THE EFFECTS OF RECYCLING AGENTS ON ASPHALT MIXTURES WITH HIGH RECYCLED MATERIALS CONTENT

A Dissertation

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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May 2019

Major Subject: Civil Engineering

ABSTRACT

Economic and environmental benefits motivate transportation agencies to increase the amount of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) used in asphalt mixtures. In the U.S., materials cost savings in 2017 totaled approximately $2.2 billion with RAP and RAS materials replacing virgin asphalt binder and aggregate in asphalt mixtures. However, recycled asphalt mixtures with high RAP and RAS content are usually less workable, difficult to compact in the field, and more prone to cracking, raveling, and other durability-related pavement distresses, primarily due to the presence of the severely aged, substantially stiffer and more brittle RAP/RAS binders. To meet these challenges, mixture adjustments are recommended including the use of recycling agents, or rejuvenators, to reduce mixture stiffness and improve cracking performance.

The main objectives of this study were to provide tools for selecting the appropriate dose of recycling agent; optimizing recycled materials type and content; evaluating the effect of various factors on the long-term performance of rejuvenated asphalt mixtures; and providing practice-ready guidelines for evaluation, materials selection and optimization, and design of recycled asphalt mixtures with recycling agent.

In this study, a summary of the current knowledge related to the use of recycling agents in the asphalt pavement industry was first provided, including recycling agent definition, advantages, and challenges. Rejuvenation mechanism of recycling agents, the effectiveness of recycling agents in improving the rheology and performance of recycled binder blends and recycled asphalt mixtures, and cost-effectiveness associated with the use of recycling agents were also reviewed. Then, different recycling agent dose selection methods were evaluated based on rheological parameters of the recycled binder blend. Furthermore, blending charts to balance recycled binder blend proportions and blending charts to select the appropriate dose of recycling agent to be added to an asphalt mixture during mix design was also established and verified. Then, the performance of rejuvenated asphalt mixtures produced in five field projects in the U.S. that include a wide spectrum of materials, mix designs, and climate was evaluated. Finally, a proposed method to quantify the available or effective RAP binder was introduced, and can be used to adjust the virgin binder content in RAP mixtures to ensure that the mix design optimum binder content is achieved.

DEDICATION

To my God: my creator, my strong pillar, and my source of inspiration.

To my beloved parents, wife, and children

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my committee chair, Dr. Amy Epps Martin, for her valuable support, patience, and consistent encouragement. Her guidance and scholarly inputs helped me in all the time of research and writing of this dissertation. I could not have imagined having a better advisor and mentor for my Ph.D. study. My appreciation also goes to Dr. Jon A. Epps, Dr. Robert L. Lytton, and Dr. Charles J. Glover, for serving as my committee members. I would like to thank Dr. Epps for sharing with me his extensive knowledge and valuable experience, would like to thank Dr. Lytton for all his scholarly inputs in the graduate-level courses within our civil engineering department, and would like to thank Dr. Glover for his inputs in NCHRP 9-58 project that ultimately helped in shaping my knowledge and research ideas. I also acknowledge the National Cooperative Highway Research Program and the Texas A&M Transportation Institute for supporting this study.

My sincere thanks also goes to Dr. Edith Arámbula-Mercado for her advice, support, encouragement, friendship, and the valuable time she offered me to share and discuss research ideas. Thanks also go to Rick Canatella, Tony Barbosa, Ross Taylor, and Ethan Karnei, from the Texas A&M Transportation Institute, for their valuable help in the laboratory. Thanks to my friends and colleagues for making my time at Texas A&M University a great experience, particularly Dr. Lorena Garcia Cucalon, Dr. Fan Yin, and Dr. Charles F. Gurganus.

Last but not least, I would like to thank my family: my parents Mwafaq Kaseer and Awatif Jazrawi, for giving birth to me in the first place and supporting me spiritually throughout my life. Thanks to my lovely wife, Dima Allo, and my lovely children, Farah and Fabian, for their patience and for standing by my side throughout the process.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Professor Amy Epps Martin as a committee chair, Professors Jon Epps and Robert Lytton of the Zachry Department of Civil Engineering, and Professor Charles Glover of the Department of Chemical Engineering.

The analyses depicted in Chapter III were conducted in part by Edith Arámbula-Mercado, Fan Yin, and Lorena Garcia Cucalon of the Texas A&M Transportation Institute and were published in 2018. All other work conducted for the dissertation was completed by the student independently.

Funding Sources

This work was made possible in part by the National Cooperative Highway Research Program (NCHRP) under NCHRP project 9-58. Its contents are solely the responsibility of the author and do not necessarily represent the official views of NCHRP.

NOMENCLATURE

AMPT	Asphalt Mixture Performance Tester
ANOVA	Analysis Of Variance
APA	Asphalt Pavement Analyzer
BAF	Binder Availability Factor
BBR	Bending Beam Rheometer
BBR_m	Bending Beam Rheometer for Asphalt Mixtures
CA	Carbonyl Area
CI	Coatability Index
CRI	Cracking Resistance Index
DOT	Departments of Transportation
DSR	Dynamic Shear Rheometer
E*	Dynamic Modulus
FI	Flexibility Index
G*	Complex Shear Modulus
G-R	Glover-Rowe Parameter
HMA	Hot Mix Asphalt
HSD	Tukey's Honest Significant Difference Test
HWTT	Hamburg Wheel-Track Test
IDT	Indirect Tensile Strength Test
I-FIT	Illinois Flexibility Index Test

LMLC	Laboratory-Mixed Laboratory-Compacted
LTOA	Long-Term Oven Aged
M_R	Resilient Modulus
m-value	Stress Relaxation
MWAS	Manufacture Waste Asphalt Shingles
NMAS	Nominal Maximum Aggregate Size
OT	Overlay Test
PAV	Pressure Aging Vessel
PG	Performance Grade
PGH	High-Temperature Performance Grade
PGL	Low-Temperature Performance Grade
RAP	Reclaimed Asphalt Pavement
RAS	Recycled Asphalt Shingles
RBR	Recycled Binder Ratio
RTFO	Rolling Thin-Film Oven
S	Creep Modulus
SAR-AD™	Saturates, Aromatics, Resins, Asphaltene Determinator
SCB	Semi-Circular Bending
STOA	Short-Term Oven Aged
TOAS	Tear-Off Asphalt Shingles
UTSST	Uniaxial Thermal Stress and Strain Test
WMA	Warm-Mix Asphalt

δ	Binder Phase Angle
φ	Mixture Phase Angle

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CHAPTER I

INTRODUCTION

Overview

The use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in hot-mix asphalt (HMA) and warm-mix asphalt (WMA) mixtures can reduce construction costs, maintain dwindling natural resources, conserve valuable landfill space, and improve sustainability. In the U.S., the total estimated RAP tonnage recycled in asphalt mixtures in 2017 was 76.2 million tons, and this represents more than 3.8 million tons of asphalt binder conserved, along with the replacement of about 72 million tons of virgin aggregate. The total estimated amount of recycled RAS in 2017 was about 1.4 million tons. The combined savings of asphalt binder and aggregate from using RAP and RAS in asphalt mixtures is estimated at more than $2.2 billion during 2017 (NAPA 2018).

State Departments of Transportation (DOTs) and contractors alike have long recognized these benefits. As the percentage of RAP and/or RAS increases in asphalt mixtures, their economic and environmental benefits also increase. However, utilization of higher amounts of these aged materials presents concerns that the recycled asphalt mixtures are less workable and difficult to compact during construction and more prone to cracking during pavement service life due to their stiff, brittle nature (Kim et al. 2007; Mogawer et al. 2012). To accommodate the severely aged and substantially stiffer binder in RAP and RAS, and thus provide adequate performance in the field, some adjustments to the recycled asphalt mixtures should be considered, including using a softer base (virgin) binder in terms of performance grade (PG), using recycling agents, or a combination of both.

The use of recycling agents, or rejuvenators, has gained more attention in recent years due to increased availability, ease of addition to asphalt mixtures, and often lower costs as compared to the use of softer virgin binders. Many studies indicated that adding recycling agents to recycled asphalt mixtures can significantly reduce their stiffness (Tran et al. 2012; Carvajal Munoz et al. 2015). Other studies showed the effectiveness of recycling agents in improving the cracking performance of recycled asphalt mixtures by mitigating the brittleness of the recycled binder in the RAP and RAS (Mogawer et al. 2013; Im et al. 2014; and Yan et al 2014). However, recent studies suggested that the reduction in stiffness and improvement in cracking resistance of recycled binder blends (base binder and recycled binders) and corresponding recycled asphalt mixtures due to the addition of recycling agent is diminished with long-term aging, particularly when low recycling agent doses are utilized (Yin et al. 2017; Kaseer et al. 2017).

The short- and long-term effectiveness of recycling agents in recycled asphalt mixtures depends on a number of factors such as the type and amount of recycled materials, the source and grade of the base binder, the type and dose of the recycling agent, and mixing time and temperature. Among these factors, special emphasis is given to the dose of the recycling agent because this is commonly the most flexible design variable for the engineer to optimize.

Recycling agent dose balances the performance of the asphalt mixture in terms of cracking and rutting resistance while maintaining durability. An insufficient recycling agent dose may reduce the stiffness and brittleness of the recycled binder in RAP and RAS, but may not have a pronounced effect in improving the cracking resistance of the recycled asphalt mixture. Conversely, an excessive recycling agent dose may soften the recycled binder but could be potentially detrimental to the rutting performance of the recycled asphalt mixture, especially during its early life. The recycling agent dose also affects the rheological and chemical changes in the rejuvenated binder after long-term aging (Yin et al. 2017; Kaseer et al. 2017). In previous research efforts, blending between base binders, recycled binders, and recycling agents has been investigated to determine the optimum dose of the recycling agent using blending charts.

Some researchers have selected the recycling agent dose according to blending charts based on the viscosity and/or penetration of the blends of the recycled binder with various amounts of recycling agent (Little et al. 1981; Zaumanis et al. 2013; Yan et al. 2014; and Zaumanis et al. 2014). Other researchers have used the PG system to evaluate the changes in the stiffness of the recycled binder due to the addition of the recycling agent and determined the minimum dose needed to restore the performance properties of the recycled binder (Shen and Ohne 2002; Shen et al. 2007; Tran et al. 2012; Zaumanis et al 2014).

Despite previous research efforts, there are several aspects with respect to optimizing recycling agent usage, considering a wide variety of virgin and recycled materials, that have not been established. These aspects include:

- A recycling agent dose selection method that ensures adequate long-term performance for recycled asphalt mixtures has not been standardized.
- Methods to optimize recycled materials content and proportions that also affect the dose of the recycling agent have not been investigated.
- A comprehensive study to evaluate the effect of various factors such as the type, source, and amount of recycled materials, and the source and grade of the base binder on the long-term performance of asphalt mixtures has not been undertaken.
- Practice-ready guidelines for evaluation, materials selection and optimization, and design of mixtures with high recycled materials contents and recycling agent have not been produced.
- A method to quantify the available or effective RAP binder in recycled or rejuvenated asphalt mixtures has not been established. Quantifying the effective RAP binder can help adjusting the virgin binder content in RAP mixtures, during the mix design process, to ensure that the optimum binder content is achieved. Most state DOTs assume 100% effective RAP binder, which is not realistic.

Research Objectives and Methodology

Based on the previously discussed aspects and the literature review, the following objectives were set for this study:

1. Recommend a method to determine the appropriate dose of recycling agent, including:
    - Develop and evaluate various recycling agent dose selection methods

   - Establish and verify blending charts to balance base/RAP/RAS binders in recycled binder blends. This can be a tool to optimize the type and amount of recycled materials and also to control the maximum dose of recycling agent.
   - Utilize blending charts for selection of the recommended dose of recycling agent to be added to a mixture during the mix design process that requires minimum laboratory testing.

2. Assess the effectiveness of recycling agents at the recommended dose to:
   - Fully or partially restore recycled binder blend rheology, considering short- and long-term aging.
   - Improve the short- and long-term mixture cracking performance without adversely affecting rutting resistance.
3. Develop practice-ready guidelines to optimize RAP/RAS and base binder proportions, and recycling agent dose, to assist in decision-making for asphalt recycling projects considering short- and long-term performance that can be translated into cost-effectiveness.
4. Propose a method to quantify the RAP binder availability (effective RAP binder) to be utilized during the mix design process of asphalt mixtures with RAP.

Materials used in this study correspond to five field projects located in five states across the U.S.: Texas, Nevada, Indiana, Wisconsin, and Delaware. The following factors were considered in selecting the field projects in order to include a wide spectrum of materials, mix design, and field conditions: climate (wet-freeze, dry-freeze, dry-no freeze, and wet-no freeze); asphalt binder performance grade (PG); recycled materials (RAP and RAS) content, source, and type (including manufacture waste asphalt shingles [MWAS] and tear-off asphalt shingles [TOAS]); and recycling agent dose and type. Raw materials including asphalt binders, aggregates, RAP and RAS, and recycling agents were obtained from each field project. Additional asphalt binders and recycled materials were collected from other states including New Hampshire, Minnesota, and California; and additional types of recycling agents were obtained from their manufacturers. These materials were used to prepare the binder blends and to fabricate laboratory-mixed laboratory-compacted (LMLC) mixture specimens. Figure 1 presents the research methodology used herein.

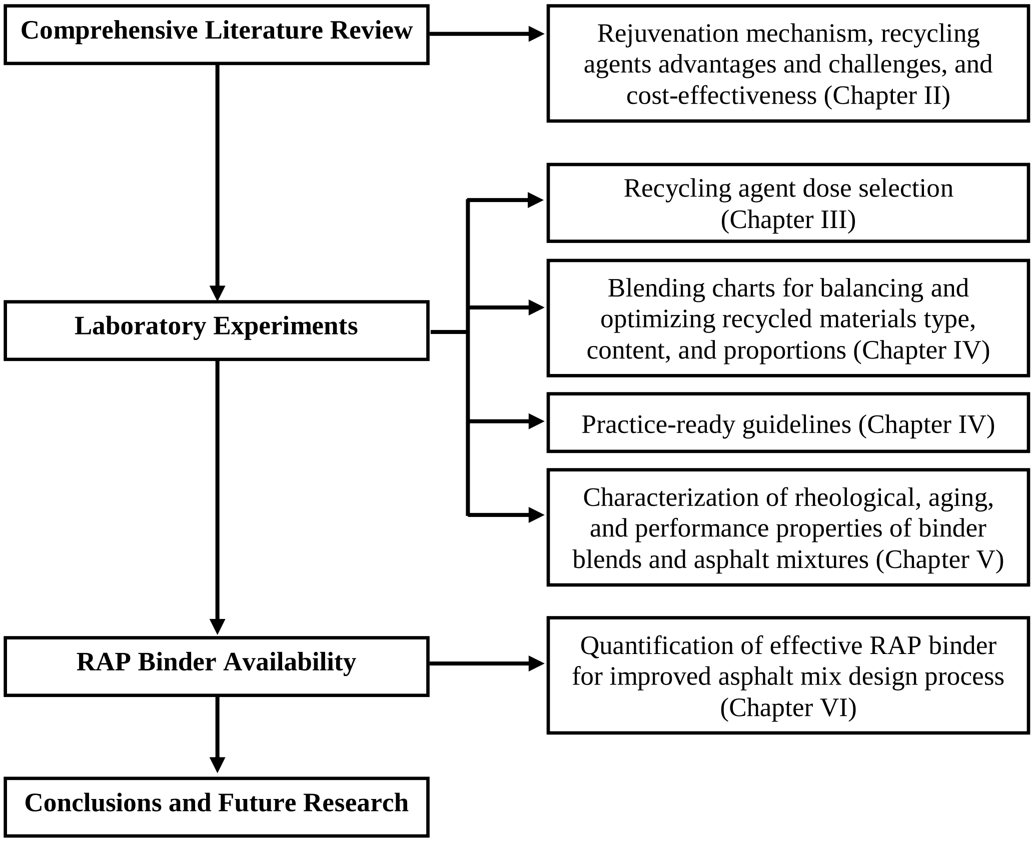

Figure 1. Research methodology.

Dissertation Outline

This dissertation consists of seven chapters. The present chapter (Chapter I) demonstrates the significance of the research topic, describes the research objectives and methodology, and provides the dissertation outline.

Chapter II summarizes current knowledge related to the use of recycling agents in the asphalt pavement industry, including properties of recycled and rejuvenated asphalt mixtures. This information is further used to identify current and future challenges that could prevent utilization of recycling agents and production of rejuvenated asphalt mixtures with adequate performance. The contents are reprinted with minor revisions from a paper submitted to the Journal of Construction and Building Materials (2019).

Chapter III evaluates different recycling agent dose selection methods based on rheological parameters of the recycled binder blend, that is, the blend of base (virgin) binder, recycled binder from RAP/RAS, and recycling agent. The contents are reprinted with minor revisions from a paper published in the Journal of Construction and Building Materials (2018)

Chapter IV establishes and verifies blending charts to balance recycled binder blend composition (as a tool to optimize the type and amount of recycled materials). In addition, blending charts for selection of the appropriate dose of recycling agent to be added to an asphalt mixture during mix design (that requires minimum laboratory testing at the binder blend level) is introduced. Finally, the improvement in the rheological, aging, and performance properties of the recycled binder blend and asphalt mixture with the selected dose of recycling agent was verified. The contents are reprinted with minor revisions from a paper published in the Journal of the Association of Asphalt Paving Technologists (2018).

Chapter V evaluates the performance of rejuvenated asphalt mixtures produced in five field projects in the U.S. that include a wide spectrum of materials (base binder PG; recycled materials content, source, and type; and recycling agent type and dose), mix designs, and climate. Chapter IV also evaluate the performance of rejuvenated asphalt mixtures with the selected dose of recycling agent recommended in Chapter III. The contents are reprinted with minor revisions from a paper published in the International Journal of Pavement Engineering (2018).

Chapter VI proposes a method to estimate the RAP Binder Availability Factor (BAF), which quantifies the available or effective RAP binder; the binder that is released from the RAP, becomes fluid, and blends with the virgin binder under typical mixing temperatures. The percentage of available or effective RAP binder in the asphalt mixture is usually less than 100% and difficult to quantify, which could yield a dry asphalt mixture with a high air void content; potentially leading to premature distress. BAF can be used to adjust the virgin binder content in RAP mixtures to ensure that the mix design optimum binder content is achieved. The contents are reprinted with minor revisions from a paper published in the Transportation Research Record: Journal of the Transportation Research Board (2019).

Chapter VII summarizes the main findings and conclusions of this study. In addition, recommendations for future research are provided.

References

Carvajal Munoz, J. S., F. Kaseer, E. Arambula, and A. Epps Martin. Use of the Resilient Modulus Test to Characterize Asphalt Mixtures with Recycled Materials and Recycling Agents. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2506, 2015, pp. 45–53.

Im, S., F. Zhou, R. Lee, and T. Scullion. Impacts of Rejuvenators on Performance and Engineering Properties of Asphalt Mixtures Containing Recycled Materials. *Construction and Building Materials,* Vol. 53, 2014, pp. 596-603.

Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin. Stiffness Characterization of Asphalt Mixtures with High Recycled Materials Contents and Recycling Agents. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2633, 2017, pp. 58-68.

Kim, S., T. Byron, G. A. Sholar, and J. Kim. Evaluation of Use of High Percentage of Reclaimed Asphalt Pavement (RAP) for Superpave Mixtures. Report No. FL/DOT/SMO/07-507, Florida Department of Transportation, 2007.

Little, D.N., R.J. Holmgreen, and J.A. Epps. Effect of recycling agents on the structural performance of recycled asphalt concrete materials. *Journal of the Association of Asphalt Paving Technologists,* Vol. 50, 1981, pp. 32–63.

Mogawer, W., T. Bennert, J. Daniel, R. Bonaquist, A. J. Austerman, and A. Booshehrian. Performance Characteristics of Plant Produced High RAP Mixtures. *Journal of the Road Materials and Pavement Design,* Vol. 13, 2012, pp. 183-208.

Mogawer, W.S., A. Booshehrian, S. Vahidi, and A.J. Austerman. Evaluating the Effect of Rejuvenators on the Degree of Blending and Performance of High RAP, RAS, and RAP/ RAS Mixtures. *Journal of the Road Materials and Pavement Design,* Vol. 14, Supplement 2, 2013, pp.193-213.

NAPA. Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2017." National Asphalt Pavement Association, Lanham, MD, 2018.

Shen, J. and Y. Ohne. Determining rejuvenator content for recycling reclaimed asphalt pavement by SHRP binder specifications. *International Journal of Pavement Engineering,* Vol. 3, No. 4, 2002, pp. 261–268.

Shen, J., S. Amirkhanian, J.A. Miller. Effects of rejuvenating agents on Superpave mixtures containing reclaimed asphalt pavement. *Journal of the American Society of Civil Engineers,* Vol. 19, No. 5, 2007, pp. 376–384.

Tran, N. H., A. Taylor, and R. Willis. Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents. NCAT Report No. 12-05, National Center for Asphalt Technology, Auburn, AL, 2012, 70 pp.

Yan, J., Z. Zhang, H. Zhu, F. Li, and Q. Liu. Experimental Study of Hot Recycled Asphalt Mixtures with High Percentages of Reclaimed Asphalt Pavement and Different RAs. *ASTM Journal of Testing and Evaluation*, Vol. 42, No. 5, 2014. 1183–1190.

Yin, F., F. Kaseer, E. Arámbula-Mercado, and A. Epps Martin (2017) "Characterising the Long-Term Rejuvenating Effectiveness of Recycling Agents on Asphalt Blends and Mixtures with High RAP and RAS Contents." Road Materials and Pavement Design, Vol. 18, Sup. 4, pp. 273-292.

Zaumanis, M., R. Mallick, and R. Frank. Evaluation of different recycling agents for restoring aged asphalt binder and performance of 100% recycled asphalt. *Materials and Structures,* Vol. 48, No. 8, 2014, pp. 2475–2488.

Zaumanis, M., R. Mallick, and R. Frank. Evaluation of rejuvenator's effectiveness with conventional Mix testing for 100% reclaimed asphalt pavement mixtures. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2370, 2013, 17–25.

Zaumanis, M., R. Mallick, R. Frank. Determining optimum rejuvenator dose for asphalt recycling based on Superpave performance grade specifications. *Construction and Building Materials,* Vol. 69, 2014, pp. 159–166.

CHAPTER II

USE OF RECYCLING AGENTS IN ASPHALT MIXTURES WITH HIGH RECYCLED MATERIALS CONTENTS IN THE UNITED STATES: A LITERATURE REVIEW[1]

Overview

Aging and Recycling of Asphalt Binders

Asphalt binders can be represented by a colloidal model consisting of a highly polar insoluble asphaltene phase dispersed in a soluble maltene phase (saturates, aromatics, and resins). In this dispersion medium, the asphaltenes (dispersed phase) form groups but are unable to create a continuous network (asphaltene clusters). The balance between the asphaltene and the maltene phases has been related to the asphalt binder physical and rheological properties. A soft asphalt binder with high ductility has a larger proportion of the maltene phase with higher dispersive power. As the asphalt binder ages, the lighter oils in the maltene phase volatilize and some of the maltene medium is transformed into the asphaltene phase due to the oxidation process, resulting in higher asphaltene and lower maltene contents (Petersen 2009; Qin et al. 2014). This leads to stiffening and embrittlement of the asphalt binder, which influences its ability to stretch without breaking. In addition to total asphaltene content, asphalt binder rheology is also

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affected by the size of the asphaltene clusters and the dispersive power of the maltene phase. Asphalt binders with the same asphaltene content can exhibit different physical and rheological characteristics, and maltenes in different asphalt binders can have different dispersive powers that affect the asphaltene clusters (Petersen 2009; Altgelt and Harle 1975).

Recycling heavily aged asphalt binders into new asphalt pavements has a number of benefits. The use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS), both manufactured waste asphalt shingles (MWAS) and tear-off asphalt shingles (TOAS), to produce recycled asphalt mixtures can reduce production costs, maintain dwindling natural resources, conserve valuable landfill space, and protect the environment. However, it is challenging to incorporate large quantities of RAP and RAS materials into new asphalt pavements while maintaining adequate pavement durability. Recycled asphalt mixtures with high RAP/RAS contents can be excessively stiff and brittle; thus, these mixtures are usually less workable, difficult to compact in the field, and prone to cracking, raveling, and other durability-related pavement distresses as compared to their virgin counterparts without recycled materials (Kim et al. 2007; Mogawer et al. 2012; Carvajal Munoz et al. 2015; Kaseer et al. 2017a). Different strategies that would allow for responsible, increased use of recycled materials without sacrificing performance include: using a softer base (virgin) binder in terms of performance grade (PG), incorporating a warm mix asphalt (WMA) technology, adding a recycling agent (also referred to as a rejuvenator), or a combination of these mixture modifications.

Recycling Agent Definition, Advantages, and Challenges

Recycling agents are products with chemical and physical characteristics designed to restore the rheological properties of aged asphalt binders by improving the asphaltene to maltene ratio, reducing the size of asphaltene clusters, improving the dispersive power of the continuous maltene phase, and increasing molecular mobility. This, in turn, reduces the viscosity, stiffness, and embrittlement of the recycled asphalt binder, and increases its ductility. In the literature, recycling agents are sometimes referred to as rejuvenators, rejuvenating agents, reclaiming agents, softening additives, or softening agents; though as discussed subsequently, there is a difference between recycling agents and softening agents.

Much of the early work with recycling agents dating back to the late 1970’s and early 1980’s Davidson et al. 1977; Dunning and Mendenhall 1978; Escobar and Davidson 1979; Epps et al. 1980; Kari et al. 1980) led to the development of ASTM D4552 that classifies recycling agents into six grades (or groups) mainly through viscosity measured at 60°C (140°F) in order to help selecting the proper type of recycling agent for long-term performance. For the asphalt paving industry, some recycling agents have been available for several decades; but the use of these products has recently received renewed attention in the past two decades with the shift towards more sustainable practices, including the use of large quantities of RAP and RAS as a reaction to the significant increase of the cost of petroleum derivatives. The usefulness of recycling agents, however, is often questioned due to limited understanding of their short- and long-term effectiveness in improving the performance of recycled asphalt mixtures, and their overall cost-to-benefit ratio.

The use of recycling agents in recycled asphalt mixtures is associated with several advantages that can be classified into three main categories: *(1)* workability improvements, *(2)* performance improvements, and *(3)* economic and environmental benefits.

Asphalt mixture workability can be defined as a property that describes the ease with which an asphalt mixture can be placed, worked by hand, and compacted in the field (Gudimettla et al. 2003). Adequate workability is important in mixing, handling, and compaction of asphalt mixtures in order to obtain the desired pavement smoothness and density after compaction. Due to the presence of the extremely aged and stiff binders in RAP/RAS materials, recycled asphalt mixtures with large quantities of these materials are usually stiffer and less workable; hence, inadequate workability could prevent proper compaction in the field. Moreover, pavements achieving less than their target density after compaction may experience performance problems such as premature raveling and increased rate of asphalt binder oxidative aging due to high air voids content, thereby reducing the service life of the pavement (Gudimettla et al. 2003; Haghshenas et al. 2016). Previous studies suggested that the addition of recycling agents can significantly reduce the stiffness of recycled asphalt mixtures and improve their workability. In some cases, adding an appropriate dose of the recycling agent can reduce the stiffness of the recycled asphalt mixtures and make it equivalent to that of virgin mixtures (Carvajal Munoz et al. 2015; Kaseer et al. 2017a; Tran et al. 2012; Mogawer et al. 2013a).

Cracking and rutting in asphalt pavements are common distresses that affect the performance of asphalt mixtures. Cracking, in particular, has become the primary distress in asphalt pavements in recent years, driving the need for rehabilitation. Cracking in asphalt pavements occurs in response to several factors including poor mix design, repetitive traffic loading, low temperatures, moisture damage, and asphalt binder aging. Cracking is further exacerbated with the increase RAP and RAS contents due to the presence of the stiff, heavily aged binder in the recycled materials. Consequently, asphalt mixtures with large quantities of recycled materials are more prone to fatigue (intermediate-temperature), thermal (low-temperature), reflection, and block cracking throughout the service life of the pavement (Kaseer et al. 2018b). Previous studies have shown the effectiveness of recycling agents in improving the cracking performance of recycled asphalt mixtures by mitigating the brittleness of the recycled binder in the RAP and RAS (Kaseer et al. 2018a; Mogawer et al. 2013a; Kaseer et al. 2018b; Im et al. 2014a; Yan et al. 2014; Yin et al. 2017).

Due to the numerous challenges in terms of mixture production, compaction, and long-term performance that are associated with the use of large quantities of RAP and RAS in asphalt mixtures, maximum contents for these materials in asphalt mixtures have commonly been controlled by specifications. Most State Departments of Transportation (DOTs) allow a maximum amount of recycled materials in asphalt mixtures in terms of recycled binder ratio (RBR). RBR is defined as the percentage of recycled binder from RAP and RAS, by weight, with respect to the total binder by weight in the asphalt mixture. However, economic and environmental benefits motivate the state DOTs to maximize RAP and RAS usage, which can be accomplished successfully with the addition of recycling agents. Several studies suggested that the use of recycling agents facilitates the inclusion of larger quantities of recycled materials than what is currently allowed by the DOT specifications without sacrificing long-term performance (Kaseer et al. 2018a; Yin et al. 2017).

The main environmental advantage of asphalt mixture recycling strategies include decreasing the gas/dust emission and energy use caused by the extraction and transportation of virgin materials (virgin asphalt binder and aggregate) (Haghshenas et al. 2016). Zaumanis et al. (2016) reported that increased RAP usage reduced asphalt binder consumption and thus proportionally decreased adverse environmental effects. The authors estimated a 35% reduction of CO_2 equivalent per ton of paved asphalt mixture when producing mixtures with 100% RAP (with recycling agent) instead of a virgin asphalt mixture without recycled materials. Robinett and Epps (2010) indicated that energy savings and emissions reductions associated with producing an asphalt mixture with about 25% RAP were approximately 10% each with a conservation of natural resources of about 20-25%, as compared to virgin asphalt mixtures. The authors translated that into increased sustainability and increased environmental benefits. In addition to emission reduction, using large quantities of RAP and RAS in new asphalt pavements (with the use of recycling agents to achieve adequate performance) is an alternative solution to reduce the landfill space required for RAP and RAS disposal. Economic benefits will be discussed subsequently in section 6.

Despite these multiple benefits, there are also the following challenges related to the use of recycling agents in recycled asphalt mixtures:

1. Lack of expertise in selecting recycling agent type and determining the appropriate dose.
2. Lack of a standard test method or procedure for characterizing recycling agents.
3. Lack of expertise in incorporating (blending) recycling agents into asphalt mixtures.
4. Lack of expertise and criteria in evaluating the effectiveness of recycling agents in asphalt mixtures.
5. Lack of knowledge regarding the long-term effectiveness of recycling agents (with aging).
6. Lack of knowledge regarding the cost-effectiveness of recycling agents.

Most of these challenges are the primary reason why the majority of state DOTs in the U.S. prohibit the use of recycling agents as discussed subsequently.

Use of Recycling Agents in the United States

Web-based surveys were performed by Epps Martin et al. (2015) to assess the current state-of-the-practice on the use of recycling agents in the U.S. The questionnaires were sent to representatives of state DOTs, contractors, and recycling agent suppliers. A total of 35 out of 50 state DOTs, 10 out of 15 contractors, and 6 out of 10 recycling agent suppliers responded for a 70%, 67%, and 60% response rate, respectively. For the state DOTs, more than 80% indicated that recycling agents were not used or not allowed in their states. The main barriers to utilizing recycling agents were lack of expertise in using recycling agents, lack of a standard test method or procedure for characterizing recycling agents, and lack of tests and criteria to evaluate the performance of asphalt mixtures with recycling agents. For the contractors, 64% indicated that recycling agents were not used and the two main barriers preventing the utilization of recycling agents were lack of expertise in using recycling agents, and lack of tests and criteria to determine dose rate and/or performance of asphalt mixtures with recycling agents. Finally, for the recycling agent suppliers the survey was focused on the types, test methods, and blending protocols prescribed for field and laboratory operations. About 60% of the respondents indicated that the most common recycling agents used were tall oils and bio-based oils, and more than 80% of the respondents indicated that they have standard test methods or procedures for characterizing the recycling agent effectiveness in binder testing including the penetration test, kinematic viscosity, or performance grading (PG).

An asphalt pavement industry survey on recycled materials usage in the U.S. in 2015 conducted by Hansen and Copeland (2017) reported that most states are using softer base binders or recycling agents only when the RAP content in the asphalt mixture exceeds 20%. However, nationwide, 24% of asphalt mixtures with RAP were produced using softer base binders, and only 3% of asphalt mixtures with RAP were produced using recycling agents. These data suggest that state DOTs and contractors are reluctant to use recycling agents in the U.S. mainly due to the challenges previously provided.

Objectives

The fact that most state DOTs and contractors do not use or do not allow using recycling agents, despite the many advantages they offer, highlights the importance of encouraging their utilization. In this context, this chapter aims to summarize current knowledge on recycling agents and their application in the asphalt pavement industry. Specifically, the chapter begins by providing insight on the rejuvenation mechanism of recycling agents. Next, the effectiveness of recycling agents in improving the rheology of recycled binder blends (base and recycled RAP/RAS binders) and in improving the performance of recycled asphalt mixtures will be discussed, including key factors that affect the short- and long-term effectiveness of recycling agents. The next section summarizes the main findings obtained from the literature regarding the characterization of rejuvenated binder blends (recycled binder blends with recycling agent) and rejuvenated asphalt mixtures (recycled asphalt mixtures with recycling agent). The last section discusses cost-effectiveness associated with the use of recycling agents.

Recycling Agent Rejuvenation Mechanisms

The commonly used term “rejuvenation” does not imply, from a chemical standpoint, the reversal of the oxidation process in RAP/RAS binders by the recycling agent. Instead, it indicates the effect of recycling agents in reversing aging in terms of rheology and performance characteristics (Tabatabaee and Kurth 2017). The process in which recycling agents soften and restore the rheological properties of the aged, recycled binder has been investigated in the literature. In general, the rejuvenation mechanism depends mainly on three key factors: *(1)* uniform dispersion of the base binder, recycled binder, and recycling agent within the asphalt mixture; *(2)* diffusion of the recycling agent into the recycled binder; and *(3)* compatibility between base binder, recycled binder, and recycling agent (Tran et al. 2012; Karlsson and Isacsson 2003).

Dispersion is mixing caused by physical processes, and the recycling agent will uniformly dissipate throughout the base and recycled binders in the asphalt mixture through mechanical mixing. Mechanical mixing at the plant is usually adequate to achieve uniform dispersion of the recycling agent within the mixture, and the dispersion is a function of mixing time; the longer the mixing time, the better the dispersion.

Diffusion is the process where a constituent moves from a higher concentration to a lower concentration. When the recycling agent is in direct contact with the recycled material, the aged binder tends to quickly absorb any hydrocarbon-type liquid in the recycling agent due to the diffusion mechanism. Carpenter and Wolosick (1980) suggested that the recycling agent diffuses into the aged binder according to the following four steps:

1. The recycling agent forms a very low viscosity layer that surrounds the aged binder covering the recycled material particles.
2. The recycling agent begins to diffuse into the aged binder outer-layer, and starts softening the aged binder. The amount of the recycling agent surrounding the recycled material particles decreases as the diffusion process continues.
3. With time, diffusion of the recycling agent into the aged binder continues, decreasing the viscosity of the inner-layer and increasing the viscosity of the outer-layer of the recycled material particle.
4. Equilibrium is approached after a certain time.

To verify this diffusion mechanism, Ma et al. (2015) performed staged extraction. In this process, recycling agents were added to RAP materials at 150°C

(302°F) for 1 minute; and after cooling down, the rejuvenated RAP was placed into a net basket and immersed in trichloroethylene solvent for 45 minutes to get the outer-layer asphalt. Then, the rejuvenated RAP was immersed again in a new trichloroethylene solvent for another 45 minutes to get the inner-layer asphalt. The same process was performed on RAP materials without recycling agent. Dynamic Shear Rheometer (DSR) test results indicated that for RAP materials without recycling agent, the values of $G^*/\sin\delta$ of the outer-layer and inner-layer asphalts were similar, indicating homogeneity. However, for the rejuvenated RAP, the $G^*/\sin\delta$ of the outer-layer was much smaller than that of the inner-layer, for all types of recycling agents, indicating that the diffusion of the recycling agents did not reach equilibrium.

To estimate when equilibrium is achieved, Carpenter and Wolosick (1980) also performed a staged extraction, plotting the penetration values at 25°C for each layer as a function of time after mixing. From the results, the authors suggested that the diffusion of the recycling agents into the aged binder occurred during mixing, construction, and a period of time after construction. Wang et al. (2017) utilized image analysis (an image stripping analysis program) to detect the asphalt covered area and uncovered area in virgin aggregates due to RAP addition, with and without recycling agents. The authors indicated that eight hours was enough for achieving optimum diffusion of the recycling agent.

Wang et al. (2017) and Oliver (1975) indicated that the rate of diffusion can be accelerated with increased mixing and compaction temperatures. Adding the recycling agent to recycled materials at room temperature will slow the diffusion mechanism, as compared to adding the recycling agents to the base binder and/or recycled materials at higher temperatures. In addition, the diffusion process is affected by the type and dose of the recycling agent, and the rheological properties of the aged binder. The diffusion of a less viscous recycling agent added in high dose to a softer aged binder is expected to be higher than the diffusion of a highly viscous recycling agent added in low dose to an extremely aged binder.

It is also important to highlight that the method of adding the recycling agent in the asphalt mixture has an influence on its diffusion, and thus its effectiveness in the asphalt mixture. Better diffusion of the recycling agent is expected when it is mixed with the recycled materials before combining them with the base binder and aggregate because there is then direct contact with the recycled material to facilitate diffusion into the aged binders. However, it is also important to note that this process is difficult to practically implement in an asphalt plant where typically the recycling agent is added to the base binder, and subsequently, the blend is added to the combination of virgin aggregate and the recycled materials (Tran et al. 2012).

Zaumanis et al. (2014a) underscored that incomplete diffusion of the recycling agent into the aged binder could cause pavement distresses. If the recycling agent does not fully diffuse into the aged binder, part of the aged binder will remain as black rock which may effectively lower the active binder content in the mixture and lead to a stiff, brittle mixture with increased risk of cracking distress. Concurrently, if the recycling agent partially diffuses into the aged binder before the pavement is opened to traffic, the inactive amount of recycling agent at the outer-layer of the aged binder film may provide a soft film coating the aggregate that under the effect of traffic loading may cause early rutting distress in the pavement.

Finally, compatibility between, base binder, recycled binder, and recycling agent is required for creating a homogeneous composite. Epps Martin et al. (2016) utilized an exudation droplet test originally developed by Shell Bitumen as an indication of asphalt binder compatibility with different types of recycling agents. Test results reported by Epps Martin et al. (2016) indicated incompatibility for some recycling agents (such as paraffinic oil) with apparent phase separation caused by exudation of the aromatic compounds. Other types of recycling agents (aromatic extract, tall oil, and re-refined lube oil) showed minimal or null phase separation of the aromatic compounds. These aromatic compounds are important in the rejuvenation process, as will be discussed subsequently.

The conclusion from these observations is that the efficiency of the recycling agent depends on both dispersion and diffusion processes and its compatibility with base and recycled binders. Therefore, quantifying these properties is of great importance to achieve ideal rejuvenation of recycled materials.

Factors Affecting the Effectiveness of Recycling Agents

The short- and long-term effectiveness of the recycling agent in rejuvenated binder blends and asphalt mixtures depends on a number of mix design factors such as the type and dose of the recycling agent; the type, source, and quantity of recycled materials; and the source and grade of the base binder. In addition, the recycling agent effectiveness also depends on production factors such as mixing time and temperature, and the method by which the recycling agent is incorporated in the mixture (i.e., added to the base binder or added directly to the recycled materials), as discussed previously Kaseer et al. 2017a; Kaseer et al. 2018a; Yin et al. 2017; Garcia Cucalon et al. 2017; Garcia Cucalon et al. 2018).

Recycling Agent Type

Recycling agent type affects the rejuvenation mechanisms and the chemical compatibility of the rejuvenated binder blend. Recycling agent manufacturers and suppliers produce and supply various types of recycling agents with different chemical bases and compositions. Recycling agents could be a single component or a composite; and in general, a composite recycling agent type is able to rejuvenate more severely aged binders and is more effective as compared to a single component recycling agent (Xu et al. 2018). There are currently several types of recycling agents commercially available, which can be categorized according to NCAT (2014) as paraffinic oils, aromatic extracts, tall oils, naphthenic oils, and triglycerides and fatty acids (derived from vegetable oils). Paraffinic oils are re-refined lubricating oils, aromatic extracts are refined crude oil products and traditional recycling agents with dominant polar aromatic oil components, tall oils are by-products of paper manufacturing and typically consist of fatty acids and resins, naphthenic oils are engineered hydrocarbons for asphalt modification, and vegetable oils typically consist of a mixture of glycerides and fatty acids. Additional engineered recycling agents, such as bio-based oils and modified vegetable oils, are continuously being produced and released to the market. Bio-based oils consist mainly of fatty amine derivatives and bio solvents, while modified vegetable oils are examples of composite recycling agents with basic vegetable oil component and added chemicals. Recycling agents in emulsion form are also available and can be used in the production of hot-mix asphalt mixtures, but they are most commonly used in cold in-place recycling. The majority of the recycling agents that are commercially available are proprietary, making it difficult to offer a detailed chemical description of their composition.

Previous studies indicated that the effect of recycling agents on recycled binder blends and asphalt mixtures varied significantly among different products (Kaseer et al. 2018a; Yan et al. 2014; Zaumanis et al. 2013; Zaumanis et al. 2014b; Zhou et al. 2015; Osmari et al. 2017). Zaumanis et al. (2014b) concluded that organic products (such as waste vegetable oil, organic oil, waste vegetable grease, and distilled tall oil) required much lower doses as compared to petroleum-based products (such as aromatic extract and waste engine oil) to deliver the same effect on PG (reduce the PG of recycled asphalt binders and/or mixtures). Osmari et al. (2017) also reported that waste cooking oil and castor oil required lower doses than petroleum-based products to deliver the same effect on viscosity of aged binders. Similar conclusions were reported by Kaseer et al. (2018a) where tall oils, vegetable oils, and bio-based oils required lower doses to reduce the high-temperature PG (PGH) of the recycled binder blend as compared to petroleum-based products (i.e., aromatic extracts). However, Ali (2015) reported that a bio-based oil and a petroleum distillate are the most powerful recycling agents in reducing the PGH and viscosity of aged binder as compared to other recycling agent types such as naphthenic base oil, paraffinic oil, and conventional motor oil. Ali (2015) also reported that a cationic water-based emulsion performed significantly better than an anionic emulsion. Nabizadeh et al. (2017) compared the effectiveness of three types of recycling agents (aromatic extract, tall oil, and soybean oil) on the performance of a recycled asphalt mixture with 65% RAP. The authors indicated that the aromatic extract was more effective in reducing the stiffness and increasing the cracking resistance as compared to the other recycling agents, as measured by the dynamic modulus and semi-circular bending tests.

While some authors have compared recycling agents based on their generic description, other authors have compared them according to their chemical composition. Cong et al. (2015) indicated that a recycling agent with a low asphaltene content (3.4%) and a high resin content (28.2%) had improved effectiveness in increasing the ductility of aged binders as compared to a recycling agent with a higher asphaltene content (13%) and a lower resin content (16.7%), both applied at the same dose. Espinoza-Luque et al. (2018) suggested using a recycling agent with a high aromatic fraction and a low concentration of asphaltenes such as a heavy paraffinic distillate solvent extract. This type of recycling agent was composed of mainly aromatic hydrocarbons (>75%) and virtually no asphaltenes. The authors indicated that using this type of recycling agent, at a doses of around 6%, significantly improved the intermediate-temperature cracking resistance of recycled asphalt mixtures, while also achieving adequate rutting resistance.

Aging of rejuvenated binder blends and asphalt mixtures could also result in chemical changes in the recycling agents, and subsequent reduced dispersive power of the maltene phase. Findings reported throughout the literature suggested that different types of recycling agents have dissimilar rheological changes with aging. A loss of recycling agent effectiveness with aging has been observed in rejuvenated binder blends and asphalt mixtures, and the extent of that loss depends upon the type and dose of the recycling agent Kaseer et al. 2017a; Yin et al. 2017; Ali 2015; Menapace et al. 2018a; Cavalli et al. 2018). Ali (2015) prepared different rejuvenated binders with a PGH of 67 and compared their aging rate to a PG 67-22 virgin binder, using PG measurements after Rolling Thin-Film Oven (RTFO), 20, 40, and 60 hours of Pressure Aging Vessel (PAV) aging. The author reported that two rejuvenated binders (one with emulsion (water-based) recycling agent and one with heavy paraffinic distilled solvent extract) aged slower than the PG 67-22 virgin binder, while other two rejuvenated binders (one with bio-based oil and one with petroleum distillate) aged faster than the PG 67-22 virgin binder. However, when the asphalt mixture was tested using the Texas Overlay Test (OT), Ali (2015) reported that rejuvenated asphalt mixtures with the emulsion (water-based) and the heavy paraffinic distilled solvent extract aged faster than the virgin mixture with PG 67-22 base binder, but still the rejuvenated asphalt mixtures had an equally good or better resistance to cracking (OT cycles) when compared with the virgin mixture after long-term aging.

When discussing recycling agent type, it is important to distinguish between softening agents and recycling agents. Some authors use both terms interchangeably; however, according to Roberts et al. (1996) and Tabatabaee (2015), a distinction between softening agents and recycling agents is necessary. While softening agents are clearly aimed at lowering the viscosity of aged binders, recycling agents are added to restore the physical and chemical properties of the aged binders, by restoring the asphaltene/maltene ratio. Tabatabaee (2015) compared softening agents and recycling agents and found that in terms of binder chemistry, oxidative aging increases polarity and molecular weight, converting the non-polar or solvent phase to a polar or associated phase. Softening agents will add low polarity and/or lower molecular weight aromatic, naphthenic, or paraffinic oils; and thus, will supplement the solvent phase in the asphalt colloidal structure. Recycling agents operate by a different mechanism and will break up asphaltene clusters and agglomerations caused by aging. As a result, recycling agents have an advantage over softening agents in terms of better dose efficiency in reducing stiffness, reversing the embrittlement of the aged binder, and shifting the aged binder viscoelastic response into an elastic response. Examples of softening agents are asphalt flux oil, lube stock, and slurry oil.

Recycling Agent Dose

The amount of recycling agent or dose aims to balance the performance of the rejuvenated asphalt mixture in terms of improving its cracking resistance without compromising its rutting resistance. For a particular type of recycling agent and recycled material, a less than sufficient dose may reduce the stiffness and brittleness of the recycled RAP/RAS binders, but may not have a noticeable effect in improving the cracking resistance of the asphalt mixture. Conversely, a recycling agent dose in excess of what is needed may soften the recycled RAP/RAS binders, improving significantly the cracking resistance, but causing inadequate rutting performance of the recycled asphalt mixture. An overdose of the recycling agents can also contribute to problems such as poor adhesion and increased stripping of the rejuvenated asphalt film from the aggregate (Zaumanis et al. 2013). The recycling agent dose can also affect the rheological and chemical changes of the rejuvenated asphalt mixture after long-term aging (Kaseer et al. 2017a; Yin et al. 2017). Therefore, it is important to carefully select the recycling agent dose for a particular combination and proportion of recycled materials to optimize performance.

Typically, the recycling agent dose is selected based on experience or the recommendation of the recycling agent manufacturer. However, the dose for a particular recycling agent type cannot be the same for mixtures with different types and quantities of recycled materials, since factors such as the base binder source and grade, the level of aging of the recycled materials, and their proportion in the mixture have an effect (Arámbula-Mercado et al. 2018a).

To determine the dose of the recycling agent, previous research efforts have used blending between base binders, recycled binders, and recycling agents, and established blending charts. In blending charts, changes in the penetration, viscosity, or PG of the recycled binder blends with increasing doses of the recycling agent were evaluated (Kaseer et al. 2018a). Some studies used blending charts based on the traditional viscosity and/or penetration of the rejuvenated binder blends with various amounts of recycling agents to select the dose (Yan et al. 2014; Zaumanis et al. 2013; Ali 2015; Little et al. 1981; Oliveira et al. 2013). Other recent studies have used the PG system: a minimum dose can be determined to ensure sufficient low-temperature cracking resistance (low-temperature PG (PGL)), while a maximum dose is set to ensure adequate rutting resistance (PGH) (Tran et al. 2012; Zaumanis et al. 2014b; Zhou et al. 2015; Arámbula-Mercado et al. 2018a; Shen and Ohne 2002; Shen et al. 2007; Karki and Zhou 2016).

