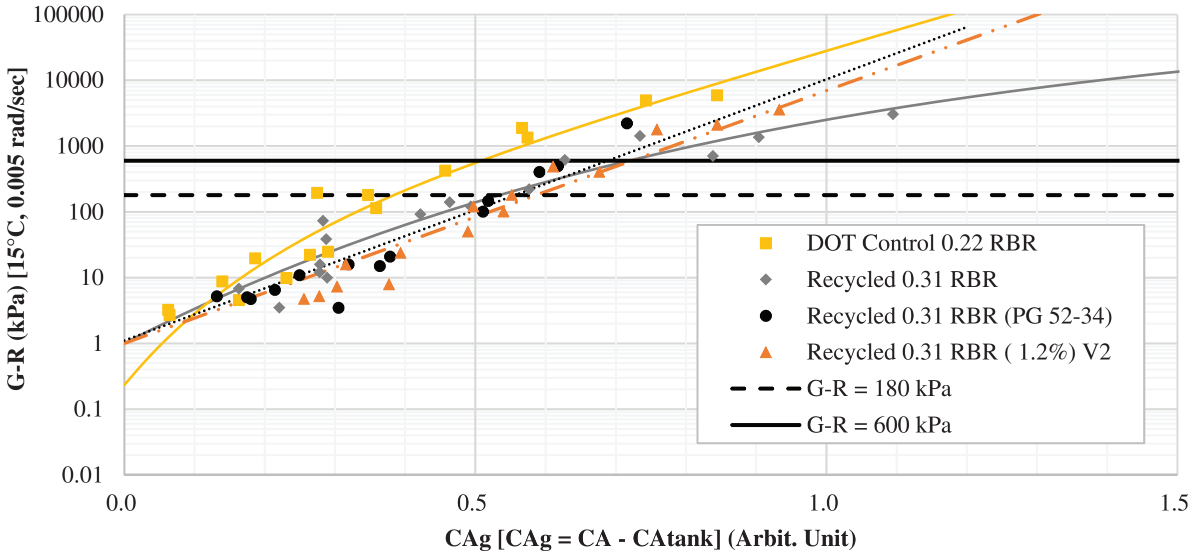

Figure F.8. Glover-Rowe Parameter at 15°C for WI Material Cluster.

APPENDIX G

Recycling Agent Characterization Data

Table G.1. G-R Data for Different Blends.

Blends	Aging	G* (kPa)	δ (°)	G-R (kPa)
Base Binder (PG 64-28)	RTFOT	96.351	68	15
	PAV 20	268.931	60	78
	PAV 40	580.183	56	225
Recycled 0.5 RBR	RTFOT	740.232	57	265
	PAV 20	1891.077	49	1053
	PAV 40	2506.389	45	1741
Rejuvenated 0.5 RBR (13.5%) A1	RTFOT	21.313	70	3
	PAV 20	92.319	62	22
	PAV 40	162.432	58	54
Rejuvenated 0.5 RBR (8%) B1	RTFOT	14.807	72	1
	PAV 20	65.647	65	13
	PAV 40	147.702	60	43
Rejuvenated 0.5 RBR (10.5%) B2	RTFOT	14.211	70	2
	PAV 20	60.880	64	14
	PAV 40	131.380	58	42
Rejuvenated 0.5 RBR (11%) P	RTFOT	21.972	63	5
	PAV 20	119.892	53	53
	PAV 40	308.093	47	197
Rejuvenated 0.5 RBR (8.5%) T1	RTFOT	12.298	72	1
	PAV 20	77.302	64	16
	PAV 40	262.047	58	84
Rejuvenated 0.5 RBR (9%) V2	RTFOT	12.525	69	2
	PAV 20	46.241	62	11
	PAV 40	124.445	57	43
Rejuvenated 0.5 RBR (8%) V3	RTFOT	13.131	68	2
	PAV 20	64.689	62	16
	PAV 40	132.498	58	45

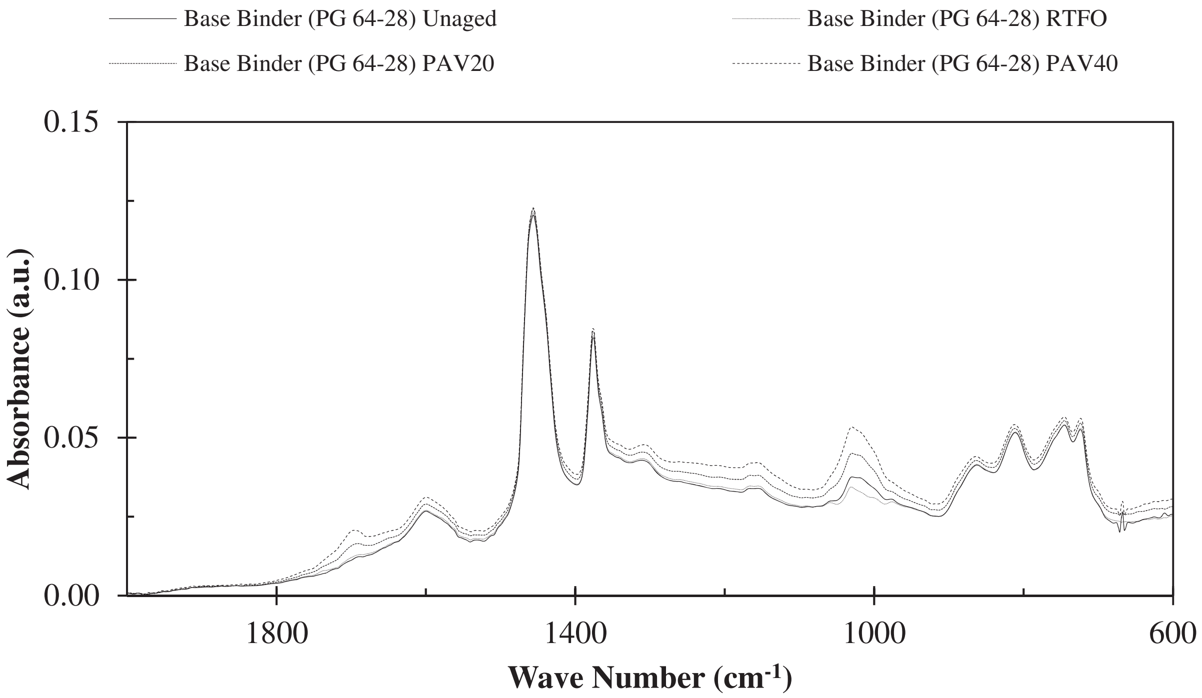

Figure G.1. FTIR Spectra for Base Binder at Different Aging Levels.

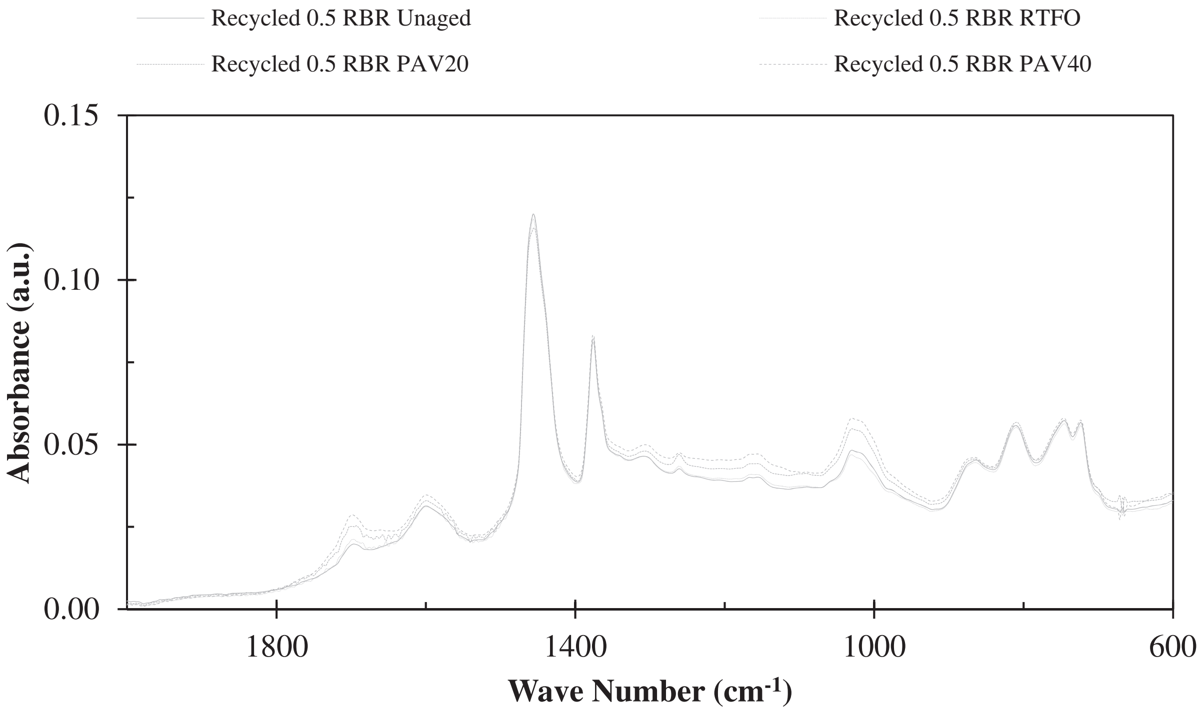

Figure G.2. FTIR Spectra for Recycled 0.5 RBR at Different Aging Levels.