These studies investigated first whether the blending rule was linear or non-linear (i.e., the reduction in PGL and PGH was linear or non-linear with increased recycling agent dose). Shen and Ohne (2002) reported a linear decrease in PGL and a non-linear decrease in PGH of recycled binder blends with increased recycling agent dose, while Tran et al. (2012) and Zaumanis et al. (2014b) reported a linear decrease in both PGH and PGL with increased recycling agent dose. Arámbula-Mercado et al. (2018a) verified a linear blending rule between recycling agent dose and both PGH and PGL (Figure 2). Zhou et al. (2015) reported a linear decrease in PGH (in recycled binder blends with RAS binder) with increased recycling agent dose only when the dose was 20% or less by weight of total binder (base and recycled binder). Beyond 20%, a non-linear decrease in PGH with dose was observed. Zhou et al. (2015) also recommended the dose that restored both the PGH and PGL of the recycled binder blend to that of the target binder PG. The target binder PG is the one required to satisfy climate and traffic requirements per the state DOT specification.

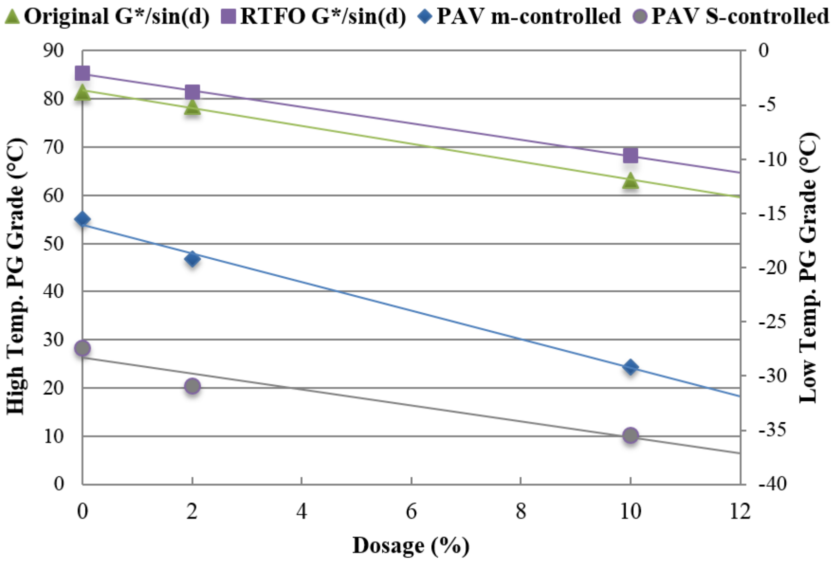

Figure 2. Linear blending rule between PGH/PGL and recycling agent dose (Arámbula-Mercado et al. 2018a).

Karki and Zhou (2016) reported that recycling agents have a greater influence on the PGL than on the PGH. Therefore, lower doses are required to restore PGL and higher doses are required to restore PGH. Arámbula-Mercado et al. (2018a) also reported that higher doses are required to restore PGH than PGL; and consequently, the dose to restore PGH can be selected, since it will ensure restoration of both PGH and PGL. The authors also reported that restoring PGL is not adequate to ensure long-term durability, based on the rheology of the binder blends. The authors recommended restoring (or matching) the continuous PGH of the recycled binder blend to that of the target binder PG. For this method, and for a target binder of PG 64-22 for instance, instead of restoring the PGH of the recycled binder blend to meet a PG 64 (with a PGH close to 69), the authors increased the dose to meet a continuous PGH of exactly 64°C. This approach has the advantage of being based only on PGH results from DSR testing that are less variable and require less effort in the laboratory as compared to PGL results that require Bending Beam Rheometer (BBR) testing. Garcia Cucalon et al. (2018) evaluated the rheology of rejuvenated binder blends (of different base binders, recycled binders, and recycling agent types) and reported that long-lasting rejuvenation is possible when the dose of the recycling agent is selected to match continuous PGH for the target climate. Similar conclusions were reported for rejuvenated binder blends (in terms of rheology) and rejuvenated asphalt mixtures (in terms of performance) (Kaseer et al. 2018a; Kaseer et al. 2018c).

Base Binder Grade and Source

In an attempt to mitigate the increased stiffness and brittleness of recycled asphalt mixtures, several state DOTs recommend the use of softer base binders, with relatively lower viscosity and lower grade (PGH and/or PGL), as compared to the target binder PG (NCAT 2009; McDaniel and Anderson 2001). Softer base binder can also be used along with a recycling agent. When a softer base binder is employed, a lower recycling agent dose is needed as compared to when using a more stiff base binder. This is true in particular when recycling agent dose is selected to restore PGL and/or PGH of the recycled binder blends, since the base binder is the largest component in the recycled binder blends and recycled asphalt mixtures when the RBR is below 0.5.

In addition to base binder grade, binder source also affects the performance of recycled and rejuvenated asphalt mixtures. In evaluating different asphalt binder sources, Anderson et al. (2011) suggested using the parameter ΔT_c as an indication of asphalt binder quality. ΔT_c refers to the difference in continuous PGL for stiffness and relaxation properties (i.e., the critical temperature when the creep modulus [S] equals 300 MPa minus the critical temperature when the stress relaxation [m-value] equals 0.30) from BBR testing. The authors suggested that asphalt binders with low (more negative) ΔT_c had less ductility and relaxation properties than asphalt binders with higher (less negative or positive) ΔT_c, and a maximum ΔT_c threshold of -5°C after 40 hours PAV aging was suggested to minimize the risk of aged-related cracking. The same concept applies to recycled and rejuvenated binder blends. A number of studies showed that rejuvenated binder blends with a high-quality base binder (less negative or positive ΔT_c) had superior characteristics as compared to blends with a low-quality base binder (more negative ΔT_c) as measured by binder blend rheology (Kaseer et al. 2018a; Garcia Cucalon et al. 2018) and by binder blend microstructural analysis using Atomic Force Microscopy. Kaseer et al. (2017a) showed that a rejuvenated asphalt mixture with a PG 64-28 base binder and a ΔT_c of +1.4 had significantly lower resilient modulus stiffness after long-term aging than the same mixture with a PG 64-22 base binder and a ΔT_c of -4.6.

Type, Source, and Quantity of Recycled Materials

The degree of aging, or stiffness, of the aged RAP/RAS binders is an influential factor that controls the effectiveness of the recycling agents in restoring certain physical and chemical properties of the aged binders (Kaseer et al. 2018a; Mogawer et al. 2013a; Epps Martin, A. et al. (2015); Karki and Zhou 2016). The higher the stiffness (and PG) of the aged binder, the higher the dose and the lower the viscosity of the recycling agent needed to restore the aged binder properties. Mogawer et al. (2013a) reported that as compared to the asphalt mixtures with RAP only, those that included RAS only or a combination of both RAP and RAS showed less significant reduction in dynamic modulus (|E*|) stiffness after incorporating the same dose of recycling agent. The poorer rejuvenating effectiveness of the recycling agent on RAS materials can be attributed to the fact that the RAS binder is more aged than the RAP binder. Epps Martin et al. (2016) indicated that recycling agents are more effective in rejuvenating RAP than RAS, and more effective in rejuvenating less heavily aged MWAS than TOAS materials. The average PGH of an extracted asphalt binder from MWAS is 131°C as compared to 178°C for an extracted asphalt binder from TOAS (Zhou et al. 2015). Arámbula-Mercado et al. (2018b) indicated that, due to the heavily aged nature of RAS binder, maximizing RAP content and minimizing RAS content to achieve a particular RBR is important to obtain adequate cracking resistance of rejuvenated asphalt mixtures.

The effectiveness of recycling agents is also dependent on the source of recycled materials. For instance, Kaseer et al. (2018a) reported that 9% recycling agent dose was required in a recycled binder blend with RAP and TOAS from New Hampshire and California, respectively, while a 14% recycling agent dose was required in a similar blend but with RAP and TOAS from Texas, to deliver the same effect on PGH of the recycled binder blend. This was due to the use of extremely aged TX RAP and TOAS (PGH of 106.6 and 178°C, respectively) in the second recycled binder blend as compared to the less aged NH RAP and CA TOAS (PGH of 90.2 and 166°C, respectively) in the first recycled binder blend.

When discussing the source of recycled materials, it is important to highlight the differences between recycled unmodified binders and recycled modified binders. Tao et al. (2010) evaluated the rejuvenation of aged polymer modified binder (PMB) with SBS (styrene-butadiene-styrene block copolymers) using two types of recycling agents: a typical recycling agent for unmodified binders and a TPS^{TM} recycling agent (recycling agent with a modifying additive contains a thermoplastic elastomer as a main ingredient). The authors compared the rejuvenation of aged PMB after 5, 10, 15, and 20 hours of PAV versus rejuvenation of unaged PMB through penetration grading tests (penetration, softening point, ductility, and elastic recovery) and PG grading tests (DSR, BBR, and Direct Tension Tester (DDT)). The authors concluded that the aging rate of rejuvenated PMB (with a typical recycling agent) was much higher than that for the unaged PMB, which indicated that the long-term durability of the rejuvenated PMB is in doubt. However, the aging rate of rejuvenated PMB with the TPS^{TM} recycling agent was lower than that for the unaged PMB, indicating even better long-term durability. This experiment by Tao et al. (2010) showed that commonly used recycling agents could not restore the SBS modified PMB, but a recycling agent together with a modifying additive (such as TPS^{TM}) could restore the characteristics of aged PMB.

Finally, the quantity of recycled materials also affects the performance of rejuvenated asphalt mixtures. As recycled materials content increases, higher doses of recycling agent are required. However, even if higher doses were used to accommodate the inclusion of higher recycled materials content, the effectiveness of the recycling agent can be jeopardized with aging. Kaseer et al. (2017a) measured the percentage reduction in mixture stiffness (i.e., resilient modulus) for rejuvenated asphalt mixtures versus corresponding recycled asphalt mixtures without recycling agent. The authors compared the percentage reduction in stiffness before and after long-term oven aging to evaluate the rejuvenating effectiveness of the recycling agents due to aging. The authors reported that the effectiveness of the recycling agents in reducing the stiffness of the recycled asphalt mixtures reduced with long-term aging; however, as compared to other recycled asphalt mixtures with lower RBR, the recycled asphalt mixture with the highest RBR (0.5) showed the most significant reduction in recycling agent effectiveness after long-term aging, even though this mixture had more than double the dose of recycling agent as compared to other mixtures.

Mixing Time and Production Temperature

As discussed previously, the dispersion of recycling agent throughout the base and recycled binders is a function of mixing time. Therefore, prolonged mixing time is preferred to ensure that the recycling agent is uniformly distributed throughout the asphalt mixture.

Mixing temperature affects the viscosity of asphalt binders, and low viscosity is important to ensure that the asphalt binder will be fluid enough to cover and adhere to the aggregates. RAP binders in recycled asphalt mixtures require higher mixing temperatures, usually around 200°C (390°F), as compared to virgin mixtures, to achieve fluid asphalt binder. Zhou et al. (2013) reported that the production temperature for mixtures with MWAS and TOAS materials from Texas should be around 260°C (500°F) and 350°C (662°F), respectively, so the recycled binders in these materials can easily flow and coat the aggregates. However, such high production temperatures are impractical for asphalt plants due to the increased cost for energy and maintenance caused by critical wear of certain components. In addition, high production temperatures increase oxidative aging of the base binder.

A benefit of adding recycling agents is that such high production temperatures can be avoided because the recycling agent will soften the recycled binder, and the binder blend will be fluid enough to coat the aggregate particles (Romera et al. 2006). A slight increase in production temperature, as compared to production temperature of virgin mixtures, will improve the recycling agent effectiveness by accelerating its rate of diffusion into the aged binder, which in turn helps the binder blend easily flow, cover, and adhere to the aggregates. Zaumanis et al. (2013) recommended increasing the mixing and compaction temperatures for some recycling agent types by approximately 22°C as compared to the base binder. This increase in mixing and compaction temperatures is more practical as compared to the required increase when recycling agents are not present, as discussed previously.

Recycling Agent Incorporation Method

The method of adding the recycling agent to the recycled materials has an influence on its diffusion, and thus, its effectiveness in the recycled asphalt mixture. Better diffusion is expected when the recycling agent is mixed with the recycled materials before combining them with the base binder and virgin aggregate. However, this process is difficult to implement in an asphalt plant due to the increase in production costs that such a procedure would require. Nevertheless, some asphalt plants are adding the recycling agents directly to the recycled materials. In a report published by the National Asphalt Pavement Association (NAPA) in 2015 (West and Copeland 2015) on practices in Japan for high RAP content asphalt pavements, the use of recycling agents is common, and the recycling agents are mixed and conditioned with heated RAP in a small pugmill for several hours prior to mixing with the hot virgin aggregate and the base binder in order to allow the recycling agent to diffuse into the heated aged RAP binder. Production of high RAP content mixtures in the U.S. is quite different, and the most obvious contrast in mixture production as compared to that in Japan, according to NAPA, is the method of heating RAP and mixing and conditioning the hot RAP with the recycling agent for several hours prior to mixing with the heated virgin aggregate and base binder. Applying these practices in the U.S. would require modifications to existing asphalt plants and equipment, but these practices appear to be promising and could result in better recycling agent effectiveness by providing direct contact with the RAP material, and subsequent increased diffusion.

Table 1 provides a summary of the materials selection, mix design, and production factors that affect the effectiveness of recycling agents in rejuvenated binder blends and asphalt mixtures.

Table 1. Factors Affecting the Effectiveness of Recycling Agents.

Factor	Rejuvenation Mechanism	Chemical Compatibility	Long-term Performance	Cracking and Rutting Resistance Balance
Recycling Agent Type	✓	✓	✓	
Recycling Agent Dose			✓	✓
Base Binder Grade and Source		✓	✓	
Type, Source, and Quantity of Recycled Materials			✓	✓
Mixing Time and Production Temperature	✓			
Recycling Agent Incorporation Method	✓			

Characterizing Rejuvenated Binder Blends and Asphalt Mixtures

The previous sections discussed how the recycling agent type and dose, properties of the base and recycled binders, production temperature, and recycling agent incorporation method have an effect on recycling agent effectiveness in restoring aged binder rheology in mixtures with recycled materials, and particularly those with high RBRs. If an adequate type of recycling agent is added in the appropriate dose at a suitable temperature for a sufficient time period, a rejuvenated asphalt mixture with adequate performance can be produced. Conversely, if the recycling agent dose is not balanced and sufficient blending is not achieved, the recycling agent may not improve the performance of the aged binder or may even adversely affect the recycled mixture performance.

Recycling agents can have varying effects on the chemical, microstructural, and rheological characteristics of the recycled binder blends, as well as on the performance of the asphalt mixtures; and these effects require careful evaluation through laboratory tests. This evaluation includes typical tests used for binder blends and asphalt mixtures, or other methods developed through research. Various research studies have reported the characteristics of rejuvenated binder blends and asphalt mixtures, and this section describes some of them.

Rejuvenated Binder Blends

During the process of asphalt binder oxidative aging, changes occur in the chemical bonds and molecular structure of the asphalt binder including the infrared active carbonyl C=O bonds. Therefore, aging of asphalt binders can be quantified by measuring the change in the amount of carbonyl C=O bonds using Fourier Transform Infrared Spectroscopy (FT-IR), and carbonyl area (CA) growth rate can be used as a surrogate for asphalt binder oxidative aging (Jemison et al. 1992). Some studies indicated that the inclusion of recycling agents had no effect on increasing the oxidation kinetics of recycled binder blends (Yin et al. 2017; Epps Martin et al. 2016).

SARA^{TM} (saturates, aromatics, resins, asphaltenes) fractionation is a frequently used technique for chemical compositional analysis of asphalt binders from different crude sources and binders subjected to various treatments (Yu et al. 2014). In this test, asphaltenes and maltenes are separated, and maltenes are later separated into saturates, aromatics, and resins. Yu et al. (2014) observed significant changes in the SARA fractions due to the addition of recycling agent to aged binder. Adding an aromatic extract recycling agent introduced more saturates and aromatics which, consequently, lowered the fractions of resins and asphaltenes as compared to the aged binder. The authors concluded that changes in the chemical fractions among the aged and rejuvenated binders were responsible for the rejuvenating effect resulting from the addition of the recycling agent. Similar observations were reported where the quantity of aromatics increased and the quantity of asphaltenes decreased with the incorporation of petroleum-based, waste cooking oil, and castor oil recycling agents (Osmari et al. 2017). Garcia Cucalon et al. (2017) compared SAR-AD^{TM} (Saturates, Aromatics, Resins, Asphaltene Determinator) and Differential Scanning Calorimetry (DSC) experiments to rheology measurements (DSR testing). DSC provides important parameters such as glass transition temperature and the range of melting temperatures of crystallites, which are important in studying the thermal behavior of asphalt binders, particularly at low temperatures. While DSC and DSR measurements showed a softening effect upon rejuvenation, the SAR-AD^{TM} compatibility indices did not show clear distinction when the recycling agents were incorporated.

Atomic force microscopy (AFM) has been previously used to investigate the microstructure of asphalt binders using standard methods. The surface microstructure of asphalt binders provides insights about molecular mobility, as it depends on the molecular interactions among different chemical species. In a typical microstructure of asphalt binder obtained from the AFM analysis, three main constituents can be observed: the catanaphase (bee-structure), paraphase, and periphase (Osmari et al. 2017; Veytskin et al. 2015; Loeber et al. 1998). Of these constituents, the most important regarding aging and rejuvenation is the "bee-structure". In most previous studies, the appearance of the “bee-structure” has been attributed to asphaltene content (Haghshenas et al. 2016, Loeber et al. 1998; Zhang et al. 2011), despite the fact that some studies suggested that some asphalt binders still showed “bee-structure” after asphaltenes were removed (Hung and Fini 2015). Osmari et al. (2017) indicated that aged binders generally presented larger “bee-structure” than virgin binders, and Haghshenas et al. (2016) showed that the addition of recycling agents to aged binders reduced the size and number of “bee-structures”, and these “bee-structure” also appeared in small chains with much smaller width than those in aged binders. Yu et al. (2014) reported that the addition of an aromatic extract recycling agent to aged binder resulted in more significant morphological changes (formation of a “bee-structure” similar to that in virgin binders) as compared to the addition of a waste vegetable oil recycling agent on the same aged binder at the same dose. This can be attributed to the fact that the aromatic extract recycling agent is petroleum-based, and its chemistry is closer to that of the maltene fraction in the asphalt binder. Menapace et al. (2018b) showed the ability of recycling agents to diffuse into recycled binders and increase molecular mobility through AFM testing. Improved binder blend rheology can be attributed to increased molecular mobility.

Multiple stress creep recovery (MSCR) and linear amplitude sweep (LAS) tests were performed by Mogawer et al. (2013a) to characterize fatigue of recovered asphalt binders from mixtures containing RAP and RAS, with and without recycling agents. Analysis of the master curves of the recovered asphalt binders were correlated with the data resulting from MSCR and LAS tests and led to the conclusion that hardness of the aged asphalt binders reduced with the incorporation of recycling agents. The MSCR results indicated that adding the recycling agent to base binders increased the non-recoverable creep compliance, while the results from the LAS test showed an increased number of cycles to failure, as an indication of the softening effect of the recycling agent.

DSR frequency sweep tests have been performed at different temperatures and frequencies on recycled and rejuvenated binder blends to explore their fundamental rheological properties (i.e., shear complex modulus $|G^*|$ and phase angle δ) which represent both binder blend stiffness and embrittlement. Larger values of $|G^*|$ correspond to stiffer asphalt binders, while larger values of δ correspond to a larger viscous component of the complex modulus. The inclusion of recycled materials 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 reversal of the impact of aging on asphalt, from a rheological standpoint, the inclusion of recycling agents is expected to reduce $|G^*|$ and increase δ (Kaseer et al. 2018a). A number of studies indicated this effect of recycling agents in reducing $|G^*|$ and increasing δ (Kaseer et al. 2018a; Yin et al. 2017; Osmari et al. 2017; Oliveira et al. 2013; Karki and Zhou 2016; Yu et al. 2014; Grilli et al. 2017). Yu et al. (2014) indicated that the addition of recycling agents into artificially aged binders decreased $|G^*|$ and increased δ to different extents, depending on both the sources of the artificially aged binders and the recycling agent types. The authors indicated that a waste vegetable oil recycling agent had more impact in reducing |G*| and increasing δ as compared to an aromatic extract (petroleum-based) recycling agent, both used at the same dose. Osmari et al. (2017) indicated that waste cooking oil and castor oil recycling agents had more impact in reducing |G*| but similar impact on δ as compared to the petroleum-based recycling agent,. Haghshenas et al. (2016) indicated that a tall oil recycling agent had more impact in reducing |G*| than soybean oil and petroleum-based types of recycling agents.

In addition to the use of |G*| and δ as individual parameters, they can also be combined in a Black space diagram with two Glover-Rowe (G-R) damage curves: one with $|G^*| \cos^2 \delta / \sin \delta = 180\ kPa$ and the other with $|G^*| \cos^2 \delta / \sin \delta = 600\ kPa$. The former threshold indicates damage initiation or onset of cracking, while the latter threshold refers to significant damage (i.e., cracking). The G-R parameter was originally defined by Glover et al. (2005) and reformulated for greater practical use by Rowe (2011), in a discussion of Anderson et al. (2011), and has been successfully utilized to assess the effectiveness of recycling agents in restoring the rheology of aged recycled binders (Kaseer et al. 2018a; Yin et al. 2017; Garcia Cucalon et al. 2017; Zhou et al. 2015; Arámbula-Mercado et al. 2018a; Karki and Zhou 2016). The data plotted in the Black space diagram corresponds to |G*| and δ as measured at 0.005 rad/s and 15°C by applying a 0.1% strain on 8-mm parallel plate geometry samples, and typically measured after RTFO and PAV aging. Therefore, the Black space diagram offers an indication of the long-term cracking resistance at intermediate temperature. Figure 3 is an example of a Black space diagram of recycled and rejuvenated binder blends (Kaseer et al. 2018a).

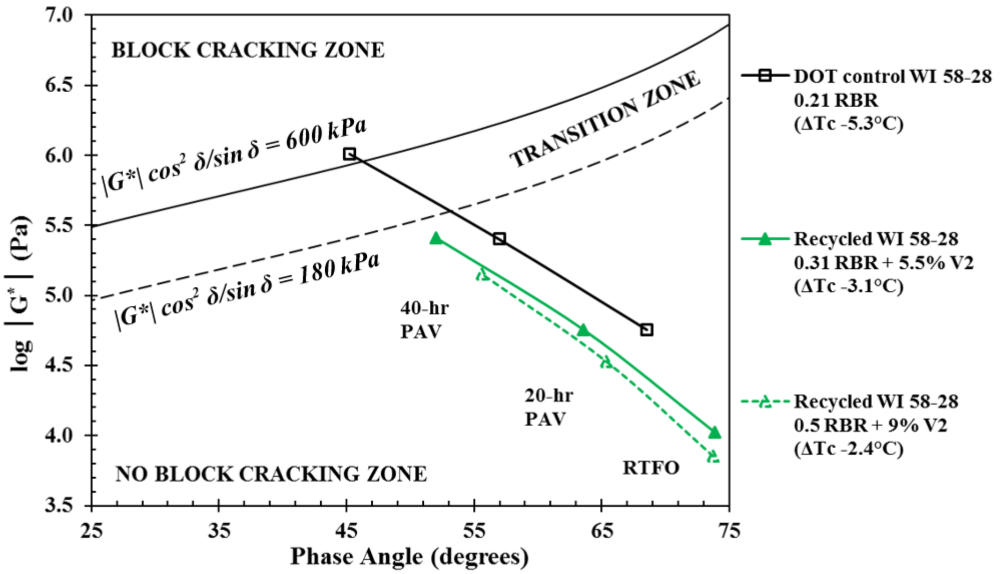

Figure 3. |G*| and δ in Black space for the recycled and rejuvenated binder blends with a target PG 58-28 climate (Kaseer et al. 2018a).

Yin et al. (2017) indicated that recycling agent addition reduced |G*| and increased δ of recycled binder blends, but the rejuvenating effectiveness of recycling agents diminished with long-term aging. Similar conclusions were reported by Garcia Cucalon et al. (2017) with diminished rejuvenation effectiveness upon long-term aging, where there was a rapid increase in |G*| and decrease in δ with aging as compared to recycled blends without recycling agent. Nevertheless, all rejuvenated binder blends showed improved performance (lower |G*| and higher δ) as compared to recycled binder blends without recycling agent. Arámbula-Mercado et al. (2018a) indicated that adding recycling agents at high doses yielded acceptable restoration of the recycled binder blend properties (lower |G*| and higher δ) with sustained benefits after long-term aging, even when rejuvenated binder blends with high RBR were compared to recycled binder blends (without recycling agents) with lower RBR; corroborating the added value of using recycling agents to increase the RBR in asphalt mixtures.

In addition to |G*| and δ, other DSR frequency sweep parameters have been used to assess the effectiveness of recycling agents, including rheological index (R), crossover frequency (ω_c), and crossover temperature ($T_{\delta=45^\circ}$) (Garcia Cucalon et al. 2018; Grilli et al. 2017). Grilli et al. (2017) concluded that rejuvenated binders tend to age faster than virgin binders as observed by changes in rheological parameters such R, ω_c, and |G*|. Garcia Cucalon et al. (2018) reported that long-lasting rejuvenation is possible when the dose of the recycling agent is selected to match continuous PGH for the target climate as observed by measuring the crossover temperature ($T_{\delta=45^\circ}$) of rejuvenated binder blends.

Rejuvenated Asphalt Mixtures

Many studies indicated that adding RAP and/or RAS increased the stiffness of asphalt mixtures and incorporating recycling agents can balance that effect, as measured by Dynamic Modulus (|E*|) and Resilient Modulus (M_R) tests Kim et al. 2007; Carvajal Munoz et al. 2015; Kaseer et al. 2017a; Tran et al. 2012; Mogawer et al. 2013a; Im et al. 2014a; Mogawer et al. 2013b). Mogawer et al. (2013a) found that as compared to recycled asphalt mixtures with RAP only, those that included RAS showed less significant reduction in |E*| stiffness after incorporating the recycling agent. Haghshenas et al. (2016) reported that a petroleum-based recycling agent had the most impact in reducing |E*| of the recycled asphalt mixture with 65% RAP as compared to soybean oil and tall oil recycling agents. Kaseer et al. (2017a) also reported a significant reduction in the stiffness of recycled asphalt mixtures with high RBR due to the addition of recycling agents, but the effectiveness of the recycling agent in reducing the stiffness diminished with long-term aging of the asphalt mixtures.

Similar to the effect on the stiffness of recycled asphalt mixtures, the addition of a recycling agent can effectively improve the intermediate-temperature cracking resistance of recycled asphalt mixtures as reported by (Im et al. 2014a; Yan et al. 2014; Yin et al. 2017; Espinoza-Luque et al. 2018; Kaseer et al. 2017b) in a variety of tests such as the Indirect Tensile (IDT) Strength Test, the Texas OT, Semi-Circular Bending (SCB), the Beam Fatigue Test (Four-Point Bending Test), and the Illinois Flexibility Index Test (I-FIT). However, the effectiveness of the recycling agents in improving cracking resistance of the rejuvenated asphalt mixtures also diminished with long-term aging as reported by (Yin et al. 2017; Arámbula-Mercado et al. 2018a) Kaseer et al (2017b) also verified the long-term recycling agent effectiveness in reducing the stiffness and improving the intermediate-temperature cracking resistance of rejuvenated asphalt mixtures when the recycling agent dose was designed to match the continuous PGH of the rejuvenated binder blend to that of the target binder PGH specified based on climate and traffic requirements, as recommended by Arámbula-Mercado et al. (2018a).

Recycled asphalt mixtures with high RBRs typically appear to develop thermal stresses more quickly than virgin mixtures, and therefore have less resistance to thermal cracking. Adding recycling agents can effectively improve the low-temperature cracking resistance of these mixtures as reported by Tran et al. 2012; Mogawer et al. 2013a; Yan et al. 2014; Epps Martin, A. et al. (2016); Zaumanis et al. 2013; Shen et al. 2004) in a variety of tests such as the Thermal Stress Restrained Specimen Test (TSRST), the IDT

Strength Test, the Three-Point Bending Test, and the Uniaxial Thermal Stress and Strain Test (UTSST). Zaumanis et al. (2013) utilized the IDT creep compliance test at −10°C, IDT strength, and fracture energy to characterize rejuvenated asphalt mixtures containing 100% RAP in terms of low-temperature cracking resistance. The authors indicated that the asphalt mixtures with less stiffness were less likely to develop low-temperature cracking, as expected. The authors also found that the IDT creep compliance increased due to the addition of the recycling agent, and thus, increasing low-temperature cracking resistance. The increase in IDT creep compliance varied among the different recycling agent types. Similarly, an increase in IDT strength at low temperatures was reported for some types of recycling agents, while other types caused a decrease in the tensile strength; thus, the effect was dependent on recycling agent type. Most recycled asphalt mixtures with recycling agents yielded an increase in fracture energy when compared to ones without recycling agents.

Recycled asphalt mixtures typically have higher stiffness compared to virgin mixtures, and thus have higher rutting resistance (Mogawer et al. 2012; Xiao et al. 2007; West et al. 2009; Zhao et al. 2012; Hussain and Yanjun 2012). Due to the effect of recycling agents in reducing the stiffness of asphalt mixtures, rutting susceptibility may increase for rejuvenated asphalt mixtures as observed by several studies (Tran et al. 2012; Mogawer et al. 2013a; Espinoza-Luque et al. 2018; Arámbula-Mercado et al. 2018a; Shen et al. 2007; Uzarowski et al. 2010). However, not all mixtures with recycling agents will fail to meet the rutting resistance requirements per state DOTs and/or highway agency requirements (Tran et al. 2012; Zaumanis et al. 2013; Espinoza-

Luque et al. 2018). An important factor affecting the rutting resistance of rejuvenated asphalt is the recycling agent dose. Arámbula-Mercado et al. (2018a) indicated that excessive recycling agent dose will significantly soften the base and recycled binders in the asphalt mixture and will negatively impact mixture resistance to rutting. Kaseer et al. (2018a) evaluated the rutting resistance of rejuvenated asphalt mixtures using the Hamburg Wheel-Track Testing (HWTT) and Asphalt Pavement Analyzer (APA), and the authors reported adequate rutting resistance when the recycling agent dose was designed to match the continuous PGH of the rejuvenated binder blend to that of the target binder PGH specified based on climate and traffic requirements.

Besides recycling agent dose, there are other factors that affect the rutting resistance of rejuvenated asphalt mixtures such as recycling agent type and the degree of aging of the recycled binder, particularly the extremely aged MWAS and TOAS binders as compared to RAP binders. When recycling agents are used, and if the recycling agent type is compatible; the RAP binder can be softened, and thus, will be more fluid and blend with the base binder. However, for the MWAS/TOAS binders, because of their very high stiffness, the recycling agent may not soften them to be fluid enough to blend with the base binder. In this case, and when the MWAS/TOAS binders act like a “black rock”, the recycling agent will likely over soften the base binder, and rutting issues may arise. Rutting susceptibility in this case will be further exacerbated with the use of softer base binders.

Table 2 provides a summary for the effect of recycling agent addition on rejuvenated binder blends and asphalt mixtures.

Table 2. Effect of Recycling Agents on Rejuvenated Binder Blends and Asphalt Mixtures.

Rejuvenated Binder Blends	
Binder Property [Parameter] (Testing Equipment)	**General Observations**
Oxidation kinetics [CA growth rate] (FT-IR)	No effect on oxidation kinetics
Chemical compositional (SARA^{TM}, SAR-AD^{TM})	No clear effect
Microstructure (AFM)	Morphological changes, and improved molecular mobility mostly depending on recycling agent type
Rheology [MSCR, LAS] (DSR)	Reduction in hardness of the aged asphalt binders
Rheology [$\lvert G^*\rvert$, δ, G-R] (DSR)	Reduction in $\lvert G^*\rvert$ and G-R, and improvement in δ depending on recycling agent type and dose, and recycled materials source and quantity
Rheology [$T_{\delta=45^\circ}$] (DSR)	Reduction in $T_{\delta=45^\circ}$, and improved binder rheology mostly depending on recycling agent type and dose
Rejuvenated Asphalt Mixtures	
Mixture Performance [Parameter] (Testing Equipment)	**General Observations**
Stiffness [$\lvert E^*\rvert$, M_R]	Reduction in stiffness depending on recycling agent dose and recycled materials type and quantity
Intermediate-temperature cracking resistance (OT, IDT, SCB, I-FIT)	Improved cracking resistance, mostly depending on recycling agent dose
Low-temperature cracking resistance (TSRST, IDT, UTSST)	Improved cracking resistance, mostly depending on recycling agent dose
Rutting resistance (HWTT, APA)	Adequate rutting resistance, depending on recycling agent dose and recycled materials type and quantity

Cost-Effectiveness Associated with the Use of Recycling Agents

According to Copeland (2011), among the four cost categories for asphalt production (materials, plant production, trucking, and lay down), the most expensive production cost category is materials, comprising 70% of the cost to produce asphalt mixtures. The use of large quantities of recycled materials can significantly reduce the cost of asphalt mixtures. However, for most state DOTs, use of a softer base binder (lower PG) is required in asphalt mixtures with more than 30% RAP content to compensate for the aged RAP binder. Furthermore, the use of a softer base binder cannot guarantee adequate performance of the recycled asphalt mixture in the field; and thus, maintenance costs could increase. In these cases, additional expenses for contractors in terms of purchasing a softer asphalt binder grade and spending more in maintenance discourage contractors to produce asphalt mixtures with high RAP contents because the savings from producing these mixtures may be outweighed by the increased expenses.

Epps Martin et al. (2016) performed an economic analysis, using material prices in Texas, U.S., and identified cost savings associated with increasing RAP contents in recycled asphalt mixtures from 20 to 40%. When considering the price of base binders, virgin aggregates, RAP, recycling agents, along with the cost information for transportation of materials; the additional savings associated with increasing the RAP content from 20 to 40% (with the use of recycling agent to achieve adequate performance) was about $10.00 per ton of asphalt mixture or about 15% of the production cost.

Im and Zhou (2014b) performed a simple cost analysis, using material prices in Texas, U.S., to compare the cost of an asphalt mixture with virgin materials (virgin binder and aggregate) to that of a similar asphalt mixture but with 19% RAP and a recycling agent. The cost analysis showed an approximate $42.8 per ton cost for the virgin mixture as compared to $35.7 per ton for the recycled asphalt mixture with recycling agent, which represent about a 16% cost saving.

Zaumanis et al. (2016) indicated that the cost per ton of a recycled asphalt mixture with 100% RAP (with the use of recycling agent to achieve adequate performance) was reduced between 50 to 70% as compared to that for a virgin mixture without RAP, as shown in Figure 4, using 2014 material prices in New Jersey, U.S.

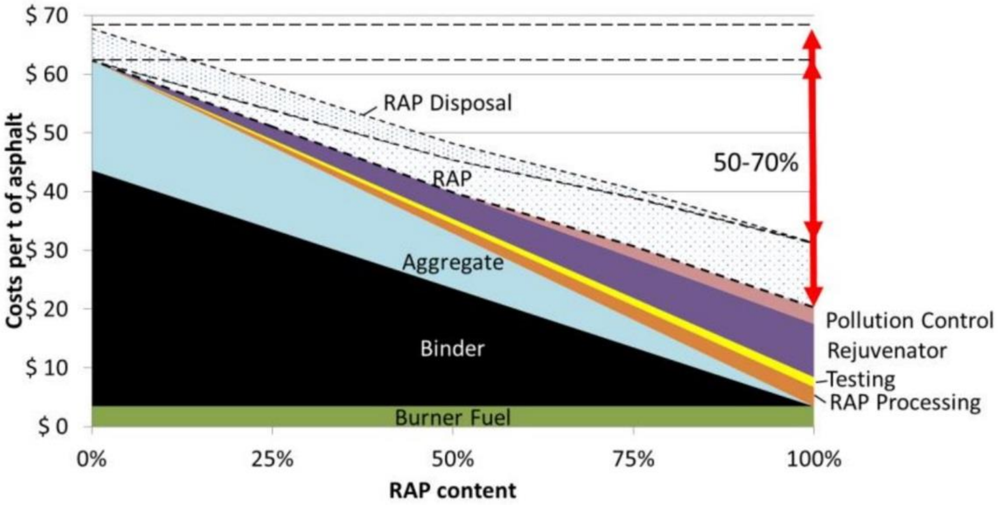

Figure 4. Material related costs of virgin and 100% RAP mixtures (Zaumanis et al. 2016).

A cost analysis carried out by Veeraragavan (2016), using material prices in Maine, U.S., identified a considerable cost savings accomplished by using high RAP contents and recycling agents. When considering the price of base binders, virgin aggregates, RAP, and recycling agents; the authors observed savings of 40% in total cost when increasing the RAP content from 0 to 50% (with the use of a waste vegetable oil recycling agent), and a savings of 34% when increasing the RAP content from 0 to 50% (with the use of a tall oil recycling agent).

Conclusions

Economic and environmental benefits drive the inclusion of large quantities of RAP and RAS in asphalt mixtures. However, due to the stiff and brittle nature of the asphalt binder in these materials, recycled asphalt mixtures are usually less workable, difficult to compact in the field, and prone to cracking, raveling, and other durability-related pavement distresses as compared to their virgin mixture counterparts. Recycling agents are products designed to restore the rheological properties of RAP/RAS binders by restoring the original asphaltenes to maltenes ratio, reducing the size of asphaltene clusters, improving the dispersive power of the continuous maltene phase, and increasing molecular mobility. The use of recycling agents in recycled asphalt mixtures is associated with several advantages including improvements in workability and performance, as well as economic benefits. If the RAP/RAS binders are properly "rejuvenated", higher recycled materials contents can be utilized in producing new asphalt mixtures without compromising their performance.

Considering the survey information from the existing literature, it was concluded that most state DOTs and contractors do not use, or do not allow using, recycling agents. The main barriers were lack of expertise in using recycling agents, lack of standard test methods or procedures for characterizing and selecting the type and dose of recycling agents, and lack of tests and criteria to evaluate the performance of rejuvenated asphalt mixtures. In addition, literature references mention concerns regarding the long-term durability of the rejuvenated asphalt mixtures. The fact that most state DOTs and contractors do not use recycling agents, despite the many advantages they offer, highlights the importance of addressing the challenges previously mentioned to encourage the utilization of these products in an effort to increase the RAP/RAS content in asphalt mixtures.

In summary, studies presented thus far demonstrated that the short- and long-term effectiveness of recycling agents in recycled binder blends and asphalt mixtures depends on a number of mix design factors such as the type and dose of the recycling agent; the type, source, and quantity of recycled materials; and the source and grade of the base binder. In addition, recycling agent effectiveness also depends on production factors such as mixing time and production temperature, and the method by which the recycling agent is incorporated in the asphalt mixture. Therefore, the importance of appropriate materials selection and their combinations in producing recycled asphalt mixtures with large quantities of recycled materials should be considered, and practice-ready guidelines are needed for materials selection/optimization, design, evaluation, and production of these mixtures.

Overall, it is evident that some challenges need to be addressed. The current classification system for recycling agents, detailed in ASTM D4552, is based on kinematic or capillary viscosity at 60°C (140°F), flash point, and viscosity ratio with short-term aging. These tests were designed to classify traditional petroleum-based recycling agents used when the standard was developed. However, with more engineered recycling agents products being released to the market every year, rheological and chemical properties of different types of recycling agents need to be investigated, with long-term aging, and using modern equipment as compared to old tests prescribed in ASTM D4552. In addition, the vast majority of available studies on recycling agents were done using unmodified asphalt binders. Limited studies show that typical recycling agents are not able restore the rheological properties of polymer modified binders. Thus, research is needed to investigate the effect and interaction of recycling agents on polymer modified binders.

It is noteworthy that there are several ongoing national and state-level research projects with the objective of evaluating the effectiveness of recycling agents and overcoming some of the challenges identified previously. Therefore, it is expected that new information will be available in the next few years, which will contribute to the goal of increasing recycling agent utilization and producing cost-effective rejuvenated asphalt mixtures with high recycled materials contents that provide adequate performance.

References

Ali, H (2015) Long-Term Aging of Recycled Binders. Florida Department of Transportation, Tallahassee, FL.

Altgelt, K. H., and Harle, O. L. (1975) “The effect of asphaltenes on asphalt viscosity.” Industrial & Engineering Chemistry Product Research and Development, Vol. 14, No. 4, pp. 240−246.

Anderson, R. M., G. N. King, D. I. Hanson, and P.B. Blankenship (2011) “Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking.” Journal of the Association of Asphalt Paving Technologists, Vol. 80, pp. 615-649.

Arámbula-Mercado, E., A. Epps Martin, and F. Kaseer (2018b) “Case study on balancing mixtures with high recycled materials contents.” Advances in Materials and Pavement Performance Prediction, proceedings, pp. 239-242.

Arámbula-Mercado, E., F. Kaseer, A. Epps Martin, F. Yin, and L. Garcia Cucalon (2018a) “Evaluation of Recycling Agent Dosage Selection and Incorporation Methods for Asphalt Mixtures with High RAP and RAS Contents.” Construction and Building Materials, Vol. 158, pp. 432-442.

Carpenter, S. H., and J.R. Wolosick (1980) “Modifier Influence in the Characterization of Hot-Mix Recycled Material.” Transportation Research Record: Journal of the Transportation Research Board, No. 777, pp. 15-22.

Carvajal Munoz, J. S., F. Kaseer, E. Arambula, and A. Epps Martin. (2015) “Use of the Resilient Modulus Test to Characterize Asphalt Mixtures with Recycled Materials and Recycling Agents.” Transportation Research Record: Journal of the Transportation Research Board, No. 2506, pp. 45–53.

Cavalli, M. C., M. Zaumanis, E. Mazza, M. N. Partl, and L. D. Poulikakos (2018) “Effect of ageing on the mechanical and chemical properties of binder from RAP treated with bio-based rejuvenators” Composites Part B, Vol. 141, pp. 174-181.

Cong, P., W. Luo, P. Xu, and H. Zhao (2015) “Investigation on recycling of SBS modified asphalt binders containing fresh asphalt and rejuvenating agents”. Construction and Building Materials, Vol. 91, pp. 225-231.

Copeland, A. (2011) Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice. Report No. FHWA-HRT-11-021, Office of Infrastructure Research and Development Federal Highway Administration, 55 p.

Davidson, D., W. Canessa, and S. Escobar (1977) “Recycling of Substandard or Deteriorated Asphalt Pavements -A Guideline for Design Procedures.” Journal of the Association of Asphalt Paving Technologists, Vol. 46.

Davis, C., and C. Castorena (2015) “Implications of Physico-Chemical Interactions in Asphalt Mastics on Asphalt Microstructure” Construction and Building Materials, Vol. 94, pp. 83–89.

Dunning, R. and R. Mendenhall (1978) “Design of Recycling Asphalt Pavement and Selection of Modifiers.” ASTM STP 662.

Epps Martin, A. et al. (2015) The Effects of Recycling Agents On Asphalt Mixtures with High RAS and RAP Binder Ratios. NCHRP Interim Report, National Cooperative Highway Research Program, Washington, DC. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3645 (As of July 2018)

Epps Martin, A. et al. (2016) The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios. NCHRP Interim Report, National Cooperative Highway Research Program, Washington, DC. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3645 (As of July 2018)

Epps, J. A., D. N. Little, R. J. Holmgreen, and R. L. Terrel (1980) Guidelines for Recycling Pavement Materials. NCHRP Report 224, National Cooperative Highway Research Program, Washington, D.C.

Escobar, S. and D. Davidson (1979) “Role of Recycling Agents in the Restoration of Aged Asphalt Cements.” Journal of the Association of Asphalt Paving Technologists, Vol. 48, pp 375-402.

Espinoza-Luque, A. F., I. L. Al-Qadi, and H. Ozer (2018) “Optimizing rejuvenator content in asphalt concrete to enhance its durability” Construction and Building Materials, Vol. 179, pp. 642-648.

Garcia Cucalon, L., F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, N. Morian, S. Pournoman, and E. Hajj (2018) “The Crossover Temperature: Significance and Application towards Engineering Balanced Recycled Binder Blends.” Road Materials and Pavement Design, 2018.

Garcia Cucalon, L., G. King, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, T. Turner, and C. Glover (2017) “Compatibility of Recycled Binder Blends with Recycling Agents: Rheological and Physicochemical Evaluation of Rejuvenation and Aging Processes.” Industrial & Engineering Chemistry Research, Vol. 56, Iss. 29, pp. 8375-8384.

Glover, C. J., R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr, and S. H. Jung (2015) Development of a New Method for Assessing Asphalt Binder Durability with Field Validation, Texas A&M Transportation Institute, College Station, TX, 334 p.

Grilli, A., M. I. Gnisci, and M. Bocci (2017) “Effect of ageing process on bitumen and rejuvenated bitumen.” Construction and Building Materials, Vol. 136, pp. 474-481.

Gudimettla, J. M., L. Cooley, and E. Brown. (2003) Workability of Hot Mix Asphalt. NCAT Report No. 03-03, National Center for Asphalt Technology, Auburn, AL, 53 pp.

Haghshenas, H., H. Nabizadeh, Y-R. Kim, and K. Santosh (2016) Research on High-RAP Asphalt Mixtures with Rejuvenators and WMA Additives. Report No. SPR-P1(15) M016, Nebraska Department of Roads, Lincoln, NE, 66 p.

Hansen, K. R., and A. Copeland (2017) Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2015. National Asphalt Pavement Association, Lanham, MD, 40 p.

Hung, A. M., and E. H. Fini (2015) “AFM study of asphalt binder “bee” structures: Origin, mechanical fracture, topological evolution, and experimental artifacts”. RSC Advances Vol. 5, Iss. 117, pp. 96972-96982.

Hussain, A., and Q. Yanjun (2012) “Evaluation of Asphalt Mixes Containing Reclaimed Asphalt Pavement for Wearing Courses.” International Conference on Traffic and Transportation Engineering (ICTTE 2012), pp. 43-48.

Im, S., and F. Zhou (2014b) Field Performance of RAS Test Sections and Laboratory Investigation of Impact of Rejuvenators on Engineering Properties of RAP/RAS Mixes. Report No. FHWA/TX-14/0-6614-3, Texas A&M Transportation Institute, College Station, TX, 102 pp.

Im, S., F. Zhou, R. Lee, and T. Scullion (2014a) “Impacts of Rejuvenators on Performance and Engineering Properties of Asphalt Mixtures Containing Recycled Materials.” Construction and Building Materials, Vol. 53, pp. 596-603.

Jemison, H., B. Burr, R. Davison, J. Bullin, and C. Glover (1992) “Application and use of the ATR, FT-IR method to asphalt aging studies” Fuel Science and Technology International, Vol. 10, Iss. 4-6, pp. 795–808.

Kari, W. J., N. E. Andersen, D. D. Davidson, H. L. Davis, R. N. Doty, S. J. Escobar, D. L. Kline, and T. K. Stone (1980) “Prototype Specifications for Recycling Agents Used in Hot-Mix Recycling.” Journal of the Association of Asphalt Paving Technologists, Vol. 49, pp. 177-192.

Karki, P., and F. Zhou (2016) “Effect of Rejuvenators on Rheological, Chemical, and Aging Properties of Asphalt Binders Containing Recycled Binders.” Transportation Research Record: Journal of the Transportation Research Board, No. 2574, pp. 74-82.

Karlsson, R., and U. Isacsson (2003) “Laboratory studies of diffusion in bitumen using markers” Journal of Materials Science, Vol. 38, pp. 2835–2844.

Kaseer, F., E. Arámbula-Mercado, L. Garcia Cucalon, and A. Epps Martin (2018c) “Mixture Validation of Recycling Agents Dosage Selection Method in Asphalt Mixtures with High Recycled Materials Contents.” The 97th Annual Meeting of the Transportation Research Board, Washington, D.C., extended abstract.

Kaseer, F., F. Yin, E. Arámbula-Mercado, A. Epps Martin, Jo. Daniel, and S. Salari (2018b) “Development of an Index to Evaluate the Cracking Potential of Asphalt Mixtures Using the Semi-Circular Bending Test.” Construction and Building Materials, Vol. 167, pp. 286-298.

Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin (2017b) “Characterization of Asphalt Mixtures with High RAP/RAS Contents and Recycling Agents.” Presentation at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin. (2017a) “Stiffness Characterization of Asphalt Mixtures with High Recycled Materials Contents and Recycling Agents.” Transportation Research Record: Journal of the Transportation Research Board, No. 2633, pp. 58-68.

Kaseer, F., L. Garcia Cucalon, E. Arámbula-Mercado, A. Epps Martin, and J. Epps. (2018a) “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, Vol. 87.

Kim, S., T. Byron, G. A. Sholar, and J. Kim. (2007) Evaluation of Use of High Percentage of Reclaimed Asphalt Pavement (RAP) for Superpave Mixtures. Report No. FL/DOT/SMO/07-507, Florida Department of Transportation, 103 p.

Little, D. N., R. J. Holmgreen, and J. A. Epps (1981) “Effect of Recycling Agents on the Structural Performance of Recycled Asphalt Concrete Materials.” Journal of the Association of Asphalt Paving Technologists, Vol. 50, pp. 32-63.

Loeber, L., G. Muller, J. Morel, and O. Sutton (1998) “Bitumen in colloid science: a chemical, structural and rheological approach” Fuel, Vol. 77, Iss. 13, pp. 1443-1450.

Ma, T., X. Huang, Y. Zhao, and Y. Zhang (2015) “Evaluation of the diffusion and distribution of the rejuvenator for hot asphalt recycling” Construction and Building Materials, Vol. 98, pp. 530 536.

McDaniel, R., and Anderson R. M. (2001) “Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method: Technician’s Manual.” NCHRP Report 452, National Cooperative Highway Research Program, Washington, D.C. 49 p.

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, Vol. 158, pp. 61-74.

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, Vol. 170, pp. 725-736.

Mogawer, W., A. Austerman, L. Mohammad, and M. E. Kutay (2013b) “Evaluation of High RAP WMA Asphalt Rubber Mixtures.” Road Materials and Pavement Design, Vol. 14, pp. 129-147.

Mogawer, W., T. Bennert, J. Daniel, R. Bonaquist, A. J. Austerman, and A. Booshehrian (2012) “Performance Characteristics of Plant Produced High RAP Mixtures.” Road Materials and Pavement Design, Vol. 13, pp. 183-208.

Mogawer, W.S., A. Booshehrian, S. Vahidi, and A.J. Austerman (2013a) “Evaluating the Effect of Rejuvenators on the Degree of Blending and Performance of High RAP, RAS, and RAP/ RAS Mixtures.” Road Materials and Pavement Design, Vol. 14, Supplement 2, pp.193-213.

Nabizadeh, H., H. F. Haghshenas, Y-R. Kim, and F. T. Aragão (2017) “Effects of rejuvenators on high-RAP mixtures based on laboratory tests of asphalt concrete (AC) mixtures and fine aggregate matrix (FAM) mixtures.” Construction and Building Materials, Vol. 152, pp 65-73.

National Center for Asphalt Technology (2009) “Hot-Mix Asphalt Materials, Mixture Design and Construction.” NAPA Research and Education Foundation, Lanham, MD, 720 pp.

National Center for Asphalt Technology (2014) “NCAT Researchers Explore Multiple Uses of Rejuvenators.” Asphalt Technology News, Vol. 26, No. 1. http://www.eng.auburn.edu/research/centers/ncat/info-pubs/newsletters/. (As of July 2018).

O'Sullivan, K. A. (2011) Rejuvenation of Reclaimed Asphalt Pavement (RAP) in Hot Mix Asphalt Recycling with High RAP Content. MS Thesis, Worcester Polytechnic Institute, University of Worcester, MA, 45 p.

Oliveira, J. R., H. Silva, C. Jesus, L. Abreu, and S. Fernandes (2013) "Pushing the Asphalt Recycling Technology to the Limit." International Journal of Pavement Research and Technology, Vol. 6, Iss. 2, pp. 109-116.

Oliver, J. W. H. (1975) Diffusion of Oils in Asphalts. Australian Road Research Board, Report No. 9, Vermont, Victoria, Australia 3733.

Osmari, P. H., F. T. Aragão, L. F. Leite, R. A. Simão, L. M. Motta, and Y-R. Kim (2017) "Chemical, Microstructural, and Rheological Characterizations of Binders to Evaluate Aging and Rejuvenation." Transportation Research Record: Journal of the Transportation Research Board, No. 2632, pp. 14-24.

Petersen, J. C. (2009) "A Review of the Fundamentals of Asphalt Oxidation." Transportation Research Circular E-C140; Transportation Research Board, National Research Council, Washington, DC, pp 1−78.

Qin, Q., J. F. Schabron, R. B. Boysen, and M. J. Farrar (2014) "Field aging effect on chemistry and rheology of asphalt binders and rheological predictions for field aging." Fuel, Vol. 121, pp. 86-94.

Roberts, F. L., P. S. Kandhal, E. R. Brown, D-Y. Lee, and T. W. Kennedy (1996) Hot mix asphalt materials, mixture design, and construction. National Asphalt Pavement Association Research and Education Foundation, Lanham, MD, 603 p.

Robinett, C. J. and J. A. Epps (2010) "Energy, Emissions, Material Conservation, and Prices Associated with Construction, Rehabilitation, and Material Alternatives for Flexible Pavement." Transportation Research Record: Journal of the Transportation Research Board, No. 2179, pp. 10-22.

Romera R., A. Santamaría, J. J. Peña, M. E. Muñoz, M. Barral, E. García, and V. Jañez (2006) "Rheological Aspects of the Rejuvenation of Aged Bitumen." Rheologica Acta, Vol. 45, No. 4, pp. 474-478.

Rowe, G. M. (2011) "Prepared Discussion for the AAPT paper by Anderson et al.: Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking." Journal of the Association of Asphalt Paving Technologists, Vol, 80, pp. 649-662.

Shen, J., and Y. Ohne (2002) "Determining Rejuvenator Content for Recycling Reclaimed Asphalt Pavement by SHRP Binder Specifications." The International Journal of Pavement Engineering, Vol. 3, No. 4, pp. 261-268.

Shen, J., B. Huang, and Y. Hachiya (2004) “Validation of Performance-Based Method for Determining Rejuvenator Content in HMA.” The International Journal of Pavement Engineering, Vol. 5, No. 2, pp. 103-109.

Shen, J., S. Amirkhanian, and J. A. Miller (2007) “Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement.” Journal of Materials in Civil Engineering, Vol. 19, No. 5, pp. 376-384.

Tabatabaee, H. A. (2015) “Bio-based Rejuvenation of Highly Aged Asphalt: Rejuvenation vs. Softening.” Presentation to Transportation Research Board AFK20 Committee, Washington, DC.

Tabatabaee, H. A., and T. L. Kurth (2017) “Analytical investigation of the impact of a novel bio-based recycling agent on the colloidal stability of aged bitumen.” Road Materials and Pavement Design, Vol. 18, pp 131-140.

Tao, M., H. Xiaoming, Z. Yongli, and H. Bahia (2010) “Compound rejuvenation of polymer modified asphalt binder” Journal of Wuhan University of Technology, Vol. 25, Iss. 6, pp 1070 1076.

Tran, N. H., A. Taylor, and R. Willis. (2012) Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents. NCAT Report No. 12-05, National Center for Asphalt Technology, Auburn, AL, 70 pp.

Uzarowski, L., H. Prilesky, E. Berube, V. Henderson, and R. Rizvi (2010). "Laboratory Testing of Vancouver HMA Mixes Containing Recycled Asphalt Shingles." The 2010 Annual Conference of the Transportation Association of Canada, Halifax, Nova Scotia.

Veeraragavan, R. K. (2016) An Investigation of the Performance of Hot Mix Asphalt (HMA) Binder Course Materials with High Percentage of Reclaimed Asphalt Pavement (RAP) and Rejuvenators. MS Thesis, Worcester Polytechnic Institute, University of Worcester, MA, 61 p.

Veytskin, Y., C. Bobko, and C. Castorena (2015) :Nanoindentation and Atomic Force Microscopy Investigations of Asphalt Binder and Mastic” Journal of Materials in Civil Engineering, Vol. 28, pp. 1–16.

Wang, F., Z. Wang, C. Li, Y. Xiao, S. Wu, and P. Pan (2017) “The Rejuvenating Effect in Hot Asphalt Recycling by Mortar Transfer Ratio and Image Analysis.” Materials, Vol. 10, Iss. 6, pp 1-11.

West, R., A. Kvasnak, N. Tran, B. Powell, and P. Turner (2009) “Testing of Moderate and High RAP Content Mixes: Laboratory and Accelerated Field Performance at the

National Center for Asphalt Technology Test Track." Transportation Research Record: Journal of the Transportation Research Board, No. 2126, pp. 100-108.

West. R., and A. Copeland (2015) High RAP Asphalt Pavements: Japan Practice - Lessons Learned. National Asphalt Pavement Association, Lanham, MD, 62 p.

Xiao, F., S. Amirkhanian, and C. Juang (2007) "Rutting Resistance of Rubberized Asphalt Concrete Pavements Containing Reclaimed Asphalt Pavement Mixtures." Journal of Materials in Civil Engineering, Vol. 19, Iss. 6, p. 475-483.

Xu, G., H. Wang, and W. Sun (2018) "Molecular dynamics study of rejuvenator effect on RAP binder: Diffusion behavior and molecular structure" Construction and Building Materials, Vol. 158, pp. 1046-1054.

Yan, J., Z. Zhang, H. Zhu, F. Li, and Q. Liu (2014) "Experimental Study of Hot Recycled Asphalt Mixtures with High Percentages of Reclaimed Asphalt Pavement and Different Recycling Agents." ASTM Journal of Testing and Evaluation, Vol. 42, No. 5.

Yin, F., F. Kaseer, E. Arámbula-Mercado, and A. Epps Martin (2017) "Characterising the Long-Term Rejuvenating Effectiveness of Recycling Agents on Asphalt Blends and Mixtures with High RAP and RAS Contents." Road Materials and Pavement Design, Vol. 18, Sup. 4, pp. 273-292.

Yu, X., M. Zaumanis, S. Santos, and L. D. Poulikakos (2014) "Rheological, microscopic, and chemical characterization of the rejuvenating effect on asphalt binders". Fuel, Vol. 135, pp. 162 171.

Zaumanis, M., R. B. Mallick, and R. Frank (2016) "100% hot mix asphalt recycling: challenges and benefits." Transportation Research Procedia, Vol. 14, pp 3493-3502.

Zaumanis, M., R. Mallick, and R. Frank (2013) "Evaluation of Rejuvenator's Effectiveness with Conventional Mix Testing for 100% Reclaimed Asphalt Pavement Mixtures." Transportation Research Record: Journal of the Transportation Research Board, No. 2370, pp. 17-25.

Zaumanis, M., R. Mallick, and R. Frank (2014a) "Evaluation of Different Recycling Agents for Restoring Aged Asphalt Binder and Performance of 100 % Recycled Asphalt." Materials and Structures, Vol. 48, Iss. 8, pp 2475–2488.

Zaumanis, M., R. Mallick, and R. Frank (2014b) "Determining Optimum Rejuvenator Dose for Asphalt Recycling Based on Superpave Performance Grade Specifications." Construction and Building Materials, Vol. 69, pp. 159-166.

Zhang, H., H. Wang, and J. Yu (2011) “Effect of aging on morphology of organomontmorillonite modified bitumen by atomic force microscopy” Journal of Microscopy, Vol. 242, Iss. 1, pp. 37-45.

Zhao, S., B. Huang, X. Shu, X. Jia, and M. Woods (2012) “Laboratory Performance Evaluation of Warm-Mix Asphalt Containing High Percentages of Reclaimed Asphalt Pavement.” Transportation Research Record: Journal of the Transportation Research Board, No. 2294, pp. 98-105.

Zhou, F., L. Hongsheng, S. Hu, J. Button, and J. Epps (2013) Characterization and Best Use of Recycled Asphalt Shingles in Hot-Mix Asphalt. Report No. FHWA/TX-13/0-6614-2, Texas Transportation Institute, College Station, TX, 88 pp.

Zhou, F., S. Im, D. Morton, R. Lee, S. Hu, and T. Scullion (2015) “Rejuvenator Characterization, Blend Characteristics, and Proposed Mix Design Method.” Journal of the Association of Asphalt Paving Technologists, Vol. 74, pp. 675-704.

CHAPTER III

EVALUATION OF RECYCLING AGENT DOSE SELECTION AND INCORPORATION METHODS FOR ASPHALT MIXTURES WITH HIGH RAP AND RAS CONTENTS[2]

Overview

The scarcity and increased cost of virgin aggregates and binders employed in the construction of asphalt pavements, along with more stringent environmental regulations, motivate state and local transportation agencies to increase the amount of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) used in their roadways. In recent years, researchers have explored technical issues associated with the use of higher amounts of recycled materials in mixtures and the incorporation of a recycling agent in an effort to improve performance.

Recycled mixtures that incorporate large quantities of recycled materials are usually more stiff and brittle as compared to their virgin counterparts, leading to increased rutting resistance but higher cracking susceptibility (Copeland 2011; Mogawer et al. 2012). In an attempt to mitigate the increased stiffness and brittleness of the recycled mixture, several state highway agencies recommend the use of softer virgin binders (i.e., substitute binders) with relatively lower viscosity. However, even when a

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substitute binder is employed, the resulting mixture may still be very brittle, especially if heavily aged RAP and/or RAS materials are used or their proportion in the mixture is high. Therefore, in addition to employing a substitute binder, the use of a recycling agent can further restore the stiffness and phase angle of the mixture, especially in mixtures with a high recycled binder ratio (RBR) as defined in Equation 1 (NCAT 2014a):

$$RBR = RAPBR + RASBR = \frac{Pb_{RAP} \times P_{RAP}}{Pb_{total}} + \frac{Pb_{RAS} \times P_{RAS}}{Pb_{total}} \qquad \text{Equation 1}$$

Where: Pb_{RAP} = binder content in the RAP,
P_{RAP} = percentage of RAP by weight of mixture,
Pb_{RAS} = binder content in the RAS,
P_{RAS} = percentage of RAS by weight of mixture,
Pb_{total} = total binder content in the mixture,
$RAPBR$ = RAP binder ratio, and
$RASBR$ = RAS binder ratio.

A recycling agent is added to recycled mixtures to: (a) restore the aged recycled binder by decreasing the stiffness for construction purposes and mixture performance in the field; (b) restore the recycled mixture in terms of resistance to cracking by increasing the phase angle of the binder; and (c) increase the availability of recycled binder to coat the recycled and virgin aggregates and satisfy mix design requirements (Kandhal and Mallick 1997; Epps et al. 1980; Newcomb et al. 1981; Newcomb et al. 1984). The advantages of incorporating a recycling agent in the recycled mixture include (Yu et al. 2014; Zaumanis et al. 2014a):

- Can be easily added to the substitute binder at the asphalt plant using a pump or a liquid additive dose system,
- Can be easily stored at ambient temperature,

- Can be proportioned at a selected dose, and
- Can be incorporated directly to the RAP and/or RAS.

Various commercially available types of recycling agents according to the National Center for Asphalt Technology (NCAT) are listed in Table 3.

Table 3. Common Types of Recycling Agents (Willis and Tran 2015).

Category	**Types**	**Description**
Paraffinic Oils	Waste Engine Oil (WEO) Waste Engine Oil Bottoms (WEOB) Valero VP 165® Storbit®	Refined used lubricating oils
Aromatic Extracts	Hydrolene® Reclamite® Cyclogen L® Valero 130A®	Refined crude oil products with polar aromatic oil components
Naphthenic Oils	SonneWarmix RJ™ Ergon HyPrene®	Engineered hydrocarbons for asphalt modification
Triglycerides & Fatty Acids	Waste Vegetable Oil Waste Vegetable Grease Brown Grease Delta S*	Derived from vegetable oils *Has other key chemical elements in addition to triglycerides and fatty acids
Tall Oils	Sylvaroad™ RP1000 Hydrogreen®	Paper industry by-products. Same chemical family as liquid antistrip agents and emulsifiers

The dose of the recycling agent should be carefully selected since the amount of recycling agent added to the mixture will affect its performance. An excessive recycling agent dose will significantly soften the recycled binder, but may negatively impact the mixture’s resistance to rutting. Conversely, a very low recycling agent dose may help reduce the brittleness of the recycled binder, but may not have a pronounced effect in improving cracking resistance. Therefore, when using a recycling agent, it is important to determine the optimum dose for a particular combination and proportion of recycled materials and substitute binder. Normally, the recycling agent dose is selected based on experience or the producer recommendation. However, the dose for a particular recycling agent cannot be the same for mixtures with different types and amounts of recycled materials, since factors such as the substitute binder source and grade, the level of aging of the recycled materials, and their proportion in the mixture have an effect on the recycling agent dose.

Some researchers have selected the recycling agent dose according to blending charts based on the viscosity and/or penetration of the blends of the recycled binder with various amounts of recycling agent (Zaumanis et al. 2014a; Little et al. 1981; Zaumanis et al. 2013). Other researchers have used the performance grade (PG) system to evaluate the changes in the stiffness of the recycled binder due to the addition of the recycling agent and determined the minimum dose needed to restore the performance properties of the recycled binder (Shen and Ohne 2002; Shen et al. 2007; Tran et al. 2012; Zaumanis et al. 2017b). Typically, a minimum dose is determined to ensure sufficient cracking resistance (intermediate- and low-temperature PG or PGL), while a maximum dose is determined to ensure adequate rutting resistance (high-temperature PG or PGH) (Zaumanis et al. 2017b). In addition to PG, ΔT_c, which is the difference in the bending beam rheometer (BBR) test temperatures when the creep stiffness (S) and stress relaxation rate (m-value) reach the PG specification limits of 300 MPa and 0.30, respectively, is a parameter used to quantify the brittleness of the recycled blend at a given recycling agent dose. Another rheological metric used to evaluate brittleness of recycled blends is the Glover-Rowe (G-R) parameter, which is calculated with stiffness and phase angle measurements at a temperature of 15°C and frequency of 0.005 rad/s. The G-R parameter was originally defined by Ruan et al. (2013) as shown in Equation 2 and reformulated for practical use by Rowe et al. (2011) in a discussion of Anderson et al. (2011) as shown in Equation 3:

$$G'/(\eta'/G') \qquad \text{Equation 2}$$

$$G'/(\eta'/G') = |G^*| \times (\cos\delta)^2/(\sin\delta) \qquad \text{Equation 3}$$

Objectives

As mentioned previously, several approaches have been used to select the recycling agent dose, but no standard recycling agent dose selection method is available. Therefore, the objectives of this chapter are to:

1. Evaluate three recycling agent dose selection methods based on PGH, PGL, ΔT_c, and G-R parameter of the recycled blend, that is, the blend of substitute binder, recycled binder, and recycling agent.
2. Provide guidance with regard to the incorporation of the recycling agent in mixtures based on aggregate coatability.

Description of the Recycling Agent Dose Selection Methods

The recycling agent dose selection methods evaluated in this chapter assume prior proper selection of the type of recycling agent based on material availability and compatibility with substitute and recycled binders. The recycling agent dose is determined as a function of the target and/or substitute binder PG as well as the type of recycled materials (i.e., RAP and/or RAS), their level of aging, and their proportion in the mixture (i.e., RBR). The target binder PG is the one needed to satisfy climate and traffic requirements, while the substitute binder PG is the one required when recycled materials are incorporated in the mixture per agency specifications. The substitute binder usually has a lower PGH and/or PGL as compared to the target binder PG.

After all materials have been properly designated, the recycling agent dose selection methods comprise the following general steps:

1. Recycled Blends Preparation
2. Laboratory Measurements
3. Dose Selection

Recycled Blends Preparation consists of extracting and recovering the binder from the RAP and/or RAS materials per ASTM D2172 (test method A: centrifuge extraction) for extraction and ASTM D5404 for recovery, and formulating blends using the recycled binder, the substitute binder, the recycling agent at various doses, and other additives if applicable. A minimum of three recycled blends are prepared, one with no recycling agent (i.e., recycled control), one with a low recycling agent dose (usually 2-5% by weight of total binder), and one with a high recycling agent dose (usually 8-10% by weight of total binder). The total binder is the sum of substitute and recycled binder in the mixture. The next step is to conduct Laboratory Measurements to obtain the PGH and PGL of the recycled blends per AASHTO M 320 using the dynamic shear rheometer (DSR) and BBR. Unaged and rolling thin film oven (RTFO) aged recycled blends are characterized in the DSR to obtain PGH, while further pressure aging vessel (PAV) aged recycled blends are used to obtain the S and m-value for the PGL.

Once the Laboratory Measurements step is complete, the information is plotted as shown in Figure 5. In this example, the selected materials consist of a PG 64-22 substitute binder, RAP from a Texas source at 0.10 RAPBR (i.e, 10% by total weight of mixture), Manufactured Waste Asphalt Shingles (MWAS) from a Texas source at 0.18 RASBR (i.e., 5% by total weight of mixture), and a tall oil recycling agent. Three blends including a recycled control blend with 0% recycling agent, a recycled blend with 2% recycling agent, and a recycled blend with 10% recycling agent by weight of total binder were prepared and tested. In Figure 5, PGH is shown on the primary y-axis, while the PGL is shown on the secondary y-axis. The original and RTFO PGH results are shown with the triangle and square symbols, respectively, along with the S and m-controlled results for the PAV aged blends in the circle and diamond symbols, respectively. The fitted regression line and equation for each case are also shown in Figure 5.

The PG blending chart is then used for Dose Selection according to one of the methods described below. The PG blending chart in Figure 5 showed a linear relationship between recycling agent dose and the PGH and PGL of the recycled binder blends, and this was verified for all the blends regardless of substitute binder PG, type, and source of recycled materials, and their proportion (RBR).

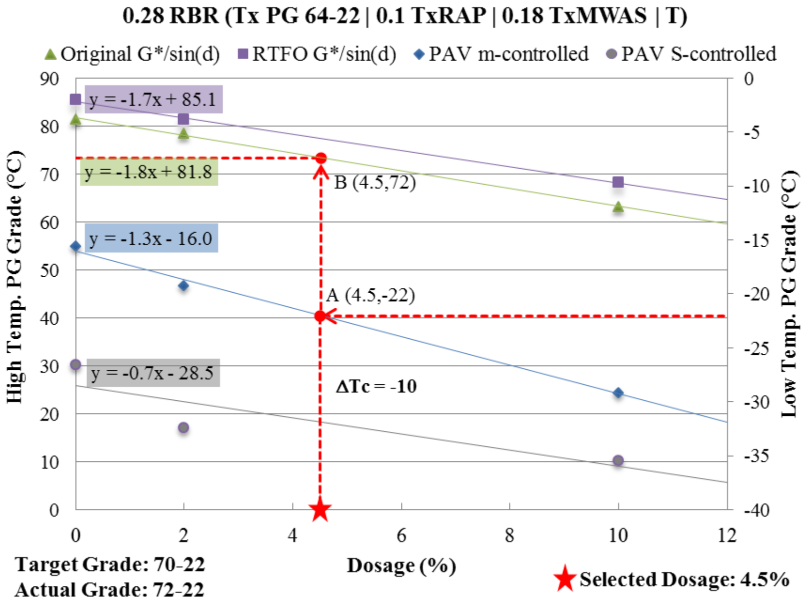


Figure 5. PG blending chart with selected dose for a 0.28 RBR recycled blend.

Method 1: Restoring PGL and Verifying PGH

To determine the amount of recycling agent needed to match the PGL of the recycled blend to that of the target binder, which for this example is a PG 70-22, the recycling agent dose was increased in 0.5% increments to move along the warmer low-temperature regression line (the PAV aged m-controlled line in Figure 5) until the PGL matched the target binder (i.e., -22). The required dose to meet this criterion was 4.5% as shown by point “A (4.5, -22)” in Figure 5. Then, at this recycling agent dose, the PGH of the recycled blend was *verified* using the colder high-temperature regression line (the original PGH line in Figure 5) that yielded a value of 72°C as shown by point “B (4.5,72)” in Figure 5. For this example, 4.5% recycling agent was selected since it was able to restore the recycled blend to a continuous PG of 72-22, equivalent to the target binder PG 70-22 after rounding by 6°C increments per AASHTO M 320. At this selected dose, the difference in temperature between the S-controlled and m-controlled curves results in a ΔT_c value of -10°C.

Another example of the recycling agent dose selection method based on restoring PGL and verifying PGH is illustrated in Figure 6. In this case the selected materials consist of PG 64-22 substitute binder, RAP from a Texas source at 0.25 RAPBR (i.e., 23% by total weight of mixture), tear off asphalt shingles (TOAS) from a Texas source at 0.25 RASBR (i.e., 6.5% by total weight of mixture), and a tall oil recycling agent. As before, three recycled blends including a recycled control blend with 0% recycling agent, and recycled blends with 2% and 10% recycling agent by weight of total binder were prepared and tested. The target binder was a PG 70-22. The PAV aged m-controlled regression line was used to establish the dose required to meet the PGL of the target binder, which was 10.0% and marked by point “A (10.0,-22)” in Figure 6. At this recycling agent dose, the PGH of the recycled blend was *verified* based on the colder high-temperature regression line (original PGH), yielding a value of 78°C marked by point “B (10.0,78)” in Figure 6.

Since this PGH exceeded that of the target binder, the dose was increased in 0.5% increments until the PGH reached a value lower than 76°C (which rounds to a PG 70-XX per AASHTO M 320) marked by point “C (11.5, 74)” in Figure 6. Then, at this recycling agent dose the PGL of the recycled blend was estimated and yielded a value of -25°C as marked by point “D (11.5,-25)” in Figure 6, which still met the PGL of the target binder.

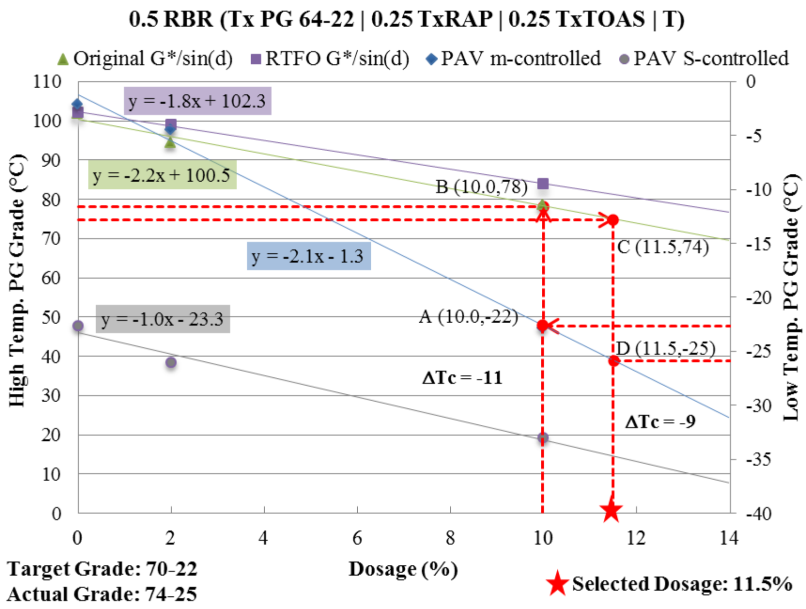


Figure 6. PG blending chart with selected dose for a 0.50 RBR recycled blend.

A dose of 11.5% was selected to restore to a continuous PG of 74-25, which was equivalent to the PG 70-22 target binder after rounding by 6°C increments per AASHTO M 320. At this selected dose, the difference in temperature between the S-controlled and m-controlled curves resulted in a ΔT_c value of -9°C.

Method 2: Achieving ΔT_c = -5°C

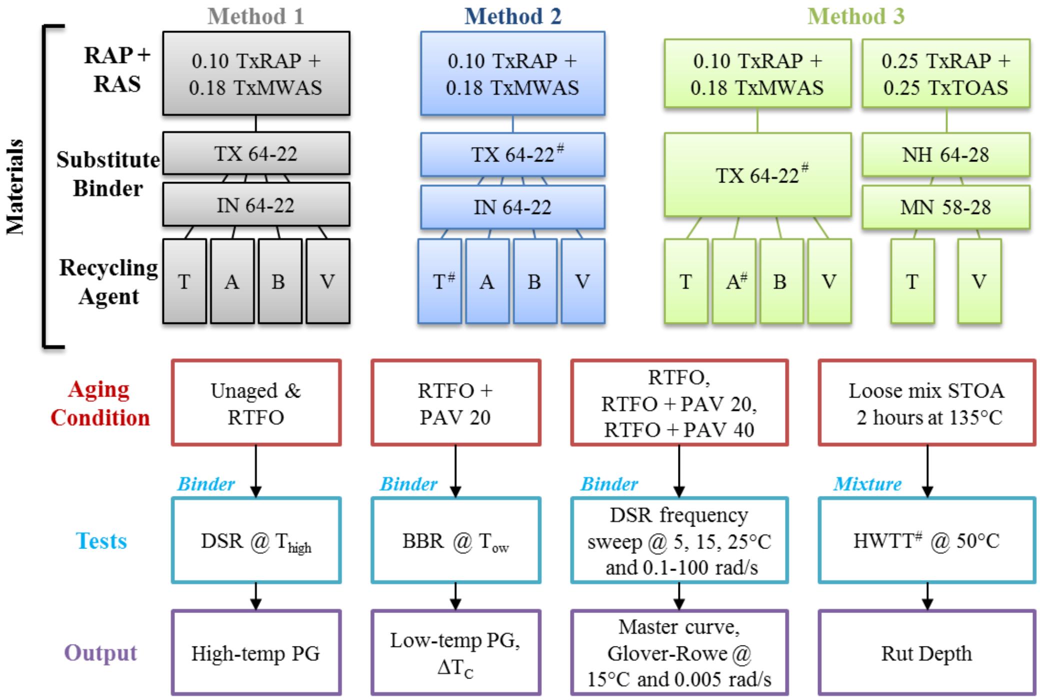
Recent work by Anderson et al. (2011) suggested a maximum ΔT_c threshold of -5°C after 40-hour PAV aging to minimize the risk of thermal cracking based on a limited set of binders. However, using this ΔT_c threshold would result in high recycling agent doses that would be costly and likely cause poor mixture rutting resistance. Thus, the dose to achieve a ΔT_c = -5°C after the standard 20-hour PAV aging was used in this second dose selection method. For the examples presented in Figure 5, a recycling agent dose of 12.5% is needed to achieve a ΔT_c value of -5°C after 20-hour PAV aging, with a resulting continuous PG 58-32 for the recycled blend. For the example illustrated in Figure 6, a dose of 14.5% is required to achieve a ΔT_c value of -5°C after 20-hour PAV aging, with a resulting continuous PG 68-32 for the recycled blend. Compared to the first method, this second approach significantly increases the recycling agent dose in most cases.

Method 3: Restoring PGH

The third dose selection method follows a similar approach to the one recommended for optimum binder content selection during mix design, where as much binder is added to improve the durability and cracking resistance of the mixture, while precluding rutting. Similarly, enough recycling agent dose is added to the recycled blend to match the continuous PGH to that of the target binder to improve cracking resistance, without causing a rutting issue. In this case, the recycling agent dose resulted in values between the ones obtained using the first method to restore PGL and verify PGH, and the second method to achieve ΔT_c = -5°C. For the example presented in Figure 5, a recycling agent dose of 6.0% is needed to achieve a PGH of 70°C with a continuous PG 70-23 and a ΔT_c value of -9°C for the recycled blend. For the example illustrated in Figure 6, a dose of 13.5% is required to achieve the target PGH with a resulting continuous PG 70-30 for the recycled blend and a ΔT_c value of -6°C.

Evaluation of the Recycling Agent Dose Selection Methods

The recycling agent dose selection methods were evaluated using the materials and binder and mixture test methods listed in Figure 7. As can be observed in this figure, methods 1 and 2 used the same materials, while the evaluation of method 3 an additional combination of RAP/RAS and substitute binders was introduced. The various outputs of each test method are also noted in Figure 7.



STOA = Short-term Oven Aging; HWTT = Hamburg Wheel Tracking Test performed on combinations denoted by #.

Figure 7. Materials, aging conditions, test methods, and outputs used in the evaluation of the recycling agent dose selection methods.

Method 1 and Method 2: Recycling Agent Dose, PG, and ΔT_c

The first two recycling agent dose selection methods were evaluated using various types and sources of materials as shown in Table 4. The methods were applied to a number of 0.28 RBR recycled blends considering a PG 70-22 target binder. The results, including the continuous PG and resulting ΔT_c values for each blend, are listed in

Table 4. Binders from Texas and Indiana with the same PG (i.e., 64-22) were used in the recycled blends. Both binders were m-controlled with respect to PGL, but the Texas binder had a ΔT_c = -4.6°C, while the Indiana binder had a ΔT_c = -1.2°C. In general, binders with larger (i.e., less negative) ΔT_c values are preferred due to their better stress relaxation ability.

Table 4. Materials Used to Prepare Recycled Blends and Evaluate Recycling Agent Dose Selection Methods 1 and 2.

Blend RBR	**RAP Source & RAPBR (% RAP[*])**	**RAS Source & RASBR (% RAS[*])**	**Binder Source & PG (ΔT_c[#])**	**Recycling Agent Type**	**Method 1 % Dose Restore PGL (ΔT_c[#]) [Blend PG]**	**Method 2 % Dose ΔT_c=-5°C[#] [Blend PG]**
0.28	Texas 0.10 (10%)	Texas MWAS 0.18 (5%)	Texas 64-22 (-4.6°C)	–	(-12°C) [81-16]	–
				Tall Oil (T)	4.5 (-10°C) [72-22]	12.5 [58-32]
				Aromatic Extract (A)	5.5 (-8°C) [71-22]	9.5 [66-27]
				Vegetable Oil (V)	4.0 (-10°C) [74-22]	8.5 [64-32]
				Bio-Based Oil (B)	4.0 (-8°C) [74-22]	7.0 [69-28]
	Texas 0.10 (10%)	Texas MWAS 0.18 (5%)	Indiana 64-22 (-1.2°C)	Tall Oil (T)	2.0 (-4°C) [74-22]	–
				Aromatic Extract (A)	2.0 (-5°C) [75-22]	2.0 [75-22]
				Vegetable Oil (V)	1.0 (-5°C) [75-22]	1.0 [75-22]
				Bio-Based Oil (B)	1.0 (-5°C) [75-22]	1.0 [75-22]

[*] *By total weight of mixture.* [#] *ΔT_c values after 20 hours of PAV aging.*

From the resulting recycling agent dose after applying the first two dose selection methods to the blends with 0.28 RBR, it is apparent that the use of a binder with a larger ΔT_c was indeed beneficial. The dose to restore PGL and verify PGH for the blends prepared with the Texas binder yielded ΔT_c values between -8°C and -10°C, requiring an increased recycling agent dose to achieve ΔT_c = -5°C. In contrast, the dose to restore PGL and verify PGH for the blends prepared with the Indiana binder yielded ΔT_c values between -4°C and -5°C, which was enough to also satisfy the criteria for the second dose selection method.

Method 1 and Method 2: Recycling Agent Effectiveness with Aging

To evaluate and compare the performance of the recycled blends, their rheological properties (i.e., stiffness and phase angle) were measured using the DSR frequency sweep tests at 5°C, 15°C, and 25°C with an angular frequency range of 0.1 – 100 rad/sec (with six frequency points per decade). The results were used to construct a master curve using the Rhea software (http://www.abatech.com/RHEA.htm). The stiffness and phase angle at a temperature of 15°C and frequency of 0.005 rad/s were then determined from the master curve data and plotted in Black space. Two limits corresponding to 180kPa and 600kPa for the G-R parameter in Black space, which were established for field sections located in a PG 58-28 climate using equivalent binder ductility values of 5 cm and 3 cm, respectively (Ruan et al. 2003; Kandhal 1977), are shown in the Black space diagram. These limits, which represent the onset of block cracking and significant block cracking, and delineate the No Block Cracking Zone, Transition Zone, and Block Cracking Zone, 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 should be considered but was outside the scope of this study. In addition, to track the rejuvenating effectiveness of the recycled blends, the combined materials were aged in the RTFO and PAV for periods of 20 and 40 hours.

Figure 8 and Figure 9 present the Black space results for the recycled blends with the Texas PG 64-22 substitute binder corresponding to the recycling agent dose selection methods 1 and 2, respectively. The DOT control, which refers to the recycled blend using material proportions as currently allowed by DOT specifications without the use of a recycling agent (i.e., first row in Table 4), is included in the graphs as reference. As shown in Figure 8, the first dose selection method (i.e., restore PGL and verify PGH) did not provide enough restoration of the recycled blend properties. After RTFO (i.e., points located near the bottom right corner in Black space), the recycled blends seemed less stiff and had larger phase angle values as compared to the DOT control, especially for the tall oil (T) and aromatic extract (A). With aging, however, the rejuvenating effectiveness for all recycled blends was lost. After 20-hour PAV, all recycled blends were located within the Transition Zone, and in the Block Cracking Zone after 40-hour PAV aging.

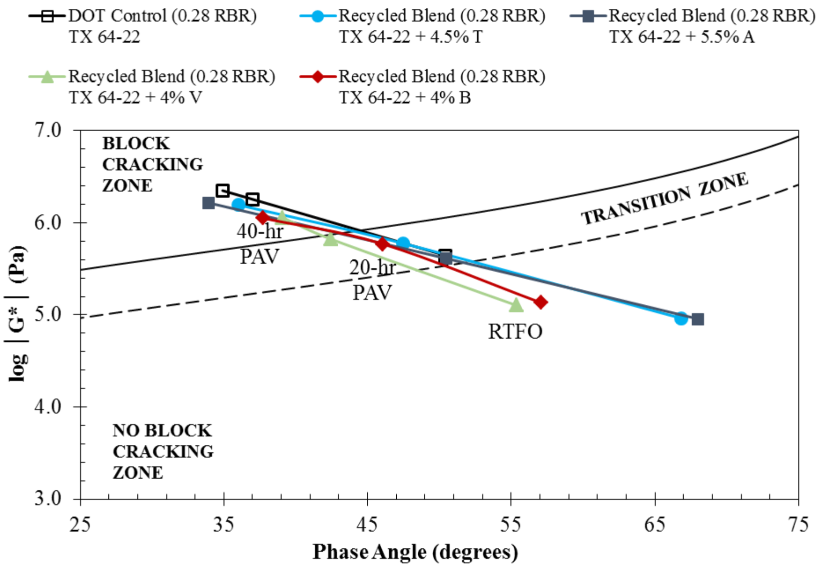


Figure 8. Stiffness and phase angle results in Black space for the Texas PG 64-22 0.28 RBR recycled blends using recycling agent dose selection method 1.

The dose to achieve ΔT_c = -5°C for the recycled blends prepared with the Texas PG 64-22 binder provided sufficient stiffness reduction and phase angle restoration as shown in Figure 9. All recycled blends are in the No Block Cracking Zone after 20-hour PAV aging, and none of the results fell within the Block Cracking Zone after 40-hour PAV aging. Besides, there is a clear separation between the results of the recycled blends and those of the DOT control.

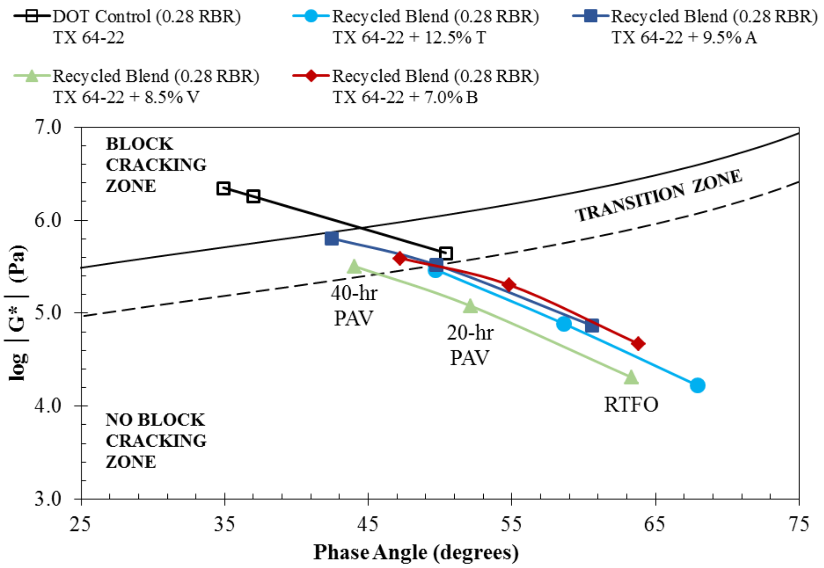


Figure 9. Stiffness and phase angle results in Black space for the Texas PG 64-22 0.28 RBR recycled blends using recycling agent dose selection method 2.

The results for the Indiana binder shown in Figure 10 yield a somewhat different conclusion because the stiffness and phase angle results in Black space after 20-hour PAV aging were within the Transition Zone, and the results after 40-hour PAV aging in the Block Cracking Zone for all recycled blends. However, there is still a clear distinction between the results of the DOT control versus the recycled blends (especially with respect to phase angle), despite the low recycling agent dose (i.e., 1.0 – 2.0%) used in the recycled blends prepared using the Indiana PG 64-22 binder.

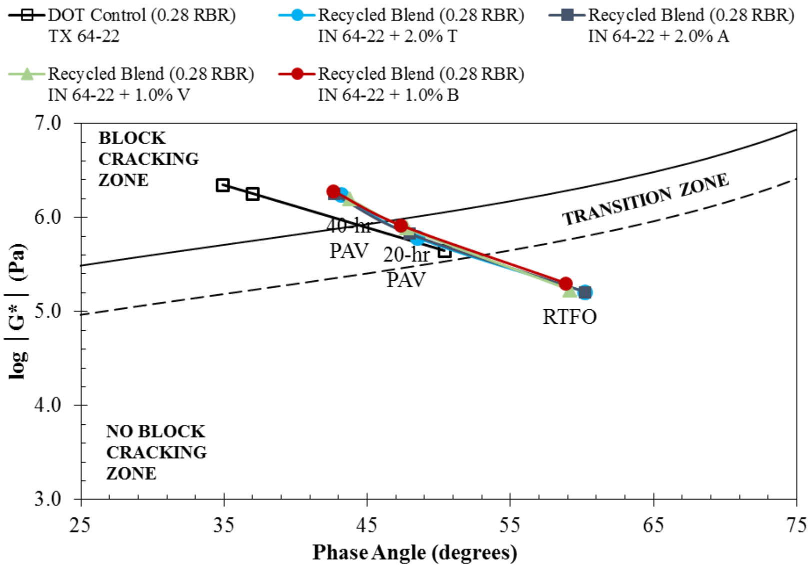


Figure 10. Stiffness and phase angle results in Black space for the Indiana PG 64-22 0.28 RBR recycled blends.

These results indicate that even though the use of a binder with a larger ΔT_c value, and thus less prone to embrittlement, yielded lower recycling agent doses and partially restored the phase angle of the recycled blend, the dose selection method to achieve ΔT_c = -5°C was not adequate to determine an optimum recycling agent amount. Besides, for binders with smaller (i.e., more negative) ΔT_c values such as the Texas PG 64-22, the recycling agent dose determined with this second selection method resulted in recycled blends with low PGH values (i.e., 58°C- 69°C as shown in Table 4), which could generate rutting issues at the mixture level.

Method 2: Mixture Rutting Susceptibility

To investigate mixture rutting susceptibility, the tall oil (T) that resulted in the lowest PGH for the recycled blend prepared with the Texas PG 64-22 binder blend (i.e., PG 58-32 in Table 4) as well as the lowest stiffness and highest phase angle values (as shown by the point with 12.5% tall oil (T) located near the bottom right corner in Black space in Figure 9) was used to prepare mixtures for the Hamburg Wheel Tracking Test (HWTT) per AASHTO T 324. The materials used to produce the mixtures were collected from a field project constructed in June 2014 in Texas. The mixtures employed dolomitic limestone and sandstone with a nominal maximum aggregate size (NMAS) of 12.5 mm, and an optimum binder content of 4.9%. The mixtures were prepared in the laboratory using a short-term oven aging protocol that consisted of conditioning the loose mix before compaction for 2 hours at 135°C (Epps Martin et al. 2014; Newcomb et al. 2015a).

This mixture with 12.5% tall oil (T) failed the HWTT (at a test temperature of 50°C) with a rut depth of 12.5 mm after 2,300 load cycles. Usually, mixtures with a target PG 70-XX climate are required to sustain at least 15,000 load cycles before achieving 12.5 mm rut depth at 50°C. This result confirmed that the dose selection method to achieve $\Delta T_c = -5°C$ produced excessive recycling agent dose for the recycled blends that employed the Texas PG 64-22 binder and possibly insufficient recycling agent dose for the recycled blends that employed the Indiana PG 64-22 binder.

Method 3

The third dose selection method (restore PGH) was evaluated using recycled blends prepared with the Texas PG 64-22 binder as well as two other binder grades and sources with better embrittlement characteristics: Minnesota PG 58-28 with $\Delta T_c = 0°C$, and New Hampshire PG 64-28 with $\Delta T_c = +1.2°C$ as listed in Table 5. Furthermore, for these two binders, a larger 0.5 RBR was explored, and a more heavily aged TOAS from a Texas source was used. Only the tall oil (T) and vegetable oil (V) were employed on the recycled blends with 0.5 RBR. The proportion of the RAP and TOAS to meet the 0.5 RBR was selected arbitrarily.

Table 5. Types and Sources of Materials Used to Prepare Recycled Blends to Evaluate Recycling Agent Dose Selection Method 3.

Blend RBR	**RAP Source & RAPBR (% RAP*)**	**RAS Source & RASBR (% RAS*)**	**Binder Source & PG ($\Delta T_c{}^{\#}$)**	**Recycling Agent Type**	**Method 3 % Dose Restore PGH ($\Delta T_c{}^{\#}$) [Blend PG]**
0.28	Texas 0.10 (10%)	Texas MWAS 0.18 (5%)	Texas 64-22 (-4.6°C)	Tall Oil (T)	6.0 (-9°C) [70-23]
				Aromatic Extract (A)	6.5 (-8°C) [70-23]
				Vegetable Oil (V)	5.5 (-8°C) [70-26]
				Bio-Based Oil (B)	6.5 (-8°C) [70-27]
0.50	Texas 0.25 (23%)	Texas TOAS 0.25 (6.5%)	Minnesota PG 58-28 (0.0°C)	Tall Oil (T)	16.5 (-5°C) [70-26]
				Vegetable Oil (V)	16.5 (-10°C) [70-34]
			New Hampshire 64-28 (+1.2°C)	Tall Oil (T)	15.5 (-4°C) [70-30]
				Vegetable Oil (V)	17.5 (-3°C) [70-41]

* *By total weight of mixture.* $^{\#}$ *ΔT_c values after 20 hours of PAV aging.*

Blends with 0.28 RBR

The recycling agent dose amounts required to restore the PGH of the recycled blends with the 0.28 RBR were between the ones obtained by the other two methods (Table 4). Similarly, the results in Black space for these blends were also midway with respect to the results obtained when the other two recycling agent dose selection methods were employed (previously shown in Figure 8 and Figure 9). HWTT at 50°C on the Texas PG 64-22 mixture with 6.5% aromatic extract (A) resulted in 10,300 load cycles to reach a 12.5 mm rut depth, which although below the desired threshold for a PG 70-XX climate, represents a significant improvement as compared to the performance of the mixture with Texas PG 64-22 and 12.5% tall oil (T) per recycling agent dose selection method 2. In addition, the stiffness and phase angle results for the third recycling agent dose selection method, shown in Figure 11, illustrate that after 20-hour PAV aging, the recycled blends are within the Transition Zone, but only two of the recycling agents (i.e., T and A) fall within the Block Cracking Zone after 40-hour PAV aging.

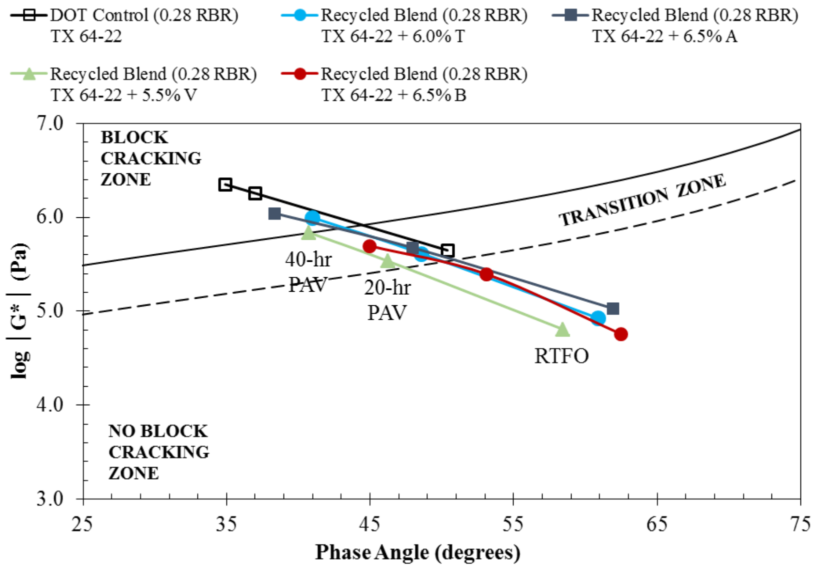


Figure 11. Stiffness and phase angle results in Black space for the Texas PG 64-220.28 RBR recycled blends using recycling agent dose selection method 3.

Blends with 0.50 RBR

In the case of the recycled blends with 0.5 RBR, using substitute binders with larger ΔT_c values resulted in reasonable recycling agent doses (i.e., less than 18%), despite the substantial increase in RBR, and the inclusion of more heavily aged RAS material. In addition, as shown in Figure 12, significant improvement was observed in the stiffness and phase angle results shown when compared to the DOT control blend, which had a lower RBR and was prepared using MWAS (i.e., first row in Table 4). The recycled blends prepared with the vegetable oil (V) were within the No Block Cracking Zone even after 40-hour PAV aging. For the recycled blends with the tall oil (T), the RTFO and 20-hour PAV aging results were within acceptable limits, although the 40-hour PAV aging results were close to or in the Block Cracking Zone.