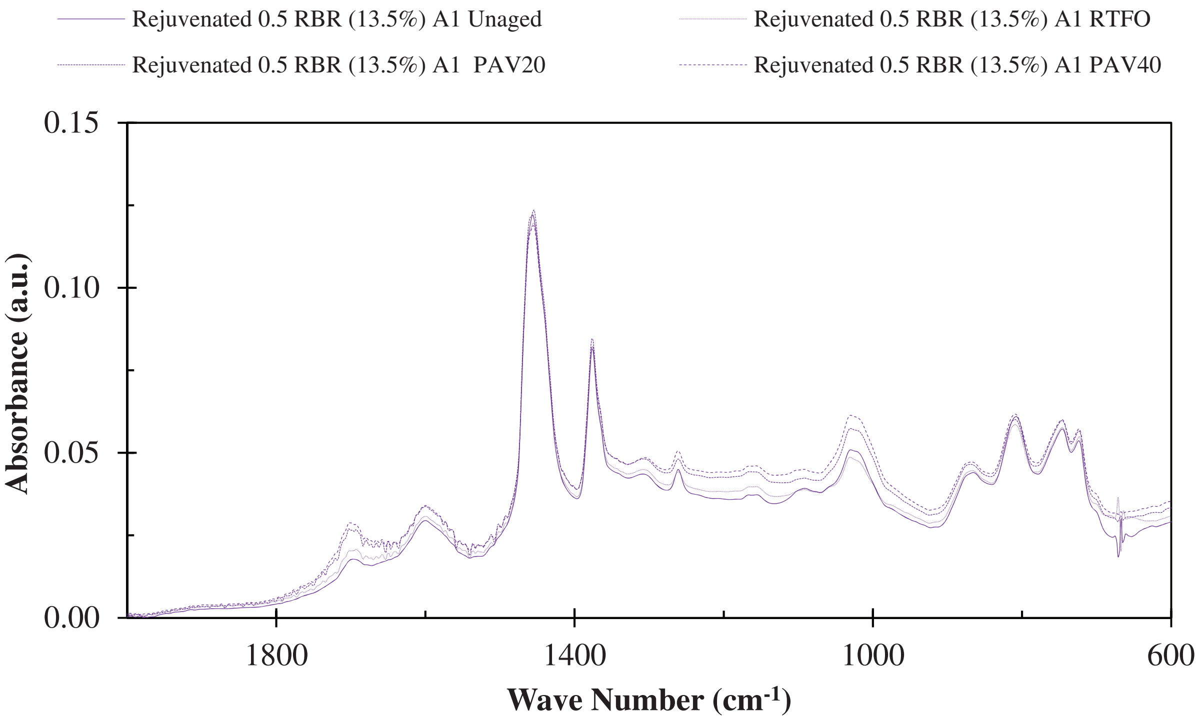

Figure G.3. FTIR Spectra for Recycled 0.5 RBR (13.5%) A1 at Different Aging Levels.

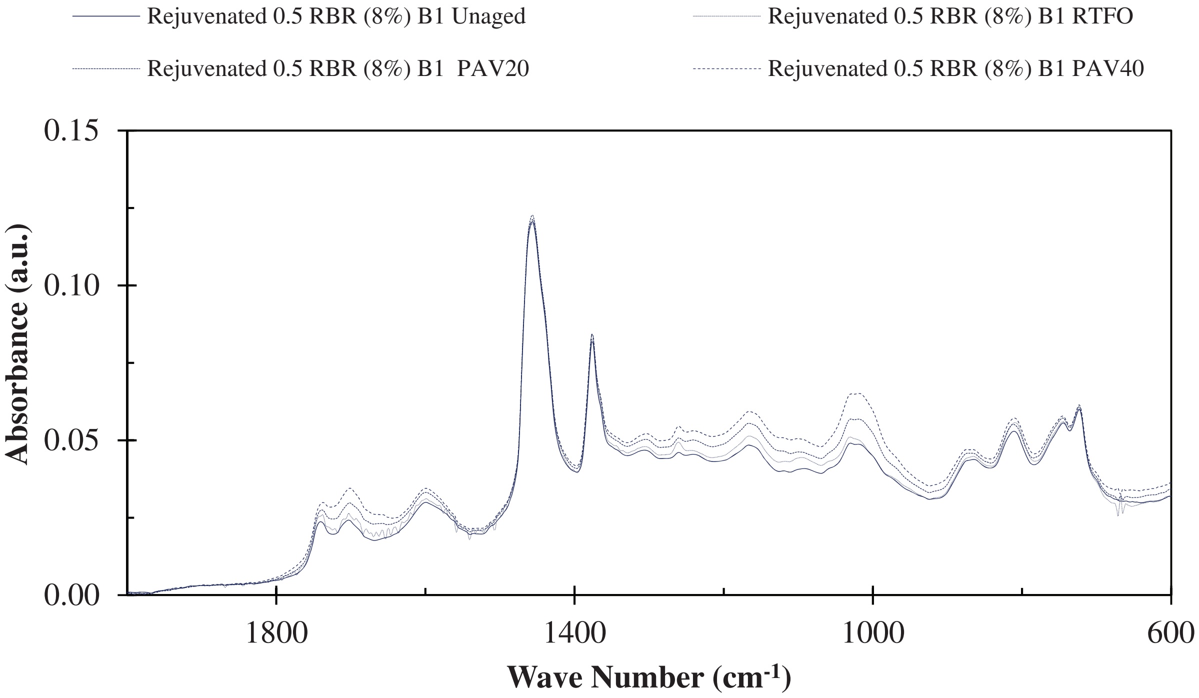

Figure G.4. FTIR Spectra for Recycled 0.5 RBR (8%) B1 at Different Aging Levels.

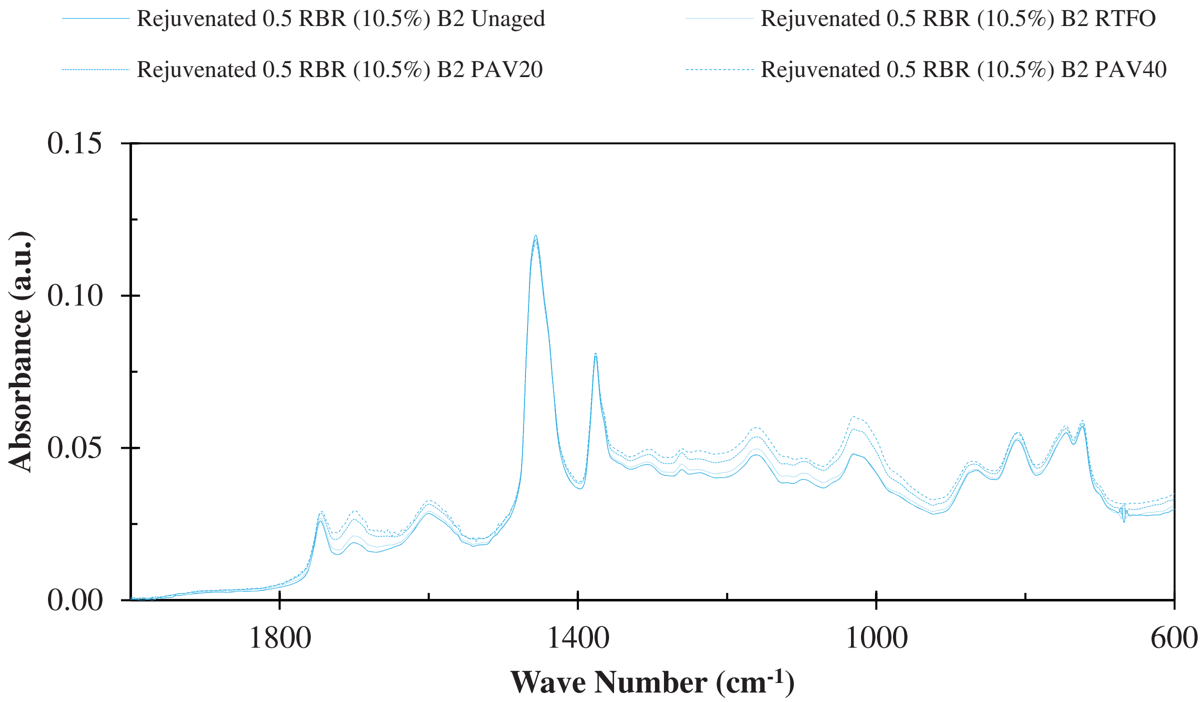

Figure G.5. FTIR Spectra for Recycled 0.5 RBR (10.5%) B2 at Different Aging Levels.

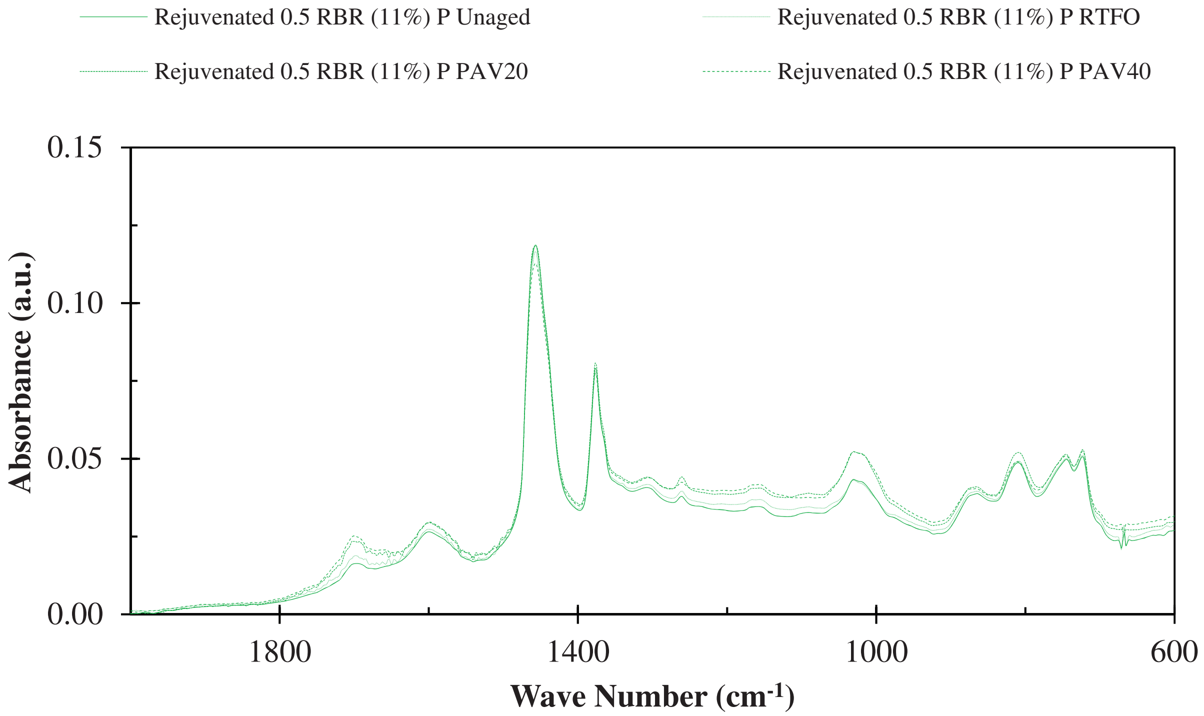

Figure G.6. FTIR Spectra for Recycled 0.5 RBR (11%) P at Different Aging Levels.