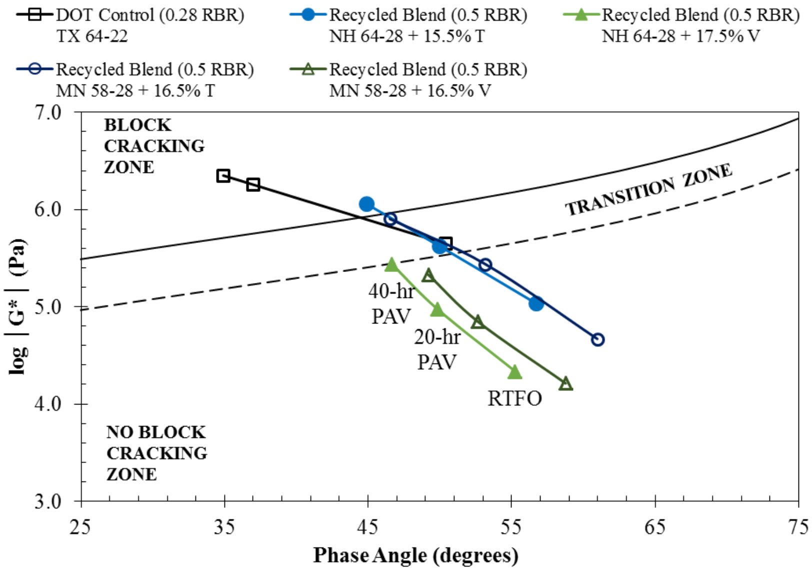


Figure 12. Stiffness and phase angle results in Black space for the Minnesota PG 58-28 and New Hampshire PG 64-28 0.5 RBR recycled blends.

It is also interesting to note that the curves corresponding to the recycled blends prepared with the vegetable oil (V) are located closer to the left bottom corner of the Black space diagram. This may be an indication of incompatibility of the recycled materials, substitute binder, and/or recycling agent. As previously mentioned, the recycling agent dose selection methods included in this chapter assume proper selection of the recycling agent type considering material availability and compatibility. Therefore, although it was outside the scope of this chapter to delve into the topic of recycling agent selection, that initial step is critical and should not be overlooked.

Recycling Agent Incorporation Method

The most common practice for incorporating recycling agent in mixtures is to follow the producer recommendation with regard to dose and proportion of the recycling agent with respect to the total binder content. 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 total binder content (i.e., addition method); whereas when the recycling agent dose is more than 2.0%, the total binder content is reduced by the recycling agent amount (i.e., replacement method). By following this practice in this study, inadequate aggregate coating by the binder was observed in mixtures containing RAS and more than 5.0% recycling agent.

To assess the degree of coating, the modified aggregate absorption method proposed by Newcomb et al. (2015b) was used in this study. The method is based on the assumption that an aggregate particle that is completely coated with binder, when submerged in water for a short period (i.e., 1 hour), cannot absorb water because water cannot penetrate through the binder film surrounding the aggregate surface. Conversely, a partially coated aggregate is expected to have detectable water absorption because water is able to penetrate and be absorbed by the uncoated portions of the particle. The difference between the saturated surface dry water absorption of the uncoated and coated coarse aggregate fraction (larger than 9.5 mm) of the mixture after soaking in water for 1 hour is reported as the coatability index (CI). Larger CI values indicate better aggregate coating.

To develop a recommended method of incorporating the recycling agent in the mixture at specific doses, two mixtures with high recycling agent doses (i.e., 9.5% and 12.5%) were prepared using three methods: 1) no replacement of the total binder content, 2) replacement of the total binder content by the portion representing half of the recycling agent amount, and 3) replacement of the total binder content by the portion representing the full recycling agent amount. The recycling agent was incorporated in the binder before the mixing process. Figure 13 presents the CI results for the two mixtures. The constituents of the mixture labeled ‘0.4 RBR’ consist of a PG 64-22 substitute binder, RAP from a Texas source at 0.4 RAPBR, and aromatic extract (A) recycling agent at a 9.5% dose selected using method 1, while the mixture labeled 0.5 RBR consists of a PG 64-28 substitute binder, RAP from a Texas source at 0.25 RAPBR, TOAS from a Texas source at 0.25 RASBR, and tall oil (T) recycling agent at 12.5% dose selected using method 1.

For the 0.4 RBR mixture, the CI values remained at 100% even after replacing the total binder content by the portion representing half the recycling agent amount, and above 95% for the replacement of the substitute binder by the full recycling agent amount. However, for the 0.5 RBR mixture, the CI value decreased significantly, especially when replacing the total binder content by the portion representing the full recycling agent amount. In this instance, the total binder content in the mixture was reduced from 4.9% to 4.3% to accommodate the full recycling agent amount, yielding a significant number of coarse aggregate particles visibly uncoated as illustrated in Figure 14.

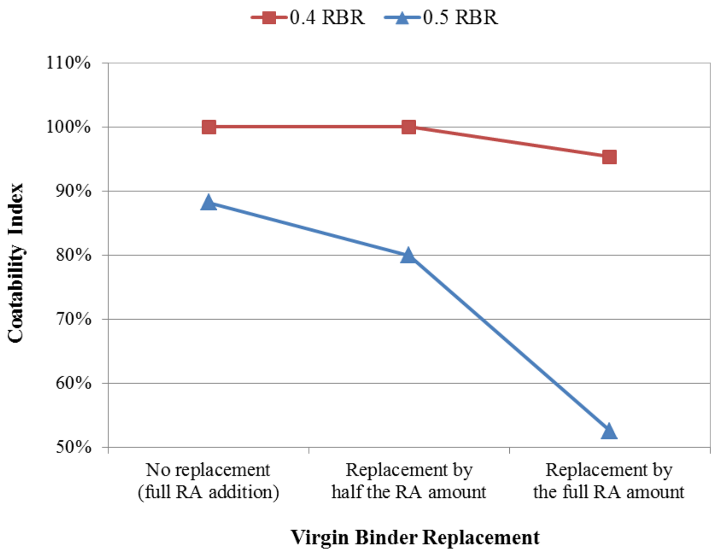


Figure 13. Coatability Index for 0.4 RBR and 0.5 RBR mixtures.

Figure 14. Coatability for a 0.5 RBR mixture with various recycling agent incorporation methods: virgin aggregate (left), aggregates after replacing the substitute binder by the full recycling agent amount (middle), and aggregates with no replacement of the substitute binder (right).

Based on these limited observations, a preliminary recommendation for mixtures containing RAS and more than 5.0% recycling agent determined with the recycling agent dose selection method 1 is to limit the replacement of the total binder content by the portion representing half of the recycling agent amount, and add the other half of the recycling agent amount. For mixtures with only RAP, no changes to the current practice are suggested.

Conclusions

In this chapter, three recycling agent dose selection methods based on the PG and ΔT_c of recycled blends were evaluated. The recycled blends consist of a proportionate mixture of virgin/substitute binder, recycled binder (i.e., extracted and recovered from the recycled materials by standard test methods), and recycling agent. The recycling agent dose selection methods consisted of: 1) restoring PGL and verifying PGH, 2) achieving $\Delta T_c = -5°C$ after 20-hour PAV aging, and 3) restoring PGH. When restoring/verifying the PGL or PGH of the recycled blend, the target binder PG specified based on climatic and traffic requirements was considered.

The proposed recycling agent dose selection methods were evaluated based on the resulting recycling agent dose, ΔT_c value, PG of the recycled blend, as well as on the stiffness and phase angle after RTFO and PAV aging. The first dose selection method, restore PGL and verify PGH, yielded low recycling agent doses, which appeared to improve the stiffness and phase angle of the recycled blend after RTFO, but the benefit was lost with additional PAV aging. The second dose selection method, achieve $\Delta T_c = -5°C$ after 20-hour PAV aging, yielded larger recycling agent doses and improved the stiffness and phase angle results in Black space. However, the reduction in stiffness was excessive as demonstrated by the resulting PGH of the recycled blends prepared with the Texas PG 64-22 substitute binder, and verification of rutting susceptibility at the mixture level with the HWTT. In addition, for the recycled blends prepared with the Indiana PG

64-22 substitute binder, this second dose selection method yielded very low doses that did not significantly improve the stiffness of the recycled blends with respect to the DOT control blend (i.e., recycled blend without recycling agent).

The third recycling agent dose selection method, restore PGH, provided better results, with resulting recycling agent doses, ΔT_c values, and PG of the recycled blends midway between the first two methods. The stiffness and phase angle results for this dose selection method also showed acceptable restoration of the recycled blend properties with sustained benefits after aging. There was also better differentiation between the various recycling agent types employed in this study, with the bio-based and vegetable oil showing a more significant reduction of the brittleness of the recycled blend. Recycled blends at higher RBR and employing a more heavily aged RAS type were also evaluated using this third recycling agent dose selection method. Two binder sources with less negative ΔT_c values (i.e., less prone to embrittlement) were employed in these blends. The results showed the importance of considering ΔT_c in selecting substitute binders with better characteristics that can more effectively reduce the likelihood of premature embrittlement and cracking.

Guidance with regard to the incorporation of the recycling agent in mixtures (i.e., replacement of the total binder content by the recycling agent amount) based on coatability was for mixtures containing RAS and more than 5.0% recycling agent to limit the replacement of the total binder content by the portion representing half of the recycling agent amount, and add the other half of the recycling agent amount. For mixtures with only RAP, no changes to the current practice of adding the full amount for recycling agent doses by weight of total binder of 2.0% or lower (i.e., addition method) and reducing the total binder content by the portion of the full recycling agent amount when the recycling agent dose is more than 2.0% (i.e., replacement method) are suggested.

References

Anderson, R.M., King, G.N., Hanson, D.I., and Blankenship, P.B. (2011) “Evaluation of the Relationship Between Asphalt Binder Properties and Non-Load Related Cracking”, *Asphalt Paving Technology: Journal of the Association of Asphalt Paving Technologists*, Vol. 80, pp. 615-649.

Copeland, A. (2011) “Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice”, *Report No. FHWA-HRT-11-021*, Federal Highway Administration, Washington, D.C.

Epps Martin, A., E. Arambula, F. Yin, L. Garcia Cucalon, A. Chowdhury, R. Lytton, J. Epps, C. Estakhri, and E.S. Park (2014) “Evaluation of the Moisture Susceptibility of WMA Technologies”, *NCHRP Report 763*, National Cooperative Highway Research Program, Washington, D.C.

Epps, J.A., D.N. Little, R.J. Holmgreen, and R.L. Terrel (1980) “Guidelines for Recycling Pavement Materials”, *NCHRP Report 224*, National Cooperative Highway Research Program, Washington, DC.

Kandhal, P.S. (1977) “Low-Temperature Ductility in Relation to Pavement Performance”, *STP 628: Low-Temperature Properties of Bituminous Materials and Compacted Bituminous Paving Mixtures*, C.R. Marek, Ed., American Society for Testing and Materials, Philadelphia, PA, pp. 95-106.

Kandhal, P.S., and R.B. Mallick (1997) “Pavement Recycling Guidelines for State and Local Governments—Participant’s Reference Book”, *Report No. FHWA-SA-97*, Chapter 7: Hot Mix Asphalt Recycling (Materials and Mix Design), National Center for Asphalt Technology, Auburn, AL.

Little, D.N., R.J. Holmgreen, and J.A. Epps (1981) “Effect of Recycling Agents on the Structural Performance of Recycled Asphalt Concrete Materials.” *Journal of the Association of Asphalt Paving Technologists*, Vol. 50, pp. 32-63.

Mogawer, W., T. Bennert, J. Daniel, R. Bonaquist, A. J. Austerman, and A. Booshehrian (2012) “Performance Characteristics of Plant Produced High RAP Mixtures”, *Journal of the Road Materials and Pavement Design*, Vol. 13, pp. 183-208.

NCAT (2014a) “How Should We Express RAP and RAS Contents?” *Asphalt Technology News*, Vol. 26, No. 2 (Fall), Accessed July 2016 https://eng.auburn.edu/research/centers/ncat/info-pubs/newsletters/atnfall2014.pdf.

Newcomb, D.E., A. Epps Martin, F. Yin, E. Arambula, E.S. Park, A. Chowdhury, R. Brown, C. Rodezno, N. Tran, E. Coleri, D. Jones, J.T. Harvey, and J.M. Signore

(2015a). “Short-Term Laboratory Conditioning of Asphalt Mixtures”, *NCHRP Report 815*, National Cooperative Highway Research Program, Washington, D.C.

Newcomb, D.E., and J.A. Epps (1981) “Asphalt Recycling Technology: Literature Review and Research Plan”, *Report No. ESL-TR-81-42*, Air Force Engineering and Services Center, Florida.

Newcomb, D.E., Arambula, E., Yin, F., and Zhang, J. (2015b) “Properties of Foamed Asphalt for Warm Mix Asphalt Applications”, *NCHRP Report 807,* National Cooperative Highway Research Program, Washington, D.C.

Newcomb, D.E., B.J. Nusser, B.M. Kiggundu, and D.M. Zallen (1984) “Laboratory Study of the Effects of Recycling Modifiers on Aged Asphalt Cement”, *Transportation Research Record*, No. 968, pp. 66-77.

Rowe, G.M. (2011) “Prepared Discussion for the AAPT paper by Anderson et al.: Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking”, *Asphalt Paving Technology: Journal of the Association of Asphalt Paving Technologists*, Vol. 80, pp. 649-663.

Ruan, Y. R.R. Davison, and C.J. Glover (2003) “An Investigation of Asphalt Durability: Relationships between Ductility and Rheological Properties for Unmodified Asphalts”, *Petroleum Science and Technology*, Vol. 21, Nos. 1 & 2, pp. 231-254.

Shen, J., and Y. Ohne (2002) “Determining Rejuvenator Content for Recycling Reclaimed Asphalt Pavement by SHRP Binder Specifications”, *The International Journal of Pavement Engineering*, Vol. 3, No. 4, pp. 261-268.

Shen, J., S. Amirkhanian, and J.A. Miller (2007) “Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement”, *ASCE Journal of Materials in Civil Engineering*, Vol. 19, No. 5, pp. 376-384.

Tran, N.H., A. Taylor, and R. Willis (2012) “Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents”, *NCAT Report 12-05*, National Center for Asphalt Technology, Auburn, AL.

Willis, R., and N.H. Tran (2015) “Bringing Life Back to Aging Asphalt Binder”, *Asphalt Pavement Magazine,* Vol. 20, No. 4, July/August, pp. 36-41.

Yan, J., Z. Zhang, H. Zhu, F. Li, and Q. Liu (2014) “Experimental Study of Hot Recycled Asphalt Mixtures with High Percentages of Reclaimed Asphalt Pavement and Different Recycling Agents”, *Journal of Testing and Evaluation*, Vol. 42, No. 5, pp. 1183-1190.

Yu, X., M. Zaumanis, S. Santos, and L.D. Poulikakos (2014) “Rheological, Microscopic, and Chemical Characterization of the Rejuvenating Effect on Asphalt Binders”, *Fuel*, Vol. 135, pp. 162-171.

Zaumanis, M., R. Mallick, and R. Frank (2013) “Evaluation of Rejuvenator’s Effectiveness with Conventional Mix Testing for 100% Reclaimed Asphalt Pavement Mixtures”, *Transportation Research Record*, No. 2370, pp. 17-25.

Zaumanis, M., R. Mallick, and R. Frank (2014a) “Evaluation of Different Recycling Agents for Restoring Aged Asphalt Binder and Performance of 100 % Recycled Asphalt”, *Materials and Structures*, Vol. 48, Issue 8, pp. 2475-2488.

Zaumanis, M., R. Mallick, and R. Frank (2014b) “Determining Optimum Rejuvenator Dose for Asphalt Recycling Based on Superpave Performance Grade Specifications”, *Construction and Building Materials*, Vol. 69, pp. 159-166.

CHAPTER IV

PRACTICAL TOOLS FOR OPTIMIZING RECYCLED MATERIALS CONTENT AND RECYCLING AGENT DOSE FOR IMPROVED SHORT- AND LONG- TERM PERFORMANCE OF REJUVENATED BINDER BLENDS AND MIXTURES[3]

Overview

Economic and environmental demands motivate State Departments of Transportation (DOTs) and contractors to increase the amount of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) used in in hot-mix asphalt (HMA) pavements. However, recycled mixtures that incorporate large quantities of recycled materials are usually less workable, difficult to compact in the field, and more prone to cracking and raveling as compared to their virgin counterparts (Xinjun et al. 2008; Zhou et al. 2011; Mogawer et al. 2012; Kaseer et al. 2017a). These negative effects can be mitigated by the use of softer base (virgin) binders with lower high and low temperature performance grades (PG) and the use of recycling agents (often referred to as rejuvenators).

The binder content in RAP ranges from 3–7% by weight, and RAP contents below 30% are commonly used in recycled asphalt mixtures without compromising performance. However, with higher RAP contents (i.e., 30% and higher), many studies

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indicate a decrease in cracking resistance of the recycled asphalt mixture (Li et al. 2008; Hajj et al. 2009; Mogawer et al. 2012; Hussain and Yanjun 2012; Mogawer et al. 2013a).

The binder content in RAS is usually 20–30% of its total weight. Two types of RAS are available: tear-off asphalt shingles (TOAS) that are removed during re-roofing projects, and manufacture waste asphalt shingles (MWAS) that are generated as waste during the manufacturing process. State DOTs allow smaller amounts of TOAS in asphalt mixtures as compared to MWAS due to the more aged and stiffer TOAS binders with an average high-temperature PG (PGH) of 178°C as compared to MWAS binders with an average PGH of 131°C (Zhou et al. 2015). These binders in RAS are heavily oxidized and significantly stiffer than paving grade binders.

Recycling agents, or rejuvenators, can restore the rheological characteristics of the recycled binders and recycled binder blends (base and recycled binders) to the desired performance specifications (Arambula-Mercado et al. 2018; Garcia Cucalon et al. 2017a). The commonly used term “rejuvenation” does not imply, from a chemical standpoint, the reversal of the oxidation process in RAP and RAS binders by the recycling agent. Instead, it indicates the effect of recycling agents in reversing aging in terms of rheology and performance characteristics (Tabatabaee and Kurth, 2017). Rejuvenation has been characterized utilizing advanced microstructural, physical, and chemical techniques (Tabatabaee and Kurth 2017, Garcia Cucalon et al. 2017b, Menapace et al. 2017); while continuation of fundamental studies is recommended, rheological characterization of recycled binders currently provides practical answers and facilitates correlations to pavement performance.

The effectiveness of the recycling agent in recycled binders and mixtures depends on a number of factors such as the type, source, and amount of recycled materials, the source and grade of the base binder, and the type and dose of the recycling agent. Among these factors, special emphasis is given to the type and dose of the recycling agent because these are commonly the most flexible design variables for the engineer to optimize.

The type of the recycling agent affects the rejuvenation mechanisms and the chemical compatibility of the rejuvenated binder blends (base and recycled binders with recycling agent). There are currently several different types of recycling agents that are commercially available, and they can be categorized according to NCAT (2014) as tall oils, aromatic extracts, paraffinic oils, naphthenic oils, and triglycerides and fatty acids (derived from vegetable oils). However, more engineered recycling agents are produced and released to the market continuously. Previous studies indicated that the effect of recycling agents on recycled binders and mixtures varied significantly among the different products (Zaumanis et al. 2013; Yan et al. 2014; Zhou et al. 2015). Recycling agent dose balances the performance of the asphalt mixture in terms of cracking and rutting resistance. For a particular type of recycling agent, a low dose may slightly reduce the stiffness and brittleness of the recycled binder, but may not have a noticeable effect in improving the short- and long-term cracking resistance of the asphalt mixture. Conversely, an excessive dose may soften the recycled binder, but could be detrimental to the rutting performance of the corresponding asphalt mixture. Both type and dose of the recycling agent affect the rheological and chemical changes after long-term aging

(Yin et al. 2017; Kaseer et al. 2017a). In previous research efforts to determine the optimum dose of the recycling agent, blending of base binders, recycled binders, and recycling agents was investigated; and blending charts were used for this purpose where the changes in the PG of the recycled binder blends with increased recycling agent dose was evaluated. (Shen et al. 2007; Tran et al. 2012; Zaumanis et al. 2014; Zhou et al. 2015; Karki and Zhou 2016).

Other factors such as the base binder source and grade, and recycled materials type and amount have an effect on the overall compatibility of the final rejuvenated blend, and also have an effect on the recycling agent dose. Therefore, all of these variables interact with each other. Despite previous research efforts, there are several aspects with respect to optimizing the recycling agent dose considering a wide variety of virgin and recycled materials and combinations that have not been established. In particular, guidelines and tools for a systematic design approach and performance evaluation of rejuvenated asphalt mixtures are needed.

Objectives

The objectives of this chapter are to:

1. Establish and verify blending charts to balance base/RAP/RAS binders (recycled binder blend) as a tool to optimize the type and amount of recycled materials.
2. Utilize blending charts for selection of the optimum dose of recycling agent to be added to an asphalt mixture during the mix design that requires minimum laboratory testing at the binder blend level.

3. Verify the improvement in the rheological, aging, and performance properties of the recycled binder blends and asphalt mixtures with the selected dose of recycling agent.

Background

Many efforts have been reported in the literature to evaluate the blending between base, RAP, and RAS binders with and without recycling agents, including blending recycled binders at different recycled binder ratios (RBRs). The RBR is the percentage of recycled binder from RAP and/or RAS by weight with respect to the total binder by weight in the asphalt mixture. This section will summarize the literature with respect to establishing and verifying blending charts to balance base/RAP/RAS binders and to select an optimum dose of recycling agent.

Recycled Binder Blends

Zhou et al. (2013) investigated blending between base/RAP binders in recycled binder blends at different RBRs, and they confirmed a linear blending rule where the PGH of the recycled binder blends increases linearly with added RAP binder. However, the blending of the base/RAS binders was found to be linear only when the RAS binder percentage is less than 30%. The authors also evaluated the blending characteristics among base/RAP/RAS binders together and indicated that at fixed RAS contents, the base/RAP binders follow a linear blending rule. When the RAP binder content is fixed, the base/RAS binder blending was non-linear, but the linear blending rule was confirmed when the RAS binder percentage was less than 30 % (0.3 RBR).

Rejuvenated Binder Blends with Recycling Agents

A number of studies have investigated blending between base binders, recycled binders, and recycling agents in an effort to determine the optimum dose of the recycling agent; and blending charts have been used for this purpose. Using blending charts, the changes in the PG of the recycled binder blends with increased recycling agent dose can be evaluated. A minimum dose can be determined to ensure sufficient low temperature cracking resistance (low-temperature PG (PGL)), while a high dose should be limited to ensure adequate rutting resistance (PGH) (Shen and Ohne 2002; Shen et al. 2007; Tran et al. 2012; Zaumanis et al. 2014; Zhou et al. 2015; Karki and Zhou 2016). A number of these studies investigated whether the blending trend was linear or non-linear (i.e., the reduction in PGH and PGL was linear or non-linear with increased recycling agent dose).

Shen and Ohne (2002) reported a non-linear decrease in PGH and a linear decrease in PGL of recycled binder blends with increased recycling agent dose. Tran et al. (2012) and Zaumanis et al. (2014) reported a linear decrease in both PGH and PGL with increased recycling agent dose. Zhou et al. (2015) reported a non-linear decrease in PGH with increased recycling agent dose; however, the authors indicated that a regional linear-blending rule can be used for selecting recycling agent dose, based on PGH, as long as the dose is 20% or less by weight of total binder (base and recycled binder). The authors defined the optimum dose as the dose that restores both the PGH and PGL of the recycled binder blend to that of the target binder PG (i.e., PG 70-22 for Texas climate). The target binder is the one required to satisfy climate and traffic requirements per agency specifications. Karki and Zhou (2016) reported that recycling agents have a greater influence on the PGL than on the PGH. As such, higher doses are required to restore PGH than PGL; and, consequently, the dose to restore PGH can be used as the optimum dose since it will ensure restoration of both.

Arámbula-Mercado et al. (2018) verified a linear correlation between recycling agent dose and both PGH and PGL and evaluated different dose selection methods to: (1) restore PGL of the recycled binder blend to that of the required target binder PG, or (2) match the continuous PGH of the recycled binder blend to that of the target binder PG. For the second method, and for a target binder of PG 64-XX for instance, instead of restoring the PGH of the recycled binder blends to meet a PG 64 (with a PGH close to 69), the goal was to further increase the dose to meet a continuous PGH of exactly 64°C. This approach has the advantage of being based on only PGH results (from dynamic shear rheometer [DSR] testing) that are less variable and require less effort in the laboratory as compared to PGL results from bending beam rheometer (BBR) testing.

The authors evaluated and compared the performance of the rejuvenated binder blends by analyzing their rheological properties (i.e., stiffness [$|G^*|$] and phase angle [δ]) in Black space. In Black Space, the complex shear modulus $|G^*|$ is plotted as a function of the phase angle (δ). The results showed that the first method (restore PGL) yielded low doses and appeared to reduce $|G^*|$ and increase δ of the recycled blends after rolling thin-film oven (RTFO), but the benefit was lost with pressure aging vessel (PAV) aging, Figure 15. The second method (match continuous PGH) yielded higher doses, and provided better results where the |G*| and δ results showed better restoration of the recycled blend properties with sustained benefits after aging, Figure 16.

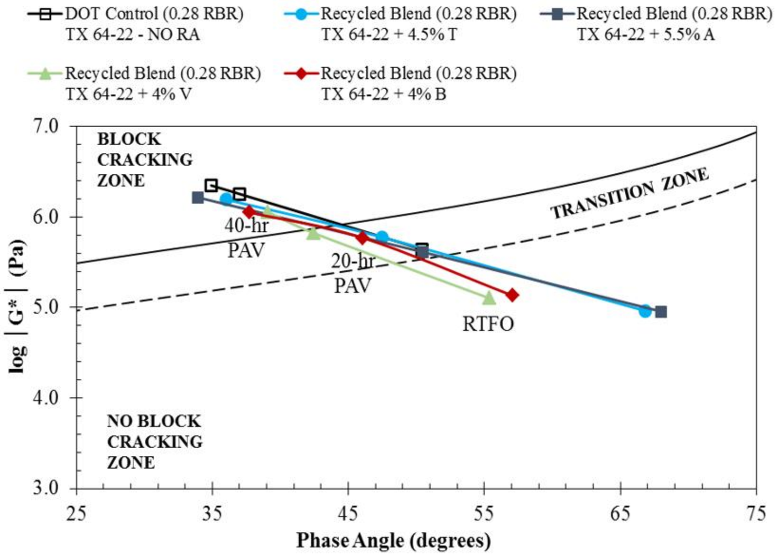


Figure 15. |G*| and δ in Black space for the recycled (DOT Control) and rejuvenated binder blends (at the dose to restore PGL) (Arámbula-Mercado et al. 2018).

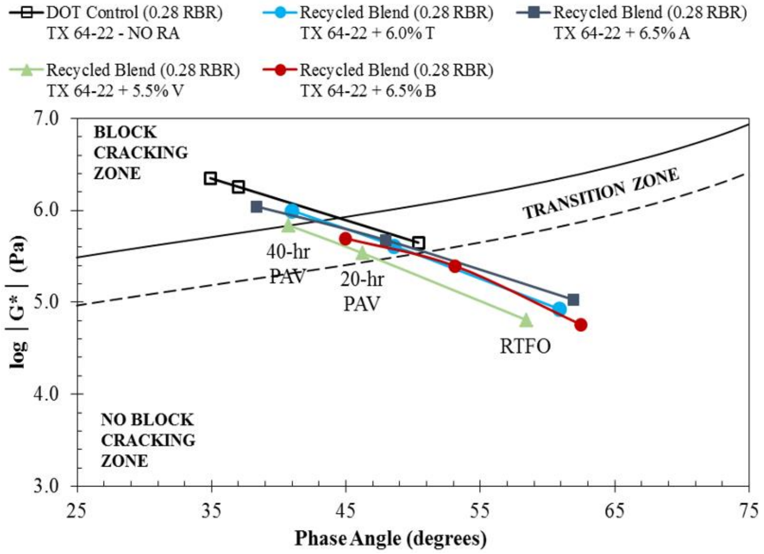


Figure 16. |G*| and δ in Black space for the recycled (DOT Control) and rejuvenated binder blends (at the dose to match PGH) (Arámbula-Mercado et al. 2018).

Garcia Cucalon et al. (2017a) reported that long-lasting rejuvenation of high RBR blends (of different base binders, recycled binders, and recycling agents) is possible when the dose of the recycling agent in the recycled binder blends is optimized to match continuous PGH for the target climate.

Rejuvenated Asphalt Mixtures

Rejuvenation of asphalt mixtures has been reported as successful in multiple studies to reduce the stiffness of recycled asphalt mixtures (Tran et al. 2012; Mogawer et al. 2013a; Carvajal Munoz et al 2015; and Kaseer et al. 2017) and to improve cracking performance (Mogawer et al. 2013a; Im et al 2014; and Yan et al 2014). However, recent studies by Yin et al. (2017) and Kaseer et al. (2017a) suggested a diminished effectiveness of the recycling agent with long-term aging, in both recycled binder blends and recycled asphalt mixtures, when a recycling agent dose to restore PGL of the target climate was used. Kaseer et al (2017b) verified the long-term recycling agent effectiveness in reducing the stiffness and improving the cracking resistance of rejuvenated asphalt mixtures when the dose to match continuous PGH of the target climate was used.

Economic and environmental benefits drive the inclusion of increased amounts of recycling materials in asphalt mixtures, which can be accomplished successfully with the addition of recycling agents. Adding small doses of recycling agents restores the initial properties of the recycled mixture, but performance tends to diminish with aging, and long-term economic benefits are not achieved. Conversely, inclusion of large doses of recycling agents may guarantee longer durability of the recycled mixture, but the initial cost will be prohibitive. There is a strong industry need for tools and guidelines to assist in decision making for recycling projects considering short- and long-term performance that can be translated into cost-effectiveness.

Design Tools and Performance Evaluation of Binder Blends

Materials Selection

Materials were collected from different states across the United States with various climate conditions and used to prepare binder blends with diverse combinations of base binders, recycled binders, RBRs, and recycling agent types and doses. Eight different base binders, including a polymer modified binder, with different chemical, rheological, and aging characteristics were considered. Six types of RAP, three types of MWAS, and two types of TOAS from different sources were also considered. Table 6 summarizes the characteristics of the base binders and recycled binders from RAP and RAS. The selected materials presented in Table 6 are part of the ongoing National Cooperative Highway Research Program (NCHRP) Project 09-58: The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios (Epps Martin et al. 2017).

ΔT_c listed in Table 6 refers to the difference in BBR test temperatures when the creep stiffness (S) and stress relaxation rate (m-value) match the PG specification limits of 300 MPa and 0.30, respectively. Anderson et al. (2011) suggested that a binder with low (more negative) ΔT_c had less ductility and relaxation properties than a binder with higher (less negative or positive) ΔT_c.

Table 6. Characteristics of the Base Binders and Recycled Binders.

Material	**Source**	**PG**	**Continuous PGH (°C)**	**Continuous PGL (°C)**	**ΔT_c (°C)**	**m**	**S**
Base (virgin) Binders	Texas	64-22	68.2	-24.6	-4.6	-24.6	-29.2
	New Hampshire	64-28	66.9	-28.0	+1.2	-29.2	-28.0
	Nevada[1]	64-28P	65.6	-32.4	-1.7	-32.4	-34.1
	Indiana	64-22	66.2	-25.3	-1.2	-25.3	-26.5
	Indiana	58-28	59.9	-28.2	-8.0	-28.2	-36.2
	Minnesota	58-28	58.6	-28.0	+0.1	-28.1	-28.0
	Wisconsin	58-28	59.4	-28.6	-3.4	-28.6	-32.1
	Delaware	64-28	66.5	-29.0	+0.1	-29.1	-29.0
Recycled Materials RAP	Texas	—	106.6	-2.4	-9.8	-2.4	-12.2
	Indiana	88-10	90.4	-13.7	-6.2	-13.7	-19.9
	Nevada	82-16	84.4	-20.4	-3.4	-20.4	-23.8
	New Hampshire	88-16	90.2	-20.6	-2.1	-20.6	-22.6
	Wisconsin	82-10	83.5	-10.9	-7.3	-10.9	-18.3
	Delaware	82-10	86.2	-13.8	-4.4	-13.8	-18.2
MWAS	Texas	—	130.7	—	—	—	—
	Indiana	—	123.3	—	—	—	—
	Delaware	—	146.0	—	—	—	—
TOAS	Texas	—	178.0	—	—	—	—
	California	—	166.0	—	—	—	—

[1] Polymer modified binder

— = result was not available: RAS binders were very stiff and did not meet the m-value criteria (>0.3) using the regular BBR, even at high (positive) testing temperatures.

Initial correlations by Anderson et al. (2011) showed that ΔT_c values of -5°C or higher were desirable based on a correlation to Glover-Rowe (G-R) parameter thresholds (the onset of block cracking and significant block cracking), while later studies suggested that there is no unique correlation between these parameters (Rowe 2017). In this study, ΔT_c values after 20 hours of PAV aging were classified as follows: a positive value is considered excellent, a value below -5°C is considered poor, and values in between are considered marginal.

Seven different recycling agents were considered including: tall oils (labeled T1 and T2), aromatic extracts (labeled A1 and A2), vegetable oil (labeled V1), modified vegetable oil (labeled V2), and bio-based oil (labeled B). The recycling agents used are proprietary products and have been labeled by generic descriptors that define the origin of the product. Tall oils are by-products of paper manufacture. Aromatic extracts are refined crude oil products and traditional recycling agents with dominant polar aromatic oil components. V1 is a vegetable oil consists of a mixture of glycerides and fatty acids, and V2 is an engineered (modified) vegetable oil. B is a bio-based oil consisting of fatty amine derivatives and bio solvents

A total of 15 different recycled binder blends and 32 different rejuvenated binder blends were prepared. Table 7 summarizes the components and characteristics of the recycled and rejuvenated binder blends evaluated in this chapter. The target climates investigated to design the tools for selecting recycling agent optimum dose were PG 70-22 and PG 64-28, and the recycling agent doses were optimized such that the continuous PGH of the recycled binder blend matches that of the target binders

Table 7. Components and Characteristics of the Recycled and Rejuvenated Binder Blends.

Base Binder PG	Total RBR	RAP Binder RBR (source)	MWAS Binder RBR (source)	TOAS Binder RBR (source)	Measured Continuous PGH (°C)[1]	Recycling Agent Dose (%)						
						T1	**T2**	**A1**	**A2**	**V1**	**V2**	**B**
TX 64-22	0.28	0.1 (TX)	0.18 (TX)	—	81.2	6/**9.5**	—	6.5/**11**	—	5.5/**8.5**	—	6.5/**10**
IN 64-22		0.1 (TX)	0.18 (TX)	—	77.9	5/**8.5**	—	6.5/**12**	—	3.5/**6**	—	4/**7.5**
MN 58-28		0.1 (TX)	0.18 (TX)	—	70.8	0.5/**4.5**	—	1/**7.5**	—	0.5/**3.5**	—	0.5/**4**
NV 64-	0.3	0.3 (NV)	—	—	73.4	—	1.5/**4**	—	1.5/**5.5**	—	—	—
WI 58-28	0.31	0.31 (WI)	—	—	67.7	—	—	—	—	—	—/**2**	—
TX 64-22	0.4	0.4 (TX)	—	—	84.5	8/**12**	—	12/**17**	—	—	—	—
NH 64-28		0.4 (TX)	—	—	83.2	—	—	9.5/**13.5**	—	—	—	—
DE 64-28	0.41	0.24 (DE)	0.17 (DE)	—	80.3	—	—/**8.5**	—	—	—	—	—
IN 58-28	0.42	0.14 (IN)	0.28 (IN)	—	76.8	—	3/**6**	—	—	—	—	—
WI 58-28	0.5	0.5 (WI)	—	—	72.5	—	—	—	—	—	—/**5.5**	—
NH 64-28		0.4 (NH)	—	0.1 (CA)	85.7	10/**13.5**	—	—	—	—	11/**15.5**	—
NV 64-28		0.25 (TX)	—	0.25 (TX)	102.5	16/**19.5**	—	—	—	—	—	—
NH 64-28		0.25 (TX)	—	0.25 (TX)	103	15.5/**18.5**	—	—	—	17.5/**20.5**	—	19.5/**23**
MN 58-28		0.25 (TX)	—	0.25 (TX)	98.9	16.5/**19.5**	—	20/**24**	—	16.5/**20**	—	16/**19**
NH 64-28	0.7	0.7 (NH)	—	—	86.6	—	—	—	—	—	—	8.5/**11.5**

— = component was not part of the blend

[1] Without recycling agent

(70 and 64°C), since this dose yielded the best performance for rejuvenated binders and corresponding mixtures (Arámbula-Mercado et al. 2018; Kaseer et al .2017b; Garcia Cucalon et al. 2017a). It is important to highlight that when these doses were utilized, the PGL for all blends met the -22 and -28 PGL requirements.

Binder Blends Preparation

The recycled binders from RAP, MWAS, and TOAS were extracted and recovered in accordance with ASTM D 2172 (Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures) and ASTM D 5404 (Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator), respectively. To prepare the recycled and rejuvenated binder blends, the preheated base binder was combined with the recycling agent (if used) at the selected dose, and then blended with the preheated recycled binders from the RAP and RAS at the selected RBR.

To determine the recycling agent dose to match continuous PGH for the target climate, three binder blends were prepared: one with no recycling agent, one with 2-5%, and one with 10%. The recycling agent % is by weight of total binder, and the total binder refers to the total weight of base and recycled binders. Laboratory measurements were performed to obtain PGH of these three blends per AASHTO M 320, and the optimum dose to match continuous PGH of the target binder was selected using the linear correlation between recycling agent dose and PGH of the binder blends.

Blending Charts

Superpave performance grading per AASHTO M 320 was performed using the DSR to characterize the PGH of the base binders, recycled binders, recycled binder blends, and rejuvenated binder blends.

Blending Charts for Recycled and Base Binders

The PGH of the base binders, recycled binders, and recycled binder blends were utilized to establish base/RAP binders blending charts. Figure 17 presents an example of a blending chart for a recycled binder blend with different RBRs, where (0 RBR) represent 100% base binder and (1 RBR) represent 100% RAP binder. Therefore, the value in the left y-axis corresponds to the base binder PGH and the value in the right y axis corresponds to the RAP binder PGH, and the values in-between correspond to the PGH of the recycled binder blends with different RBR. It is clear from Figure 17 that the base/RAP binder blends are following a linear blending rule. It was difficult to illustrate base/RAP/RAS binders blending charts in one figure; however, according to Zhou et al. (2013), the linear blending rule is valid for base/RAP/RAS binder blending as long as the RAS binder percentage is less than or equal to 30% (0.3 RBR), which is the case in this study. With these observations, the linear blending rule expressed in Equation 4 can be used to calculate the PGH of the recycled binder blend when the PGH of the base and recycled binders is available.

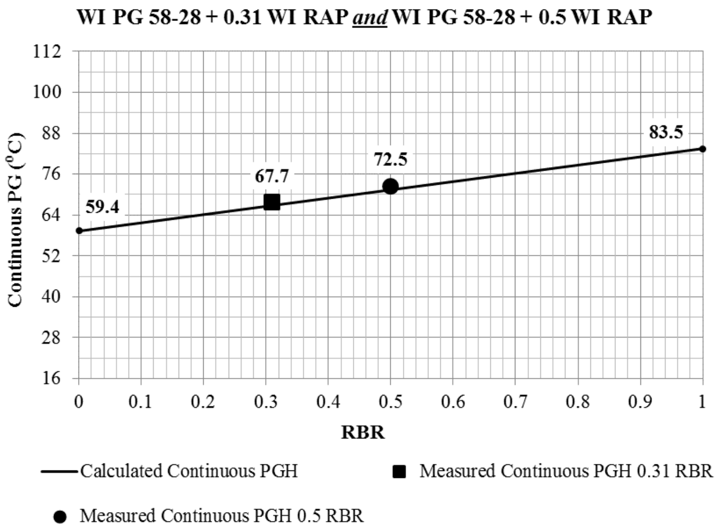


Figure 17. Base/RAP binders blending charts.

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

Equation 4

Where:

PGH_{Blend} = Continuous PGH of the recycled binder blend (°C);

RAP_{BR} = RAP binder ratio (RAP binder% by weight with respect to the total binder);

PGH_{RAP} = Continuous PGH of the RAP binder (°C);

RAS_{BR} = RAS binder ratio (RAS binder% by weight with respect to the total binder);

PGH_{RAS} = Continuous PGH of the RAS binder (°C);

B_{BR} = Base binder ratio (base binder% by weight with respect to the total binder); and

PGH_{Base} = Continuous PGH of the base binder (°C).

To validate the blending chart based on Equation 4, the measured continuous PGHs of different combinations of recycled binder blends without recycling agent in Table 7 were compared to the corresponding calculated PGHs of the same blends (using Equation 4), and the results are illustrated in Figure 18. The calculated and the measured

PGH for the different combinations agree and align around the line of equality. Therefore, the blending charts based on Equation 4 can be used to estimate the PGH of the recycled binder blends without laboratory testing.

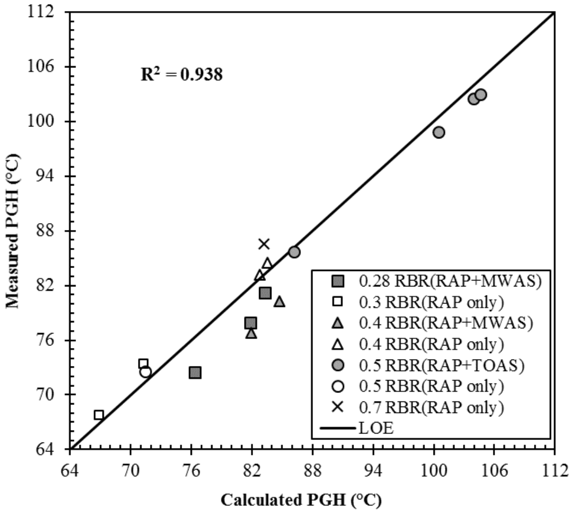


Figure 18. Calculated versus measured PGH of the recycled binder blends without recycling agent.

While accuracy in PGH may be reduced when using Equation 4, it enables consideration of multiple factors with minimum testing efforts. It is recommended to continue to measure PG of the recycled binder blend, if possible, for design and quality control documentation.

Blending Charts for Rejuvenation and Climate-Based Dose Selection

From Table 7, the measured continuous PGHs of recycled binder blends were plotted versus the recycling agent dose required to match continuous PGH for target climates of 70 and 64°C, for seven recycling agent types (four different recycling agent categories), and the results are illustrated in Figure 19. A strong correlation was observed between the continuous PGH of the recycled binder blends and the required recycling agent optimum dose for various base binders, recycled materials, RBRs, and recycling agent types.

According to the slope of each linear regression (trendline) in Figure 19, tall oils produce a larger change in the continuous PGH with increased dose as compared to vegetable and bio-based oils, while aromatic extracts produce the least change in the continuous PGH with increased dose.

The linear correlation for each recycling agent category can be used for the determination of the optimum recycling agent dose for corresponding recycled asphalt mixtures to achieve desired performance. These linear correlations can be used in practical applications for estimating the dose needed, for each recycling agent category when no data is available. It is also feasible to establish new relationships for different categories of recycling agents using DSR testing of limited blends.

The combination of Equation 4 (to calculate the PGH of the recycled binder blend without testing) and the slope for each recycling agent category in Figure 19 (to estimate the optimum dose to match the continuous PGH to that of the target climate without testing) can be used to determine the optimum recycling agent dose for any materials combination and target climate, as expressed in Equation 5.

$$Recycling\ Agent\ (\%) = \left(PGH_{Blend} - PGH_{Target}\right) / \text{ slope rate} \qquad \text{Equation 5}$$

Where: PGH_{Blend} = Continuous PGH of the recycled binder blend (°C) calculated from Equation 4; and

PGH_{Target} = Continuous PGH of the target climate (64 or 70°C).

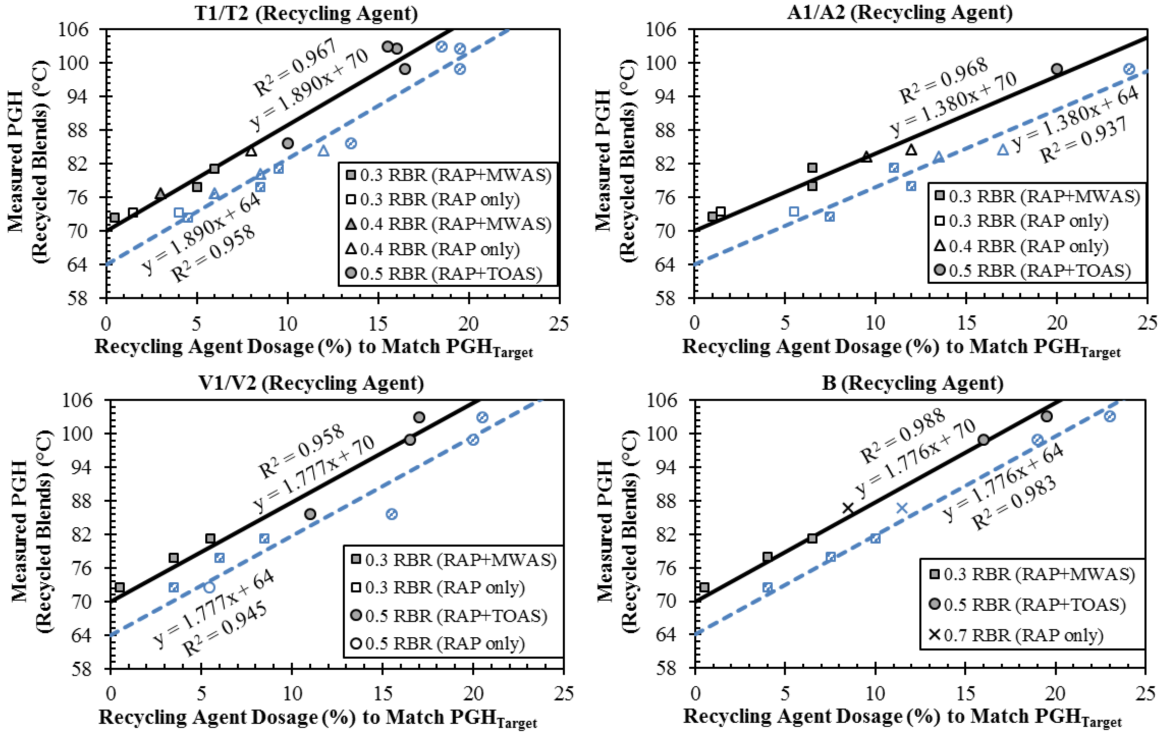


Figure 19. Optimum doses to match the PGH of the recycled blends to PGH target for various recycling agent types.

To provide a more universal recycling agent dose estimation method that can be applied across different recycling agent categories, all the measured continuous PGHs of recycled binder blends for all recycling agent categories in Table 7 except the petroleum base products (A1/A2 recycling agents) (for multiple base binders, recycled materials, and RBRs) were plotted versus the recycling agent doses required to match continuous PGH to that of the target climate. Figure 20 illustrates the recycling agent doses required to match PGH to 70 and 64°C, respectively. Again, a strong correlation was observed between the measured continuous PGH of the recycled binder blends and recycling agent optimum dose for various base binders, recycled materials, and RBRs, regardless of the type of recycling agent. The petroleum products (A1/A2) were excluded since these recycling agents exhibited a flatter slope (1.38) as compared to other recycling agents (1.89, 1.77, and 1.77 for T1/T2, V1/V2, and B, respectively), as illustrated in Figure 19. Removing A1/A2 reduced the variability in Figure 20 and will minimize the risk of over-softening the binder blends, since A1/A2 require the highest doses to match PGH.

The linear correlation shown in Figure 20 can be used to estimate the optimum dose required, without the need for testing, regardless of the type of recycling agent. While accuracy in PGH may be reduced when dosing recycling agents using this approach, it enables consideration of multiple factors with minimum testing efforts. It is recommended to continue to measure PG of the blend with the selected dose of recycling agent for design and quality control documentation.

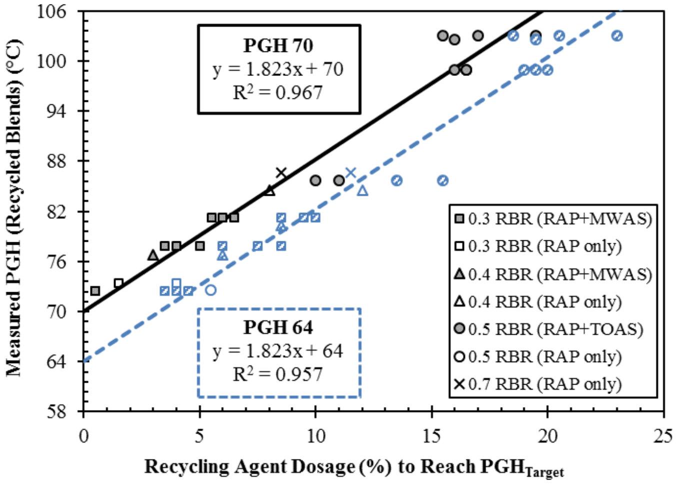


Figure 20. Optimum doses to match the PGH of the recycled blends to PGH$_{Target}$.

Equation 6 provides a universal recycling agent dose estimation method for all recycling agent types except the petroleum base products. However, Equation 2 for a specific recycling agent type is recommended if historical or laboratory test data of the recycling agent is available.

$$Recycling\ Agent\ (\%) = \left(PGH_{Blend} - PGH_{Target}\right)/\ 1.82 \qquad \text{Equation 6}$$

Where: PGH_{Blend} = Continuous PGH of the recycled binder blend (°C) calculated from Equation 4; and
PGH_{Target} = Continuous PGH of Target Climate.

Equation 6 for estimating recycling agent optimum dose was developed using the material combinations in Table 7. In order to validate Equation 6, a different set of materials is required, and the material combinations used for validation are listed in Table 8. These combinations were selected from several research studies where the recycling agent doses were 20% or less (Tran et al. 2012; Zaumanis et al. 2014; Zhou et al. 2015; Karki and Zhou 2016; Xie et al. 2017), and the measured recycling agent dose to match continuous PGH for target climates of 70 and 64°C were obtained using the trend lines of the measured data from these studies.

The measured recycling agent doses from Table 8 were compared to the corresponding estimated doses using Equation 6, and both align around the line of equality with an R^2 of 0.921 and 0.889 for 70 and 64°C, respectively, as shown in Figure 21. Figure 21 indicates a preliminary validation for Equation 6, while further validation is needed.

Table 8. Measured Recycling Agent Doses for Several Material Combinations from Previous Research Studies.

Authors	**Base Binder PG**	**Total RBR**	**RAP Binder RBR (source)**	**MWAS Binder RBR (source)**	**Recycling Agent**	
					Dose (%)[1]	**Type**
Zhou et al. 2015	TX 64-22	0.29	0.11 (TX)	0.18 (TX)	5.6/**8.4**	Tall Oil
					6.7/**9.7**	Aromatic Extract
Karki and Zhou 2016	TX 64-22	0.29	0.11 (TX)	0.18 (TX)	4.7/**7.7**	R1 (Not specified)
					5.7/**9**	R2 (Not specified)
	TX 64-22	0.3	0.3 (TX)	—	3.7/**7.1**	R1 (Not specified)
					3.6/**6.7**	R2 (Not specified)
Zaumanis et al. 2014	—	1.0	1.0 (NJ)	—	13.8/**17**	Waste Vegetable Oil
					14.7/**18.4**	Organic Oil
					13.8/**17**	Waste Vegetable Grease
					15/**18.8**	Distilled Tall Oil
Tran et al. 2012	—	1.0	1.0 (AL)	—	20/**24.2**	Naphthenic Oil
Xie et al. 2017	—	1.0	1.0 (AL)	—	23.5/**27**	Vegetable Oil

— = component was not part of the blend

[1] measured dose to match continuous PGH to (70°C/**64°C**)

The recycling agent optimum dose determination can be summarized as follow:

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 using Equation 4, and
3. Determine recycling agent optimum dose using Equation 6 (or Equation 5 if the recycling agent category is known), for a target PG climate.

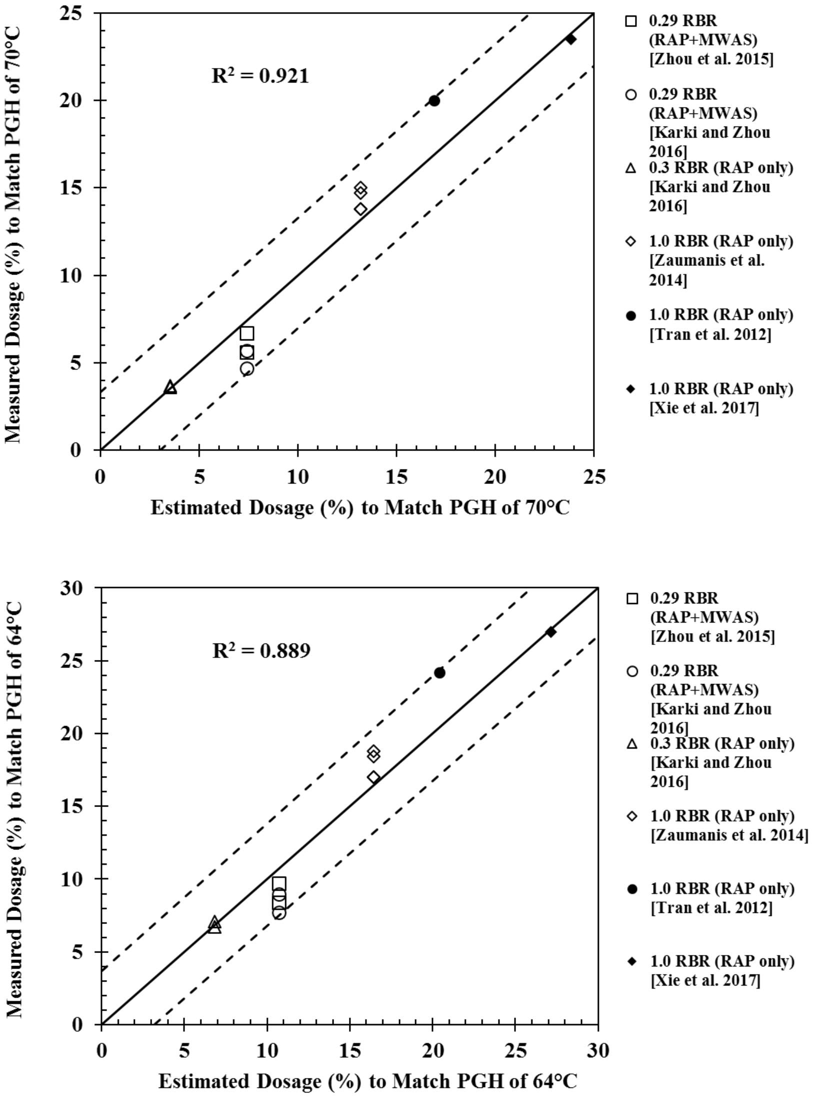


Figure 21. Measured versus estimated recycling agent doses to match PGH of 70 and 64°C.

Long-Term Performance Evaluation of Rejuvenated Binder Blends

To evaluate and compare the performance of the recycled and rejuvenated binder blends, and to evaluate their long-term durability, the rheological properties ($|G^*|$ and δ) were measured using the DSR frequency sweep test at three aging states [RTFO, 20 and 40 hours in the PAV at 100°C]. The 20-hour PAV is the standard long-term aging protocol, while the extended 40-hour PAV was performed to ensure adequate performance for long-term durability. A DSR frequency sweep was performed at three different temperatures of 5°C, 15°C, and 25°C, and an angular frequency range of 0.1 to 100 rad/s (with six frequency points per decade). The results were used to construct a master curve using the RHEA^{TM} software (Abatech 2011), and $|G^*|$ and δ at a temperature of 15°C and frequency of 0.005 rad/s were then determined from the master curve and plotted in Black space. This temperature-frequency combination corresponds to the G-R parameter that has a strong correlation to the ductility test at 15°C, and according to Rowe (2011), ductility thresholds of 3 and 5 cm translate to G-R parameter thresholds of 180 kPa and 600 kPa for the onset of block cracking and significant block cracking, respectively (labeled in this study as No Block Cracking Zone and Block Cracking Zone). The ductility, and later G-R, thresholds were based on pavement durability data in Pennsylvania (Kandhal 1977) with a PG 58-28 target climate. These thresholds were used to evaluate the results despite the fact that an adjustment to account for the target PG 70-22 and PG 64-22 climates used in this study versus the original PG 58-28 climate may be required, but determination of this adjustment was outside the scope of this study.

The 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 three different target climates: PG 70-22, PG 64-22, and PG 58-28. Table 9 summarizes the components and characteristics of the recycled and rejuvenated binder blends evaluated in Black space. In Table 9, the recycling agent doses to match the continuous PGH for the target climate were measured for some binder blends as explained previously and reported in Table 7, and were estimated (using equation 5) for the binder blends that are not listed in Table 7.

In Table 9, the DOT control blends (with gray shading) refer to the recycled binder blends without recycling agent with a RAP/RAS binder content within the maximum allowable content per the different DOTs specifications (TX, IN, DE, and WI). 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 allowed by the DOTs.

In Table 9, some of the recycled and rejuvenated binder blends were designed to have a balanced combination of RBR from RAP and RAS. A balanced combination refers to maximize RAP and minimize RAS content to balance the PGH contribution from RAP and RAS in the recycled blends or mixtures, rather that equal proportioning. A number of studies have suggested lowering RAS content in asphalt mixtures (and increasing RAP content to maintain similar RBR) since RAS binders have significantly higher PGH as compared to RAP binders.

Table 9. Materials Characteristics of the Binder Blends.

Target Climate	**Materials**						**Recycling Agent**	
	Base Binder PG	**Blend Label**	**Total RBR**	**RAP Binder RBR (source)**	**MWAS Binder RBR (source)**	**TOAS Binder RBR (source)**	**Type**	**Dose (%)**
PG 70-22	TX 64-22	DOT control TX 64-22 0.28 RBR	0.28	0.1 (TX)	0.18 (TX)	—	—	—
		Recycled TX 64-22 0.28 RBR + 6% T1	0.28	0.1 (TX)	0.18 (TX)	—	T1	6.0[#]
		Recycled TX 64-22 0.28 RBR + 6.5% A1					A1	6.5[#]
		Recycled TX 64-22 0.28 RBR + 5.5% V1					V1	5.5[#]
		Recycled TX 64-22 0.28 RBR + 6.5% B					B	6.5[#]
	NH 64-28	Recycled NH 64-28 0.28 RBR + 7% T1					T1	7.5[*]
	NH 64-28	Recycled NH 64-28 0.5 RBR + 15.5% T1	0.5	0.25 (TX)	—	0.25 (TX)	T1	15.5[#]
		Recycled NH 64-28 0.5 RBR + 17.5% V1					V1	17.5[#]
	MN 58-28	Recycled MN 58-28 0.5 RBR + 16.5% T1					T1	16.5[#]
		Recycled MN 58-28 0.5 RBR + 16.5% V1					V1	16.5[#]
	NH 64-28	Recycled NH 64-28 0.5 RBR(NH/CA) + 9%	0.5	0.4 (NH)	—	0.1 (CA)	T1	9.0[*]
		Recycled NH 64-28 0.5 RBR(NH/CA) +					V2	9.0[*]
		Recycled NH 64-28 0.5 RBR(TX) + 14% T1		0.4 (TX)	—	0.1 (TX)	T1	14.0[*]
		Recycled NH 64-28 0.5 RBR(TX) + 14% V2					V2	14.0[*]
PG 64-22	IN 58-28	DOT control IN 58-28 0.32 RBR	0.32	0.25 (IN)	0.07 (IN)	—	—	—
		Recycled IN 58-28 0.42 RBR + 8.0% T2	0.42	0.28 (IN)	0.14 (IN)	—	T2	8.0[*]
		Recycled IN 58-28 0.5 RBR + 9.5% T2	0.5	0.36 (IN)	0.14 (IN)	—	T2	9.5[*]
PG 58-28	WI 58-28	DOT control WI 58-28 0.21 RBR	0.21	0.21 (WI)	—	—	—	—
		Recycled WI 58-28 0.31 RBR + 5.5% V2	0.31	0.31 (WI)	—	—	V2	5.5[*]
		Recycled WI 58-28 0.5 RBR + 9% V2	0.5	0.5 (WI)			V2	9.0[*]

Measured doses * Estimated doses using Equation 5

Zhou et al. (2013) suggested controlling the maximum MWAS binders to 0.2 RBR, but for TOAS binders, the maximum binder percentage should be significantly reduced. Epps Martin et al. (2015) conducted a state DOT survey of current RAS practices in different states and reported an allowed RAS content of 3-5% in the asphalt mixture, which corresponds to about 0.1 to 0.2 RBR, depending on the total binder content in the asphalt mixture.

A balanced combination of 0.4 RAP and 0.1 TOAS was investigated in this study versus a combination in equal proportions of 0.25 RAP and 0.25 TOAS. In this study the effect of recycling, aging, and rejuvenation on binder performance at intermediate temperatures are discussed using Black space diagrams, the G-R parameter, and respective cracking thresholds. Figure 22 illustrates the typical direction for the shifts observed in Black space with the inclusion of recycled materials, rejuvenation, and aging considering binders without polymer modification. A new asphalt binder without polymer modification has a relatively lower $|G^*|$ and higher δ, therefore it is found toward the lower right corner of the Black space diagram. The inclusion of recycled materials (labeled recycling in Figure 22) 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 reversal of the impact of aging on asphalt, from a rheological standpoint, the inclusion of recycling agents is expected to reduce $|G^*|$ and increase δ.

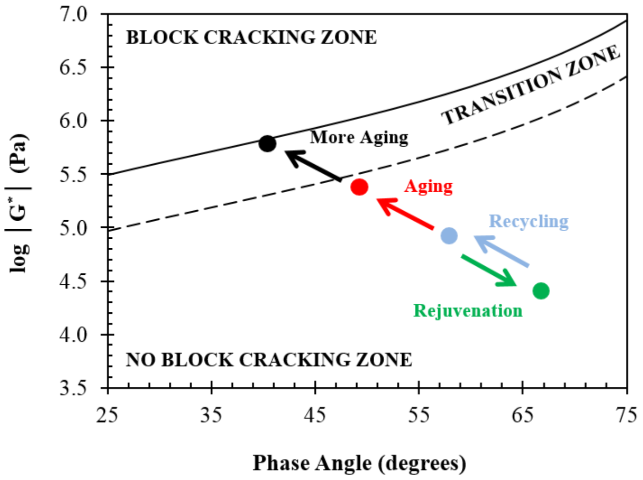
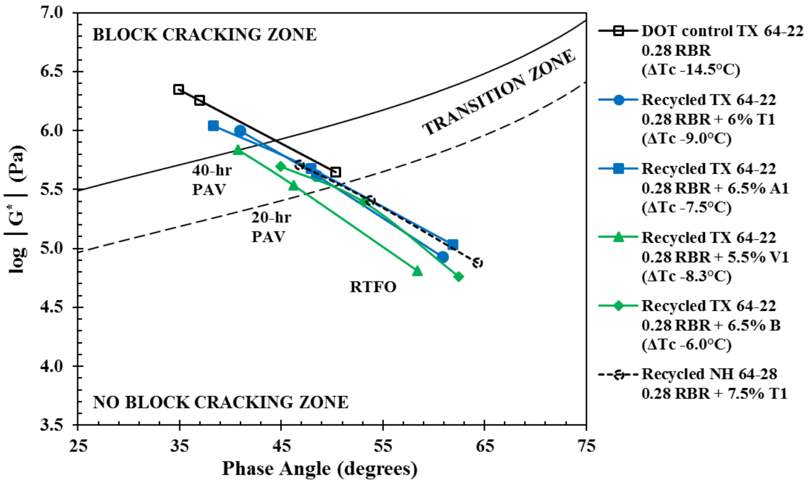
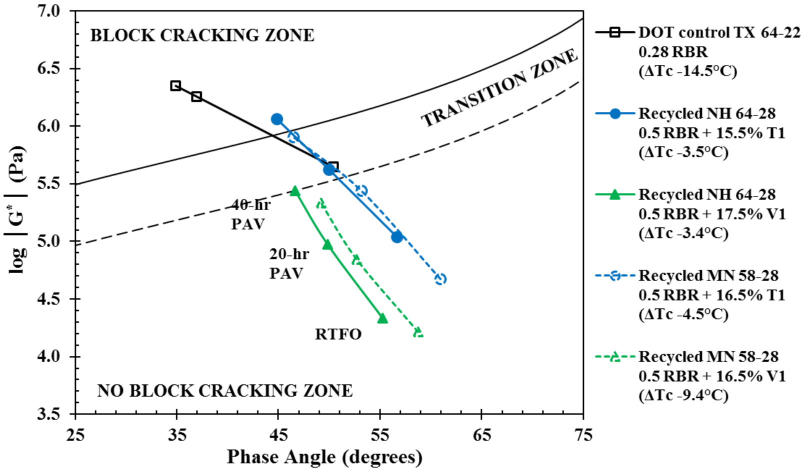


Figure 22. Illustration of |G*| and δ changing with recycling, aging, and rejuvenation in Black space.

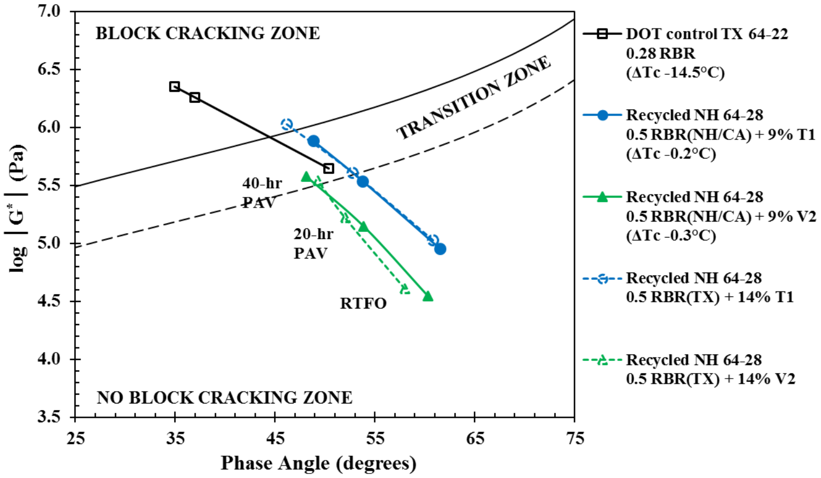
Figure 23 (a through c) presents the Black space results for the recycled and rejuvenated binder blends for a PG 70-22 target climate. With PAV aging, all the blends showed the expected increase in $|G^*|$ and decrease in δ with aging, indicating loss of ductility with aging.



(a)



(b)



(c)

Figure 23. |G*| and δ in Black space for the recycled and rejuvenated binder blends with a target PG 70-22 climate.

The DOT control blend with 0.28 RBR in Figure 23 (a) was located within the Block Cracking Zone after 20-hour PAV aging exhibiting very high $|G^*|$ and low δ. Considering the -14.5°C ΔT_c value of this control blend, all binder parameters indicate that the corresponding asphalt mixture may show high cracking potential. The rejuvenated binder blends with 0.28 RBR had less $|G^*|$ and larger δ values as compared to the DOT control indicating restored ductility, yet the different additives (dosed to meet PGH) did not necessarily follow similar rejuvenating paths in Black space. After 20-hour PAV aging, all the rejuvenated binder blends were within or below the Transition Zone, and after the extended 40-hour PAV aging only the blends with T1 and A1 were in the Block Cracking Zone. Considering ΔT_c, all blends had poor ΔT_c values less than -5.0°C after 20-hour PAV aging, with the B recycling agent showing the best ΔT_c value of -6.0°C. Figure 23 (a) also shows that the blend with NH PG 64-28 binder (7.5% T1) was below the Block Cracking Zone after 40-hour PAV aging as compared to the similar blend with TX PG 64-22 (6.5% T1) which was in the Block Cracking Zone after 40-hour PAV aging. These results demonstrate the benefit of using a high quality base binder with a higher ΔT_c value (+1.2 for NH PG 64-28 as compared to -4.6 for TX PG 64-22).

In Figure 23 (b), most of the rejuvenated binder blends are within or below the Transition Zone after 40-hour PAV aging, despite the fact that these blends have 0.5 RBR with the use of heavily aged TOAS binders (0.25 RAP + 0.25 TOAS) as compared to 0.28 RBR with MWAS binder in the DOT control blend (0.1 RAP + 0.18 MWAS). These blends were designed to see if the recycling agent could facilitate the use of higher quantities of recycled materials (higher RBR) as compared to the DOT control blend (lower RBR). Considering the proposed cracking thresholds, the rejuvenated binder blends with V1 recycling agent showed superior performance as compared to other recycling agents. However, these blends showed very low $|G^*|$ due to the significantly high recycling agent dose while restoration of δ was not as pronounced. This may in fact indicate an unbalanced materials combination (i.e., very high RAS content). The ΔT_c values for the 0.5 RBR rejuvenated blends with T1 and V1 recycling agents in combination with the NH binder are similar, while in combination with the MN PG 58-28 binder, the blend with V1 resulted in significantly lower ΔT_c than the blend with T1. These findings support the need for optimizing materials combinations for successful rheological restoration and highlight the importance of utilizing a high quality base binder for improved intermediate and low temperature performance of recycled and rejuvenated blends with aging.

Figure 23 (c) shows the rejuvenated binder blends with a balanced combination of recycled materials of NH PG 64-28 with 0.4 RAP and 0.1 TOAS with V2. As compared to the unbalanced combination in Figure 23 (b) (NH PG 64-28+0.25 RAP + 0.25 TOAS) with V1, a slight increase in δ was observed but the difference overall was not noticeable when balancing the RBR. More investigation at the mixture level is presented subsequently.

Figure 24 presents the Black space results for the recycled and rejuvenated binder blends for a target PG 64-22 climate. The two rejuvenated binder blends with balanced recycled materials combination (0.42 and 0.5 RBR with 8.0 and 9.5% T2 respectively) had lower $|G^*|$ and larger δ values as compared to the DOT control, indicating improved performance.

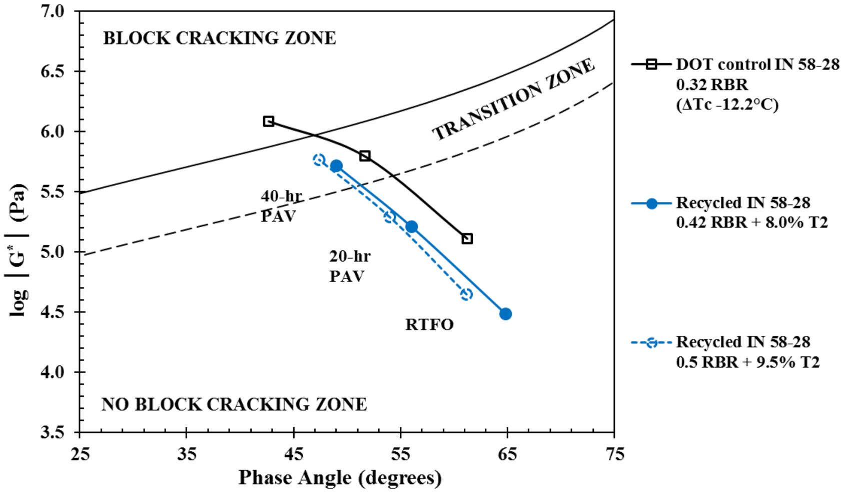


Figure 24. |G*| and δ in Black space for the recycled and rejuvenated binder blends with a target PG 64-22 climate.

Finally, Figure 25 presents the Black space results for the recycled and rejuvenated binder blends for a target PG 58-28 climate, which also shows the effectiveness of the recycling agent V2 in decreasing the $|G^*|$ and increasing δ values, and yielding binder blends below the Transition Zone after 40-hour PAV aging. To investigate possible rutting issues with the combination of 0.5 RBR and 9% V2, a corresponding asphalt mixture with this combination was evaluated as described subsequently.

Overall, optimization of binder blends requires proper material selection and proportioning. Considering the blending chart presented in Figure 17 and the recommended dose to meet PGH based on Equation 6, the recycling agent can be selected based on achieving the best performance with aging. In terms of G-R, for some blends the reduction in $|G^*|$ was much more dramatic as compared to the restoration of δ, raising concerns with regard to the selection and/or proportioning of materials.

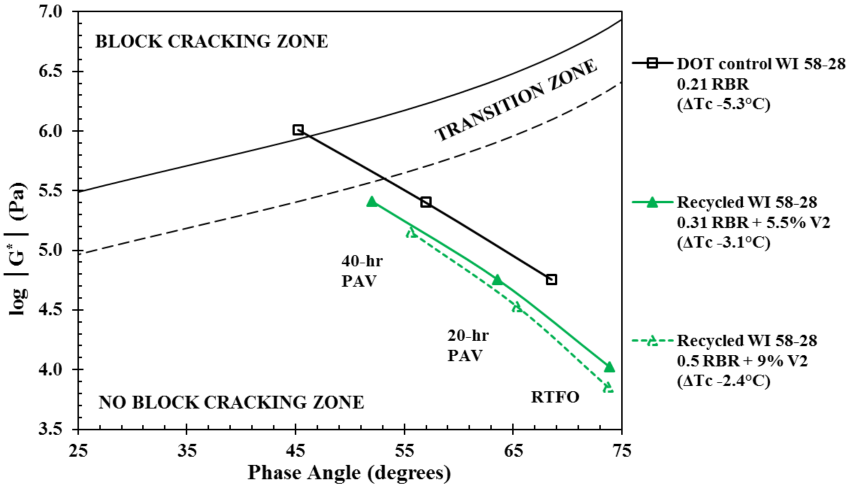


Figure 25. |G*| and δ in Black space for the recycled and rejuvenated binder blends with a target PG 58-28 climate.

Performance Characteristics of Recycled Mixtures

The previous discussions focused on characterization of recycled and rejuvenated binder blends. However, at the mixture level, while the binder is a key component, the mixture properties control performance. In order to address the concerns regarding binder versus mixture characterization, and the possible incomplete blending between base, RAP, and RAS binders with the recycling agent, evaluation of rejuvenated asphalt mixtures is important.

Materials Selection

A number of materials combinations from Table 9 were selected to produce asphalt mixtures. The base binders, recycled materials, and recycling agents were collected from three field projects in TX, IN, and WI, with two additional base binders from NH and MN. The characteristics of the asphalt mixtures are listed in Table 10. Gray shading indicates DOT control mixtures with the recycled materials contents within the maximum allowable limit per current TX, IN, and WI DOTs specifications. The mixtures in Table 10 were selected to see if the recycling agent at the doses needed to match continuous PGH could facilitate the use of higher quantities of recycled materials (higher RBR) as compared to the DOT control mixtures (lower RBR), without sacrificing long-term performance.

Specimen Preparation

For all asphalt mixtures shown in Table 10, laboratory-mixed laboratory-compacted (LMLC) specimens were fabricated. The virgin aggregate was heated overnight at the mixing temperature, and then combined with the recycled materials two hours prior to mixing. The base (virgin) binder was heated at the mixing temperature two hours prior to mixing, and the recycling agent (if used) was blended with the base binder 10 minutes prior to mixing with the virgin aggregate and recycled materials. The loose mixtures were short-term oven aged (STOA) for two hours at 135°C prior to compaction, and the compacted specimens were long-term oven aged (LTOA) for 5 days at 85°C per AASHTO R 30.

Mixture Laboratory Tests

The Asphalt Pavement Analyzer (APA) that meets all provisions for AASHTO T324 in dry condition was used to investigate rutting susceptibility of the recycled mixtures with high recycling agent doses.

Table 10. Materials Characteristics of the Recycled and Rejuvenated Asphalt Mixtures.

Target Climate	**Base Binder PG**	**Mixture Label**	**Binder Content (%)[1]**	**Total RBR**	**RAP Binder RBR (source)**	**MWAS Binder RBR (source)**	**TOAS Binder RBR (source)**	**RAP/RAS Content[2]**	**Recycling Agent Type and Dose (%)[3]**
PG 70-22 (Texas)	TX 64-22	DOT control TX 64-22 0.28 RBR	4.9	0.28	0.1 (TX)	0.18 (TX)	—	10% RAP 5% RAS	—
	MN 58-28	Recycled MN 58-28 0.5 RBR + 16.5% V1		0.5	0.25 (TX)	—	0.25 (TX)	23% RAP 6.5% RAS	16.5 V1
	NH 64-28	Recycled NH 64-28 0.5 RBR(TX) + 14% T1		0.5	0.4 (TX)	—	0.1 (TX)	37% RAP 2.5% RAS	14.0 T1
		Recycled NH 64-28 0.5 RBR + 14% V2						37% RAP 2.5% RAS	14.0 V2
PG 64-22 (Indiana)	IN 58-28	DOT control IN 58-28 0.32 RBR	5.8	0.32	0.25 (IN)	0.07 (IN)	—	28% RAP 2% RAS	—
		Recycled IN 58-28 0.42 RBR + 8.0% T2		0.42	0.28 (IN)	0.14 (IN)	—	31% RAP 4% RAS	8.0 T2
		Recycled IN 58-28 0.5 RBR + 9.5% T2		0.5	0.36 (IN)	0.14 (IN)	—	40% RAP 4% RAS	9.5 T2
PG 58-28 (Wisconsin)	WI 58-28	DOT control WI 58-28 0.21 RBR	5.6	0.21	0.21 (WI)	—	—	27% RAP	—
		Recycled WI 58-28 0.31 RBR + 5.5% V2	5.4	0.31	0.31 (WI)	—	—	36% RAP	5.5 V2
		Recycled WI 58-28 0.5 RBR + 9% V2		0.5	0.5 (WI)			58% RAP	9.0 V2

[1] Total binder in the mixture (base + recycled)
[2] Percentage of total weight of the mixture
[3] Percentage of total binder in the mixture

Resilient Modulus (M_R) was measured for stiffness characterization in accordance with ASTM D7369 (Standard Test Method for Determining the Resilient Modulus of Bituminous Mixtures by Indirect Tension Test) with the linear variable differential transducers (LVDTs) externally attached across the diameter of the cylindrical specimen of 150 mm diameter and 61 mm height with air void content of 7.0 ± 0.5%. During the test, a repetitive haversine compressive load was applied in the vertical diametral plane of the cylindrical specimen, and the horizontal deformation occurring in the specimen registered through the LVDTs, and used to calculate M_R. The test was conducted at a temperature of 25°C.

The Illinois Flexibility Index Test (I-FIT) was performed for intermediate-temperature cracking resistance in accordance with AASHTO TP 124. The cylindrical specimens from the M_R test were utilized to prepare the semicircular test specimens with a notch along the axis of symmetry 15 mm deep. During the test, a monotonic load was applied in a three-point bending configuration along the vertical radius of the specimen at a rate of 50 mm/min until failure. The load and load line displacement were measured during the test, and the load-displacement curve was plotted. The flexibility index (FI), the primary output parameter from the I-FIT, was calculated. The air void content of the specimens was 7.0 ± 0.5%, and the test was performed at 25°C. Asphalt mixtures with higher FI values are expected to have better cracking resistance than those with lower FI values. A number of studies have reported that the FI is sensitive to the inclusion of RAP, RAS, and recycling agents and that it correlates well with field cracking performance (Al-Qadi et al. 2015; Yin et al. 2017; Kaseer et al. 2017b).

The Bending Beam Rheometer for Asphalt Mixtures (BBR_m) was performed for low-temperature cracking resistance in accordance with AASHTO TP 125. Thin beams (12.7 mm wide, 6.35mm thick, and 127 mm long) were prepared from cylindrical specimens and tested in the BBR. The testing temperature equals the PGL of the target binder + 10°C. Romero (2016) plotted the low-temperature mixture Black space diagram using creep modulus (S) and m-values from the BBR_m and developed tentative thresholds based on field performance of seven field projects in Utah. These tentative thresholds for S and m value proposed by Romero (2016) may not be applicable to mixtures with different target climates but were used in this study for comparing the various mixtures against the same limits.

For most of the mixtures shown in Table 10, two replicates were considered for the APA, three replicates for the M_R test, a minimum of four replicates for the I FIT, and a minimum of five replicates for the BBR_m test. To compare the M_R and I FIT results, a statistical analysis at a 95% confidence level was performed including analysis of variance (ANOVA) and Tukey’s honestly significant differences (HSD).

Short - and Long Term Performance of Recycled and Rejuvenated Asphalt Mixtures

The APA was used to investigate rutting susceptibility of TX mixtures with 0.5 RBR that yielded high recycling agent doses. The first mixture employed the MN PG 58-28 and 16.5% V1 with an unbalanced combination of 0.25 RAP + 0.25 TOAS, and the second mixture utilized the NH PG 64-28 and 14.0% V2 with a balanced combination of 0.4 RAP + 0.1 TOAS. According to the rejuvenated binder blends results, both mixtures were designed to have a continuous PGH of 70°C.

APA test results showed that the mixture with 16.5% V1 significantly failed the minimum rutting requirements with a rut depth of 12.5 mm after about 4,800 load cycles at a test temperature of 50°C. Usually, mixtures with a target PG 70-XX climate are required to sustain at least 15,000 load cycles before achieving a 12.5 mm rut depth (TxDOT 2014). However, the mixture with 14% V2 (with a balanced RBR combination with more RAP and less RAS) passed the minimum rutting requirements with a rut depth of 12.5 mm after about 16,500 load cycles at a test temperature of 50°C.

Even though both mixtures with balanced and unbalanced combinations of RAP/RAS were designed to have a continuous PGH in the recycled binder blend of 70°C, and both had similar recycling agent doses (14.0 versus 16.5%) of vegetable oils, the APA results showed different rutting susceptibility. These results highlighted the importance of producing asphalt mixtures with balanced RAP/RAS proportions, with limited RAS content.

The APA was also used to investigate rutting susceptibility of the WI recycled mixture with 0.5 RAP only and 9.0% V2 after STOA. This mixture represented the worst possible case for rutting susceptibility due to the use of a soft base binder (PG 58-28) and high recycling agent dose of 9.0%. APA results of two replicates demonstrated that the mixture passed the minimum rutting requirements with a rut depth of 12.5 mm after about 11,000 load cycles. Usually, mixtures with a target PG 58-XX climate are required to sustain at least 5,000 load cycles before achieving a 12.5 mm rut depth (WisDOT). This result confirmed that the dose to match continuous PGH of the target climate (PG 58-28 in this case) was not excessive in terms of being detrimental to the rutting performance of the corresponding recycled asphalt mixture.

Figure 26 and Figure 27 present M_R and I-FIT test results of TX, IN and WI mixtures for both STOA and LTOA specimens. For each mixture, the stacked shaded column represents the M_R and FI after STOA, and the stacked hatched column represents the M_R and FI after LTOA. The error bars on each column represent ± one standard deviation from the average value based on the replicate measurements, and the letters inside each column represent Tukey's HSD in which mixtures with a dissimilar letter are considered significantly different.

M_R stiffness results shown in Figure 26 demonstrated that adding a recycling agent at the dose to match continuous PGH facilitated the use of higher quantities of recycled materials (0.5 RBR for TX, 0.42 and 0.5 RBR for IN, and 0.31 and 0.5 RBR for WI) as compared to the DOT control mixtures (0.28 RBR for TX, 0.32 RBR for IN, and 0.21 RBR of WI) as demonstrated by the statistically lower or equivalent stiffness regardless of aging level. Particularly for TX mixtures where the recycling agent facilitated the use of almost double the RBR of the DOT control mixture, with the use of the heavily aged TOAS versus the MWAS used in the DOT control mixture.

I-FIT results shown in Figure 27 demonstrated that adding a recycling agent at the dose to match continuous PGH facilitated the use of higher quantities of recycled materials for TX, IN, and WI mixtures with statistically equivalent or better cracking resistance as compared to the DOT control mixtures regardless of aging level.

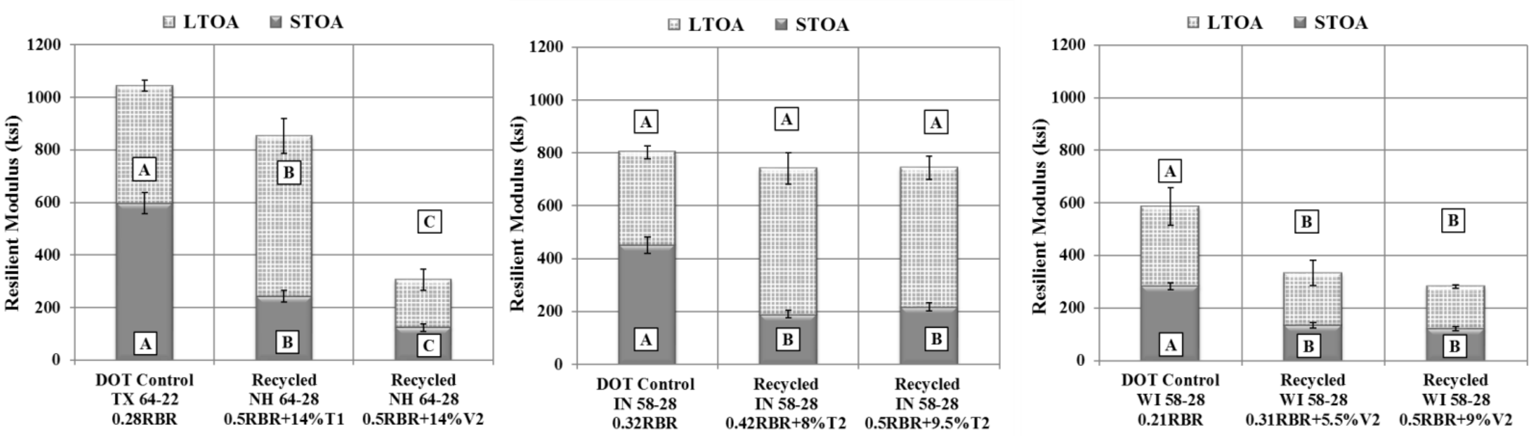


Figure 26. M_R Stiffness results for TX, IN and WI mixtures respectively.

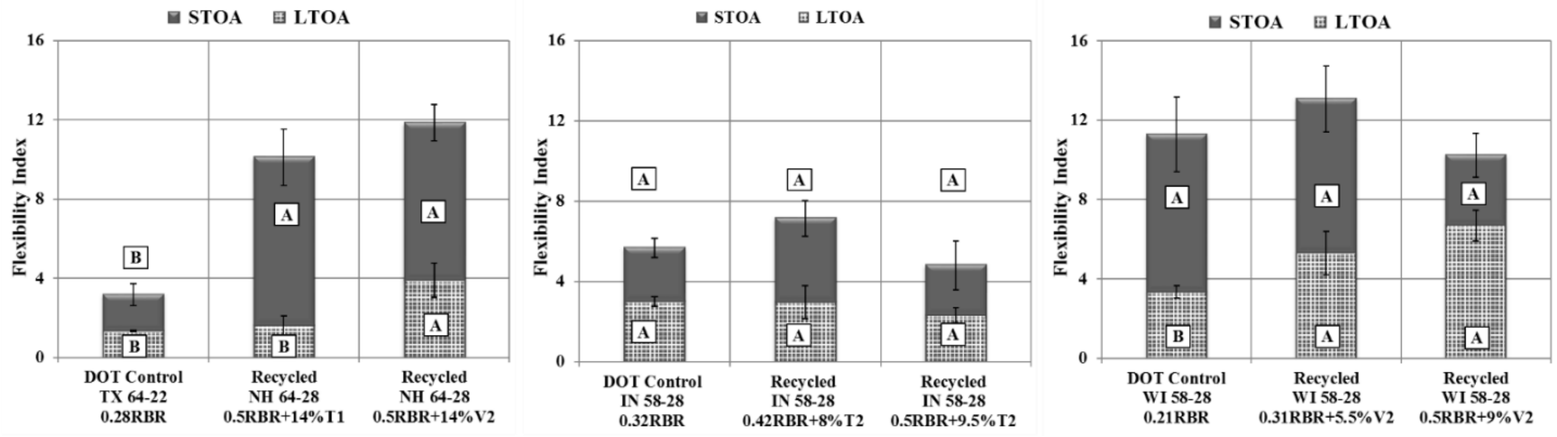


Figure 27. I-FIT results for intermediate-temperature cracking resistance for TX, IN and WI mixtures respectively.

The low-temperature mixture Black space diagram is shown in Figure 28 along with the cracking thresholds developed by Romero (2016). The BBR_m results had reasonable variability, with coefficients of variation (COV) of S and m-value of 20% or less. The empty symbols represent the STOA results, and the filled symbols represent the LTOA results.

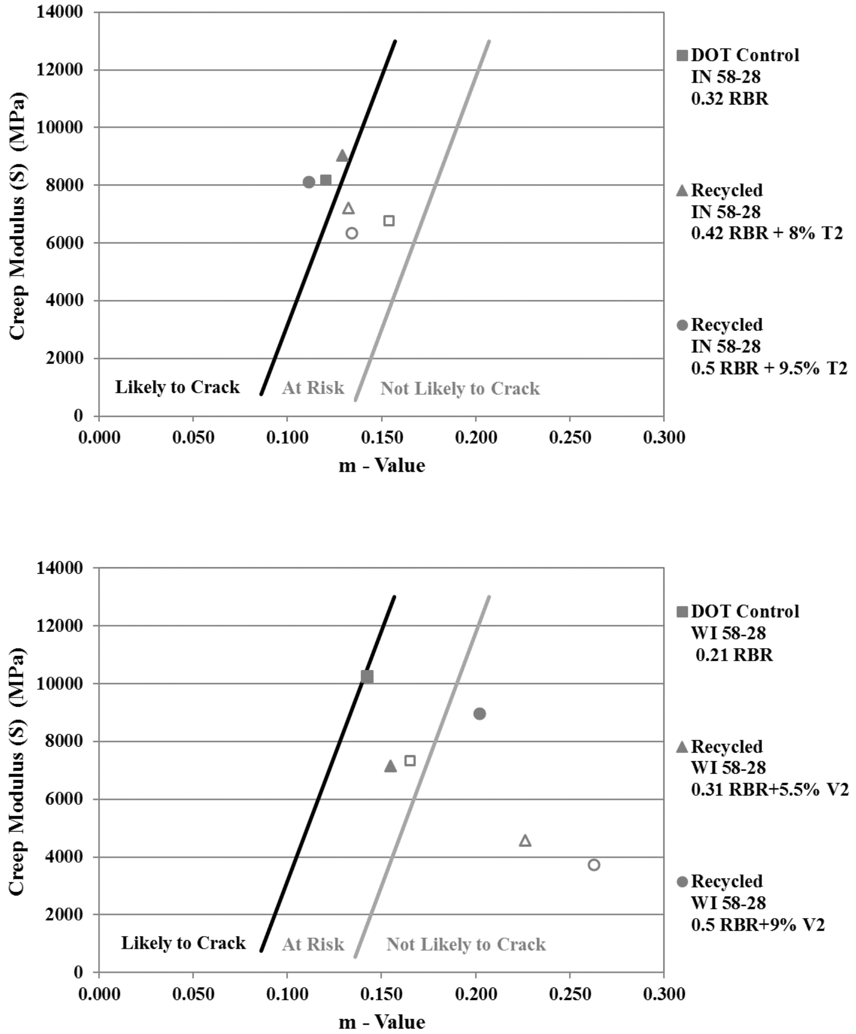


Figure 28. BBR_m results for low-temperature cracking resistance for IN and WI mixtures respectively.

For IN mixtures after STOA, the DOT control mixture and the mixtures with recycling agent were all in the “at risk” zone. After LTOA, the DOT control mixture and the mixtures with recycling agent were close to each other, and in the “likely to crack” zone, indicating comparable low-temperature cracking performance. For WI mixtures and after STOA, the DOT control mixture was in the “at risk” zone, while the mixtures with recycling agent were in the “not likely to crack” zone. After LTOA, the DOT control mixture moved toward the “likely to crack” zone, the recycled mixture with 5.5% recycling agent was in the “at risk” zone, and the recycled mixture with 9.0% recycling agent was still in the “not likely to crack” zone, indicating better low-temperature cracking performance than the DOT control that had less RBR. The tentative cracking thresholds from Romero (2016) may not be applicable to IN and WI mixtures, and therefore cannot indicate possible cracking in the field, but were used for comparing the various mixtures against the same limits.

Balancing RAP/RAS Combinations and Controlling Maximum Recycling Agent Dose

Blend preparation described previously results in complete and uniform blending of the base binder, recycled binder, and recycling agent. Such conditions may not represent recycled asphalt mixture production, in the laboratory or in the field, since part of the recycled binder may not be available to blend completely with the base binder and the recycling agent during mixing, particularly for stiffer materials such as those containing RAS (Mogawer et al. 2013b). Mixing temperatures of asphalt mixtures were designed to ensure uniform distribution of the base (virgin) binder to coat the aggregates uniformly. It is difficult to increase mixing temperatures to promote a more uniform distribution of RAP and/or RAS binders since that would require extremely high temperatures to make the binders in those materials fluid, which may not be practical, and more importantly, will accelerate the aging of the base binder (Zhou et al. 2013).

For example, for an IN PG 58-28 binder the mixing temperature ranges between 150–157°C (302–315°F) according to the viscosity guidelines in the Asphalt Institute Superpave Mix Design (SP-2). At that mixing temperature, it is possible that the IN RAP binder with a PGH 90.4°C will not be fluid enough to fully blend with the base binder and completely coat the aggregate, but a partial blending will occur, and can be enhanced by a recycling agent if available. In contrast, at the same mixing temperature, a MWAS binder with a PGH 123.3°C will probably not be fluid enough to even partially blend with the base binder, yielding a recycled mixture with less available binder and possibly leading to cracking susceptibility. Even if a recycling agent is introduced, a significant portion of MWAS binder may not blend with the binder available in the mixture, and thus, a larger proportion of the MWAS could act as a “black rock”. In this case, the recycling agent will likely over soften the base binder. An excess of 3-4% recycling agent that instead of blending with and softening the recycled binders, will over softens the base binder and could lead to a reduction in PGH of the recycled blend by about 7.3°C (roughly a full PG or more) based on the slope of the blending charts presented previously in Figure 20.

The comparison between the mixture with the balanced combination (0.4 RAP + 0.1 TOAS) versus the mixture with the unbalanced combination (0.25 RAP + 0.25

TOAS) provides an example in line with the concept of binder availability previously described. Both combinations have a continuous PGH of 70°C, both have similar doses of vegetable oils, and both showed comparable $|G^*|$ and δ values in the binder blends Black space as shown in Figure 23 (b) and (c). However, different rutting behavior was observed in corresponding mixtures, where the mixture with larger proportion of TOAS (assumed to be less likely to blend with the recycling agent and base binder) exhibited significantly higher rutting.

Epps Martin et al. (2017) reported that the total RBR should be controlled and a maximum RBR for RAS materials should be considered to ensure adequate mixture performance at recycling agent doses up to approximately 10-15% based on an economic analysis. The economic analysis identified cost savings associated with increasing RAP contents in asphalt mixtures from 20 to 40%, and assumed that mixtures with 40% RAP and 10% recycling agent yielded equivalent pavement service life as virgin mixtures. When considering the price/cost information for transportation of materials, base (virgin) binders, virgin aggregates, RAP, and recycling agents, the additional saving associated with increasing the RAP content from 20 to 40% was about $10.00 per ton of asphalt mixture or about 15% of the production cost.

In summary, using recycling agents is a cost effective method to increase the RBR when the dose is around 10%, and these recycled asphalt mixtures are expected to have adequate short- and long-term performance based on laboratory results (Epps Martin et al. 2017). Based on Figure 20, a 10% recycling agent dose indicates a maximum PGH of the recycled blend of 87 and 81°C for target climates of 70 and 64, respectively, which equals PGH_{Target} + 17°C. RBRs in recycled asphalt mixture should be controlled to yield this level of PGH or lower, and blending charts presented in Figure 17 and expressed in Equation 4 can be used for this purpose.

Conclusions

This chapter provided tools for estimating recycling agent dose based on a target climate with minimum laboratory efforts by considering the type, source, and amount of the recycled materials, and the source and grade of the base binder. Blending charts of base and recycled binders were established and verified, and later used to develop relationships to estimate the optimum dose of the recycling agent. The recycling agent optimum doses were determined such that the continuous PGH of the recycled binder blend matches that of the target climate, as this dose yielded the best performance for rejuvenated binders and mixtures.

This approach, of using blending charts and estimating recycling agent dose, was promising in optimizing the rejuvenated binder blends considering an ideal scenario of complete blending. The approach was validated at the mixture level, and cracking resistance was improved while a rutting problem was noticed in only one situation where an excessive amount of RAS was utilized, which highlighted the importance of optimizing the RAP/RAS combination (toward more RAP and less RAS), and also highlighted the importance of evaluating rutting susceptibility of rejuvenated asphalt mixtures after STOA.