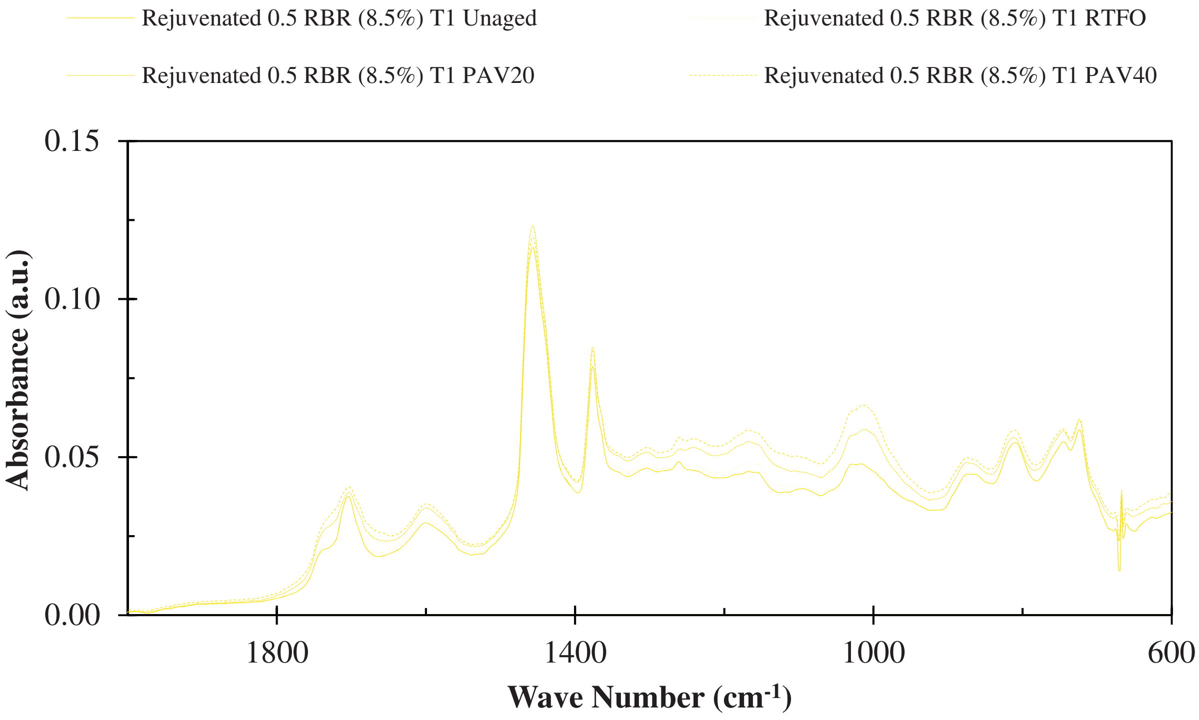

Figure G.7. FTIR Spectra for Recycled 0.5 RBR (8.5%) T1 at Different Aging Levels.

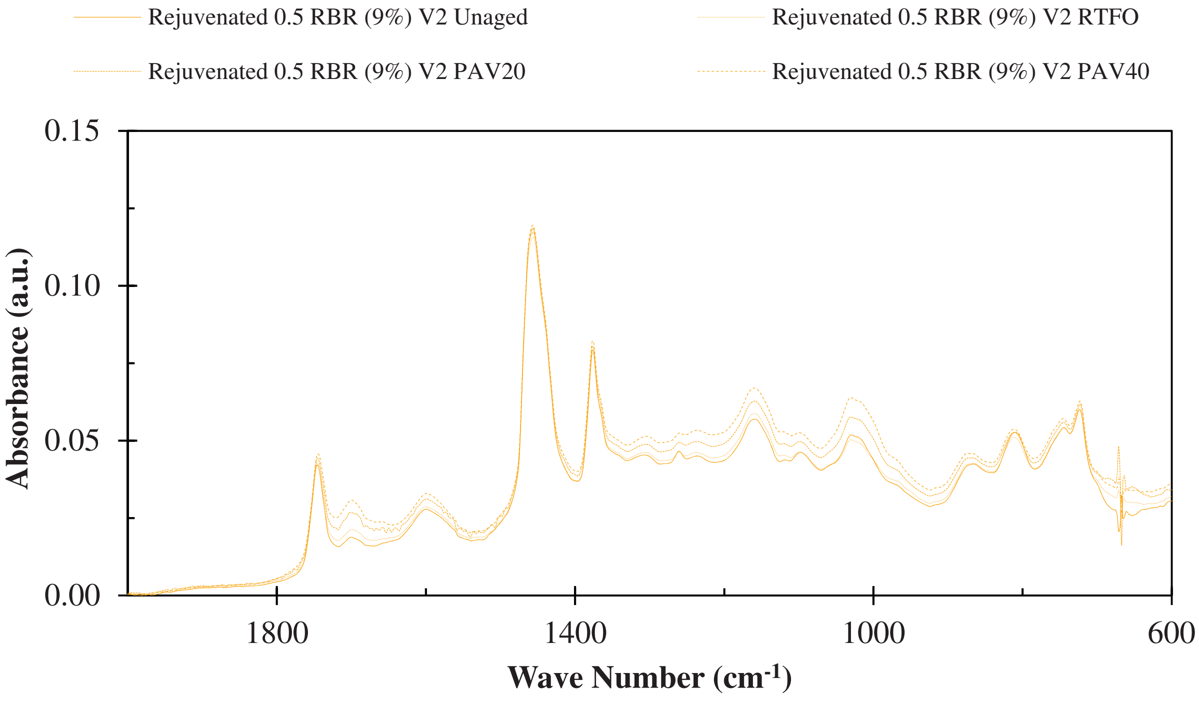

Figure G.8. FTIR Spectra for Recycled 0.5 RBR (9%) V2 at Different Aging Levels.

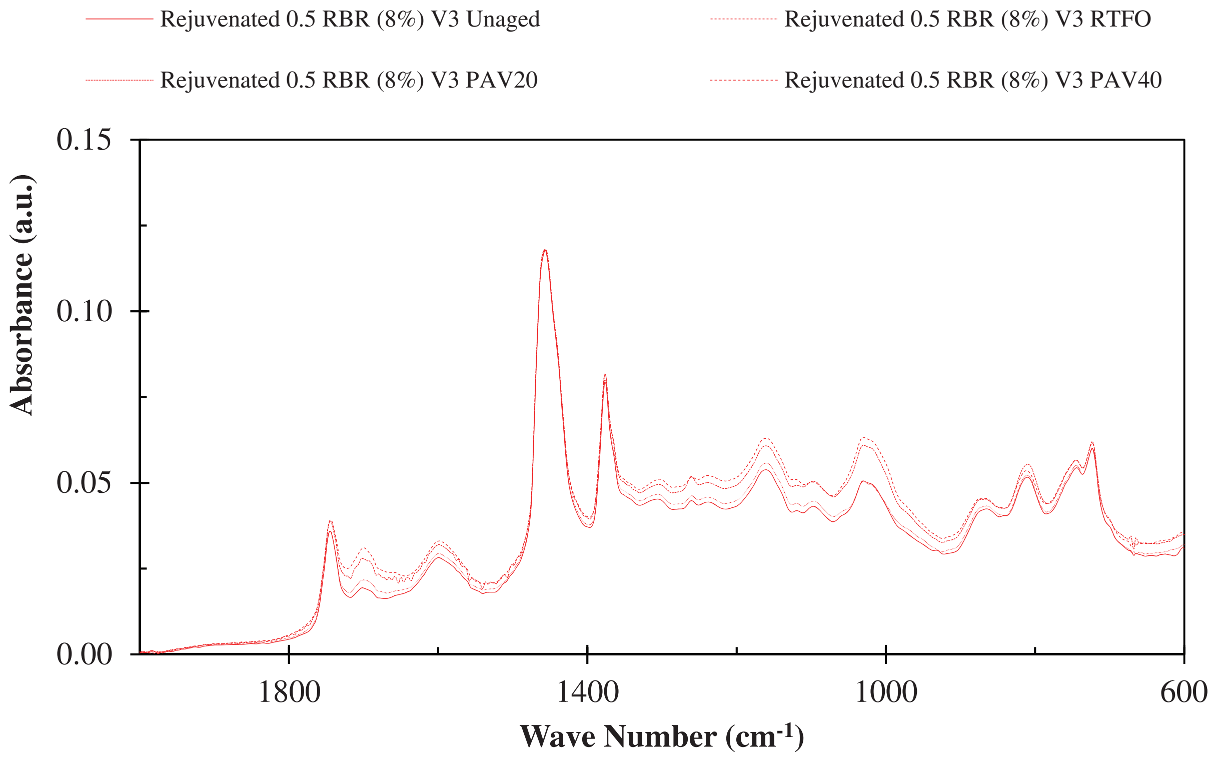

Figure G.9. FTIR Spectra for Recycled 0.5 RBR (8%) V3 at Different Aging Levels.

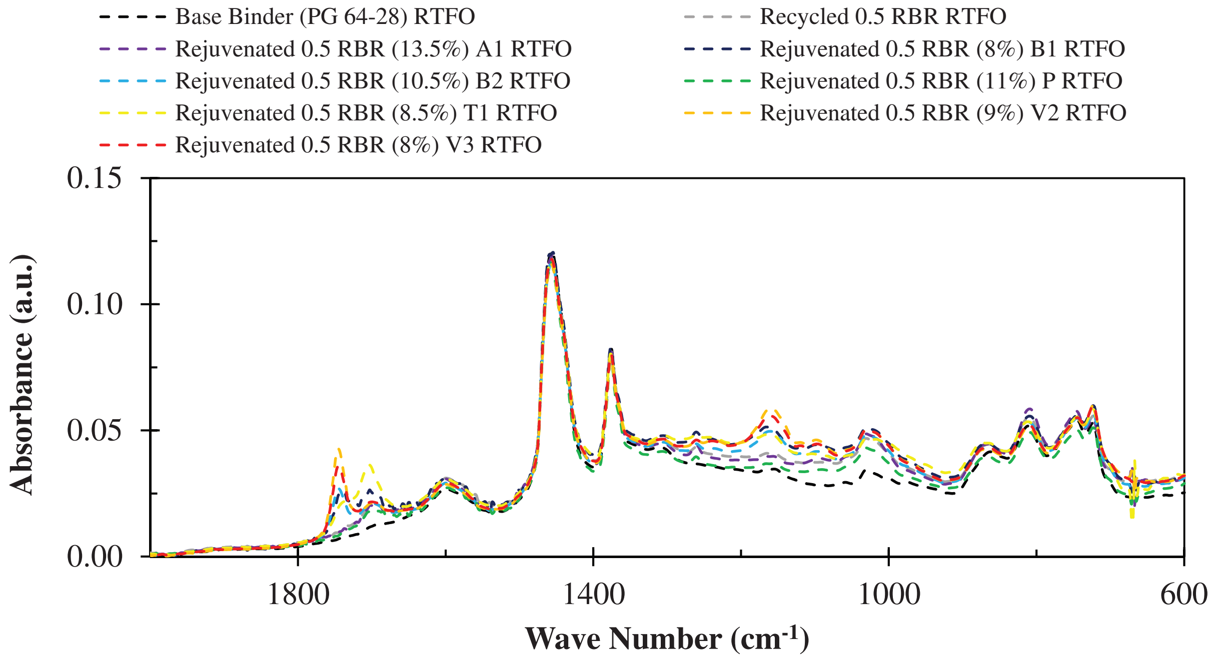

Figure G.10. FTIR Spectra for Different Blends at RTFO Aging.