The findings in terms of binder blend and mixture performance ranked in various tests after long-term aging are summarized in Table 11, suggesting an overall reasonable agreement between binder blend and mixture level results. The TX and IN DOT control binder blends which exhibited poor performance in terms of G-R and ΔT_c also performed poorly at the mixture level considering various experiments (except IN DOT I-FIT results which indicated marginal performance). The WI DOT binder blend showed marginal G-R values and poor ΔT_c and similarly at the mixture level ranked marginally by M_R and I-FIT; and poorly with BBR_m. The comparison across rejuvenated binder blends and mixtures resulted in variable conclusions; while several binder blends and mixtures ranked similarly (specifically when recycling agent V2 was used: TX 0.5RBR + 14%V2, WI 0.31RBR + 5.5%V2, and WI 0.5RBR + 9% V2), others ranked inconsistently (TX 0.5RBR + 14%T1, IN 0.42RBR + 8%T2, and IN 0.5RBR+9.5%T2). It is important to reconcile that the uniformity and homogeneity of a rejuvenated binder blend does not represent field conditions. For a more definitive/reliable answer regarding long-term mixture performance, LTOA and performance testing at the mixture level is recommended.

Practice Ready Recommendations

This study presented a robust experimental matrix including a variety of materials, aging conditions, and experimental methods at a range of binder blend and asphalt mixture levels in order to produce practice-ready guidelines for evaluation and design of recycling projects with minimal testing requirements. The following tools are available to practitioners:

1. Estimate PGH of recycled blends with different RBR using a blending chart that requires only measured PGH for base and recycled binders.

2. Estimate required recycling agent dose using a blending chart to rejuvenate to a target PG climate based on the estimated PGH of any given recycled blend.
3. Recommend balanced RAP/RAS combination for improved performance, and considering economic aspects a maximum PGH of PGH_{Target} + 17°C is suggested in order to rejuvenate effectively with up to 10% recycling agent.
4. Conduct long-term performance evaluation at the mixture level.

The empirical methodologies presented as blending charts may not be the most accurate for use in mechanistic type models, but certainly provide sufficiently accurate information for preliminary designs, decision making, and economic evaluation for recycling projects considering available materials. For validating a mixture design and/or obtaining mechanical properties with the purpose of modeling performance, it is recommended to characterize and verify the quality of the mixture.

Table 11. Performance Summary of Recycled and Rejuvenated Blends and Mixtures.

Target Climate	**Performance Ranking**	**Short-Term Aging**	**Long-Term Aging**				
		APA	**Binder G-R (40-hour PAV)**	**Binder ΔT_c (20-hour PAV[1])**	**Mixture M_R**	**Mixture I-FIT**	**Mixture BBR_m**
70-22	Satisfactory	0.5RBR +14% V2	0.5RBR+14%V2		0.5RBR+14%V2		NA
	Marginal		0.5RBR+14%T1			0.5RBR +14%V2	
	Poor	0.5RBR + 16.5% V1	DOT control	DOT control	DOT control 0.5RBR+14%T1	DOT control 0.5RBR+14%T1	
64-22	Satisfactory	NA	0.42RBR+8%T2 0.5RBR+9.5%T2				
	Marginal				0.42RBR+8%T2 0.5RBR+9.5%T2	DOT control 0.42RBR+8%T2 0.5RBR+9.5%T2	
	Poor		DOT control	DOT control	DOT control		DOT control 0.42RBR+8%T2 0.5RBR+9.5%T2
58-28	Satisfactory	0.5RBR+9%V2	0.31RBR+5.5%V2 0.5RBR+9%V2		DOT control 0.31RBR+5.5%V2 0.5RBR+9%V2	0.31RBR+5.5%V2 0.5RBR+9%V2	0.5RBR+9%V2
	Marginal		DOT control	0.31RBR+5.5%V2 0.5RBR+9%V2		DOT control	0.31RBR+5.5%V2
	Poor			DOT control			DOT control
Performance Guidelines[2]	Satisfactory	Maximum rut depth at minimum load cycles per climate PG	< 600 kPa	> 0	< 600 ksi	> 4	Not Likely to Crack
	Marginal		Slightly passed 600 kPa	0 to -5	600 to 800 ksi	2 to 4	At Risk
	Poor		>> 600 kPa	< -5	> 800 ksi	< 2	Likely to Crack

[1] ΔT_c values are not available for some rejuvenated binder blends

[2] M_R and I-FIT guidelines are based on the differences in the HSD statistical analysis

References

Abatech Inc. 2011. RHEA, Blooming Glen, Pennsylvania.

Al-Qadi, I. L., et al., *"Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS,"* Report No. FHWA-ICT-15-017, Illinois Center for Transportation, Urbana, IL, 2015, 80 pp.

Anderson, R. M., G. N. King, D. I. Hanson, and P.B. Blankenship, "Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking." *Journal of the Association of Asphalt Paving Technologists*, Vol. 80, 2011, pp. 615-649.

Arámbula-Mercado, E., F. Kaseer, A. Epps Martin, F. Yin, and L. Garcia Cucalon, "Evaluation of Recycling Agent Dosage Selection Methods for Asphalt Mixtures with High RAP and RAS Contents," *Construction and Building Materials*, Vol. 158, 2018, pp. 432-442.

Carvajal Munoz, J. S., F. Kaseer, E. Arambula, and A. Epps Martin, "Use of the Resilient Modulus Test to Characterize Asphalt Mixtures with Recycled Materials and Recycling Agents," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2506, 2015, pp. 45–53.

Epps Martin, A. et al. *"The Effects of Recycling Agents On Asphalt Mixtures with High RAS and RAP Binder Ratios,"* NCHRP Interim Report, National Cooperative Highway Research Program, 2015, Washington, DC.

Epps Martin, A. et al. *"The Effects of Recycling Agents On Asphalt Mixtures with High RAS and RAP Binder Ratios,"* NCHRP Interim Report, National Cooperative Highway Research Program, 2017, Washington, DC.

Garcia Cucalon, L., F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, N. Morian, S. Pournoman, E. Hajj, and C. Glover, "The Crossover Temperature: Significance and Application Towards Engineering Balanced Recycled Binder Blends," Petersen Asphalt Research Conference, 2017(a), Laramie, WY.

Garcia Cucalon, L., G. King, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, T. Turner, and C. Glover, "Compatibility of Recycled Binder Blends with Recycling Agents: Rheological and Physicochemical Evaluation of Rejuvenation and Aging Processes," *Journal of Industrial & Engineering Chemistry Research*, Vol. 56, Iss. 29, 2017, pp. 8375–8384. 2017(b).

Hajj, E. Y., P. E. Sebaaly, and R. Shresta, “Laboratory Evaluation of Mixes Containing Recycled Asphalt Pavement (RAP),” *International Journal of Road Materials and Pavements Design,* Vol. 10, No. 3, 2009.

Hussain, A., and Q. Yanjun, “Evaluation of Asphalt Mixes Containing Reclaimed Asphalt Pavement for Wearing Courses,” International Conference on Traffic and Transportation Engineering (ICTTE), 2012, pp. 43-48.

Im, S., F. Zhou, R. Lee, and T. Scullion, “Impacts of Rejuvenators on Performance and Engineering Properties of Asphalt Mixtures Containing Recycled Materials,” *Construction and Building Materials,* Vol. 53, 2014, pp. 596-603.

Kandhal, P. S., “Low-Temperature Ductility in Relation to Pavement Performance,” *American Society for Testing and Materials,* 1977, Philadelphia, PA.

Karki, P., and F. Zhou, “Effect of Rejuvenators on Rheological, Chemical, and Aging Properties of Asphalt Binders Containing Recycled Binders.” *Transportation Research Record: Journal of the Transportation Research Board,* No. 2574, 2016, pp. 74-82.

Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin, “Characterization of Asphalt Mixtures with High RAP/RAS Contents and Recycling Agents,” 96th Annual Meeting of the Transportation Research Board, 2017(b), Washington, DC.

Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin, “Stiffness Characterization of Asphalt Mixtures with High Recycled Materials Contents and Recycling Agents.” *Transportation Research Record: Journal of the Transportation Research Board,* No. 2633, 2017(a), pp. 58-68.

Li, X., M. O. Marasteanu, R.C. Williams, and T.R. Clyne, “Effect of RAP (Proportion and Type) and Binder Grade on the Properties of Asphalt Mixtures,” *Transportation Research Record: Journal of the Transportation Research Board,* No. 2051, 2008, pp. 90-97.

Menapace, I., L. Garcia Cucalon, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, E. Masad, and G. King, “Effect of Recycling Agents in recycled asphalt binders observed with microstructural and rheological tests,” *Construction and Building Materials,* 2017, forthcoming.

Mogawer, W., A. Austerman, L. Mohammad, and M.E. Kutay, “Evaluation of High RAP WMA Asphalt Rubber Mixtures,” *Road Materials and Pavement Design,* Vol. 14, 2013(a), pp. 129-147.

Mogawer, W., A. Booshehrian, S. Vahidi, and A.J. Austerman, “Evaluating the Effect of Rejuvenators on the Degree of Blending and Performance of High RAP, RAS, and

RAP/ RAS Mixtures," *Road Materials and Pavement Design,* Vol. 14, Supplement 2, 2013(b), pp. 193-213.

Mogawer, W., T. Bennert, J. Daniel, R. Bonaquist, A. J. Austerman, and A. Booshehrian, "Performance Characteristics of Plant Produced High RAP Mixtures," *Road Materials and Pavement Design,* Vol. 13, 2012, pp. 183-208.

National Center for Asphalt Technology (NCAT), "How Should We Express RAP and RAS Contents?" Asphalt Technology News, Vol. 26, No. 2, 2014, https://eng.auburn.edu/research/centers/ncat/info-pubs/newsletters/atnfall2014.pdf (As of August 15, 2017).

Petersen, J. C, "A Review of the Fundamentals of Asphalt Oxidation," *Transportation Research Circular E-C140; Transportation Research Board,* 2009, Washington, DC, pp 1−78.

Romero, P., *"Using the Bending Beam Rheometer for Low Temperature Testing of Asphalt Mixtures,"* Report UT- 16.09, Utah Department of Transportation, Salt Lake City, 2016, 70 p.

Rowe, G., "Understanding Cracking Performance with Linear Visco-Elastic Parameters," Petersen Asphalt Research Conference, 2017, Laramie, WY.

Rowe, G., Prepared discussion for the AAPT paper by Anderson et al. "Evaluation of the Relationship Between Asphalt Binder Properties and Non-Load Related Cracking," *Journal of the Association of Asphalt Paving Technologists,* Vol. 80 ,2011, pp. 649-662.

Shen, J., and Y. Ohne, "Determining Rejuvenator Content for Recycling Reclaimed Asphalt Pavement by SHRP Binder Specifications," *The International Journal of Pavement Engineering,* Vol. 3, No. 4, 2002, pp. 261-268.

Shen, J., S. Amirkhanian, and J.A. Miller, "Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement," *Journal of Materials in Civil Engineering,* Vol. 19, No. 5, 2007, pp. 376-384.

Tabatabaee, H. A., and T. L. Kurth, "Analytical investigation of the impact of a novel bio-based recycling agent on the colloidal stability of aged bitumen," *Road Materials and Pavement Design,* Vol. 18, 2017, pp 131-140.

Texas Department of Transportation. Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges. 2014, Austin, Texas.

Tran, N. H., A. Taylor, and R. Willis, *"Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents,"* NCAT Report 12-05, National Center for Asphalt Technology, Auburn, AL, 2012, 70 pp.

Wisconsin Department of Transportation. Standard Specifications, 2017, Madison, Wisconsin.

Xie, Z., P. Turner, A. Taylor, and N. Tran, *"Laboratory Evaluation of Performance Properties of Asphalt Binders and Mixtures Containing POET Green Chemistry Rejuvenator,"* NCAT Report 17-17, National Center for Asphalt Technology, Auburn, AL, 2017, 81 pp.

Xinjun, L., M. Marasteanu, R. Christopher Williams, and T. Clyne, "Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures," *Transportation Research Record: Journal of the Transportation Research Board,* No. 2051, 2008, pp. 90-97.

Yan, J., Z. Zhang, H. Zhu, F. Li, and Q. Liu, "Experimental Study of Hot Recycled Asphalt Mixtures with High Percentages of Reclaimed Asphalt Pavement and Different RAs," *ASTM Journal of Testing and Evaluation,* Vol. 42, No. 5, 2014.

Yin, F., F. Kaseer, E. Arámbula-Mercado, and A. Epps Martin, "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,* 2017.

Zaumanis, M., R. Mallick, and R. Frank, "Determining Optimum Rejuvenator Dose for Asphalt Recycling Based on Superpave Performance Grade Specifications," *Construction and Building Materials,* Vol. 69, 2014, pp. 159-166.

Zaumanis, M., R. Mallick, and R. Frank, "Evaluation of Rejuvenator's Effectiveness with Conventional Mix Testing for 100% Reclaimed Asphalt Pavement Mixtures," *Transportation Research Record: Journal of the Transportation Research Board,* No. 2370, 2013, pp. 17-25.

Zhou, F., L. Hongsheng, S. Hu, J. Button, and J. Epps, "*Characterization and Best Use of Recycled Asphalt Shingles in Hot-Mix Asphalt,"* Report No. FHWA/TX-13/0-6614-2, Texas Transportation Institute, College Station, TX, 2013, 88 pp.

Zhou, F., S. Hu, G. Das, and T. Scullion, *"High RAP Mixes Design Methodology with Balanced Performance."* Report No. FHWA/TX-11/0-6092-2, Texas Transportation Institute, College Station, Texas, 2011, 46 p.

Zhou, F., S. Im, D. Morton, R. Lee, S. Hu, and T. Scullion, “Rejuvenator Characterization, Blend Characteristics, and Proposed Mix Design Method.” *Journal of the Association of Asphalt Paving Technologists,* Vol. 74, 2015, pp. 675-704.

CHAPTER V

PERFORMANCE OF ASPHALT MIXTURES WITH HIGH RECYCLED MATERIALS CONTENT AND RECYCLING AGENTS[4]

Overview

The use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in asphalt mixtures can reduce construction costs, maintain dwindling natural resources, conserve valuable landfill space, and improve sustainability. State Departments of Transportation (DOTs) and contractors alike have long recognized these benefits. In the U.S., the total estimated RAP tonnage used in asphalt mixtures in 2016 was 76.9 million tons, and this represents more than 3.8 million tons (21.5 million barrels) of asphalt binder conserved, along with the replacement of about 73 million tons of virgin aggregate. The total estimated amount of RAS used in asphalt mixtures in 2016 was about 1.4 million tons. The combined savings of asphalt binder and aggregate from using RAP and RAS in asphalt mixtures is estimated at more than $2.2 billion (Hansen and Copeland 2017).

While the average amount of RAP used in recycled asphalt mixtures in the U.S. is about 20 percent, in other countries like Japan, for instance, the average amount of RAP is about 47 percent (Hansen and Copeland 2017, West and Copeland 2015). As the

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percentage of RAP and/or RAS increases in asphalt mixtures, their economic and environmental benefits also increase. However, utilization of higher amounts of these aged materials presents concerns that the recycled asphalt mixtures could be less workable and difficult to compact during construction, and more prone to cracking during the service life of the pavement due to their stiff, brittle nature (Kim *et al.* 2007, Mogawer *et al.* 2012, Carvajal Munoz *et al.* 2015, Kaseer *et al.* 2017). To accommodate the aged and substantially stiffer binder in RAP and RAS, and thus provide adequate performance in the field, some adjustments to the recycled asphalt mixtures should be considered, including using a softer virgin or base binder measured in terms of performance grade (PG), using recycling agents, or a combination of both.

The use of rejuvenators or recycling agents has gained attention in recent years due to increased product availability, ease of addition to asphalt mixtures, and their cost-effectiveness when high amounts of recycled materials are utilized. A number of studies showed that recycling agent addition can reduce the viscosity, stiffness, and embrittlement of RAP/RAS aged asphalt binders, and increase their ductility (Kaseer *et al.* 2018a, Garcia Cucalon *et al.* 2018, Menapace *et al.* 2018a). Many studies have shown that adding recycling agents to recycled asphalt mixtures can significantly reduce their stiffness. In some cases, with the use of an appropriate recycling agent dose, the stiffness of the recycled asphalt mixtures can be equivalent to that of a virgin mixture without recycled materials (Tran *et al.* 2012, Mogawer *et al.* 2013, Carvajal Munoz *et al.* 2015, Kaseer *et al.* 2017). Other studies have shown the effectiveness of recycling agents in improving the cracking resistance of recycled asphalt mixtures, by mitigating the brittleness of the recycled binder in the RAP and RAS (Mogawer *et al.* 2013, Im *et al.* 2014, Yan *et al.* 2014, Kaseer *et al.* 2018b). However, recent studies suggest that the reduction in stiffness and improvement in cracking resistance of recycled binder blends (base binder plus recycled binders) and recycled asphalt mixtures due to the addition of recycling agents diminishes with long-term aging, particularly when low recycling agent doses are utilized (Yin *et al.* 2017, Kaseer *et al.* 2017, Kaseer *et al.* 2018b, Menapace *et al.* 2018b). The long-term effectiveness of the recycling agent in recycled binder blends and recycled asphalt mixtures depends on a number of mix design factors such as the type, source, and amount of recycled materials (RAP/RAS); the type and dose of the recycling agent; and the source and grade of the base binder (Garcia Cucalon *et al.* 2017, Kaseer *et al.* 2018a, Garcia Cucalon *et al.* 2018). In addition, the effectiveness of the recycling agent depends also on production factors such as mixing time and temperature, and the method by which the recycling agent is incorporated in the mixture (i.e., added to the base binder or added directly to the recycled materials).

Among these factors, special emphasis should be given to the dose of the recycling agent, because it is usually the most flexible mix design variable for the engineer to optimize (Kaseer *et al.* 2018a). Recycling agent dose balances the performance of the rejuvenated asphalt mixture (recycled asphalt mixture with recycling agent) in terms of cracking and rutting resistance. A low recycling agent dose may partially reduce the stiffness and brittleness of the recycled binder in RAP and RAS, but may not have a significant effect in improving the cracking resistance of the rejuvenated asphalt mixture. Conversely, a high recycling agent dose may soften the recycled binder but could be potentially detrimental to the rutting performance of the rejuvenated asphalt mixture, especially during its early life. The recycling agent dose can also affect the rheological and chemical changes of the rejuvenated asphalt mixture after long-term aging (Yin *et al.* 2017, Kaseer *et al.* 2017).

Typically, the recycling agent dose is selected based on experience or the recommendation of the recycling agent manufacturer. In recent research efforts, blending between base binders, recycled binders, and recycling agents has been investigated to determine the optimum dose of the recycling agent using blending charts. Some studies have used blending charts (based on the viscosity and/or penetration of the blends of the recycled binder with various doses of recycling agents) to select an optimum dose (Zaumanis *et al.* 2013, Yan *et al.* 2014). Other recent studies have used the PG system to evaluate the changes in the recycled binder due to the addition of the recycling agent and determined the minimum dose needed to restore the performance properties of the recycled binder (Shen and Ohne 2002, Shen *et al.* 2007, Tran *et al.* 2012, Zaumanis *et al.* 2014).

Various recycling agent dose selection methods were investigated by Arámbula-Mercado *et al.* (2018) for multiple materials combinations of base binders, recycled materials (RAP and RAS), recycled binder ratios (RBR), and recycling agents. RBR is the percentage of recycled binder from RAP and RAS by weight with respect to the total weight of binder in the mixture. The objective of these methods was to restore the recycled binder rheology to that of the target binder PG needed to satisfy climate and traffic requirements while guaranteeing long-term performance with aging. Recycled binders were first extracted and recovered from RAP and RAS and then combined with base binders and a recycling agent at various doses to formulate recycled binder blends at the selected RBR. The recycled binder blends were then characterized in the dynamic shear rheometer (DSR) and bending beam rheometer (BBR) to determine their PG. Linear relationships between recycling agent dose and the high-temperature PG (PGH) and low-temperature PG (PGL) of the recycled binder blends were verified. Finally, three different methods were utilized to calculate the dose of the recycling agent to: *(1)* restore PGL of the recycled binder blend to that of the required target binder, *(2)* achieve a ΔT_c value of -5°C for the recycled binder blend, and *(3)* match the continuous PGH of the recycled binder blend to that of the required target binder (Arámbula-Mercado *et al.* 2018). ΔT_c is a parameter that represents the difference in continuous PGL for stiffness and relaxation properties (i.e., the critical temperature when the creep modulus (*S)* equals 300 MPa minus the critical temperature when stress relaxation (*m*-value) equals 0.30) from BBR testing. According to Arámbula-Mercado *et al.* (2018), the first dose selection method to restore PGL yielded insufficient recycling agent doses in terms of long-term durability and cracking potential. The second method to achieve $\Delta T_c = -5°C$ yielded excessive recycling agent doses (over softening of the binder) and the corresponding rejuvenated asphalt mixtures exhibited poor rutting resistance in the Hamburg Wheel-Track Testing (HWTT). The third method to match continuous PGH, resulted in recycling agent doses between those determined by the first and second methods and provided the best results where as much recycling agent is included for durability and cracking resistance while maintaining the rejuvenated asphalt mixture rutting resistance.

These recycling agent dose selection methods were evaluated at the binder level to determine the dose to restore the rheological properties of recycled binder blends, but they were not verified at the mixture level to evaluate the long-term durability and cracking potential of corresponding rejuvenated asphalt mixtures.

Objectives

The objectives of this chapter are to:

1. Evaluate the performance of rejuvenated asphalt mixtures produced in five field projects in the U.S. that include a wide spectrum of materials (base binder PG; recycled materials content, source, and type; and recycling agent type and dose), mix design, and climate, and
2. Evaluate the performance of rejuvenated asphalt mixtures with the selected dose of recycling agent to match the continuous PGH, as proposed by Arámbula-Mercado *et al.* (2018), after short- and long-term aging.

To fulfill these objectives, field cores from each test section were procured and tested, and visual distress surveys were performed for the test sections in these five field projects. Raw materials including virgin aggregate, base binders, recycled materials, and recycling agents were collected from these field projects to prepare laboratory mixed – laboratory compacted (LMLC) specimens that replicate the rejuvenated asphalt mixtures from the test sections and to produce additional rejuvenated asphalt mixtures at the selected recycling agent dose to match the continuous PGH of the target climate.

Field Projects, Asphalt Mixtures, and Specimen Fabrication

Field Projects

In total, five field projects were included in this study. Various test sections were constructed in Texas (TX), Nevada (NV), Indiana (IN), Wisconsin (WI), and Delaware (DE), as shown in Figure 29. All pavements were in need of rehabilitation at the time of construction. Each field project had at least two test sections: *(1)* a test section with a recycled asphalt mixture that met the maximum allowable recycled materials content (maximum RBR) per the corresponding state DOT specifications without recycling agent (referred to as DOT control mixture), and *(2)* a rejuvenated mixture with recycling agent. The field recycling agent doses were determined by different methods in each state.

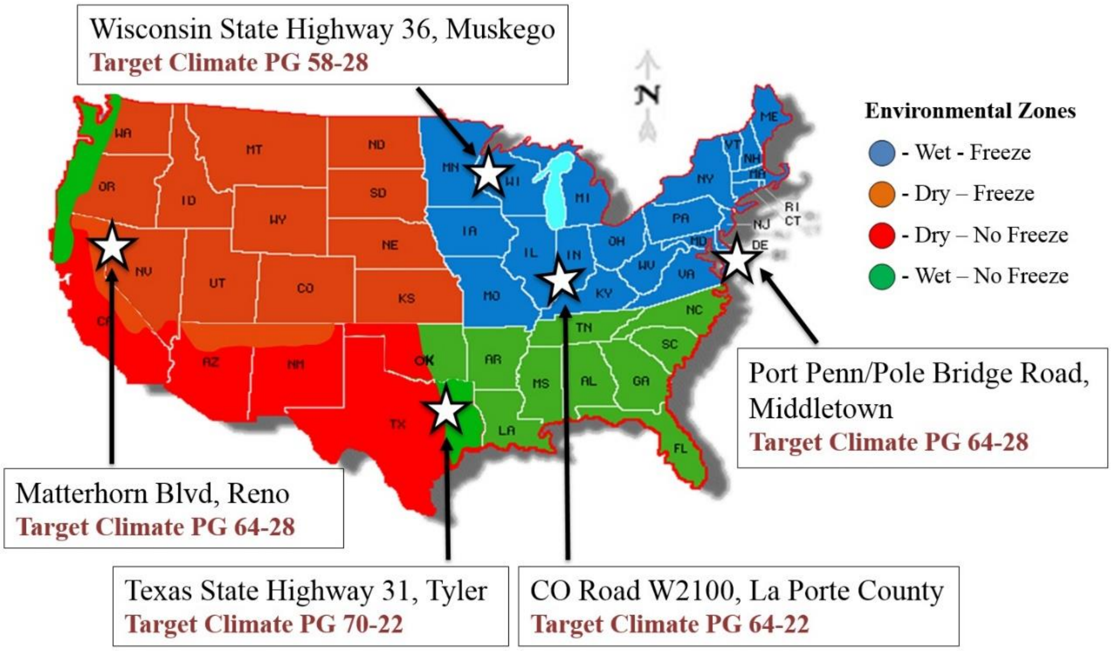

Figure 29. Constructed field projects, associated environmental zones and target binder PG for each climate.

For TX and IN, the field recycling agent doses were designed to restore PGL of the recycled binder blend to the target climate of PG XX-22; for NV and DE, the field recycling agent doses were designed to restore PGL to the target climate of PG XX-28; and for WI, the field recycling agent dose was designed to change the PG of the primary base binder in WI (PG-58-28) to that of a softer binder (PG 52-34), as the general practice is to use a softer base binder in mixtures with high recycled materials content.

Table 12 through Table 16 summarize the components and characteristics of all asphalt mixtures evaluated in this chapter, both the field test section combinations and the additional mixtures with the selected recycling agent dose to match the continuous PGH of the target climate. Gray shading indicates field test section combinations. For all asphalt mixtures within the same field project, the same virgin aggregate type and the same aggregate gradation was used. When RAP/RAS materials were included, the virgin aggregate gradation was adjusted so the final aggregate gradation (virgin and recycled) was similar for all asphalt mixtures within the same field project.

Asphalt Mixtures

For the TX test sections, two asphalt mixtures were produced in the field: *(1)* a DOT control mixture with 0.28 RBR (0.1 RAP + 0.18 RAS) and *(2)* a rejuvenated mixture with 0.28 RBR (0.1 RAP + 0.18 RAS) and 2.7% tall oil (T1) recycling agent. A warm-mix asphalt (WMA) additive was used in the DOT control mixture to alleviate compaction concerns during construction. LMLC specimens were prepared from these mixtures, and two additional rejuvenated mixtures were also produced in the laboratory at the selected recycling agent dose to match the continuous PGH of the target climate

Table 12. Characteristics of TX Mixtures

Mixture Type	**DOT Control (0.28 RBR)**	**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[1]	4.9%	4.9%	4.9%	4.9%
RAP/RAS Content[2]	10% RAP 5% RAS	10% RAP 5% RAS	10% RAP 5% RAS	10% RAP 5% RAS
RBR	0.28 *(0.1RAP + 0.18 RAS)*	0.28 *(0.1RAP + 0.18 RAS)*	0.28 *(0.1RAP + 0.18 RAS)*	0.28 *(0.1RAP + 0.18 RAS)*
Recycling agent Type and Dose[3]	---	2.7% T1	6% T1	6.5% A1
Warm Mix Additive Dose[3]	0.5%	---	---	---
Mixing Temperature	138°C	138°C	138°C	138°C

Table 13. Characteristics of NV Mixtures

Mixture Type	**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*	64-28 P	64-28 P	64-28 P	64-28 P
Binder Content[1]	5.0%	4.6%	4.6%	4.6%	4.6%
RAP Content[2]	15% RAP	33% RAP	33% RAP	33% RAP	33% RAP
RBR	0.15 RAP	0.3 RAP	0.3 RAP	0.3 RAP	0.3 RAP
Recycling agent Type and Dose[3]	---	2% T2	2% A2	3.5% T2	5.5% A2
Mixing Temperature	168°C	168°C	168°C	168°C	168°C

Table 14. Characteristics of IN Mixtures

Mixture Type	**DOT Control (0.32 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
Binder Content[1]	5.8%	5.8%	5.8%	5.8%
RAP/RAS Content[2]	28% RAP 2% 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 *(0.28 RAP + 0.14 RAS)*	0.5 *(0.36 RAP + 0.14 RAS)*
Recycling agent Type and Dose[3]	---	3.5% T2	8% T2	9.5% T2
Mixing Temperature	152°C	152°C	152°C	152°C

Table 15. Characteristics of WI Mixtures

Mixture Type	**DOT Control (0.22 RBR)**	**Rejuvenated (0.31 RBR) + 1.2% V2**	**Rejuvenated (0.31 RBR) + 5.5% V2**	**Rejuvenated (0.5 RBR) + 9% V2**
Binder PG	58-28	58-28	58-28	58-28
Binder Content[1]	5.6%	5.4%	5.4%	5.4%
RAP Content[2]	27% RAP	36% RAP	36% RAP	58% RAP
RBR	0.22	0.31	0.31	0.5
Recycling agent Type and Dose[3]	---	1.2% V	5.5% V	9% V
Mixing Temperature	160°C	160°C	160°C	160°C

Table 16. Characteristics of DE Mixtures

Mixture Type	**DOT Control (0.34 RBR)**	**Rejuvenated (0.41 RBR) +0.8% T2**	**Rejuvenated (0.41 RBR) +8.5% T2**	**Rejuvenated (0.5 RBR) +10% T2**
Binder PG	64-28	64-28	64-28	64-28
Binder Content[1]	5.4%	5.4%	5.4%	5.4%
RAP/RAS Content[2]	20% RAP 4% RAS	29% RAP 4% RAS	29% RAP 4% RAS	40% RAP 4% RAS
RBR	0.34 *(0.17RAP + 0.17 RAS)*	0.41 *(0.24RAP + 0.17 RAS)*	0.41 *(0.24RAP + 0.17 RAS)*	0.5 *(0.33RAP + 0.17 RAS)*
Recycling agent Type and Dose[3]	---	0.8% T2	8.5% T2	10% T2
Warm Mix Additive Dose[3]	0.4%	---	---	---
Mixing Temperature	154°C	154°C	154°C	154°C

[1] Total binder in the mixture (base binder + recycled binders)
[2] By percentage of total weight of the mixture
[3] By percentage of total binder in the mixture
[*] Polymer-modified binder

(i.e., PG 70-22): *(3)* a rejuvenated mixture with 0.28 RBR (0.1 RAP + 0.18 RAS) and 6% T1 and *(4)* a rejuvenated mixture with 0.28 RBR (0.1 RAP + 0.18 RAS) and 6.5% aromatic extract (A1) recycling agent.

For the NV test sections, three asphalt mixtures were produced in the field: *(1)* a DOT control mixture with 0.15 RBR (0.15 RAP), *(2)* a rejuvenated mixture with higher (0.3) RBR and 2% tall oil (T2) recycling agent, and *(3)* a rejuvenated mixture with 0.3 RBR and 2% aromatic extract (A2) recycling agent. LMLC specimens were prepared from these mixtures, and two additional rejuvenated mixtures were also produced in the laboratory at the selected recycling agent dose to match the continuous PGH of the target climate (i.e., PG 64-28): *(4)* a rejuvenated mixture with 0.3 RBR and 3.5% T2 and *(5)* a rejuvenated mixture with 0.3 RBR and 5.5% A2.

For the IN test sections, two asphalt mixtures were produced in the field: *(1)* a DOT control mixture with 0.32 RBR (0.25 RAP + 0.07 RAS) and *(2)* a rejuvenated mixture with higher (0.42) RBR (0.14 RAP + 0.28 RAS) and 3.5% T2. LMLC specimens were prepared from these mixtures, and two additional rejuvenated mixtures were also produced in the laboratory at the selected recycling agent dose to match the continuous PGH of the target climate (i.e., PG 64-22): *(3)* a rejuvenated mixture with 0.42 RBR (0.28 RAP + 0.14 RAS) and 8% T2 and *(4)* a rejuvenated mixture with higher (0.5) RBR (0.36 RAP + 0.14 RAS) and 9.5% T2.

For the WI test sections, two asphalt mixtures were produced in the field: *(1)* a DOT control mixture with 0.22 RBR (0.22 RAP) and *(2)* a rejuvenated mixture with higher (0.31) RBR and 1.2% modified vegetable oil (V) recycling agent. LMLC specimens were prepared from these mixtures, and two additional rejuvenated mixtures were also produced in the laboratory at the selected recycling agent dose to match the continuous PGH of the target climate (i.e., PG 58-28): *(3)* a rejuvenated mixture with 0.33 RBR and 5.5% V and *(4)* a rejuvenated mixture with higher (0.5) RBR and 9% V.

Finally, for the DE test sections, two asphalt mixtures were produced in the field: *(1)* a DOT control mixture with 0.34 RBR (0.17 RAP + 0.17 RAS) and *(2)* a rejuvenated mixture with higher (0.41) RBR (0.24 RAP + 0.17 RAS) and 0.8% T2. LMLC specimens were prepared from these mixtures, and two additional rejuvenated mixtures were also produced in the laboratory at the selected recycling agent dose to match the continuous PGH of the target climate (i.e., PG 64-28): *(3)* a rejuvenated mixture with 0.41 RBR (0.24 RAP + 0.17 RAS) and 8.5% T2, and *(4)* a rejuvenated mixture with higher (0.5) RBR (0.33 RAP + 0.17 RAS) and 10% T2.

The objective of the TX field project was to evaluate the effectiveness of the recycling agent in improving the performance of recycled asphalt mixtures with similar RBR, while the objective of the NV, IN, WI, and DE field projects was to assess if the recycling agent could facilitate the use of higher recycled materials contents (higher RBR) as compared to the DOT control mixture (lower RBR). The RAS type in TX, IN, and DE asphalt mixtures was manufactured waste asphalt shingles (MWAS).

To determine the selected dose to match the continuous PGH of the target climate, asphalt binders were first extracted and recovered from the RAP and RAS, and then combined with base binders and the recycling agent at various doses to formulate rejuvenated binder blends at the selected RBR. After that, the rejuvenated binder blends were characterized in the DSR to determine their PGH. Finally, the dose was determined as the amount of recycling agent required to match the continuous PGH of the rejuvenated binder blend to that of the target PG as described by Arámbula-Mercado *et al.* (2018).

Specimen Fabrication

For all asphalt mixtures shown in Table 12 through Table 16, LMLC specimens were fabricated by the following procedure:

1. The virgin aggregate was heated overnight at the plant mixing temperature and then combined with the recycled materials two hours prior to mixing.

2. The base binder was heated at the mixing temperature for about two hours prior to mixing (to ensure that the binder was adequately fluid without unnecessary aging), and the recycling agent was blended with the base binder 10 minutes prior to mixing with the virgin aggregate and the recycled materials.
3. After mixing, the loose mix was short-term oven aged (STOA) for two hours at 135°C prior to compaction in the Superpave gyrator compactor (SGC).
4. After compaction, the specimens were then long-term oven aged (LTOA) for 5 days at 85°C per AASHTO R 30. During the 5 days aging in the oven, the compacted specimens were covered with heat resistant PVC pipes to preserve the specimen from slump and to maintain the size and shape of the compacted specimen, and thus, preserve the integrity of the specimen.

For most of the recycled mixtures, the recycling agent was added by replacing the base binder with the full recycling agent dose. The only exception was for recycled mixtures containing RAS and more than 5.0 percent recycling agent (TX, IN, and DE mixtures); in this case, half of the recycling agent dose replaced the base binder and the other half was added. This procedure was followed to ensure adequate aggregate coating by the base binder, as proposed by Arámbula-Mercado *et al.* (2018).

Laboratory Tests and Analysis Methods

Stiffness Characterization

Resilient Modulus (M_R)

The M_R test was performed in accordance with ASTM D7369 with the linear variable differential transducers (LVDTs) externally attached across the diameter, as shown in Figure 30(a). Cylindrical specimens 150 mm in diameter and 61 mm in height were subjected to a repetitive haversine compressive load every 0.1 second with a 0.9 second rest period, and the recoverable horizontal deformation was captured by the two external LVDTs. M_R stiffness was calculated using Equation 7. The air void (AV) content of the specimens was 7.0±0.5 percent, and the test was performed at 25°C.

$$M_R = \frac{P_{cyclic}}{t * \delta_h}(I_1 - I_2 * \mu) \qquad \text{Equation 7}$$

Where M_R = resilient modulus of elasticity (MPa),
P_{cyclic} = cyclic load applied to the specimen (N),
t = thickness of the specimen (mm),
δ_h = recoverable horizontal deformation (mm),
I_1, I_2 = constant values for gauge length as a fraction of specimen diameter = 1 (I_1 = 0.27 and I_2 = -1.00), and
μ = Poisson's ratio (assumed to be 0.35 at 25°C).

Dynamic Modulus (|E*|)

The |E*| test was performed under unconfined conditions using the Asphalt Mixture Performance Tester (AMPT), shown in Figure 30(b), in accordance with AASHTO TP 79. SGC specimens were compacted to a height of 170 mm and then cored and trimmed to obtain test specimens with a diameter of 100 mm and a height of 150 mm. The test was performed at three test temperatures (4, 20, and 40°C) and seven test frequencies (25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz [for 40°C only]) at each temperature. The AV content of the specimens was 7.0±1.0 percent.

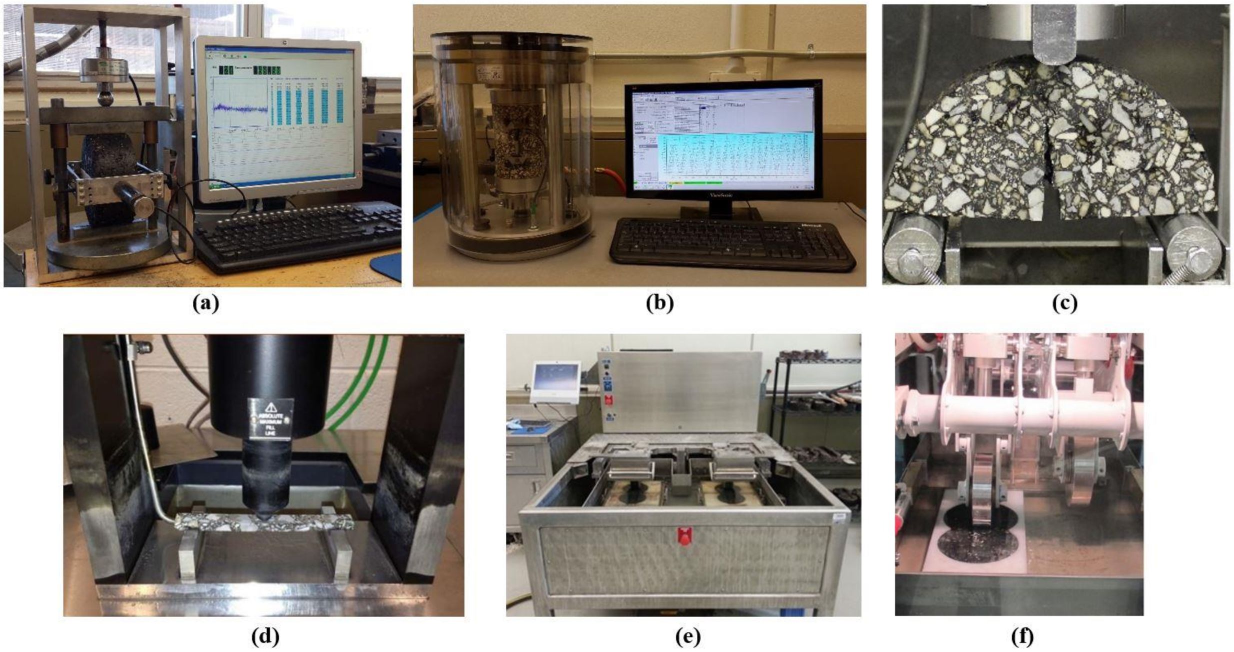

Figure 30. Laboratory Test Equipment and Setup: (a) Resilient Modulus (M_R), (b) Dynamic Modulus (|E*|), (c) Illinois Flexibility Index Test (I-FIT), (d) Bending Beam Rheometer for Asphalt Mixtures (BBR_m), (e) Hamburg Wheel-Track Testing (HWTT), and (f) Asphalt Pavment Analyzer (APA)

The |E*| test results were analyzed using a mixture Black space diagram by plotting the |E*| stiffness versus the corresponding phase angle (φ) at 15°C and 0.005 rad/s. The Rhea software (http://www.abatech.com/RHEA.htm) was used to calculate |E*| and (φ) at 15°C and 0.005 rad/s. Mensching *et al.* (2015) observed that the modified mixture Glover-Rowe parameter calculated using |E*| and φ values at 15°C and 0.005 rad/s showed a reasonable correlation with the critical cracking temperature determined in the thermal stress restrained specimen test (TSRST). Kaseer *et al.* (2017) showed that mixture Black space diagrams of |E*| versus φ at 15°C and 0.005 rad/s can discriminate asphalt mixtures with different stiffness and relaxation characteristics, including mixtures with high recycled materials contents and recycling agents.

Intermediate-Temperature Cracking Resistance

Illinois Flexibility Index Test (I-FIT)

The I-FIT was performed in accordance with AASHTO TP 124. The same cylindrical specimens from the M_R test were utilized after cutting them in half to create a semi-circular test specimen and making a notch along the axis of symmetry 15 mm deep. The semi-circular specimen was placed in a three-point bending configuration as shown in Figure 30(c) (Al-Qadi *et al.* 2015). The AV content of the specimens was 7.0±0.5 percent, and the test was performed at 25°C. During the test, a monotonic load was applied along the vertical radius of the specimen at a rate of 50 mm/min until failure. The load and load line displacement were measured during the test, and the load-displacement curve was plotted; from this curve, the work of fracture (W_f) and fracture energy (G_f) were determined by Equation 8.

$$G_f = \frac{W_f}{A} = \frac{\int (P)du}{A} \qquad \text{Equation 8}$$

Where G_f = fracture energy (J/m^2),
W_f = work of fracture (J),
P = peak load (kN),
u = load-line displacement (mm), and
A = ligament area (mm) [the ligament length × the thickness of the specimen].

From the I-FIT test, two parameters were used to distinguish and rank the asphalt mixtures based on their cracking resistance at intermediate temperature. The first parameter is the flexibility index (FI) from AASHTO TP 124, and the second parameter is the Cracking Resistance Index (CRI) proposed by Kaseer *et al.* (2018c). The two indices are correlated, but as compared to the FI, the CRI provided greater discrimination between asphalt mixtures with different characteristics, less variability, easier calculation, and facilitated characterization of brittle mixtures (Kaseer *et al.* 2018c).

FI is defined as the fracture energy (G_f) divided by the slope of the post-peak load-displacement curve at the inflection point (m), as expressed in Equation 9.

$$FI = \frac{G_f}{|m|} \times 0.01 \qquad \text{Equation 9}$$

Where FI = Flexibility index; and
m = slope at the inflection point of the post-peak load versus displacement curve.

CRI is defined as the fracture energy (G_f) divided by the peak load (P_{max}), as expressed in Equation 10.

$$CRI = \frac{G_f}{P_{max}} \qquad \text{Equation 10}$$

Where CRI = cracking resistance index; and
P_{max} = peak load.

Asphalt mixtures with higher FI and CRI values are expected to have better cracking resistance than those with lower FI and CRI values. A number of studies have reported that FI and CRI are sensitive to the inclusion of RAP, RAS, and recycling agents; and FI correlates well with field cracking resistance (Al-Qadi *et al.* 2015, Zhou *et al.* 2017, Yin *et al.* 2017, Kaseer *et al.* 2018c).

Low-Temperature Rheological Properties

Bending Beam Rheometer for Asphalt Mixtures (BBR_m)

The BBR_m test for low-temperature rheological properties of asphalt mixtures was performed in accordance with AASHTO TP 125 and used to predict low-temperature cracking resistance as recommended by Romero (2016). Thin beams (12.7 mm wide, 6.35mm thick, and 127 mm long) were prepared by slicing and trimming the M_R cylindrical specimens, and placed in the BBR controlled temperature fluid bath as shown in Figure 30(d) (Romero 2016). The test temperature is related to the environmental zone where the asphalt binder will be used; therefore, the testing temperature equals the PGL of the target binder +10°C. BBR_m beams were conditioned at the testing temperature for 60 ± 5 minutes. During the test, a constant load was applied to the mid-point of the beam, and the deflection at that location on the beam was recorded versus time using the BBR computerized data acquisition system. Creep modulus (*S*) and stress relaxation (*m*-value) were recorded.

Romero (2016) showed that when utilizing the BBR_m test for asphalt mixtures, large aggregates (12.5 mm nominal maximum aggregate size [NMAS]) did not introduce excess variability as compared to mixtures with smaller aggregates (9.5 mm or 4.75 mm NMAS) when the recommended sample dimensions were used. Romero (2016) utilized the BBR_m results to plot the low-temperature mixture Black space diagram (*S* versus *m*-value), where a lower creep stiffness (S) is favorable to decrease the thermal stresses developed in the pavements and a higher stress relaxation (m-value) is desirable to rapidly disperse any accumulated stress. The results of field cores from seven state roads in Utah (UT) showed that pavements that cracked in the field after about 2 years in-service corresponded to mixtures with high S and low m-value, while pavements that showed adequate cracking resistance in the field had a low S and high m-value. The tentative thresholds for S and m-value proposed by Romero were used to evaluate the results of this study.

Rutting Susceptibility

Hamburg Wheel-Track Testing (HWTT) and Asphalt Pavement Analyzer (APA)

The HWTT was performed in accordance with AASHTO T324 in wet condition, and the APA test was also performed in accordance with AASHTO T324 (same HWTT test configuration) but in the dry condition as shown in Figure 30(e) and 2(f). The HWTT and APA were used to investigate rutting susceptibility of the rejuvenated mixtures with high recycling agent doses, with and without the presence of water, by recording the number of load cycles when the rut depth reaches 12.5 mm.

For the asphalt mixtures shown in Table 12 through Table 16, three replicates were tested for the M_R test, a minimum of two replicates for the |E*| test, a minimum of four replicates for the I-FIT, a minimum of five replicates for the BBR_m test, and two replicates for the HWTT and APA. To compare the M_R and I-FIT results, statistical analysis at a 95% confidence level was performed including analysis of variance (ANOVA) and Tukey’s honestly significant differences (HSD).

Field Performance, Test Results, and Discussion

Field Performance and Corresponding Field Core Test Results

Table 17 summarizes the visual distress surveys performed for the five field projects, including the quantity and severity of longitudinal, transverse, and alligator cracking for each of the test sections.

For the TX field project, after 3 years in service, the test section with the rejuvenated mixture exhibited more moderate severity cracking, as compared to the DOT control test section (with WMA) that had less low severity cracking. For the IN field project, after 2 years in service, while the DOT control test section exhibited minimum visible cracking, the test section with the rejuvenated mixture exhibited a significant amount of longitudinal and transverse cracking, and in some areas these cracks were commencing to join together as alligator cracking. For the WI field project, after 1 year in service, only low severity transverse cracking was observed for both test sections. It is important to note that the entire field project had a Portland cement concrete (PCC) layer with existing transverse cracking as the underlying pavement layer, which likely caused the early reflective cracking at the surface of the asphalt concrete layer. Although the distress is likely related to the condition of the existing underlying PCC layer, the brittleness of the asphalt mixtures also likely affected the propagation rate of the reflective cracking. No or minimal distress was observed on the DE and NV test sections after 1 and 2 years in service, respectively.

Field cores were procured from each test section soon after construction. These cores were tested for M_R and I-FIT, and the results are presented in Figure 31 and Figure 32, with the error bars on each column representing one standard deviation above and below the average value based on the replicate measurements.

Table 17. Field Performance by Visual Distress Surveys.

Field Project	**Construction Date**	**Survey Date**[1]	**Field Sections**							
			DOT Control Mixture (No recycling agent)				**Rejuvenated Mixture (recycling agent at the field dose)**			
			Transverse Cracking[2]	**Longitudinal Cracking**[2]	**Alligator cracking**[3]	**Summary**	**Transverse Cracking**[2]	**Longitudinal Cracking**[2]	**Alligator cracking**[3]	**Summary**
TX	June 2014	3 years	37.72	15.13	---	Low severity longitudinal and transverse cracking	102.85	19.09	---	Moderate severity longitudinal and transverse cracking
NV	September 2015	2 years	---	---	---	No visible cracking	---	---	---	No visible cracking
IN	September 2015	2 years	1.35	0.46	0.09	Very minimum visible cracking	118.38	4.53	4.42	Significant amount of low severity transverse and longitudinal cracking, and some alligator cracking
WI	September 2016	1 year	18.29	---	---	Low severity transverse cracking, with some longitudinal cracking	12.84	---	---	Low severity transverse cracking, with some longitudinal cracking
DE	December 2016	1 year	---	---	---	No visible cracking	---	---	---	No visible cracking - but visible sign of minor mix segregation

[1] Years after construction
[2] Total feet per 100 feet of test section
[3] Percentage of total wheel path

For the TX, WI, and DE field tests sections; the M_R stiffness results in Figure 31 showed that in each field project the DOT control mixtures and the rejuvenated mixtures with the field recycling agent dose had statistically equivalent stiffness based on Tukey's HSD analysis. While for the NV and IN field projects, the rejuvenated mixtures exhibited high M_R stiffness as compared to the DOT control mixtures, as a result of increasing the RBR. Regarding the I-FIT results, Figure 32 showed that all the rejuvenated mixtures exhibited statistically lower FI values as compared to the DOT control mixtures. Although these mixtures have been in service for a relative short period, and cracking distresses may take additional time to appear, the visual distress surveys and field core test results confirmed that using the field recycling agent dose did not improve the cracking resistance of high RBR mixtures as compared to the DOT control mixtures in the five field projects.