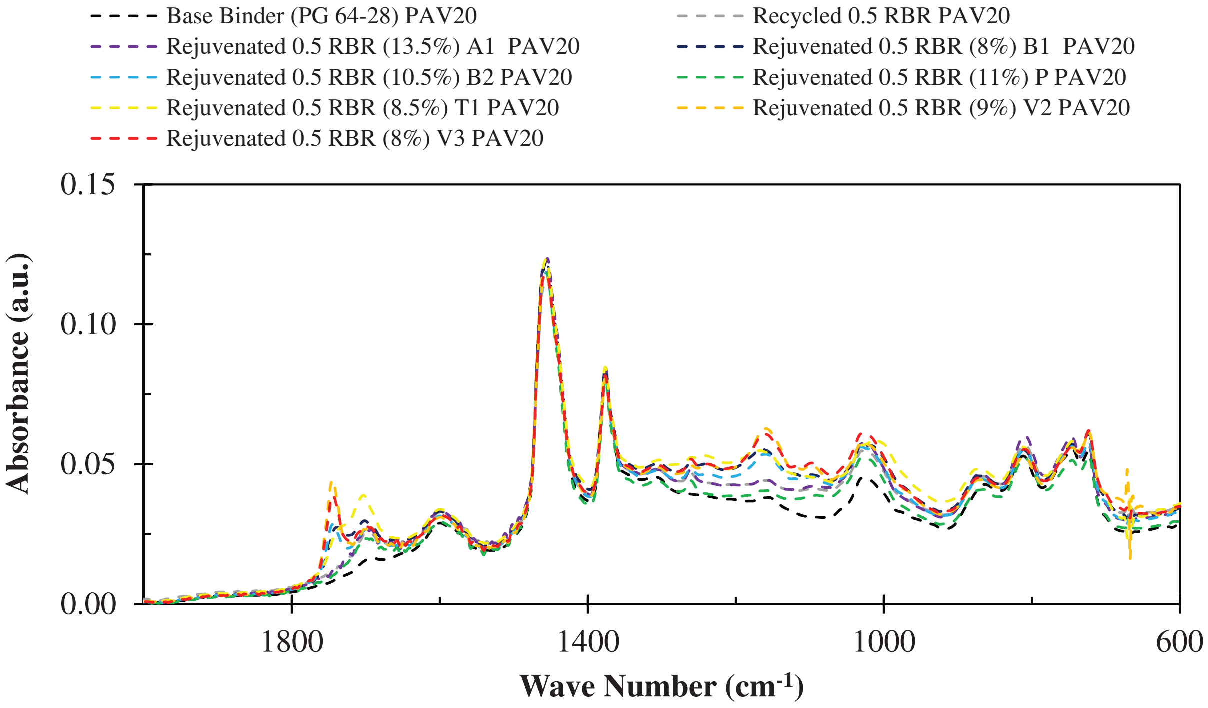

Figure G.11. FTIR Spectra Different Blends at PAV20 Aging.

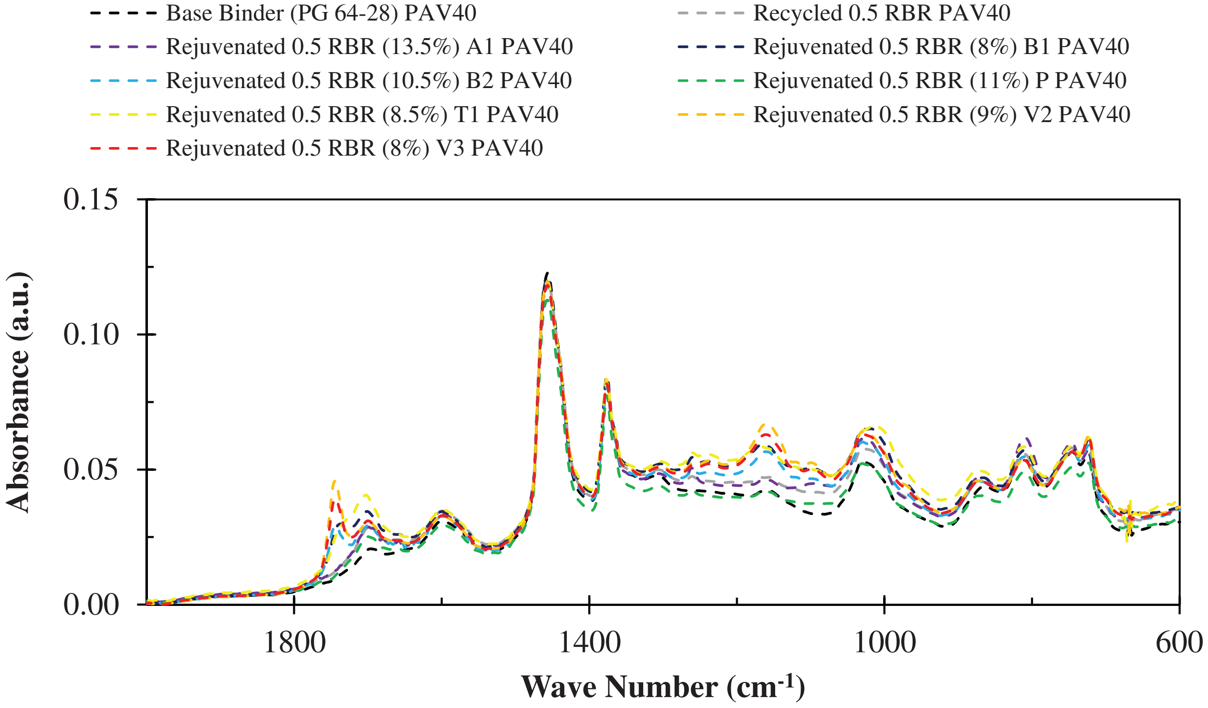

Figure G.12. FTIR Spectra Different Blends at PAV40 Aging.

Table G.2. Carbonyl Area Value and Growth with Aging for Blends.

(CA According to UNR Modified Method)	CA Value (a.u.)				CA Growth (a.u.)		
	OB	RTFO	PAV 20	PAV 40	RTFO	PAV 20	PAV40
Base Binder (PG 64-28)	0.17	0.20	0.41	0.64	0.03	0.24	0.47
Recycled 0.5 RBR	0.46	0.60	0.83	1.05	0.14	0.36	0.59
Rejuvenated 0.5 RBR (13.5%) A1	0.47	0.58	0.92	1.07	0.11	0.45	0.60
Rejuvenated 0.5 RBR (8%) B1	1.11	1.23	1.60	1.94	0.12	0.49	0.83
Rejuvenated 0.5 RBR (10.5%) B2	0.97	1.10	1.40	1.63	0.12	0.43	0.65
Rejuvenated 0.5 RBR (11%) P	0.42	0.55	0.84	0.96	0.13	0.42	0.55
Rejuvenated 0.5 RBR (8.5%) T1	1.44	1.47	1.84	2.05	0.02	0.40	0.61
Rejuvenated 0.5 RBR (9%) V2	1.35	1.47	1.77	2.08	0.13	0.42	0.73
Rejuvenated 0.5 RBR (8%) V3	1.25	1.35	1.73	1.96	0.09	0.48	0.70

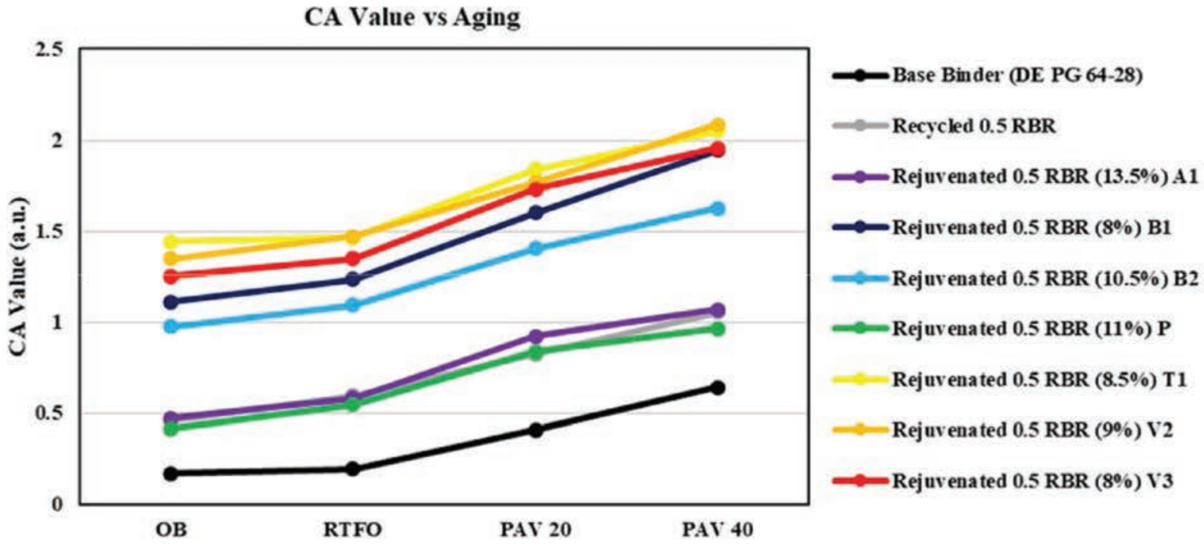

Figure G.13. Carbonyl Area Absorbance with Aging for Blends.

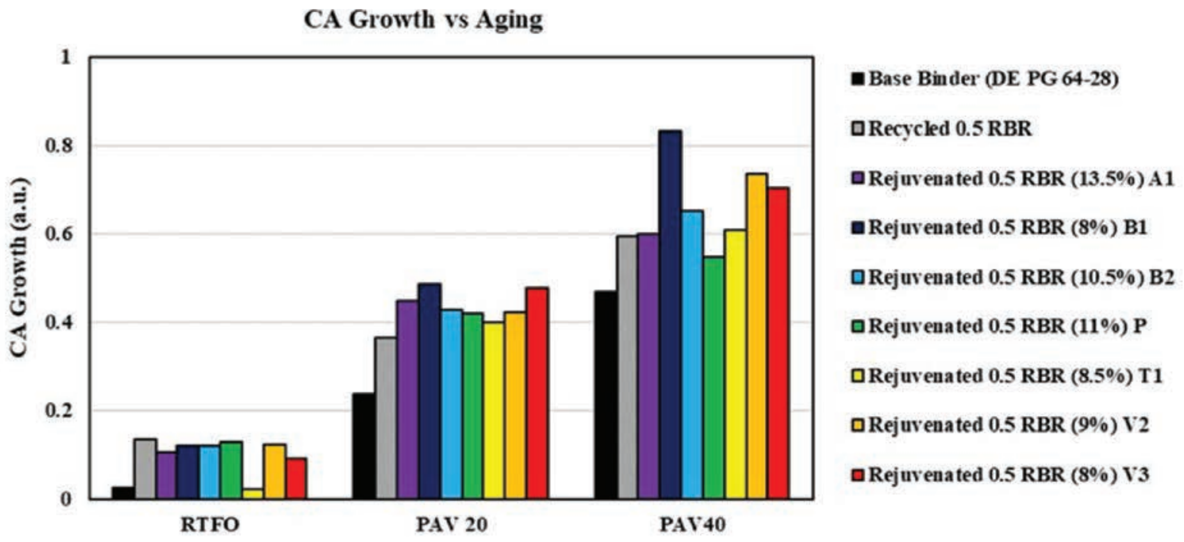

Figure G.14. Carbonyl Area Growth with Aging for Blends.

Table G.3. Complex Viscosity for Different Recycling Agents.

Recycling Agent	Complex Viscosity (η*) at 15°C & 10 rad/s (mPa.s)				Aging Index
	Unaged	RTFO	PAV20	PAV40	
A1	16440.00	20315.00	18945.00	18965.00	1.15
B1	732.85	840.35	2034.00	2110.00	2.88
B2	608.40	731.90	1408.00	1583.00	2.60
P	161.50	170.30	175.30	176.75	1.09
T1	341.25	967.80	332850.00	5557000.00	16284.25
V2	138.00	149.65	163.35	255.40	1.85
V3	55.92	99.24	16290.00	60110.00	1074.93

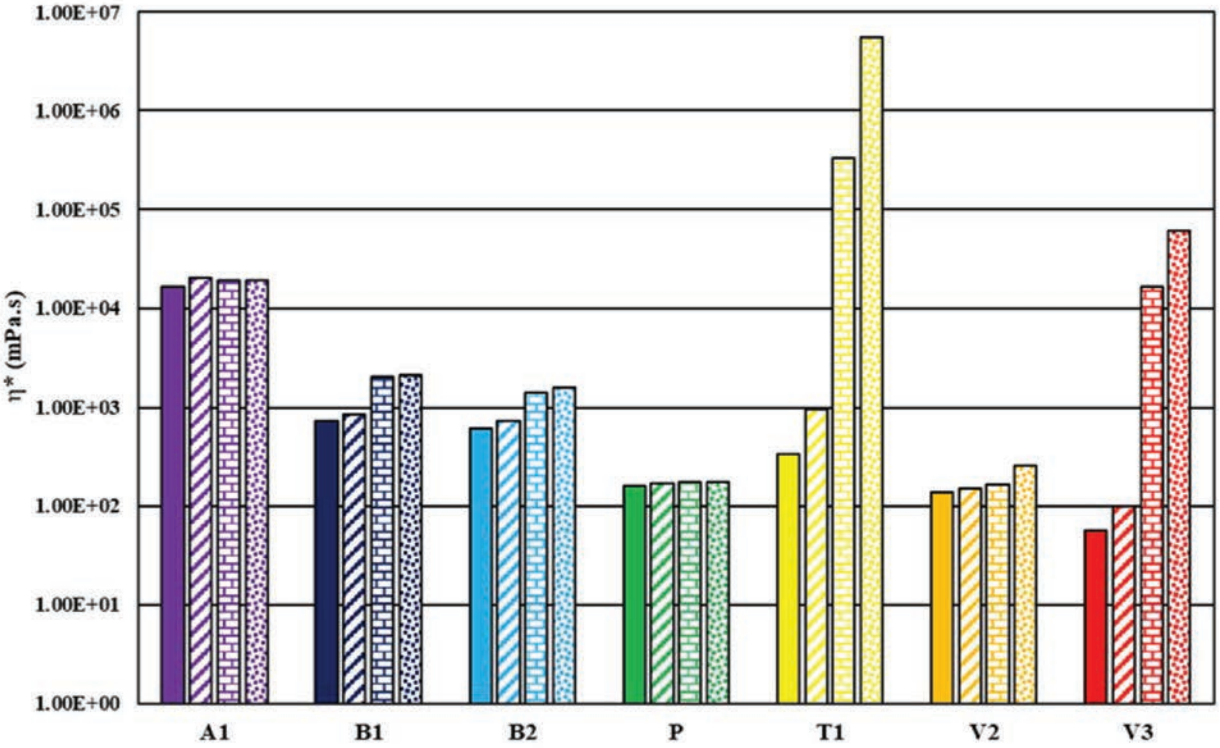

Figure G.15. Complex Viscosity for Different Recycling Agents.

Table G.4. G-R/CA_g Hardening Susceptibility for Different Blends

Blend	Aging	Log G-R (kPa)	CA_g (a.u.)	G-R/CA_g HS
Base Binder (PG 64-28)	RTFO	1.18	0.03	2.63
	PAV20	1.89	0.24	
	PAV40	2.35	0.47	
Recycled 0.5 RBR	RTFO	2.42	0.14	1.79
	PAV20	3.02	0.37	
	PAV40	3.24	0.59	
Rejuvenated 0.5 RBR (13.5%) A1	RTFO	0.43	0.11	2.67
	PAV20	1.35	0.45	
	PAV40	1.74	0.60	
Rejuvenated 0.5 RBR (8%) B1	RTFO	0.17	0.12	2.06
	PAV20	1.10	0.49	
	PAV40	1.63	0.83	
Rejuvenated 0.5 RBR (10.5%) B2	RTFO	0.25	0.12	2.62
	PAV20	1.13	0.43	
	PAV40	1.63	0.65	
Rejuvenated 0.5 RBR (11%) P	RTFO	0.71	0.13	3.73
	PAV20	1.73	0.42	
	PAV40	2.30	0.55	
Rejuvenated 0.5 RBR (8.5%) T1	RTFO	0.09	0.02	3.12
	PAV20	1.21	0.40	
	PAV40	1.93	0.61	
Rejuvenated 0.5 RBR (9%) V2	RTFO	0.25	0.13	2.26
	PAV20	1.047	0.42	
	PAV40	1.63	0.73	
Rejuvenated 0.5 RBR (8%) V3	RTFO	0.28	0.09	2.27
	PAV20	1.20	0.48	
	PAV40	1.65	0.70	

APPENDIX H

Economics Associated with the Use of Recycling Agents

H.1 INTRODUCTION

The amount of reclaimed asphalt pavement (RAP) annually available in the United States is of the order of 80 million tons. Hot mix asphalt (HMA) production on an annual basis (including warm mix asphalt (WMA) is typically in the range of 400 to 500 million tons per year. Thus, if every ton of HMA produced contained 15 to 20% RAP, all of the produced RAP would be utilized.

From a practical standpoint, the RAP is not located near the HMA production in the percentages identified above. For example, most metropolitan areas have an excess of RAP relative to the amount of HMA produced. Some rural projects also generate large quantities of RAP that can be economically transported to HMA production plants. These excess materials have been used as shoulder backing and base course materials.

From a practical and economic point of view, it is desirable to use higher percentages or RAP to produce HMA in some locations. As the percentage of RAP use increases in HMA from about 15% to higher values, HMA performance problems can occur if mixes are not properly designed and constructed and pavement thicknesses are not properly designed. Higher RAP percentages require softer binders and/or recycling agents for mix design to avoid field performance problems including raveling and cracking. Sufficient RAP quantities exist at enough locations for technology to be developed to allow for the use of RAP contents higher than 15 to 20%.

The economics of increasing RAP contents from about 20 to 40% is therefore of interest. The information contained below identifies likely cost savings associated with increasing RAP contents in HMA. The information provided defines first costs. It has been assumed that the high RAP, HMA materials will produce the same pavement life as non-RAP mixes and thus the life cycle cost savings will be reflected in the first costs savings.

Determination of the economic advantages requires price/cost information for transportation of materials, virgin binders, recycling agents, virgin aggregates and reclaimed asphalt pavement (RAP). An appreciation of HMA price/cost components is also needed. Assumptions associated with prices/costs for transportation, materials, HMA production and laydown as well as mix design are provided below. Economic comparisons are provided based on these assumptions.

H.2 TRANSPORTATION PRICES

Transportation prices for binders and aggregates are typically $0.15/ton per mile of haul. These prices usually range from about $0.12 to $0.18/ton per mile. The price of moving a ton of binder or aggregates 100 miles is about $15/ton of material. Local market conditions can be lower or higher than the prices indicated above.

H.3 ASPHALT MATERIAL PRICES

Virgin Binder

The typical price of virgin binder without polymer modification is about $350/ton at the refinery as of September 2016. Over the last decade, these prices have ranged from about $300 to $1200/ton. The prices are for typical binders graded by the PG binder system and commonly available from several refineries.

In some areas of the United States, premiums are paid for binders that are softer than conventional grades. For example, a PG 58-28 binder may be priced at $450/ton while at PG 64-22 may be priced at $350/ton.

PG binder grades containing conventional loadings of polymers typically price between $90 and $120/ton more than neat binders (binders without polymers).

Transportation prices for binders are typically $0.15/ton per mile of haul as indicated above. For a typical haul distance of from 250 to 350 miles, the price of a ton of binder at the contractors HMA plant is about $400/ton ($40 to $50/ton of haul costs plus the refinery costs of about $350/ton).

Recycling Agents

Prices for recycling agents vary widely. New products are constantly being developed and are entering the market. Prices for these new prices are in general not available at this time, as they have not been used in large quantities.

Aromatic recycling agents as defined by ASTM have been on the market since the 1950's and some price information is available for these materials. Typical prices per gallon of aromatic type recycling agents are of the order of $1.25 to $1.75 per gallon. A gallon of this type of recycling agent is about 8.07 lbs.

Since these products are manufactured at only a few locations in the United States, the transportation prices can add from $0.10 to 0.30 per lb. of material. Typical ranges in prices for aromatic type recycling agents at the contractor's plant will be in the range of from $500 to $700/ton. Typically, the prices of these recycling agents will be from $50 to $150/ton above the price of a neat binder.