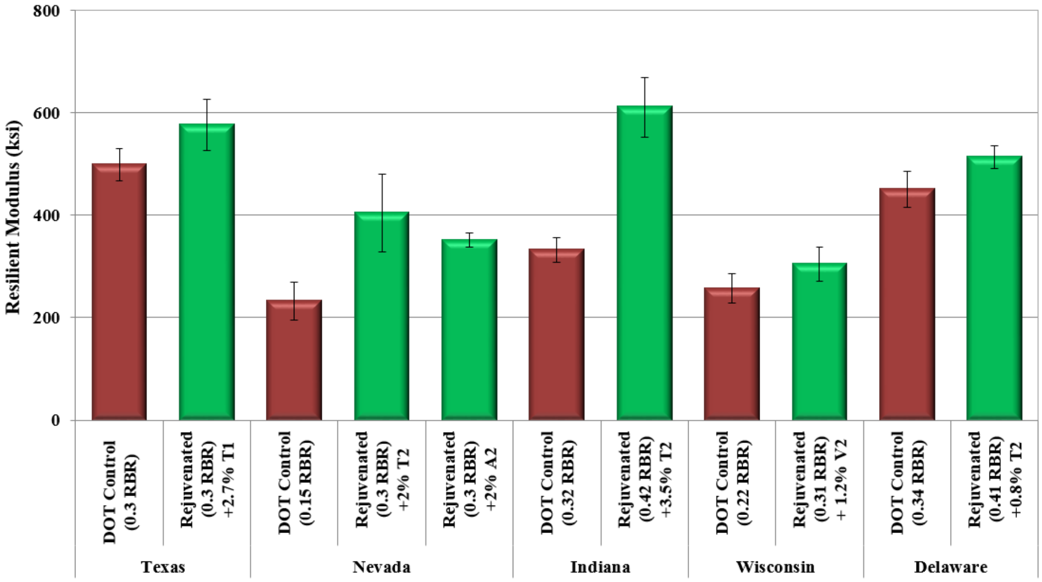

Figure 31. M_R test results of the field cores at 25°C.

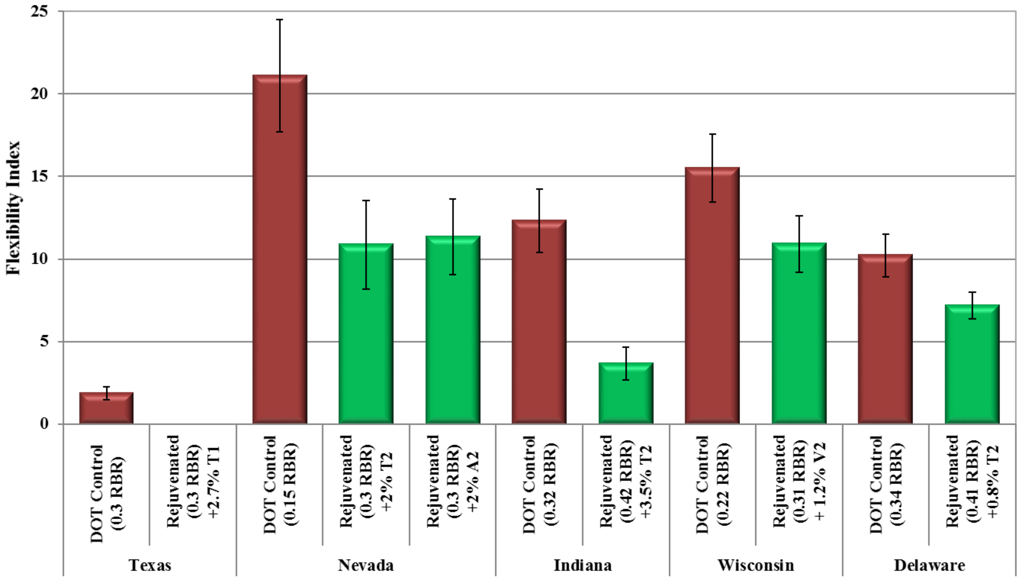

Figure 32. FI results of the field cores at 25°C.

Laboratory Test Results and Discussion

The following sections present the asphalt mixtures test results for LMLC specimens after STOA and LTOA. For the Resilient Modulus and Illinois Flexibility Index Test, the darker shade stacked column represents the M_R, FI, and CRI values after STOA, and the hatched lighter shade stacked column represents the M_R, FI, and CRI values after LTOA. The error bars on each column represent one standard deviation above and below the average value based on the replicate measurements, and the letters inside each column represent Tukey's HSD in which mixtures not connected with the same letter are considered significantly different. For the Dynamic Modulus and Bending Beam Rheometer tests, Black space diagrams are presented where the empty symbols represent the STOA specimens and the filled symbols represent the LTOA specimens.

Texas Mixtures

Figure 33 and Figure 34 present the TX mixtures test results for M_R and I-FIT. The |E*| and BBR_m mixture Black space diagrams are not available for the TX mixtures. In Figure 33, the DOT control mixture (with WMA additive) and the rejuvenated mixture with the field dose (2.7% T1) exhibited statistically equivalent M_R stiffness, after both STOA and LTOA, indicating no effectiveness of the recycling agent at the low field dose in reducing the stiffness of the rejuvenated mixture. Adding the selected recycling agent dose (6%T1 and 6.5% A1) yielded a rejuvenated mixture with statistically lower stiffness than the DOT control without recycling agent, after both STOA and LTOA.

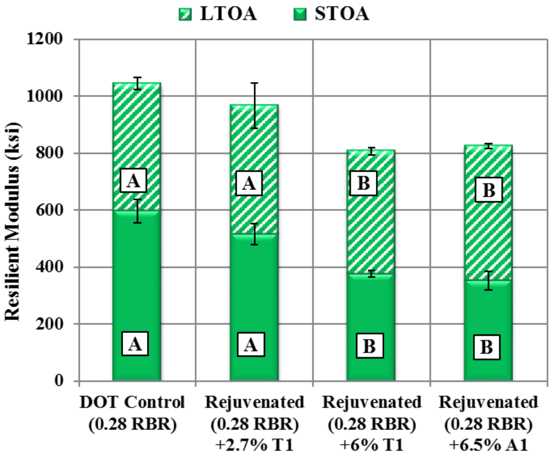

Figure 33. M_R test results for TX mixtures at 25°C.

Figure 34 also demonstrates that the recycling agent at the field dose did not improve the cracking resistance of the rejuvenated mixture as compared to the DOT control mixture, while adding the selected recycling agent dose was effective in improving the mixture cracking resistance after both STOA and LTOA, as indicated by statistically higher FI and CRI values.

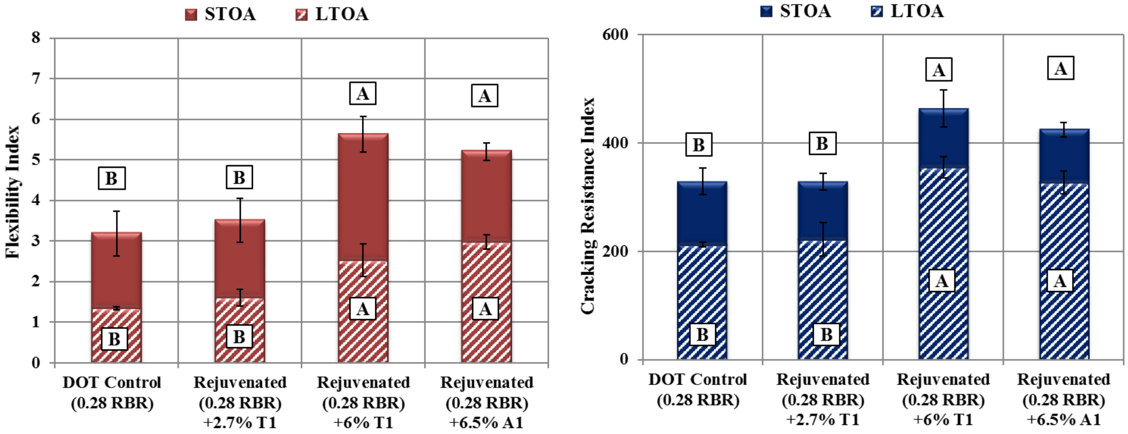

Figure 34. FI and CRI test results for TX mixtures at 25°C.

The results of the TX mixtures demonstrated that using the low field recycling agent dose did not improve the performance of the DOT control mixture after STOA and LTOA. Adding the selected recycling agent dose to match PGH of the target climate was effective in reducing the stiffness and improving the cracking resistance after both STOA and LTOA.

Nevada Mixtures

Figure 35 through Figure 37 present the NV mixtures test results for M_R, I-FIT, and BBR_m. The |E*| mixture Black space diagram, and HWTT and APA test results, were not available for the NV mixtures. In Figure 35, adding the field recycling agent dose (2% T2 and 2% A2) did not facilitate the use of higher quantities of recycled materials (0.3 RBR) as compared to the DOT control mixture with 0.15 RBR, as demonstrated by the statistically higher stiffness regardless of aging level. Adding the selected recycling agent dose (3.5%T2 and 5.5%A2) yielded rejuvenated mixtures with comparable stiffness to the DOT control mixture (with lower RBR) after both STOA and LTOA.

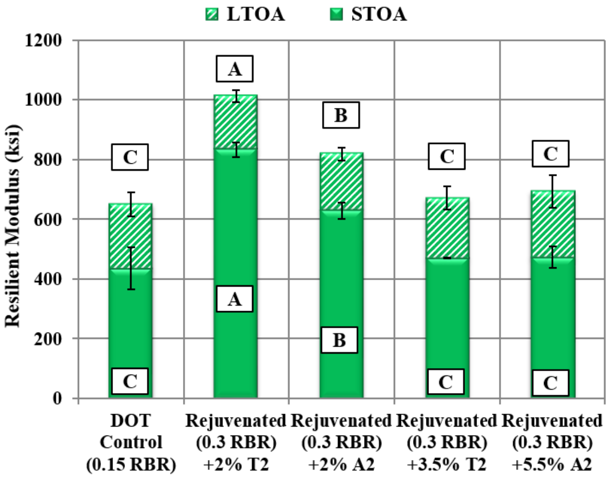

Figure 35. M_R test results for NV mixtures at 25°C.

I-FIT results shown in Figure 36 demonstrated that adding a recycling agent at the field dose was not sufficient in producing similar cracking resistance as compared to the DOT control mixture after LTOA, while adding the selected recycling agent dose facilitated the use of higher quantities of recycled materials (0.3 RBR), with statistically equivalent cracking resistance to the DOT control (0.15 RBR) regardless of aging level, as indicated by the FI and CRI values.

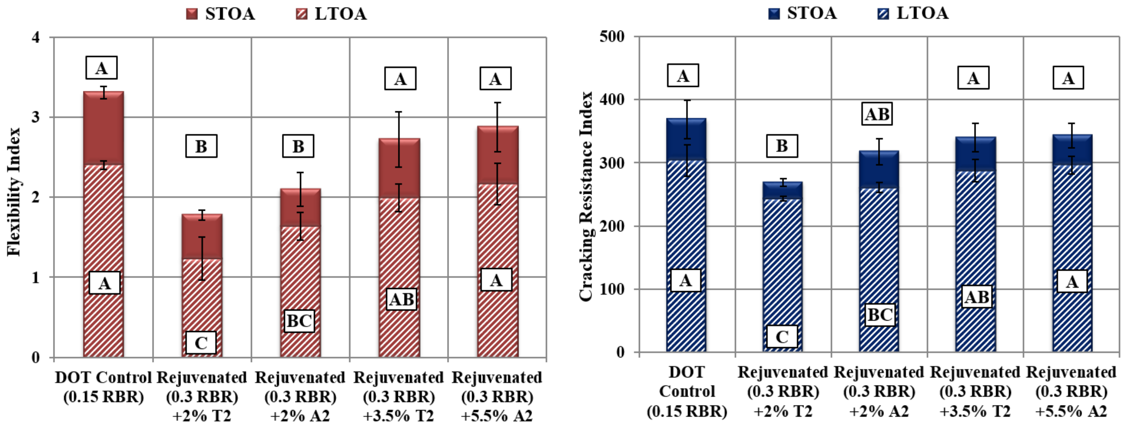

Figure 36. FI and CRI test results for NV mixtures at 25°C.

The low-temperature mixture Black space diagram for the BBR_m test is shown in Figure 37 along with the cracking thresholds developed by Romero (2016) based on field performance in UT. These tentative cracking thresholds may not be applicable to the IN mixtures but were used for the purpose of comparing the various mixtures against thresholds tied to field performance. The BBR_m results had reasonable variability, with coefficients of variation (COV) of *S* and *m*-value of 20% and below. After STOA, the DOT control mixture and the rejuvenated mixtures with the selected recycling agent dose were all at the onset of the “at risk” zone, while the rejuvenated mixtures with the field recycling agent dose were close to the “likely to crack” zone. After LTOA, the DOT control mixture and the mixtures with the selected recycling agent dose were close to each other, and at the onset of the “likely to crack” zone, while the mixture with the field recycling dose was in the top left corner of the “likely to crack” zone with higher *S* and lower *m*-value, indicating possible poor low-temperature cracking performance.

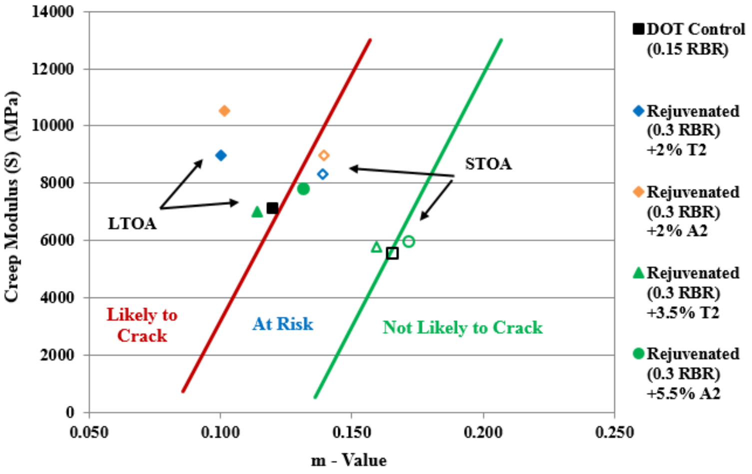

Figure 37. $\mathrm{BBR_m}$ mixture Black space test results for NV mixtures at -18°C.

The results of the NV mixtures demonstrated that using the selected recycling agent dose to match PGH of the target climate was effective in producing high RBR mixtures (0.3 RBR) with similar stiffness and cracking resistance to that of the DOT control with lower RBR (0.15).

Indiana Mixtures

Figure 38 through Figure 41 present the IN mixtures test results for both STOA and LTOA specimens. The HWTT and APA test results are not available for the IN mixtures. In Figure 38, adding the field recycling agent dose (3.5% T2) facilitated the use of higher quantities of recycled materials (0.42 RBR) when compared to the DOT control mixture with 0.32 RBR, as demonstrated by the statistically lower or equivalent stiffness regardless of aging level. Adding the selected recycling agent dose (8.0 and 9.5%T2 for 0.42 and 0.5 RBR, respectively) yielded rejuvenated mixtures with lower stiffness after both STOA and LTOA as compared to the mixture with the field recycling agent dose, and comparable stiffness to the DOT control mixture after LTOA.

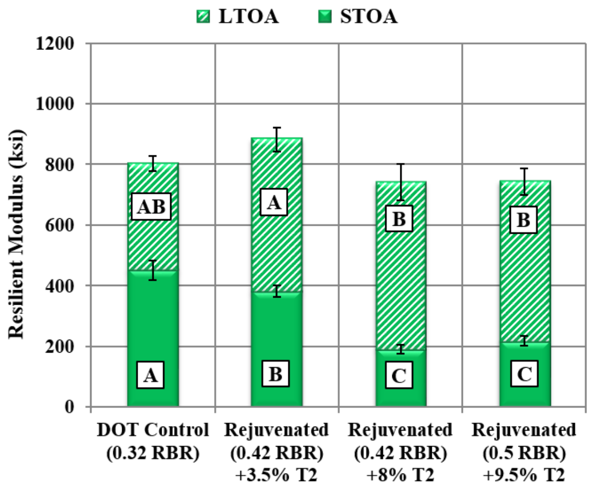

Figure 38. M_R test results for IN mixtures at 25°C.

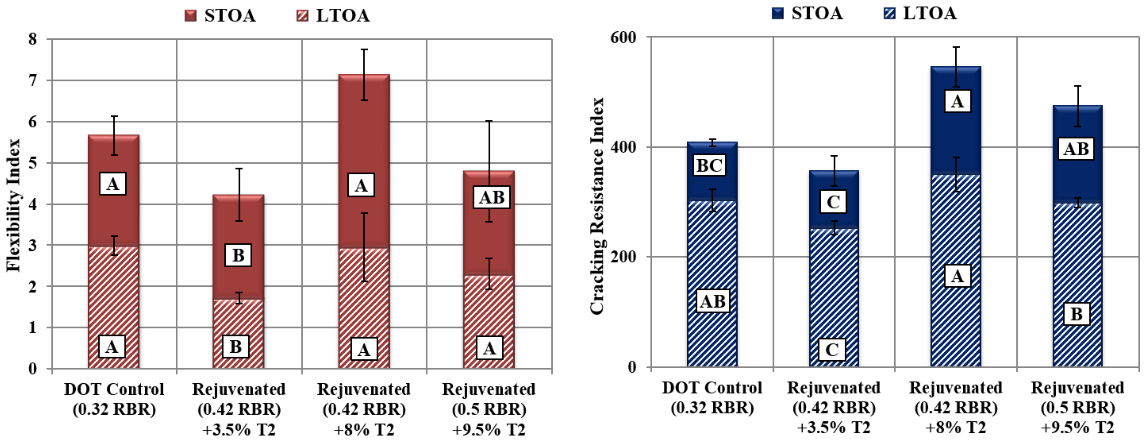

Figure 39. FI and CRI test results for IN mixtures at 25°C.

I-FIT results shown in Figure 39 for FI demonstrated that adding the field recycling agent dose was not sufficient to produce similar cracking resistance as compared to the DOT control mixture after both STOA and LTOA, while CRI results shown in Figure 39 demonstrated that both mixtures had statistically equivalent cracking resistance after STOA only. Adding the selected recycling agent dose facilitated the use of higher quantities of recycled materials (0.42 and 0.5 RBR, respectively), with statistically equivalent cracking resistance to the DOT control (0.32 RBR) regardless of aging level, as indicated by FI and CRI values.

The |E*| mixture Black space diagram is plotted in Figure 40. The three rejuvenated mixtures with recycling agent were located closer to the bottom right corner in the Black space diagram as compared to the DOT control mixture. This indicates lower |E*| and higher φ values, and likely better cracking resistance, despite the fact that the mixtures with recycling agent had higher RBR. After LTOA, however, the mixture with the field recycling agent dose showed higher |E*| and lower φ values as compared to the DOT control mixture, while the mixtures with higher RBR and recycling agent at the dose to match PGH of the target climate showed comparable |E*| and slightly higher φ values as compared to the DOT control mixture.

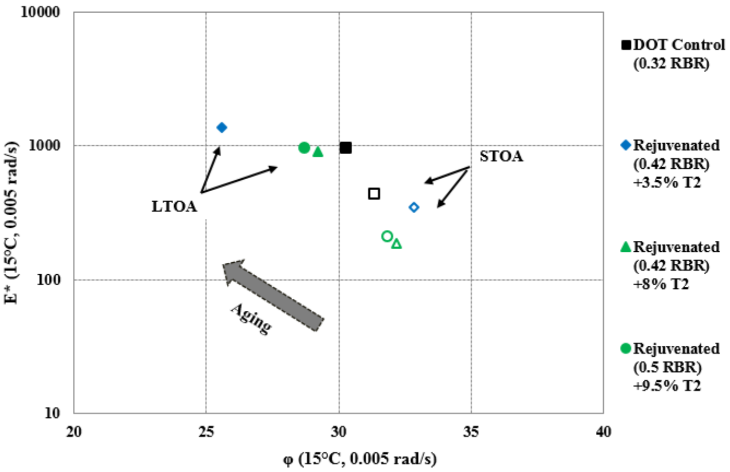

Figure 40. |E*| mixture Black space for IN mixtures.

The low-temperature mixture Black space diagram for the BBR_m test is shown in Figure 41 along with the tentative cracking thresholds developed based on field performance in UT. Again, these tentative cracking thresholds may not be applicable to the IN mixtures, but were used to compare the various mixtures against thresholds tied to field performance. After STOA, the DOT control mixture and all the rejuvenated mixtures were all in the "at risk" zone. After LTOA, the DOT control mixture and the mixtures with the selected recycling agent dose were close to each other, and at the onset of the "likely to crack" zone, while the mixture with the field recycling agent dose had much higher *S* and lower *m*-value, indicating possible poor low-temperature cracking performance.

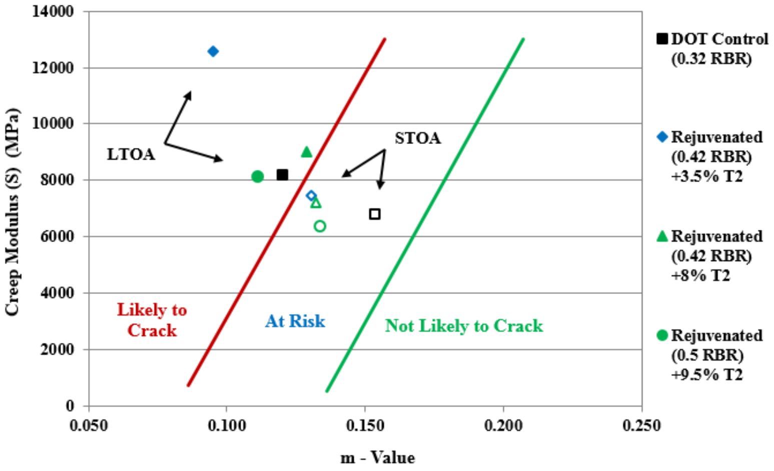

Figure 41. BBR_m mixture Black space test results for IN mixtures at -12°C.

The results of the IN mixtures demonstrated that using the selected recycling agent dose to match PGH of the target climate was effective in producing high RBR mixtures (0.42 and 0.5 RBR) with similar stiffness and cracking resistance to that of the DOT control (with lower RBR).

Wisconsin Mixtures

Figure 42 through Figure 46 present the WI mixtures test results for both STOA and LTOA specimens. In Figure 42, adding the field recycling agent dose (1.2%V) facilitated the use of higher quantities of recycled materials (0.31 RBR) when compared to the DOT control mixture with 0.22 RBR, as demonstrated by statistically equivalent stiffness regardless of aging level. Adding the selected recycling agent dose (5.5% and 9%V) with higher RBR (0.31 and 0.5) yielded lower stiffness as compared to the DOT control, regardless of aging level.

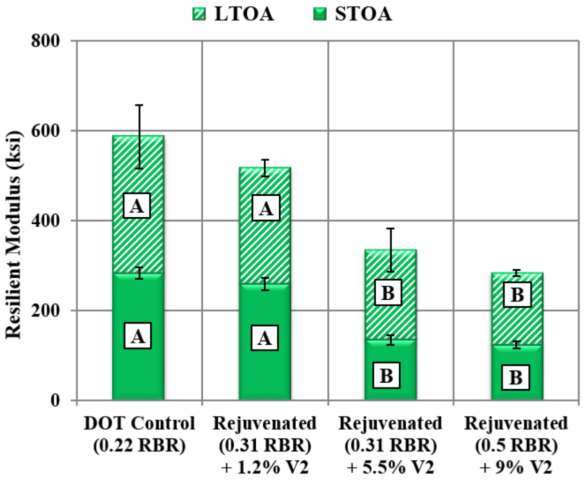

Figure 42. M_R test results for WI mixtures at 25°C.

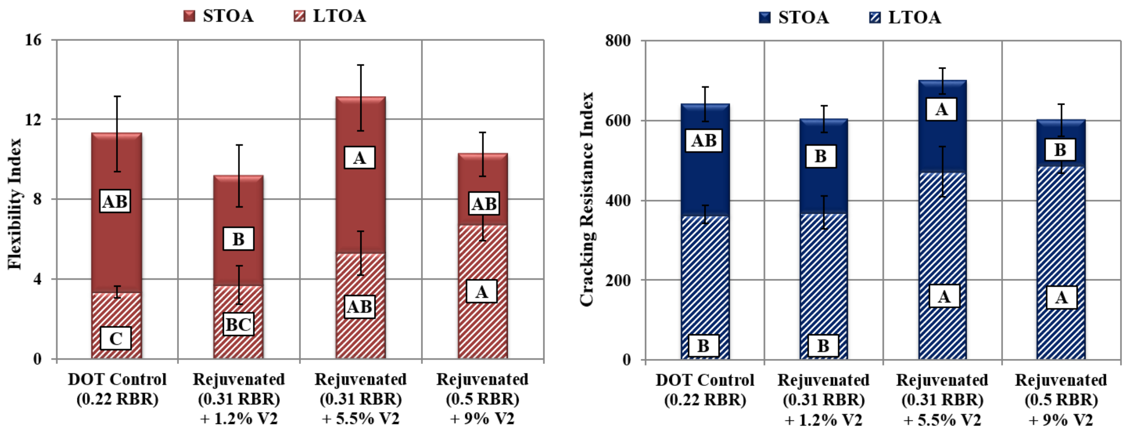

Figure 43. FI and CRI test results for WI mixtures at 25°C.

The I-FIT results shown in Figure 43 demonstrated that adding recycling agent at the field dose yielded statistically similar cracking resistance as compared to the DOT control mixture with lower RBR regardless of aging level. Adding the selected recycling agent dose in rejuvenated mixtures with higher RBRs (0.31 and 0.5) yielded higher cracking resistance after LTOA as compared to the DOT control mixture, as indicated by the FI and CRI values.

The |E*| mixture Black space diagram is plotted in Figure 44. After STOA, the rejuvenated mixtures with the selected recycling agent dose to match PGH of the target climate were located in the bottom right corner in the Black space diagram (with lower |E*|) as compared to the DOT control mixture and the rejuvenated mixture with field recycling agent dose (with higher |E*| but similar φ). After LTOA, the same trend was observed, with lower |E*| and a slightly higher φ value for the rejuvenated mixtures with the selected recycling agent dose and higher RBR (0.31 and 0.5) as compared to the DOT control mixture with lower RBR (0.22). It is important to note that a 3-degree difference in the phase angle can be attributed to experimental error in the AMPT machine, and not necessary a true difference in performance.

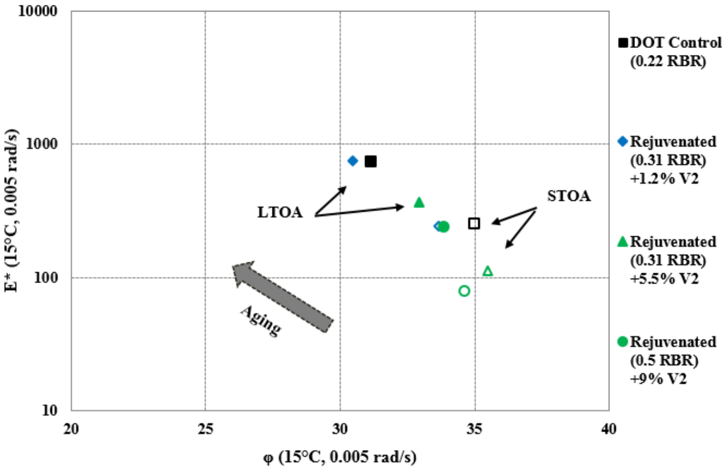

Figure 44. |E*| mixture Black space for WI Mixtures.

The low-temperature mixture Black space diagram for the BBR_m test is shown in Figure 45 along with the tentative cracking thresholds developed based on field performance in UT. Again, these tentative cracking thresholds may not be applicable to the WI mixtures, but were used to compare the various mixtures against thresholds tied to field performance. As shown in Figure 45, for the STOA specimens, the DOT control mixture and the rejuvenated mixture with field recycling agent dose were in the “at risk” zone, while the rejuvenated mixtures with the selected recycling agent dose were in the “not likely to crack” zone. After LTOA, the DOT control mixture moved toward the “likely to crack” zone, the rejuvenated mixtures with 1.2% and 5.5% recycling agent were in the “at risk” zone, and the recycled mixture with 9.0% recycling agent was still in the “not likely to crack” zone.

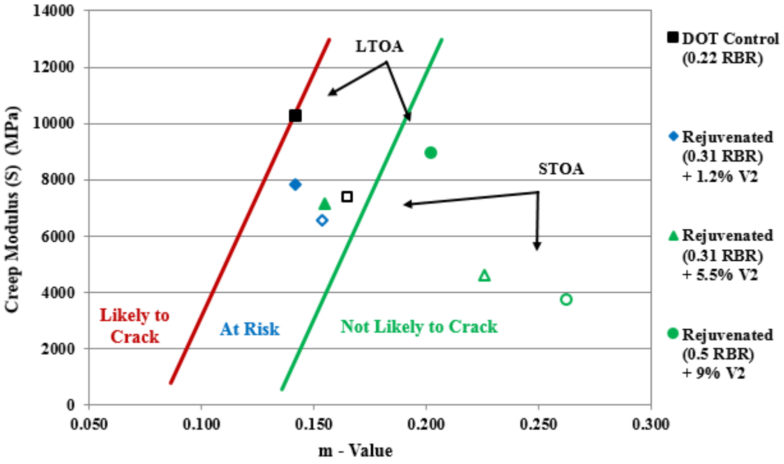

Figure 45. BBR_m mixture Black space test results for WI mixtures at -18°C.

The HWTT results (in wet condition) illustrated in Figure 46 demonstrated that the rejuvenated mixtures with recycling agent at the dose to match PGH (5.5% and 9%V) passed the minimum rutting requirements, even though there might be moisture susceptibility issues in these mixtures. In a similar climate, mixtures with a target PG 58-XX climate are required to sustain at least 5,000 load cycles before achieving 12.5 mm rut depth (Illinois DOT specifications, 2016). As expected, APA results (in dry condition) illustrated in Figure 46 demonstrated improved rutting resistance when water is not present. These results confirmed that the dose to match PGH of the target climate (PG 58-28 in this case) was not excessive in terms of being detrimental to the rutting performance of the asphalt mixture.

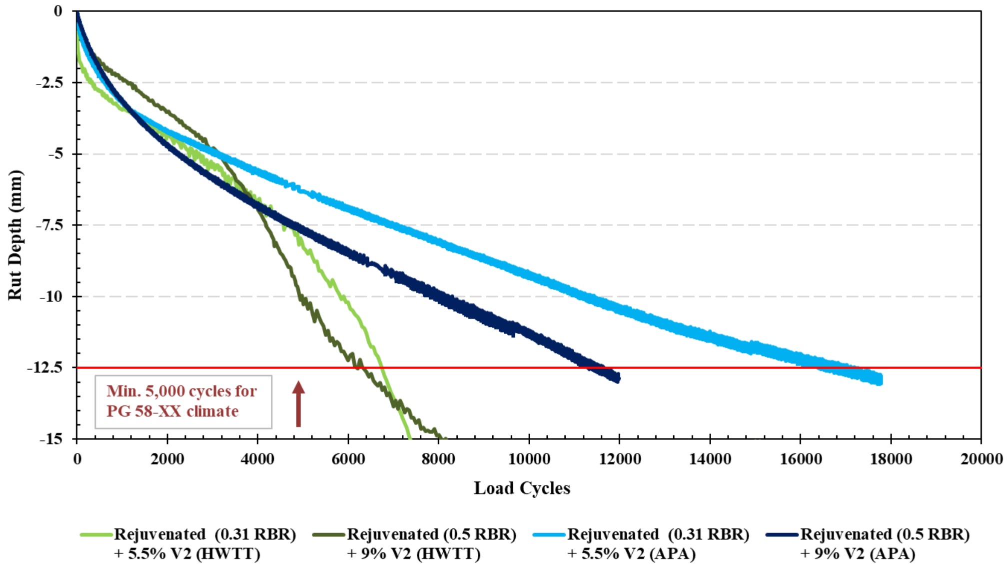

Figure 46. HWTT and APA test results for WI rejuvenated mixtures at 50°C.

The WI mixtures demonstrated that the field recycling agent dose was effective in producing high RBR recycled mixtures (0.31 RBR) with similar performance to that of the DOT control mixture with 0.22 RBR. However, the best performance was observed for rejuvenated mixtures with higher RBRs (0.31 and 0.5) and the selected recycling agent doses to match PGH of the target climate.

Delaware Mixtures

Figure 47 through Figure 51 present the DE mixtures test results for both STOA and LTOA specimens. In Figure 47, adding the field recycling agent dose (0.8%T2) facilitated the use of higher quantities of recycled materials (0.41 RBR) when compared to the DOT control mixture with 0.34 RBR (and WMA additive), as demonstrated by statistically equivalent stiffness regardless of aging level. Adding the selected recycling agent dose (8.5% and 10%T2) to rejuvenated mixtures with higher RBR (0.41 and 0.5) yielded lower stiffness as compared to the DOT control, regardless of aging level.

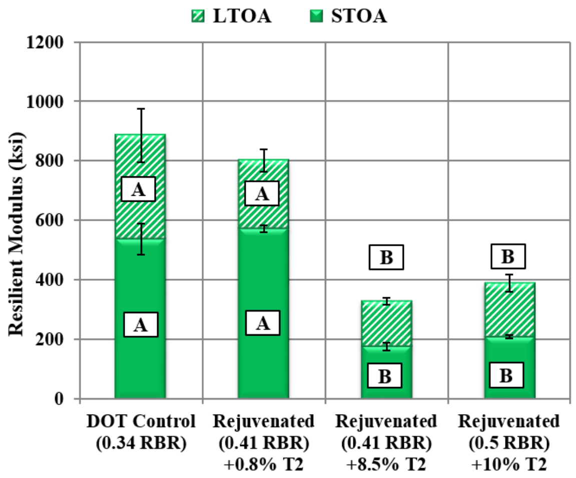

Figure 47. M_R test results for DE mixtures at 25°C.

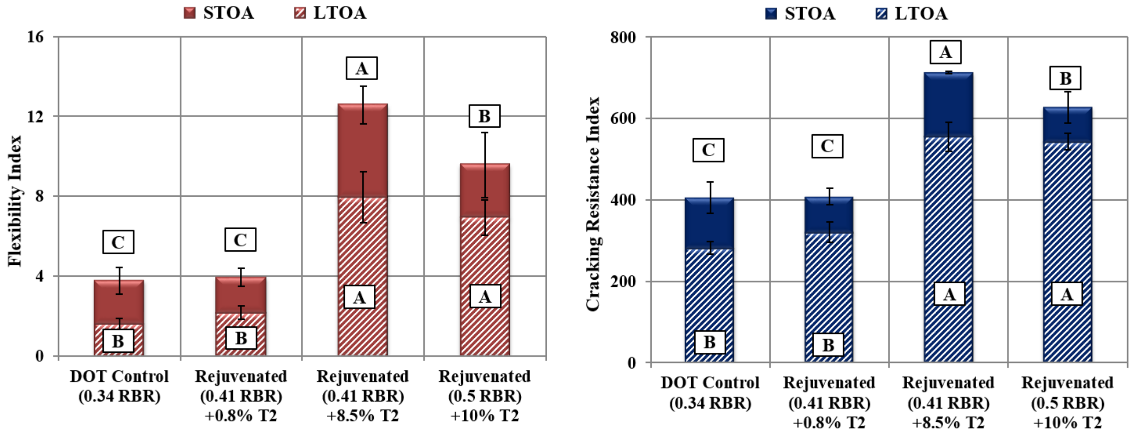

Figure 48. FI and CRI test results for DE Mixtures at 25°C.

The I-FIT results shown in Figure 48 demonstrated that adding the field recycling agent dose yielded statistically similar cracking resistance as compared to the DOT control mixture with lower RBR regardless of aging level. Adding the selected recycling agent dose to rejuvenated mixtures with higher RBRs (0.41 and 0.5) yielded higher cracking resistance after STOA and LTOA as compared to the DOT control mixture, as indicated by the resulting FI and CRI values.

The |E*| mixture Black space diagram is plotted in Figure 49. After STOA, the rejuvenated mixtures with the selected recycling agent dose were located in the bottom right corner in the Black space diagram (with lower |E*|) as compared to the DOT control mixture and the rejuvenated mixture with field recycling agent dose (with higher |E*| but similar φ). Again, a 3-degree difference in the phase angle can be attributed to experimental error in the AMPT machine, and not necessarily to a difference in performance. After LTOA, the same trend was observed, with lower |E*| and a higher φ value for the rejuvenated mixtures with higher RBR (0.41 and 0.5) and the selected recycling agent dose as compared to the DOT control mixture with lower RBR (0.34).

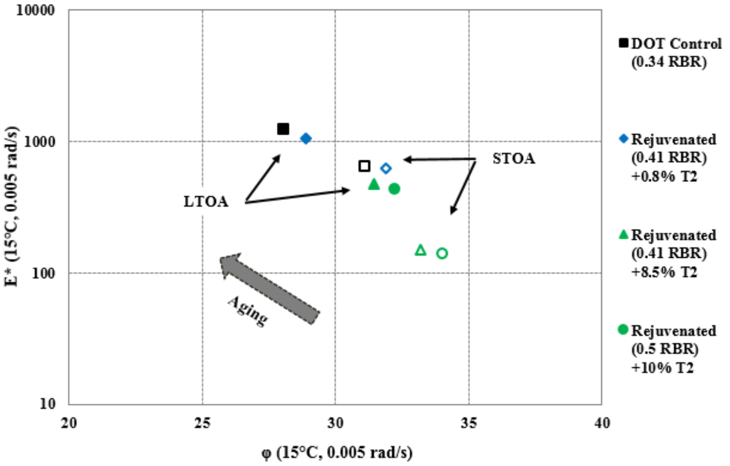

Figure 49. |E*| mixture Black space for DE mixtures.

The low-temperature mixture Black space diagram for the BBR_m test is shown in Figure 50 along with the tentative cracking thresholds developed based on field performance in UT. Again, these tentative cracking thresholds may not be applicable to the DE mixtures, but were used to compare the various mixtures against thresholds tied to field performance. As shown in Figure 50, for the STOA specimens, the DOT control mixture and the rejuvenated mixture with field recycling agent dose were in the "at risk" zone, while the rejuvenated mixtures with the selected recycling agent dose to match PGH of the target climate were in the "not likely to crack" zone. After LTOA, the DOT control mixture and the rejuvenated mixture with field recycling agent dose moved toward the "likely to crack" zone, while the rejuvenated mixtures with the selected recycling agent dose were in the "at risk" zone.

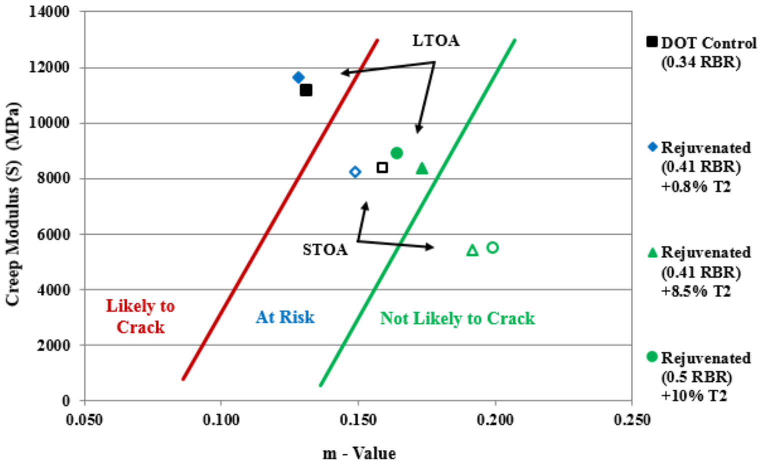

Figure 50. BBR_m mixture Black space test results for DE mixtures at -18°C.

The HWTT results (in wet condition) illustrated in Figure 51 demonstrated that the rejuvenated mixtures with recycling agent at the dose to match PGH (8.5% and 10%T2) passed the minimum rutting requirements. In a similar climate, mixtures with a target PG 64-XX climate are required to sustain at least 7,500 load cycles before achieving 12.5 mm rut depth (Illinois DOT specifications, 2016). As expected, APA results (in dry condition) demonstrated improved rutting resistance when water is not present. These results also confirmed that the dose to match PGH of the target climate (PG 64-28 in this case) was not excessive in terms of being detrimental to the rutting performance of the asphalt mixture.

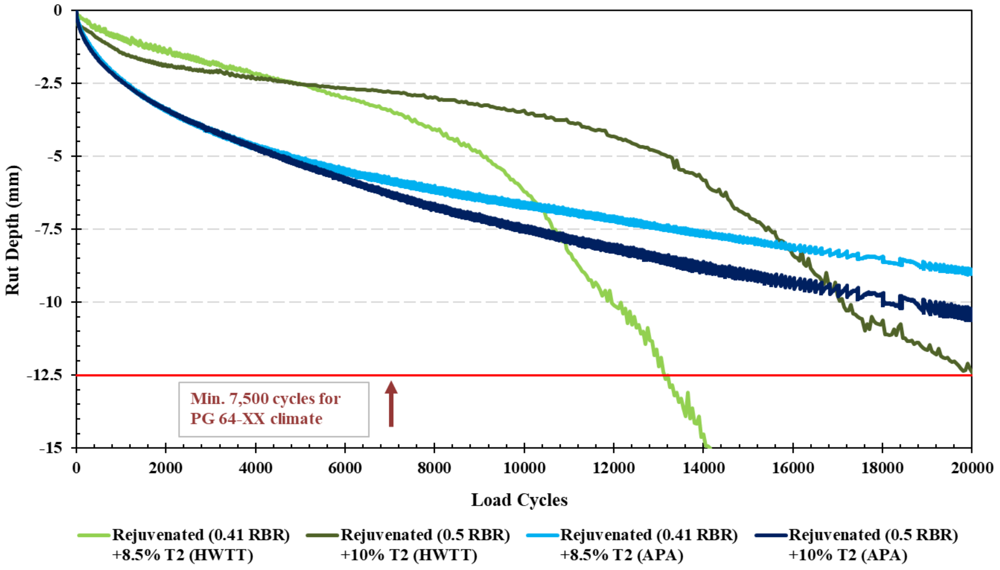

Figure 51. HWTT and APA test results for DE rejuvenated mixtures at 50°C.

The DE mixtures demonstrated that using the field recycling agent dose was effective in producing a rejuvenated mixture with high RBR (0.41 RBR) with similar performance to that of the DOT control mixture with 0.34 RBR. However, the best performance was observed for rejuvenated mixtures with higher RBRs (0.41 and 0.5) and the selected recycling agent doses to match PGH of the target climate.

Conclusions

In this chapter, the performance of rejuvenated asphalt mixtures (recycled asphalt mixture with recycling agent) from several field projects in different environmental zones across the U.S. was evaluated considering various recycling agent doses. The rejuvenated asphalt mixtures were evaluated based on the resulting intermediate-temperature stiffness (M_R and $|E^*|$), intermediate-temperature cracking resistance (I-FIT), low-temperature rheological properties (BBR_m), and rutting resistance (HWTT and APA).

The visual distress surveys and field core test results demonstrated that the recycling agent dose selected for field construction, which was lower than that to match PGH of the target climate, yielded inferior mixture performance with most cases showing lack of reduction in stiffness or lower intermediate and low-cracking resistance of the rejuvenated mixtures as compared to the recycled asphalt mixtures that met the maximum allowable recycled materials content per state DOT specifications. Laboratory test results demonstrated that adding the recycling agent dose to match the continuous PGH of the target climate yielded improved mixture performance. The rejuvenated mixtures at this higher recycling agent dose showed significant reduction in stiffness and improved cracking resistance and facilitated the use of higher quantities of recycled materials, regardless of aging level, while maintaining the rutting resistance after short-term aging. Moisture susceptibility of rejuvenated mixtures with high recycling agent doses should be investigated in future research.

References

Al-Qadi, I. L., H. Ozer, J. Lambros, A. El Khatib, P. Singhvi, T. Khan, J. Rivera-Perez, and B. Doll. *Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS*. Publication FHWA-ICT-15-017, Illinois Center for Transportation, Urbana, IL, 2015, 80 p.

Arámbula-Mercado, E., F. Kaseer, A. Epps Martin, F. Yin, and L. Garcia Cucalon. Evaluation of Recycling Agent Dosage Selection and Incorporation Methods for Asphalt Mixtures with High RAP and RAS Contents. *Construction and Building Materials,* Vol. 158, pp. 432-442, 2018.

Carvajal Munoz, J. S., F. Kaseer, E. Arambula, and A. Epps Martin. Use of the Resilient Modulus Test to Characterize Asphalt Mixtures with Recycled Materials and Recycling Agents. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2506, 2015, pp. 45–53.

Delaware Department of Transportation. Standard Specifications for Road and Bridge Construction. Dover, Delaware, 2016.

Garcia Cucalon, L., F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, N. Morian, S. Pournoman, and E. Hajj. The Crossover Temperature: Significance and Application towards Engineering Balanced Recycled Binder Blends. *Road Materials and Pavement Design*, 2018.

Garcia Cucalon, L., G. King, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, T. Turner, and C. Glover. Compatibility of Recycled Binder Blends with Recycling Agents: Rheological and Physicochemical Evaluation of Rejuvenation and Aging Processes. *Journal of the American Chemical Society*, 2017.

Hansen, K. R., and A. Copeland. Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2016. 7th Annual Survey. National Asphalt Pavement Association, Lanham, MD, 2017.

Illinois Department of Transportation. Standard Specifications for Road and Bridge Construction. Springfield, 26. Illinois, 2016.

Im, S., F. Zhou, R. Lee, and T. Scullion. Impacts of Rejuvenators on Performance and Engineering Properties of Asphalt Mixtures Containing Recycled Materials. *Construction and Building Materials,* Vol. 53, 2014, pp. 596-603.

Indiana Department of Transportation. Standard Specifications. Indianapolis, Indiana, 2016.

Kaseer, F., E. Arámbula-Mercado, L. Garcia Cucalon, and A. Epps Martin. Mixture Validation of Recycling Agents Dosage Selection Method in Asphalt Mixtures with High Recycled Materials Contents. *The 97th Annual Meeting of the Transportation Research Board, Washington, D.C.,* 2018b.

Kaseer, F., F. Yin, E. Arámbula-Mercado, A. Epps Martin, Jo. Daniel, and S. Salari. Development of an Index to Evaluate the Cracking Potential of Asphalt Mixtures Using the Semi-Circular Bending Test. *Construction and Building Materials,* Vol 167, pp. 286-298, 2018c.

Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin. Stiffness Characterization of Asphalt Mixtures with High Recycled Materials Contents and Recycling Agents. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2633, 2017.

Kaseer, F., L. Garcia Cucalon, E. Arámbula-Mercado, A. Epps Martin, and J. Epps. 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,* Vol. 87, 2018a.

Kim, S., T. Byron, G. A. Sholar, and J. Kim. *Evaluation of Use of High Percentage of Reclaimed Asphalt Pavement (RAP) for Superpave Mixtures*. Publication FL/DOT/SMO/07-507, Florida Department of Transportation, 2007.

Menapace, I., Garcia Cucalon, L., Kaseer, F., Arámbula-Mercado, E., Epps Martin, A., Masad, E., and King, G. Effect of recycling agents in recycled asphalt binders observed with microstructural and rheological tests. *Construction and Building Materials,* Vol. 158, pp. 61-74, 2018b.

Menapace, I., Garcia Cucalon, L., Kaseer, F., Masad, E., and Epps Martin, A. Application of Low Field Nuclear Magnetic Resonance to evaluate asphalt binder viscosity in recycled mixes. *Construction and Building Materials*, Vol. 170, pp. 725-736, 2018a.

Mensching, D. J., G. M. Rowe, J. S. Daniel, and T. Bennert. Exploring Low Temperature Performance in Black Space. *Road Materials and Pavement Design*, Vol. 16, Supplement 2, 2015.

Mogawer, W., T. Bennert, J. Daniel, R. Bonaquist, A. J. Austerman, and A. Booshehrian. Performance Characteristics of Plant Produced High RAP Mixtures. *Road Materials and Pavement Design*, Vol. 13, 2012, pp. 183-208.