H.4 AGGREGATE COSTS

Aggregate prices vary widely depending on local geology, quarry/pit locations and haul prices. Aggregates on the Gulf of Mexico shores are typically shipped by water several hundreds if not thousands of miles or by rail several hundreds of miles. Truck transportation from the quarry/pit to the contractor HMA plant is the most common form of transportation.

The price for aggregate in many areas of the country at the contractor HMA plant is within the range of $12 to $15/ton. As stated above a significant part of the price of aggregate is transportation with aggregate prices at the quarry/pit source of the order of $5 to $10/ton.

H.5 RECLAIMED ASPHALT PAVEMENT (RAP)

The cost of RAP in a processed stockpile at the contractor HMA plant also varies significantly. Contractors obtain RAP from their own construction projects while others obtain RAP from other contractors or public agencies.

When RAP is obtained from a contractor own construction project, the milling costs may be assigned to the project under construction while the haul costs of the milling assigned to the RAP at their HMA plant. Other contractors will assign the cost of milling or removal of RAP and the haul costs for the RAP to the project under construction.

Some contractors are able to receive RAP at no or very low costs from local government agencies or other non-HMA producing contractors. Thus, the contractor has very low RAP cost at the HMA plant.

The cost of processing RAP, which includes loading, crushing, sizing and stockpiling, is in the range of $2.50 per ton. When haul costs and processing costs are summed, RAP costs to the contractor can be in the range of $5 to $8/ton.

Representative price/cost for the various materials are shown on Table H.1.

Table H.1: Representative Prices/Costs.

Item	Unit	Price/Cost, dollars	
		Representative Range	Representative Value
Transportation	Per ton-mile	0.12 to 0.18	0.15
Virgin Binder	Per ton	400 to 800	450
Recycling Agent	Per ton	500 to 700	550
Virgin Aggregate	Per ton	12.00 to 15.00	13.00
RAP	Per ton	5.00 to 8.00	6.00

H.6 MIX DESIGN CONSIDERATIONS

Several mix design considerations are important when determining the value of RAP use in HMA. The amount of RAP utilized, the available binder in the RAP, the amount of virgin binder used and the amount of recycling agent used are among the more important variables that contribute to the cost of recycled HMA.

Amount of RAP in Mix

The amount of RAP in a HMA mix is typically 15 to 20% by weight of total mix. There is an economical incentive to increase the RAP content. Presently available HMA construction equipment limits the high RAP contents to about 40 to 50%.

Available Binder in RAP

The amount of binder available in the RAP is dependent on a number of factors. Typical ranges for available binder in RAP used by industry are between 4.0 and 4.75% by weight of RAP.

Amount of Virgin Binder in Mix

The amount of virgin binder used in an HMA mix will depend on the asphalt demand for a mix without RAP, the amount of available binder in the RAP and the amount of recycling agent. For the purposes of this economic analysis, it has been assumed that the total binder content (virgin binder plus binder available from the RAP plus the recycling agent) is of the order of 5.5% by total weight of mix.

Amount of Recycling Agent

Recycling agent contents vary considerable depending on the agent. If soft asphalt cement is used as a recycling agent and the price is the same as a conventional binder, the virgin binder and the recycling agent (soft binder) are identical. When the aromatic type recycling agents and other specialty materials are utilized the price of the recycling agent may range from $500 to $700/ton or greater. Typical recycling agent contents range from 2 to 10% by weight of total binder. Total binder is the sum of the binder available on the RAP, virgin binder and the recycling agent.

H.7 HOT MIX ASPHALT COST/PRICE

The calculations summarized are for materials costs only in the HMA. Costs for the mixing plant and equipment at the plant location, transportation to the job site, laydown and compaction, quality control/quality assurance, overhead and margins or profits are not included. Cost differences associated with materials cost are summarized. The costs savings for materials are nearly identical to those for the savings in the produced mix. Production plant costs, equipment, transportation, laydown and compaction, quality control/quality assurance, overhead and margins are little affected by the use of RAP. For reference purposes, the price of a ton of HMA materials is typically in the range of $55 to $85/ton with a representative value of approximately $70/ton. Material costs are typically in the range of 45 to 55% of total in-place price of HMA. HMA plant production prices including materials and equipment are of the order of 80 to 85% ($55 to $60 per ton) of the in-place price of HMA. Haul, laydown and compaction of the HMA are typically of the order of 15 to 20% ($10 to $15 per ton) of the in-place price of HMA.

H.8 ECONOMIC CONSIDERATIONS

A calculation spreadsheet for calculating materials costs associated with HMA production is available. This spread sheet used mix design and cost assumptions provided above and summarized in Table H.1. In addition, it has been assumed that no recycling agent has been used for mixes with 0 and 10% RAP additions, 2% recycling agent for mixes with 20% RAP, 5% recycling agent for mixes with 30% RAP and 10% RAP for mixes with 40% RAP.

Low Economic Incentive Scenario

For this scenario, the virgin binder and aggregate prices are relatively low and the recycling agent and RAP costs are relatively high with the amount of binder from the RAP at a relatively low level. The assumptions are provided below:

Virgin Binder	$400/ton
Recycling Agent	$700/ton
Virgin Aggregate	$12/ton
RAP	$8/ton
Binder in RAP	4 %

Table H.2 indicates that cost savings are of the order of $0.16 to $0.20 per percent RAP for the various RAP percentages used in the mix. For 40% RAP mixes the cost savings is approximately 12% of the production costs and 9% of the total in-place costs. The cost saving by increasing the RAP content from 20% to 40% is $2.68 or 4.9% of the production costs and 3.8% of the total in-place cost.

Table H.2: Cost Associated with Low Economic Incentive Scenario.

RAP,%	Recycling Agent,%	Materials Costs, $/ton	Cost Difference	
			$/ton of HMA	$/percent RAP
0	0	33.34	--	--
10	0	31.34	2.00	0.200
20	2	29.67	3.67	0.184
30	5	28.17	5.17	0.172
40	10	26.99	6.35	0.159

High Economic Incentive Scenario

For this scenario, the virgin binder and aggregate prices are relatively high and the recycling agent and RAP costs are relatively low with the amount of binder from the RAP at a relatively high level. The assumptions are provided below:

Virgin Binder	$800/ton
Recycling Agent	$700/ton
Virgin Aggregate	$15/ton
RAP	$5/ton
Binder in RAP	4.75 %

Note the cost of the recycling agent is below that of the virgin binder. This is not the usual case for aromatic recycling agents. This lower cost assumes that a non –petroleum base recycling agent is available at a lower cost.

Table H.3 indicates that cost savings are of the order of $0.49 per percent RAP for the various RAP percentages used in the mix. For 40% RAP mixes the cost savings is approximately 35% of the production costs and 20% of the total in-place costs. The cost saving by increasing the RAP content from 20% to 40% is $10.04 or 17% of the production costs and 11% of the total in-place cost. Considerable costs saving are evident when virgin materials costs are relatively high and recycling agent and RAP costs are relatively low. This supports the observed interest in recycling when virgin materials costs and in particular binder costs are high.

Table H.3: Cost Associated with High Economic Incentive Scenario.

RAP,%	Recycling Agent,%	Materials Costs, $/ton	Cost Difference	
			$/ton of HMA	$/percent RAP
0	0	58.18	--	--
10	0	53.34	4.84	0.484
20	2	48.47	9.71	0.485
30	5	43.50	14.68	0.489
40	10	38.43	19.75	0.494

Impact of Individual Material Costs on Using 40 versus 20% RAP

Common quantities of RAP in HMA are 15 to 20% of the total HMA weight. Typically, these mixes are made with soft, virgin binders and without recycling agent. As stated previously, the cost of the soft, virgin asphalt cements can be the same price as typical paving grade binders or in some areas of the country they are elevated in price from $60 to $120 per ton. The information presented below assumes that the price of the soft, virgin binder is about the same as a typical paving grade binder.

The information presented below (Table H.4) assumes that the total binder content by weight of mix is 5.5% and no recycling agent has been used for mixes with 0 and 10% RAP additions, 2% recycling agent for mixes with 20% RAP, 5% recycling agent for mixes with 30% RAP and 10% RAP for mixes with 40% RAP. Other assumptions for the comparisons presented were based on cost assumptions for materials that provided the lowest economic incentive. Selection of different costs for other materials would provide a higher economic benefit or difference.

The greatest cost savings associated with the increasing the RAP content from 20% to 40% is associated with changes in the virgin binder price (Table H.4). During periods when virgin binder cost saving are high, costs savings of the order of $7.50 per ton ($0.35 per percent RAP) can be appreciated. Changes in costs associated with recycling agents, virgin aggregate, RAP and the percent binder available in the RAP will also impact the costs savings when mixes are produced at 20% versus 40% RAP. These cost savings are typically of the order of $2.50 to $3.50% per ton of hot mix produced or about $0.15 per percent RAP utilized.

Tables H.2 and H.3 can also be used to illustrate potential cost saving when utilizing 40% RAP as compared to 20% RAP. The low economic incentive scenario indicates a cost saving of the order of $3.00 per ton of mix produced ($0.15 per percent RAP). The high economic incentive scenario indicates a much larger cost savings of the order of $10.00 per ton or about $0.50 per percent RAP. During periods of high material costs (virgin binder and aggregates), saving associated with the use of higher RAP contents and recycling agent (20% to 40% RAP) will be of the order of $6.00 to $8.00 per ton or from $0.30 to $0.40 per percent RAP.

Table H.4: Sensitivity Associated with Costs for Individual Mix Materials.

Variable	Cost Range, $/ton	Cost of Materials, $/ton		Cost Difference	
		20 % RAP	40 % RAP	$/ton of HMA	$/percent RAP
Virgin Binder	400	29.67	26.99	2.68	0.134
	800	48.03	40.39	7.64	0.382
Recycling Agent	500	29.45	25.89	3.56	0.178
	700	29.67	26.99	2.68	0.134
Virgin Aggregate	12	29.67	26.99	2.68	0.134
	15	31.91	28.63	3.28	0.164
RAP	5	29.07	25.79	3.28	0.164
	8	29.67	26.99	2.68	0.134
Available binder in RAP, %	4.0	29.67	26.99	2.68	0.134
	4.75	29.07	25.79	3.28	0.164

H.9 SUMMARY

The cost savings associated with the use of RAP is very dependent on the cost of virgin binder and to a lesser degree on the costs for recycling agent, virgin aggregate, RAP and the amount of binder available in the RAP.

The low economic incentive scenario (low virgin material prices (binder and aggregates) and high RAP and recycling agent prices) provides an economic incentive of the order of $0.15 to $0.20 per percent RAP utilized in the mix. A mix with 40% RAP will have a savings of about $6.25 per ton while a mix with 20% RAP will have a savings of about $3.65 per ton. The additional saving associated with increasing the RAP content from 20 to 40% is about $3.00 per ton of HMA or about 5% of the production cost of HMA.

The high economic incentive scenario (high virgin material prices (binder and aggregates) and low RAP and recycling agent prices) provides an economic incentive of the order of $0.45 to $0.50 per percent RAP utilized in the mix. A mix with 40% RAP will have a savings of about $20.00 per ton while a mix with 20% RAP will have a savings of about $10.00 per ton. The additional saving associated with increasing the RAP content from 20 to 40% is about $10.00 per ton of HMA or about 15% of the production cost of HMA.

During periods of high material costs (virgin binder and aggregates), saving associated with the use of higher RAP contents and recycling agent (20% to 40% RAP) will be of the order of $6.00 to $8.00 per ton or from $0.30 to $0.40 per percent RAP. These savings are about 10 to 15% of plant production prices and about 7 to 10% of in-place prices for HMA.

The magnitude of the potential price/cost savings is of large enough magnitude to support technology improvements to support RAP use moving from 20% to 40% for selected projects. This magnitude of cost savings is significant for the contractor and public agency. If 5 million tons of HMA were produced with 40 versus 20% RAP, the savings would be within the range $20 to $50 million per year depending primarily on the price of virgin materials (binder and aggregate).

APPENDIX I

Draft AASHTO Standard Practice

Proposed Standard Practice for

Characterization of Asphalt Mixtures with High Recycled Materials Contents and Recycling Agents

AASHTO Designation: R XX-XX

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1. SCOPE

1.1 This practice describes practical tools to evaluate the effectiveness of recycling agents (rejuvenators) initially and with aging for hot mix asphalt mixtures with large quantities of reclaimed asphalt pavement (RAP) and/or recycled asphalt shingles (RAS) (high recycled materials contents). This practice also describes component materials selection, proportioning guidelines for recycled materials, and selection of recycling agent dose.

1.2 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.*

1.3 *Rejuvenation mechanisms of RAP/RAS binders and chemical changes associated with aging are a function of recycling agent type. Different recycling agent types have different chemical composition and may respond differently to long-term aging, in rejuvenated binder blends and corresponding hot mix asphalt mixtures. Thus, selection of recycling agent type is included in the scope of this standard practice with respect to characterization of rejuvenated binder blends and hot mix asphalt mixtures.*

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2. REFERENCED DOCUMENTS

2.1 *AASHTO Standards*

- T 164, Quantitative Extraction of Asphalt Binder from Hot-Mix Asphalt (HMA)
- R 30, Mixture Conditioning of Hot-Mix Asphalt (HMA)
- T 315-12, Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)
- T 313-12, Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)
- M 320-16, Performance-Graded Asphalt Binder
- T 240, Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)
- R 28, Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)
- T 324-17, Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures
- T 342-15, Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures
- TP 124-16, Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature
- TP 125-16, Determining the Flexural Creep Stiffness of Asphalt Mixtures Using the Bending Beam Rheometer (BBR)

2.2 *ASTM Standards*

- D5404, Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator
- WK60626, Determining Thermal Cracking Properties of Asphalt Mixtures through Measurement of Thermally Induced Stress and Strain

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3. TERMINOLOGY

3.1 ΔT_c, the difference in continuous PGL temperature for stiffness and relaxation properties in the Bending Beam Rheometer (BBR) (i.e. the critical temperature when S equals 300 MPa minus the critical temperature when m-value equals 0.30).

3.2 *Base binder,* for the purposes of this specification, shall mean new (virgin) performance graded asphalt binder to be used in the new hot mix asphalt.

3.3 *Cracking Resistance Index –* CRI_{ENV}, an index intended to characterize the cracking resistance of hot mix asphalt mixtures determined through calculations of measured thermal stress and thermal strain and adjusted for in-situ environment.

3.4 *Crossover temperature – $T_{\delta=45°}$,* rheological index calculated from DSR master curve obtained experimentally from strain-controlled oscillatory measurements at 10 rad/sec. $T_{\delta=45°}$ is the temperature at which the storage modulus (G') is equal to the loss modulus (G'') and the phase angle is 45°.

3.5 *Dynamic modulus – $|E^*|$,* the absolute value of the complex modulus calculated by dividing the peak-to-peak stress by the peak-to-peak strain for a material subjected to a sinusoidal loading.

3.6 *Flexibility index – FI,* an index intended to characterize the damage resistance of hot mix asphalt mixtures per AASHTO TP 124.

3.7 *Glover-Rowe parameter – G-R,* rheological index for binders and binder blends combines the effect of stiffness (shear complex modulus $|G^*|$) and embrittlement (phase angle δ) at intermediate temperatures. A dynamic shear rheometer (DSR) master curve is obtained experimentally from strain-controlled oscillatory measurements in the linear-viscoelastic region, and G-R is calculated at 15°C and 0.005 rad/s, where $G\text{-}R = |G^*| \cos^2 \delta / \sin \delta$.

3.8 *High temperature performance grade – PGH*

3.9 *High temperature performance grade for the target climate – PGH_{Target},* the target binder is the one required to satisfy climate and traffic requirements per agency specifications.

3.10 *Low temperature performance grade – PGL*

3.11 *Manufactured waste asphalt shingles – MWAS,* rejected asphalt shingles or shingle tabs that are discarded in the manufacturing process of new asphalt shingles.

3.12 *Mixture flexural creep stiffness, – S_m,* creep stiffness obtained by fitting a second order polynomial to the logarithm of the measured stiffness, from 8.0 to 1000 seconds, as a function of the logarithm of time per AASHTO TP 125.

3.13 *Mixture Glover-Rowe parameter – $G\text{-}R_m$,* rheological index for hot mix asphalt mixture combines the effect of stiffness ($|E^*|$) and embrittlement (δ) at 20°C and 5 Hz per AASHTO T 342, where $G\text{-}R_m = |E^*| \cos^2 \delta / \sin \delta$.

3.14 *Mixture relaxation rate – $m\text{-}value_m$,* absolute value of the slope of the logarithm of the estimated creep stiffness curves versus the logarithm of the time per AASHTO TP 125.

3.15 *$N_{12.5}$,* number of load cycles to reach 12.5mm rut depth by Asphalt Pavement Analyzer (APA) and Hamburg Wheel Tracking Test (HWTT) per AASHTO TP 324.

3.16 *Phase angle – Ø*, the angle in degrees between a sinusoidally applied stress and the resulting strain in a controlled-stress test.

3.17 *Reclaimed asphalt pavement – RAP,* removed and/or processed pavement materials containing asphalt binder and aggregate.

3.18 *Recycled asphalt shingles – RAS,* manufactured shingle waste or post-consumer asphalt shingle that has been processed into a recyclable material.

3.19 *Recycled binder blend,* for the purposes of this specification, shall mean the mixture of base binder and RAP/RAS binders.

3.20 *Recycled binder ratio – RBR,* percentage of recycled binder from RAP and/or RAS by weight with respect to the total binder by weight, determined as the sum of the RAP binder ratio (RAP_{BR}) and the RAS binder ratio (RAS_{BR}).

3.21 *Recycling agent,* additive with chemical and physical characteristics designed to restore the rheological properties of aged asphalt binders in recycled asphalt mixtures. Recycling agents are often called “rejuvenators”.

3.22 *Recycling agent dose,* the recycling agent percent by mass of total binder in the asphalt mixture, including base binder and RAP/RAS binders.

3.23 *Tear-off asphalt shingles – TOAS,* asphalt shingles that are removed from the roofs of existing structures when the new roofs are being installed. Tear-off asphalt shingles are sometimes called “post-consumer shingles”.

4. SUMMARY OF PRACTICE

4.1 This practice describes the laboratory experiments and analysis needed to select the recycling agent dose and evaluate the effectiveness of the recycling agent, initially and with aging, for hot mix asphalt mixtures with high RAP and RAS contents.

5. SIGNIFICANCE AND USE

5.1 Increasing the quantity of recycled materials in hot mix asphalt mixtures provides economic and environmental benefits. However, this practice poses technical challenges in terms of hot mix asphalt mixture production, compaction, and long-term performance. To meet these challenges, appropriate mixture component selection, proportioning adjustments, and/or modifications such as employing a recycling agent at an appropriate dose are recommended.

6. HAZARDS

6.1 This practice and associated standards involve handling of hot asphalt binder, aggregates, and hot mix asphalt mixtures. It also includes the use of chemical additives. Use standard safety precautions, equipment, and clothing when handling materials and operating machinery.

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7. BINDER BLEND PREPARATION

7.1 Select the base binder content, RAP and/or RAS binder content, and recycling agent dose. Refer to section 9.1 to determine recycling agent dose.

7.2 Prepare the binder blend following the steps below:

7.2.1 Extract RAP and/or RAS binders in accordance with AASHTO T 164 (test method A: centrifuge extraction), and recover the binders in accordance with ASTM D5404 (using the rotary evaporator).

Note 1 — While using the rotary evaporator following ASTM D5404 is recommended for the binder recovery process, other AASHTO and ASTM standards can also be followed.

7.2.2 Preheat the base binder at elevated temperatures for about 15 minutes until the binder is adequately fluid. Preheat the RAP/RAS binders at elevated temperatures (160 to 200°C) until the binder is adequately fluid.

Note 2 — Considering the high stiffness and viscosity of the recycled binders, particularly RAS binders, the extracted RAP/RAS binders should be preheated and the blending process should be performed at elevated temperatures (up to 200°C) where the binder is adequately fluid. If the RAP and/or RAS binders are not adequately fluid, binder clusters will be formed preventing a homogenous binder blend.

7.2.3 Add the recycling agent to the base binder, if used, and hand-stir using a spatula for 30 seconds.

7.2.4 Heat the blend in the oven for 1 minute, and then add the RAS binder to the binder blend, if used, and hand-stir using a spatula for 30 seconds.

7.2.5 Heat the blend in the oven for 1 minute, and then add the RAP binder to the binder blend, if used, and hand-stir using a spatula for 30 seconds.

7.2.6 Heat the blend in the oven for 1 minute, and then hand-stir the blend using a spatula for 30 seconds. Repeat this step two times to ensure the final blend is homogenous.

7.2.7 Perform RTFO aging for the binder blends directly after preparing the blends to avoid additional re-heating. Additional heating may introduce further aging.

8. ASPHALT MIXTURE SPECIMEN PREPARATION

8.1 Select the base binder content, RAP and/or RAS content, recycling agent dose, and aggregate gradation. Follow the Superpave mix design procedure to determine binder content and aggregate gradation. Refer to section 9.1 to determine recycling agent dose, and refer to section 9.2 for the recycling agent incorporation method.

8.2 Prepare the asphalt mixture specimens following the steps below:

8.2.1 Preheat the virgin aggregate overnight at the specified mixing temperature.

8.2.2 Combine the RAP and/or RAS with the preheated virgin aggregate two hours prior to mixing, and place in the oven at the specified mixing temperature.

8.2.3 Preheat the base binder two hours prior to mixing at the required mixing temperature.

8.2.4 Add the recycling agent to the base binder, and blend well using a mixing drill, 10 minutes prior to mixing with the virgin aggregate and the RAP and/or RAS.

8.2.5 Mix the blend of base binder and recycling agent with the virgin aggregate and the RAP and/or RAS using mechanical mixer for about 1 minute. Ensure that the aggregate is thoroughly coated.

8.2.6 Empty the loose asphalt mixture in a flat shallow pan, and place the pan in the oven for 2 hours ± 5 minutes at the specified compaction temperature. This short-term oven aging (STOA) will simulate the conditioning that the mixtures experience during production and placement.

8.2.7 Follow AASHTO T 209 at the end of STOA period if the mixture is to be used to determine the maximum theoretical specific gravity. Otherwise, proceed with compaction.

8.2.8 Place the compacted specimens in a flat table to cool down for at least two hours at room temperature. Then, place the specimens in a storage room at low temperature (usually around 10°C) if the specimen is to be tested later. Otherwise, proceed with long-term oven aging (LTOA).

8.2.9 Place the compacted specimens in the oven for 5 days at 85°C in accordance with AASHTO R 30, or the proposed AASHTO TP Standard Method for Long-Term Conditioning of Hot Mix Asphalt (HMA) for Performance Testing.

Note 3 — when preparing specimens with a height higher than 3 inches, extra caution should be followed during LTOA. To avoid any changes in the specimen dimensions and ensure that the target air void content remains constant, the compacted specimens can be covered with heat resistant PVC pipes or wrapped in metal wire mesh secured with clamps to avoid geometry distortion and preserve their integrity.

9. RECYCLING AGENT DOSE SELECTION AND INCORPORATION METHODS

9.1 The recycling agent dose to restore the continuous PGH of the recycled binder blend to match PGH of the target climate (PGH_{Target}) yields the best performance for binder blends and corresponding hot mix asphalt mixtures, and yields binder blends that meet the PGL requirements of the target climate. The recycling agent dose selection method based on DSR testing of unaged material can be summarized in the following three steps:

9.1.1 Determine PGH of the base binder and RAP/RAS binders per AASHTO M 320.

9.1.2 Select the base binder, RBR, and RAP/RAS combination; and calculate PGH of the recycled binder blend using Equation 1:

$$PGH_{Blend} = (RAP_{BR} \times PGH_{RAP}) + (RAS_{BR} \times PGH_{RAS}) + (B_{BR} \times PGH_{Base}) \qquad (1)$$

where:

PGH_{Blend} = Continuous PGH of the recycled binder blend (°C);
RAP_{BR} = RAP binder ratio;
PGH_{RAP} = Continuous PGH of the RAP binder (°C);
RAS_{BR} = RAS binder ratio;
PGH_{RAS} = Continuous PGH of the RAS binder (°C);
B_{BR} = Base binder ratio = 1 – RBR; and
PGH_{Base} = Continuous PGH of the base binder (°C).

Note 4 — While accuracy in PGH may be reduced when using Equation 1, it enables consideration of multiple factors with minimal testing. It is recommended to continue to measure PGH of the recycled binder blend, if possible, for design and quality control documentation.

9.1.3 Estimate recycling agent dose using Equation 2, for all recycling agent types except petroleum-based aromatic extracts:

$$\text{Recycling Agent (\%)} = (PGH_{Blend} - PGH_{Target}) / 1.82 \qquad (2)$$

where:

PGH_{Blend} = Continuous PGH of the recycled binder blend (°C) calculated from Equation 1; and
PGH_{Target} = Continuous PGH of Target Climate.

Note 5 — Equation 2 provides a universal recycling agent dose selection method for all recycling agent types except petroleum-based aromatic extracts, using 1.82 as a rate of reduction in PGH per 1% recycling agent dose. For petroleum-based aromatic extracts, a rate of reduction in PGH per 1% recycling agent dose of 1.38 is recommended.

9.2 Based on recycling agent dose and recycled material type, add the recycling agent to the hot mix asphalt mixture following one of these guidelines:

9.2.1 For hot mix asphalt mixtures with only RAP and for all binder blends, the recycling agent is added 100% as a replacement for the base binder.

9.2.2 For hot mix asphalt mixtures with RAP and RAS and recycling agent doses greater than 5.0%, the recycling agent is added as 50% addition and 50% replacement for the base binder.

Note 6 — These guidelines are aimed to preclude coatability issues (partially coated aggregate with base binder) that may result from replacing the base binder by the full amount of recycling agent; thus reducing the base binder content, particularly in hot mix asphalt mixtures with high recycling agent doses. These coatability issues are more prevalent in mixtures with RAS than in those with only RAP.

10. COMPONENT MATERIALS SELECTION AND PROPORTIONING GUIDELINES

10.1 Component materials selection and proportioning guidelines are proposed in Table 1. These guidelines are provided as a system, with requirements for all applicable thresholds where data is available for a specific combination of materials in a high RBR mixture with a recycling agent.

Table 1— Component Materials Selection and Proportioning Guidelines.

Test	Parameter	Component Material			
		Base Binder	RAP	RAS	Recycling Agent
High Temperature, Short-Term Aging[a]					
DSR	PGH	≤ 64°C	≤ 100°C	≤ 150°C	---
Low Temperature, Short- and Long-Term Aging[b]					
BBR	ΔT_c	≥ -3.5°C	≥ -7.5°C	---	---
Proportioning					
RBR		---	≤ 0.5 RBR ($RAP_{BR}+RAS_{BR}$)	≤ 0.15 RAS_{BR}	---

Dose	---	---	---	< 8-10%[c]

[a] Original binder and RTFO aged by AASHTO T 240
[b] 20-hour PAV aging @ 100°C by AASHTO R 28
[c] Percent of total binder in the blend/mixture

11. BINDER BLEND RHEOLOGICAL EVALUATION TOOLS

11.1 Table 2 provides binder blend evaluation tools for use with high RBRs and recycling agents. These tools are provided as a system, with requirements recommended for at least one high-temperature and one intermediate- or low-temperature test where data are available for a specific combination of materials in a high RBR binder blend with a recycling agent.

Table 2— Binder Blend Evaluation Tools for Use with High RBRs and Recycling Agents.

Test	Parameter	Suggested Performance Threshold
High Temperature, Original and Short-Term Aging		
DSR	PGH	Target Climate
Intermediate Temperature, Track with Aging		
DSR	G-R	< 180 kPa after 20-hour PAV < 600 kPa after 40-hour PAV
DSR	$T_{\delta=45°}$	< 32°C after 20-hour PAV < 45°C after 40-hour PAV
Low Temperature, Short- and Long-Term Aging		
BBR	ΔT_c	> -5.0 after 20-hour PAV

12. MIXTURE PERFORMANCE EVALUATION TOOLS

12.1 Table 3 provides comprehensive mixture evaluation tools for use with high RBRs and recycling agents that balances mixture cracking resistance at both intermediate and low temperatures and rutting resistance at high temperature. Evaluation of hot mix asphalt mixtures is imperative, as these mixture properties control performance and allow for consideration of incomplete blending between base and recycled binders and recycling agent. These tools are provided as a system, with requirements recommended for at least one high-temperature and one intermediate- or low-temperature test where data are available for a specific materials combination in a high RBR mixture with a recycling agent.

Table 3— Mixture Evaluation Tools for Use with High RBRs and Recycling Agents.

Test	Parameter	Suggested Performance Threshold
		High Temperature, Short-Term Aging
HWTT or APA	$N_{12.5}$	$\geq$ 5,000 for PG 58-XX $\geq$ 7,500 for PG 64-XX in cold climate $\geq$ 10,000 for PG 64-XX in warm climate $\geq$ 15,000 for PG 70-XX
		Intermediate Temperature, Track with Aging
$\lvert E^*\rvert$	$G\text{-}R_m$	$\leq$ 8,000 MPa after STOA $\leq$ 19,000 MPa after LTOA
		Intermediate Temperature, Short-Term Aging
SCB	FI	$\geq$ 7 after STOA
		Low Temperature, Short- and Long-Term Aging
BBR_m	S_m and m-value$_m$	$\leq$ Romero (2016) threshold on m-value$_m$ vs. S_m after STOA
UTSST	CRI_{ENV}	$\geq$ 17 after LTOA

13. RAP Binder Availability Factor

13.1 The amount of RAP binder in the mixture is typically represented as RAP_{BR}. However, the quantity of effective or available RAP binder in the mixture is usually unknown and less than 100%, which may yield a dry mixture with a high air void content due to less total effective binder content, potentially leading to premature distress.

13.2 The term effective or available RAP binder refers to the binder that is released from the RAP, becomes fluid, and blends with the base binder under typical mixing temperatures.

13.3 RAP Binder Availability Factor (BAF), expressed as a decimal, can be used to adjust the base binder content in hot mix asphalt mixtures with RAP to ensure that the mix design optimum, and effective, binder content is achieved (see Note 7).

13.4 Based on the PGH of the RAP binder, the RAP BAF can be estimated using Equation 3 and Equation 4 for mixing temperatures of 140°C (284°F) and 150°C (302°F), respectively:

$$\text{RAP BAF} = -0.014 \times \text{PGH}_{\text{RAP}} + 1.898 \qquad (3)$$

$$\text{RAP BAF} = -0.010 \times \text{PGH}_{\text{RAP}} + 1.771 \qquad (4)$$

where:

PGH_{RAP} = Continuous PGH of the RAP binder (°C).

Note 7 — This value is suggested for use in reducing the recycled binder from the RAP to the RBR in a mixture to ensure that sufficient base binder is included during mix design.

Note 8 — It is expected that adding a recycling agent in RAP mixtures would increase the RAP BAF only at low mixing temperatures. Increasing mixing temperature has an effect equivalent to adding a recycling agent.

14. REPORT

14.1 For each mix design, report the following

14.1.1 Base binder: PG and ΔT_c

14.1.2 RAP: PGH and ΔT_c

14.1.3 RAS: PGH

14.1.4 RBR, RAP_{BR}, RAS_{BR}

14.1.5 Recycling agent type and dose

14.1.6 Selected binder blend test results (Table 2)

14.1.7 Selected mixture test results (Table 3)

15. KEYWORDS

15.1 Asphalt mixture, reclaimed asphalt pavement, recycled asphalt shingles, recycling agent, rheological properties, mixture performance

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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