Mogawer, W.S., A. Booshehrian, S. Vahidi, and A.J. Austerman. Evaluating the Effect of Rejuvenators on the Degree of Blending and Performance of High RAP, RAS, and

RAP/ RAS Mixtures. *Road Materials and Pavement Design*, Vol. 14, Supplement 2, 2013, pp.193-213.

Nevada Department of Transportation. Standard Specifications for Road and Bridge Construction. Carson City, Nevada, 2014.

Romero, P. *Using the Bending Beam Rheometer for Low Temperature Testing of Asphalt Mixture*s. Publication UT- 16.09, Utah Department of Transportation, Salt Lake City, 2016, 70 p.

Shen, J., and Y. Ohne. Determining Rejuvenator Content for Recycling Reclaimed Asphalt Pavement by SHRP Binder Specifications". *The International Journal of Pavement Engineering,* Vol. 3, No. 4, 2002, pp. 261-268.

Shen, J., S. Amirkhanian, and J.A. Miller. Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement. *ASCE Journal of Materials in Civil Engineering,* Vol. 19, No. 5, 2007, pp. 376-384.

Texas Department of Transportation. Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges. Austin, Texas, 2014.

Tran, N.H., A. Taylor, and R. Willis. *Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents.* Publication NCAT Report 12-05, National Center for Asphalt Technology, Auburn, AL, 2012, 70 pp.

West, R., and A. Copeland. High RAP Asphalt Pavements: Japan Practice - Lessons Learned. National Asphalt Pavement Association, Lanham, MD, 2015.

Wisconsin Department of Transportation. Standard Specifications. Madison, Wisconsin, 2017.

Yan, J., Z. Zhang, H. Zhu, F. Li, and Q. Liu. Experimental Study of Hot Recycled Asphalt Mixtures with High Percentages of Reclaimed Asphalt Pavement and Different RAs. *ASTM Journal of Testing and Evaluation*, Vol. 42, No. 5, 2014.

Yin, F., F. Kaseer, E. Arámbula-Mercado, and A. Epps Martin. Characterising the Long-Term Rejuvenating Effectiveness of Recycling Agents on Asphalt Blends and Mixtures with High RAP and RAS Contents. *Road Materials and Pavement Design*, Vol. 18, Supplement 4, pp. 273-292, 2017.

Zaumanis, M., R. Mallick, and R. Frank. Evaluation of Rejuvenator's Effectiveness with Conventional Mix Testing for 100% Reclaimed Asphalt Pavement Mixtures. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2370, 2013, pp. 17-25.

Zaumanis, M., R. Mallick, R. Frank. Determining optimum rejuvenator dose for asphalt recycling based on Superpave performance grade specifications. *Construction and Building Materials,* Vol. 69, 2014, pp. 159–166.

Zhou, F., S. Im, S. Hu, D. Newcomb, and T. Scullion. Selection and Preliminary Evaluation of Laboratory Cracking Tests for Routine Asphalt Mix Designs. *Road Materials and Pavement Design*, Vol. 18, Iss. 1, 2017.

CHAPTER VI

A METHOD TO QUANTIFY RECLAIMED ASPHALT PAVEMENT (RAP) BINDER AVAILABILITY (EFFECTIVE RAP BINDER) IN RECYCLED ASPHALT MIXTURES[5]

Overview

Reclaimed Asphalt Pavement (RAP) is used extensively in asphalt mixtures due to its environmental and economic benefits. These benefits are achieved by replacing a portion of the expensive virgin binder and aggregate in recycled asphalt mixtures. The quantity of RAP binder in the asphalt mixture is typically represented as asphalt binder replacement (ABR) or recycled binder ratio (RBR). Both terms are used to define the percentage of RAP binder by weight with respect to the total binder by weight in the asphalt mixture. However, the quantity of effective RAP binder in the asphalt 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 virgin binder under typical mixing temperatures. Other terms used include RAP binder contribution, RAP binder activation, degree of RAP activation, RAP working binder, and RAP binder availability. The latter will be used in this study.

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[5] Reprinted (with minor revisions) with permission from “A Method to Quantify Reclaimed Asphalt Pavement Binder Availability (Effective RAP Binder) in Recycled Asphalt Mixes” by Fawaz Kaseer, Edith Arámbula-Mercadoa, and Amy Epps Martin, 2019, Transportation Research Record: Journal of the Transportation Research Board (TRB), Copyright [2019] by TRB. https://doi.org/10.1177/0361198118821366.

When discussing RAP binder availability, it is important to distinguish between RAP binder availability and RAP binder blending (or degree of blending). Some authors use both terms interchangeably; however, the first indicates the amount of RAP binder that becomes fluid and is released in the mixture, while the second indicates how well or to what extent the RAP binder and the virgin binder blend in the mixture. If there is no active or available RAP binder, the blending would be nil. However, even if the RAP binder is fully available, complete and homogeneous blending between the RAP binder and the virgin binder may not occur. Nevertheless, the more fluid and active the RAP binder is, the more blending is expected to occur since the active or available RAP binder is expected to uniformly dissipate in the asphalt mixture through mechanical mixing at elevated temperature.

RAP binder availability is typically addressed through one of three assumptions: (1) 0% availability, where the RAP acts as a “black rock”; (2) 100% availability, where all the RAP binder becomes fluid and is available to blend with the virgin binder; or (3) partial availability, where a portion of the RAP binder becomes fluid and is available to blend with the virgin binder. Although rarely measured, it is generally accepted that the third assumption is more realistic. Many studies have consistently shown that, when RAP is mixed with virgin binder and aggregates at elevated mixing temperatures, the RAP binder is partially available *(1-5)*; that is, somewhere between 0% and 100% availability occurs in the asphalt mixture. However, in a recent survey in NCHRP Synthesis 495 (Stroup-Gardiner 2016), 77% of the responding state highway agencies consider 100% RAP binder availability, and thus, they reduce the virgin binder content in the asphalt mixture by the RAP binder content. About 6% of the respondents in this same survey consider 0% RAP binder availability, and approximately 17% consider partial RAP binder availability, assuming around 75% of the RAP binder is available *(6)*.

Designing asphalt mixtures with the assumption of 100% availability could result in asphalt 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 asphalt mixture with a high air void content; potentially leading to cracking, raveling, or premature moisture damage. On the contrary, designing asphalt mixtures with the assumption of 0% availability could result in soft mixtures with potential rutting problems, due to possibly excessive total binder content.

RAP binder availability and blending with virgin binder was first addressed in NCHRP Project 9-12 *(1)* with the purpose of knowing whether the RAP acted like a "black rock" or whether some of the RAP binder blended with the virgin binder. The authors prepared three types of specimens simulating the degree of blending as follows: (1) blending RAP, virgin aggregate, and virgin binder, as in actual practice; (2) removing all RAP binder and blending the virgin binder with the recovered RAP aggregate and virgin aggregate, simulating 0% blending; and (3) removing all RAP binder, physically blending the extracted and recovered RAP binder with the virgin binder, and then combining the blended binder with the virgin aggregate, simulating 100% blending. Superpave shear tests and indirect tensile creep and strength tests indicated that the RAP did not act like a black rock and partial blending occurred to a significant extent. The limitation of this approach is the RAP binder extraction and recovery process, since it is well known that this process can affect the binder properties, and consequently, the indirect tensile creep and strength test results.

Bonaquist (2007) *(2)* developed an approach for evaluating RAP binder availability and blending using five steps: (1) measure the dynamic modulus (|E*|) of the asphalt mixture (with RAP); (2) extract and recover the binder from the mixture; (3) measure the recovered binder shear modulus (|G*|) using the dynamic shear rheometer (DSR); (4) estimate |E*| based on measured |G*| using the Hirsh model; and (5) compare the estimated |E*| to measured |E*|. The authors assumed that overlapping or similar values indicated 100% RAP binder availability and blending; otherwise, partial RAP binder availability and blending occurred. This approach has been advocated for evaluating the binder blending issue but still has some limitations. In addition to the issue of the binder extraction and recovery process, this approach cannot determine, or estimate, how much RAP binder is available and blended (as a percentage). Furthermore, |E*| is an important property of the asphalt mixture that measures the response under loading, but even if there is no blending, the measured |E*| values may be close to those of mixtures with partial blending, as reported in other studies *(3,7)*.

D' Angelo et al. (2011) investigated the extent of RAP binder availability using the aggregate size exclusion method *(4)*. In this method, the RAP has a designated size in the mixture and the virgin aggregates have a different designated size. The authors employed asphalt mixtures containing only two distinct fractions, virgin aggregates and RAP, which could be easily separated by sieving. After mixing with the virgin binder, the RAP was separated from the virgin aggregate, which allowed for investigation of whether the binder content was the same for both materials. If the RAP had a higher binder content than the virgin aggregate, then the RAP binder was not fully available to blend with the virgin binder. In this case, most of the RAP acts like a black rock and the virgin binder coats the RAP as it does any other aggregate particle.

Previous studies have suggested that the use of recycling agents (or rejuvenators) can help activate the hardened RAP binder and mitigate its stiffness *(8-9)*, increasing its availability and ability to blend with the virgin binder *(10)*. RAP binder availability has been studied and debated for a long time; but to date, there is no standard test or method to accurately determine, or at least estimate, how much RAP binder is active and available in the asphalt mixture. The ability to quantify the percentage of available RAP is critical in determining the actual virgin binder content that needs to be added to the asphalt mixture to satisfy the optimum binder content determined by mix design.

Objectives

The objectives of this chapter are:

1. To propose a method to determine, or estimate, the percentage of active and available RAP binder in an asphalt mixture.
2. To investigate the effect of certain factors such as mixing temperature, conditioning period, RAP material source, recycling agent addition and the method of addition on the RAP binder availability.

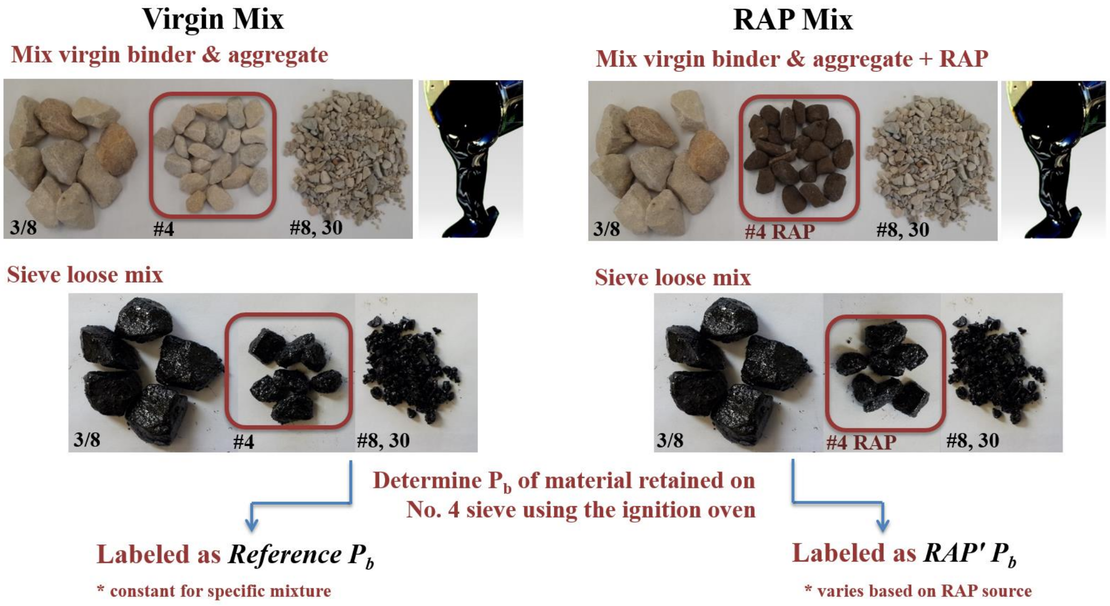
Methodology

The following methodology is proposed to estimate the RAP binder availability based on an evaluation of asphalt mixtures with specific sizes of virgin aggregate and RAP:

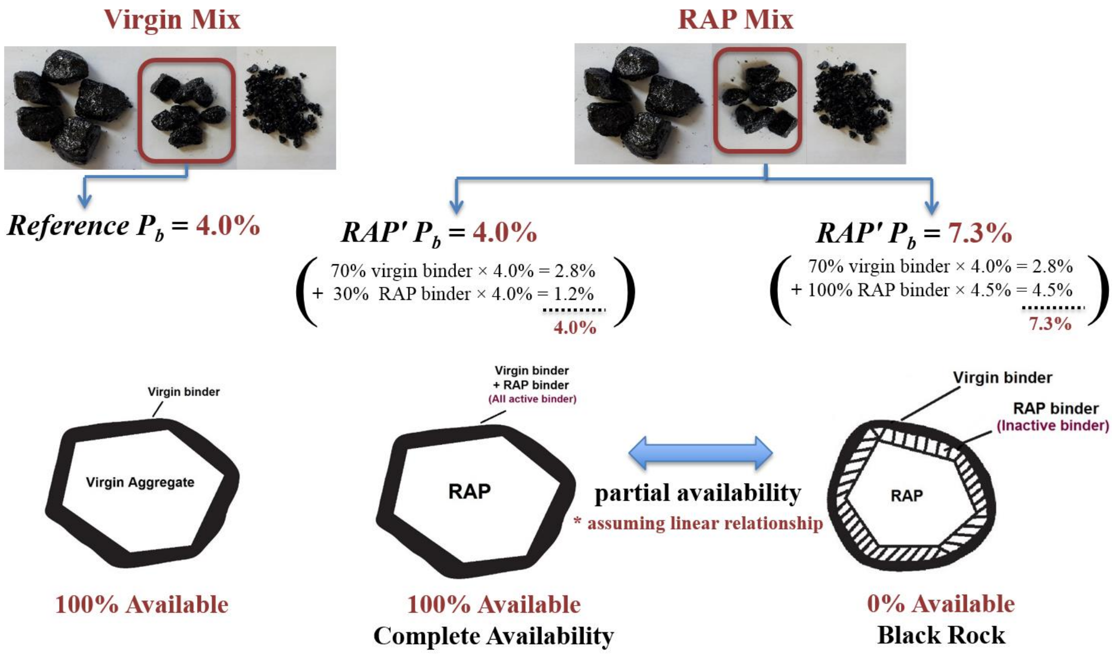
1. Prepare the virgin asphalt mixture using: *(1)* virgin binder and *(2)* virgin aggregate with three distinct fractions: a coarse size (passing the 1/2" sieve and retained on the 3/8" sieve), an intermediate size (passing the 3/8" sieve and retained on the No. 4 sieve), and fine sizes (a combination of material passing the No. 4 sieve and retained on the No. 8, and passing the No. 8 sieve and retained on the No. 30 sieve).
2. Condition the loose asphalt mixture in the oven for 2 hours at 135°C to simulate short-term aging.
3. Sieve the loose asphalt mixture to separate the coated particles into the different sizes. The sieving process should be performed while the loose mixture and the sieves are reasonably hot.
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 aggregate (retained on the No. 4 sieve) as *Reference* P_b.
5. Prepare the RAP asphalt mixture using: *(1)* virgin binder, *(2)* virgin aggregate with two distinct fractions: a coarse size (retained on the 3/8" sieve), and fine sizes (a combination of material retained on the No. 8 and No. 30 sieves), and *(3)* RAP of intermediate size (retained on the No. 4 sieve).

6. Repeat steps 2 through 4, and label the binder content of the particles retained on the No. 4 sieve (RAP material) as *RAP′* P_b.

The minimum recommended asphalt mixture mass is 4,000 gram to obtain two replicates for the ignition oven. Figure 52(a) provides an illustration of the proposed method. The binder content of the individual sizes of coated RAP (*RAP′* P_b) and coated virgin aggregate (*Reference* P_b) provides significant insight into the amount of RAP binder that is active and available.



(a)



(b)

Figure 52. (a) summary of the proposed method, and (b) possible scenarios for RAP binder availability.

To understand the methodology, consider an example of a virgin asphalt mixture consisting of virgin binder and virgin aggregate with distinct fractions with the percent retained of each fraction (by weight of total aggregate) of 28% (3/8”), 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, after the ignition oven, are 2.7%, 4.0% (*Reference* P_b), and 6.1% for sieves No. 3/8, No. 4, and (No. 8 + No. 30), respectively. The coarse aggregate is expected to absorb less binder than the intermediate and fine aggregate sizes due to smaller surface area *(11)*. The *Reference* P_b value is only valid for this particular mixture, with its specific virgin aggregate type and gradation, and the total binder content.

When using RAP (with a 4.5% binder content) to prepare a RAP asphalt mixture with 0.3 RBR (i.e., 30 percent RAP binder and 70 percent virgin binder) and a total binder content the same as in the virgin asphalt mixture (4.5%), the total binder content consists of 3.15% virgin binder (70%) plus 1.35% RAP binder (30%). Therefore, the virgin binder contents in each sieve size of aggregate should be close to 70% of the values measured in the virgin mixture with 100% virgin binder content; i.e. 1.9% (3/8”), 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 complete the binder content for each sieve size of aggregate to 2.7% (3/8”), 4.0% (No. 4), and 6.1% (No. 8 + No. 30).

In this RAP asphalt mixture, the $RAP'\ P_b$ (binder content of RAP retained on the No. 4 sieve) is measured, and the following three outcomes are plausible depending on how much RAP binder is active or available:

1. Scenario 1: $RAP'\ P_b = Reference\ P_b$ (= 4.0% in this example)

   The coated RAP particles have the same binder content as the coated virgin aggregate particles on the No. 4 sieve. This would imply that the RAP binder is fully released, and completely active and available in the mixture, and the total binder composite (virgin and RAP binders) was evenly distributed within the mixture. This scenario would represent 100% RAP binder availability as illustrated in Figure 52(b).

2. Scenario 2: $RAP'\ P_b$ = [1-RBR]×$Reference\ P_b$ + *RAP binder content*

   = 7.3% in this example

   The coated RAP particles 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 virgin 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 52(b).

   In this example, since the contribution from the virgin binder equals 2.8% (at 70% of the total binder, as calculated and verified previously when only the virgin 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.

3. Scenario 3: $Reference\ P_b < RAP'\ P_b < (Reference\ P_b + RAP\ binder\ content)$

   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 52(b).

Therefore, the concept behind this method 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 content of these particles, the RAP binder availability can be calculated.

To calculate the % RAP binder availability, a linear relationship between the two extremes can be used: scenario 1 when $RAP'\,P_b$ equal 4.0% in this example, which represents 100% availability, and scenario 2 when $RAP'\,P_b$ equal 7.3% in this example, which represents 0% availability, as shown in Equation 11 and Figure 53.

$$RAP\ BAF\ (\%) = m \times RAP'\,P_b + b \qquad \text{Equation 11}$$

Where $RAP\ BAF\ (\%)$ = RAP binder availability factor,
m = slope (-30.3 in this example),
$RAP'\,P_b$ = binder content of RAP particles retained on the No. 4 sieve,
b = intercept (221.2 in this example).

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 asphalt mixture, and can be used to adjust the virgin binder content in asphalt mixtures with RAP, to ensure that the total optimum (active) binder content as prescribed in the mix design is achieved.

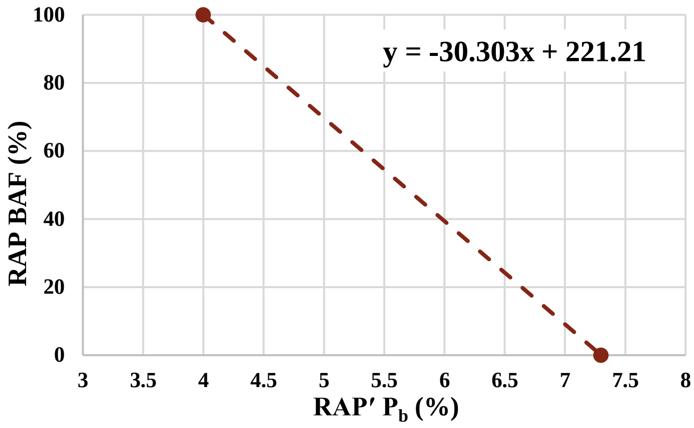


Figure 53. Example relationship between BAF and *RAP′* P_b.

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 11 can be used to calculate the BAF. Noticeably, 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 BAF calculation. In the 0% availability case (scenario 2 with *RAP′* P_b equal to 7.3% in this example), *RAP′* P_b will always equal *Reference* P_b + *RAP binder content*.

Method Limitations

The RAP BAF was estimated based on the binder content of individual fractions of the asphalt mixture, which provide a reasonable approximation. There are two main limitations to the method that may increase or decrease the actual RAP binder availability:

1. *Absorbed RAP binder:* Even if the RAP binder is very soft and completely fluid, active, and available in the asphalt mixture, there will always be some RAP binder that is absorbed by the RAP aggregate. Thus, it will be almost impossible to obtain 100% RAP binder availability with this method and the resulting values will likely be somewhat lower than actual RAP binder availability values.
2. *Aggregate gradation:* The RAP and aggregate fractions retained on the No. 4 sieve are used in this method to represent the entire RAP source and aggregate gradation in the asphalt mixture. However, RAP materials typically include a variety of sizes, mostly intermediate and fine, and less coarse. Smaller RAP sizes are expected to yield higher RAP binder availability due to their larger available surface area, higher binder content, and thicker binder film. Therefore, using the No. 4 sieve in this method may result in lower than actual RAP binder availability values. Moreover, the RAP binder performance grade (PG) varies among different RAP sizes (of the same RAP source), and that will also affect the RAP binder availability values, as discussed subsequently.

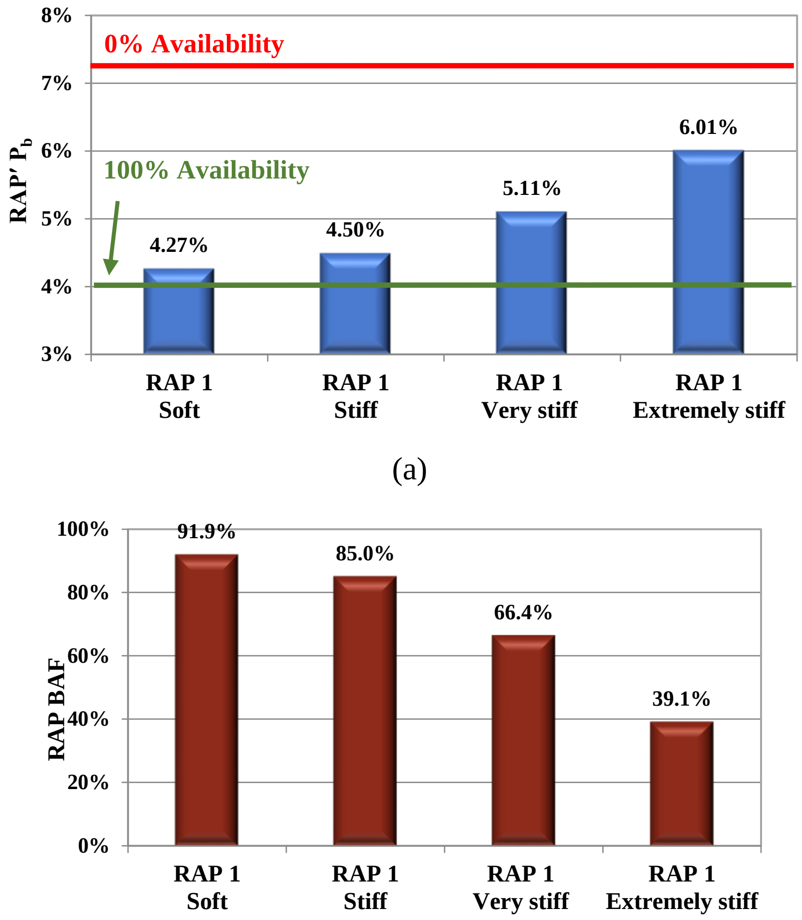
Method Verification

This method was initially verified by preparing asphalt mixtures and aging them at various levels to create artificial RAP (i.e., laboratory aged) materials. The artificial RAP was produced by mixing a PG 64-22 virgin 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.
- 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) asphalt mixtures with virgin aggregate from Texas (limestone) with the percentages retained by weight of the total aggregate equal to 28% (3/8”), 30% (No. 4), 28% (No. 8), and 14% (No. 30). The RBR in the RAP asphalt mixtures was 0.3, and the total binder content in both asphalt mixtures was 4.5%. In the virgin asphalt mixture, the *Reference* P_b was 4.0% as determined using the ignition oven (steps 1-4). In the artificial RAP mixtures, steps 5-6 were followed for each different artificial RAP, and the *RAP′* P_b values were also determined using the ignition oven.

Figure 54(a) 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 *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 *Reference* P_b (6.01% versus 4.0%). This resulted in higher BAF values for RAP 1 as compared to RAP 4, as shown in Figure 54(b). 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.



(a)

(b)

Figure 54. (a) *RAP'* P_b values, and (b) BAF values for asphalt mixtures with artificial RAPs.

Factors Affecting RAP BAF

After verifying the proposed method to estimate the RAP BAF using artificial RAP prepared in the laboratory, the method was used to estimate the RAP BAF of actual RAP materials from different sources in the U.S.: Texas (TX), Florida (FL), Indiana (IN), New Hampshire (NH), Nevada (NV), Delaware (DE), and Wisconsin (WI). These materials were utilized 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 the method of addition

The BAF of each RAP was calculated, using the proposed method, by preparing virgin and RAP asphalt mixtures. The virgin asphalt mixtures were prepared with a WI PG 58-28 virgin binder and virgin aggregate from Wisconsin (crushed rocks from Muskego, WI) with the percentages retained by weight of the total aggregate equal to 28% (3/8”), 30% (No. 4), 28% (No. 8), and 14% (No. 30). The RAP asphalt mixtures were prepared with the same virgin binder and aggregate (excluding the No. 4 sieve that was replaced by the RAP of the same size), and the RBR for the RAP mixtures was about 0.3. The total binder content in both asphalt mixtures was 4.5%. Since the RAP binder content was not the same for the different RAP sources, some RAP asphalt mixtures had a little bit less, or more, RAP binder than others, in order to maintain the same total binder content in all RAP asphalt mixtures. It was important to maintain the same total binder content for all RAP asphalt mixtures to match the virgin asphalt mixture in order to keep the calculations of $RAP'\ P_b$ and $Reference\ P_b$ valid within the same total binder content.

After following the proposed method in steps 1-6, ignition oven results showed that the $Reference\ P_b$ in the virgin asphalt mixture was 4.4%. In the RAP asphalt mixtures, the *RAP′* P_b values varied among different RAP sources. Two replicates were prepared and considered for each asphalt mixture.

Mixing Temperature and Short-Term Conditioning Period

Production (or mixing) temperature of asphalt mixtures depends on the viscosity of asphalt binders and how well the asphalt binder coats the aggregates. For virgin asphalt mixtures without RAP, general rules are well established. For example, the production temperature for a virgin mixture with a PG 58-28 binder (as used in this study) is approximately 141 to 147°C (287 to 297°F) at which the virgin binder can easily flow and coat the virgin aggregates *(12)*. However, it is not certain that this mixing temperature range is adequate for RAP asphalt mixtures, to ensure that the RAP binder is released, becomes fluid, and blends with the virgin binder.

Asphalt mixtures were prepared at two mixing temperatures: 140 and 150°C. Figure 55(a) shows the results of RAP BAF versus mixing temperature. The error bars on 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 temperature, the higher the BAF. This is expected since higher mixing temperatures help soften the RAP binder, becoming more fluid and facilitating blending with the virgin binder.

Figure 55(b) shows the estimated RAP BAF of two different short-term conditioning periods (2 hours versus 4 hours): in both cases, mixing and condition temperatures were 150 and 135°C, respectively. It seems that extending the short-term conditioning to 4 hours slightly increased the RAP BAF of FL, IN, and DE RAP sources, but statistically, there was no difference between 2 hours versus 4 hours short-term conditioning time.

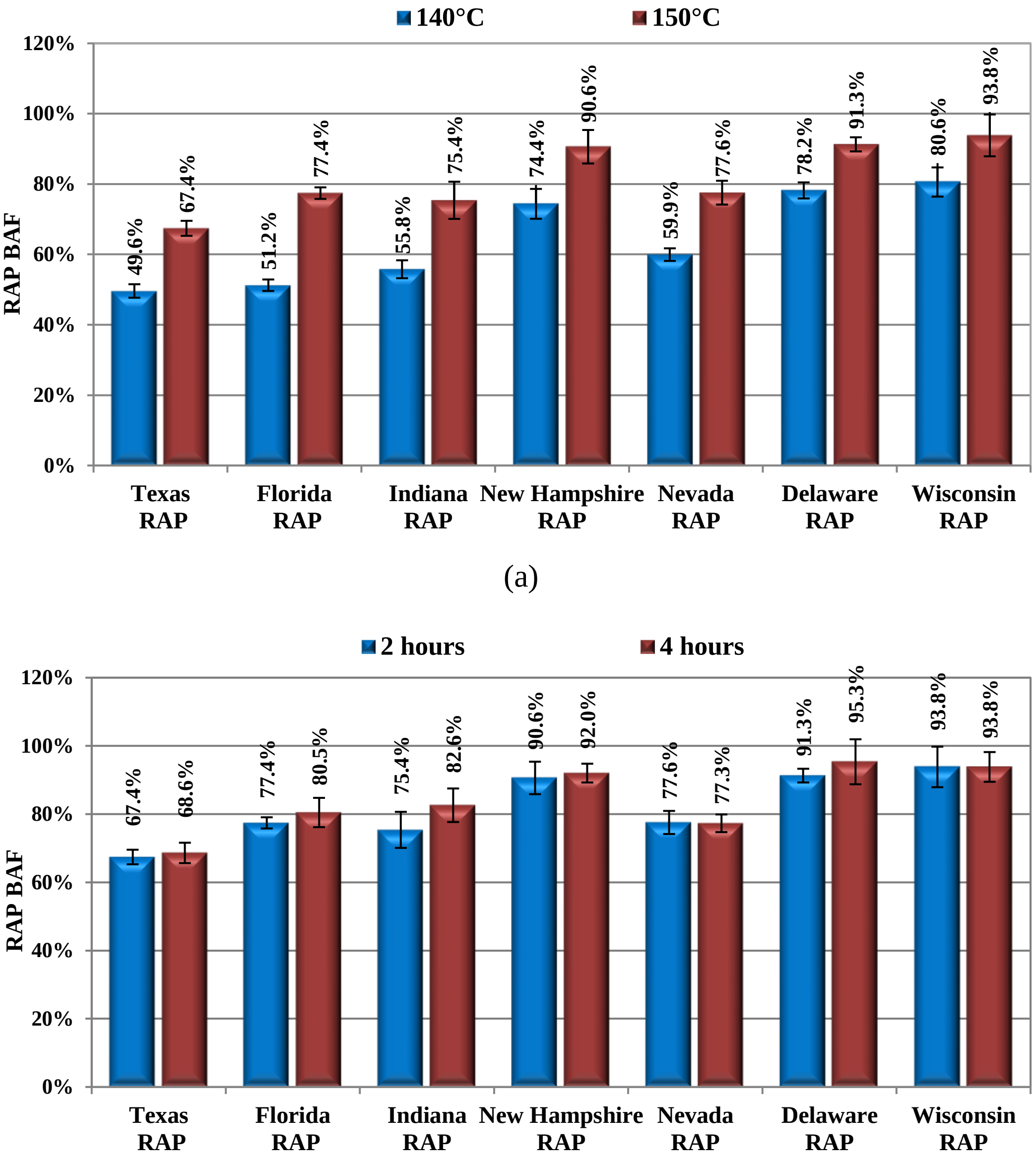
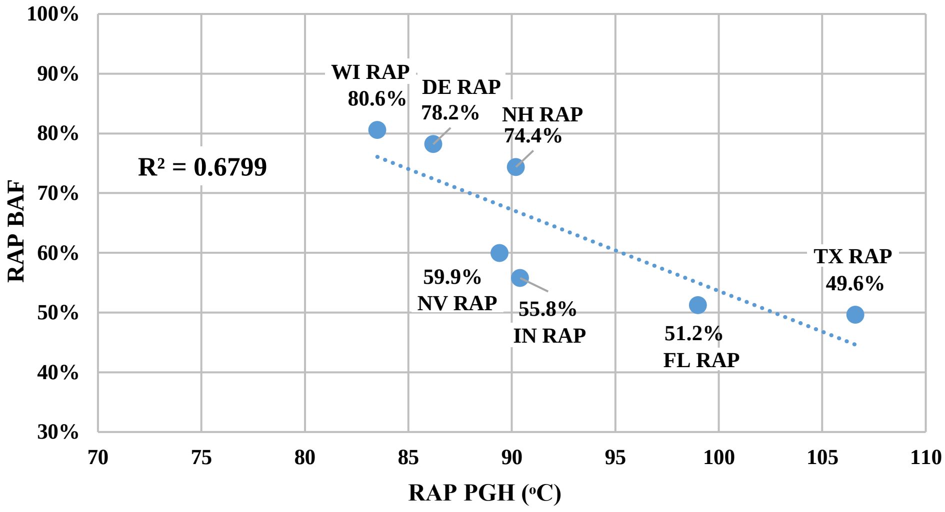


Figure 55. (a) The effect of mixing temperature on RAP BAF (b) the effect of short-term conditioning period on RAP BAF.

RAP Source and RAP Binder PG

To evaluate the effect of RAP PG on the BAF, the recycled binders from the different RAP sources were extracted in accordance with ASTM D 2172 (test method A: centrifuge extraction), and then recovered in accordance with ASTM D 5404 using the rotary evaporator. Rheological characterization was performed on the recovered RAP binders using the DSR to obtain the high-temperature PG (PGH) of each RAP binder, per AASHTO M 320, as an indication of RAP binder stiffness and the extent of aging.

Figure 56 (a and b) shows the results of RAP BAF versus RAP binder PGH at 140 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 RAP binder will be active and available in the mixture, as 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.



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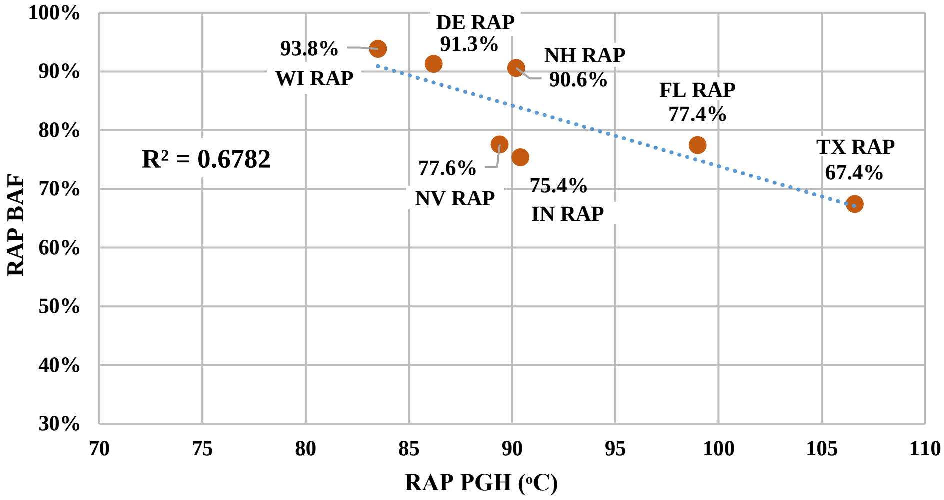


(b)

Figure 56. RAP BAF versus RAP PGH at (a) 140°C (b) 150°C mixing temperature.

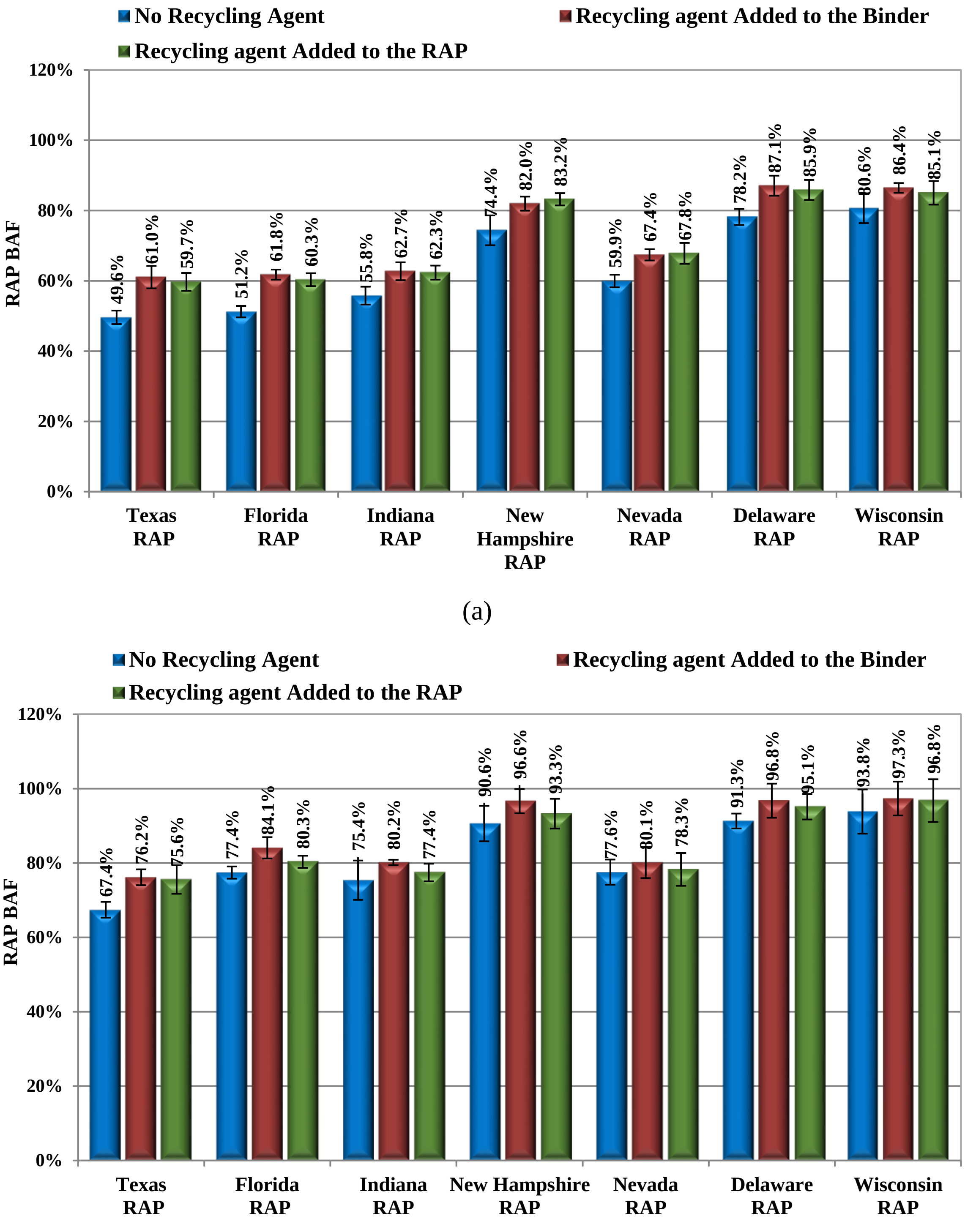
Recycling Agent Addition and the Method of Addition

Previous studies have shown the effectiveness of recycling agents in softening the RAP binder and improving the performance of recycled asphalt mixtures, by mitigating the stiffness and brittleness of the RAP binder *(10, 13-21)*. To evaluate the effect of recycling agent addition on the RAP BAF, a modified vegetable oil was added to the RAP asphalt mixtures at a dose of 5%. To evaluate the method of recycling agent addition, the recycling agent was added to the virgin binder prior to mixing with virgin aggregate and RAP in one set of RAP asphalt mixtures, while in another set the recycling agent was added directly to the RAP (at room temperature for about 5 minutes) prior to mixing with virgin aggregate and virgin binder.

Figure 57(a) shows that including the recycling agent in the asphalt 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 virgin 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 five minutes before mixing, and thus, there was not sufficient time for the recycling agent to diffuse into the RAP binder. In a report published by the National Asphalt Pavement Association (NAPA) in 2015 *(22)* to discuss practices in Japan in high RAP asphalt pavements, it was reported that recycling agents are mixed directly with the heated RAP in a small pugmill, and the hot rejuvenated RAP is then transferred to a surge bin to give additional conditioning time (2–3 hours). The merit of this approach is that it allows the recycling agent to quickly diffuse into the softened aged RAP binder. This practice would increase the RAP BAF.

Figure 57(b) 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 addition had more impact on the RAP BAF at low mixing temperatures than higher mixing temperatures. However, although increasing mixing temperature and adding a recycling agent had equivalent effects on the RAP BAF, the recycling agent had more benefit in softening the RAP binder and improving its rheology without additional aging at the higher mixing temperature. The method of adding the recycling agent to the RAP directly, as opposed to mixing it with the virgin binder at 150°C mixing temperature, also did not show any significant effect on RAP BAF.



(a)

(b)

Figure 57. The effect of recycling agent addition and the method of addition on RAP BAF at (a) 140°C (b) 150°C mixing temperature.

Conclusions

This chapter proposed a method to estimate the BAF of RAP. Since not all of the binder is released from the RAP, becomes fluid, and blends with the virgin binder under typical mixing temperatures—as is commonly assumed—the BAF can be used to adjust the virgin binder content in recycled mixtures to ensure that the mix design optimum binder content is achieved. In the proposed method, asphalt mixtures were prepared so that after mixing and conditioning, the RAP material could be separated from the virgin aggregate, allowing for a thorough evaluation of the extent of RAP binder availability in the recycled asphalt mixture.

The following conclusions are drawn based on the proposed method:

- The RAP BAF ranged from 50% to 95% depending on RAP source and mixing temperature: the lower the RAP binder PGH, the higher the BAF, and the higher the mixing temperature, the higher the BAF.
- Extending the short-term conditioning from 2 to 4 hours did not significantly increase the RAP BAF.
- Adding the recycling agent clearly increased the RAP BAF for most RAP sources at a lower mixing temperature (140°C), but did not significantly increase the RAP BAF at a higher mixing temperature (150°C).
- The method of adding the recycling agent to the RAP directly, as opposed to mixing it with the virgin binder, did not show any significant effect on RAP BAF, but time and temperature of marination were not explored.

The RAP BAF was estimated using the proposed method based on the binder content of individual fractions of the mixture, which provides a reasonable estimate of the percentage of active/available RAP binder. Using the measured BAF from this method is more appropriate than the rough estimate of 75% used by many state DOTs, as reported by NCHRP Synthesis 495 *(6)*.

Besides binder availability, the degree of blending of the RAP and virgin binders needs to be investigated since it will affect asphalt mixture performance, and stiffness or cracking resistance testing should always be performed on recycled asphalt mixtures to evaluate the effect of RAP BAF and the degree of blending. Other variables that may affect the RAP BAF and the degree of blending that need to be investigated include mixing time and different RAP/aggregate gradation.

References

Al-Qadi et al. *Determination of usable residual asphalt binder in RAP*. Publication FHWA-ICT-09-031, Illinois Center for Transportation, 2009, 100 p.

Arámbula-Mercado, E., A. Epps Martin, and F. Kaseer. Case study on balancing mixtures with high recycled materials contents. *Advances in Materials and Pavement Performance Prediction,* proceedings, 2018, pp. 239-242.

Arámbula-Mercado, E., F. Kaseer, A. Epps Martin, F. Yin, and L. Garcia Cucalon. Evaluation of Recycling Agent Dosage Selection and Incorporation Methods for Asphalt Mixtures with High RAP and RAS Contents. *Construction and Building Materials,* Vol. 158, 2018, pp. 432-442.

Bonaquist, R. Can I Run More RAP? *Hot Mix Asphalt Technology,* National Asphalt Pavement Association, Vol. 12, No. 5, 2007.

British Petroleum. Recommended Mixing and Compaction Temperatures for Paving Applications, BP Products North America Inc., 2015.

Brown, E. R., P. S. Kandhal, F. L. Roberts, Y. R. Kim, D. Lee, and T. W. Kennedy. *Hot Mix Asphalt Materials, Mixtures Design, and Construction.* NAPA Research and Education Foundation, Langham, Maryland, 2009.

Carvajal Munoz, J. S., F. Kaseer, E. Arambula, and A. Epps Martin. Use of the Resilient Modulus Test to Characterize Asphalt Mixtures with Recycled Materials and Recycling Agents. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2506, 2015, pp. 45–53.

Copland, A., R. Dongrê, and J. D' Angelo. Evaluation of RAP Binder Blending, Part II, presented at RAP ETG, Oklahoma City, Oklahoma, 2010.

D' Angelo, J. A., R. Dongrê, and A. Copland. Evaluation of the Extent of Asphalt Blending in RAP Mixes, *Proceedings of the 56th Annual Conference of the Canadian Technical Asphalt Association (CTAA),* Quebec City, Quebec, 2011, pp. 289-308.

Epps Martin, A. et al. *The Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios.* NCHRP 9-58 Interim Report, National Cooperative Highway Research Program, Washington, DC, 2016, http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3645.

Garcia Cucalon, L., G. King, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, T. Turner, and C. Glover. Compatibility of Recycled Binder Blends with Recycling Agents: Rheological and Physicochemical Evaluation of Rejuvenation and Aging

Processes. *Industrial & Engineering Chemistry Research,* Vol. 56, Iss. 29, 2017, pp. 8375-8384.

Huang, B., G. Li, D. Vukosavljevic, X. Shu, and B. K. Egan. Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1929, 2005, pp. 37-45.

Kaseer, F., E. Arámbula-Mercado, L. Garcia Cucalon, and A. Epps Martin. Performance of asphalt mixtures with high recycled materials content and recycling agents. *International Journal of Pavement Engineering,* 2018.

Kaseer, F., E. Arámbula-Mercado, and A. Epps Martin. A Method to Quantify Reclaimed Asphalt Pavement (RAP) Binder Availability (Effective RAP Binder) In Recycled Asphalt Mixes. *Transportation Research Record: Journal of the Transportation Research Board,* 2019.

Kaseer, F., F. Yin, E. Arámbula-Mercado, and A. Epps Martin. Stiffness Characterization of Asphalt Mixtures with High Recycled Materials Contents and Recycling Agents. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2633, 2017, pp. 58-68.

Kaseer, F., L. Garcia Cucalon, E. Arámbula-Mercado, A. Epps Martin, and J. Epps. 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,* Vol. 87, 2018.

McDaniel, R. and R. M. Anderson. *Recommended use of reclaimed asphalt pavement in the Superpave mix design method: Technician's Manual.* NCHRP Report 452, Transportation Research Board, National Research Council, Washington, D.C, 2001.

Menapace, I., L. Garcia Cucalon, F. Kaseer, E. Arámbula-Mercado, A. Epps Martin, E. Masad, and G. King. Effect of Recycling Agents in recycled asphalt binders observed with microstructural and rheological tests. *Construction and Building Materials,* Vol. 158, 2018, pp. 61-74.

Menapace, I., L. Garcia Cucalon, F. Kaseer, E. Masad, and A. Epps Martin. Application of Low Field Nuclear Magnetic Resonance to evaluate asphalt binder viscosity in recycled mixes. *Construction and Building Materials,* Vol. 170, 2018, pp. 725-736.

Mogawer, W. S., A. Booshehrian, S. Vahidi, and A.J. Austerman. Evaluating the Effect of Rejuvenators on the Degree of Blending and Performance of High RAP, RAS, and RAP/ RAS Mixtures. *Road Materials and Pavement Design,* Vol. 14, Supplement 2, 2013, pp.193-213.

Stroup-Gardiner, M. *Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures*. NCHRP Synthesis 495, National Cooperative Highway Research Program, Washington, DC, 2016, 124 p.

West. R., and A. Copeland. *High RAP Asphalt Pavements: Japan Practice - Lessons Learned.* National Asphalt Pavement Association, Lanham, MD, 2015, 62 p.

Yin, F., F. Kaseer, E. Arámbula-Mercado, and A. Epps Martin. Characterising the Long-Term Rejuvenating Effectiveness of Recycling Agents on Asphalt Blends and Mixtures with High RAP and RAS Contents." *Road Materials and Pavement Design,* Vol. 18, Sup. 4, 2017, pp. 273-292.

CHAPTER VII

CONCLUSIONS AND FUTURE RESEARCH

Conclusions

The use of RAP and RAS in HMA and WMA mixtures can reduce construction costs, maintain dwindling natural resources, conserve valuable landfill space, and improve sustainability. Highway agencies and contractors alike have long recognized these benefits, and as the percentage of RAP and/or RAS increases in asphalt mixtures, their economic and environmental benefits also increase. However, utilization of higher amounts of these aged materials presents concerns that the recycled asphalt mixtures are less workable and difficult to compact during construction and more prone to cracking during pavement service life due to their stiff, brittle nature (Kim et al. 2007; Mogawer et al. 2012). To accommodate the severely aged and substantially stiffer binder in RAP and RAS, and thus provide adequate performance in the field, some adjustments to the recycled asphalt mixtures can be considered, including using recycling agents.

The use of recycling agents has gained more attention in recent years due to increased availability, ease of addition to asphalt mixtures, and often lower costs as compared to the use of softer virgin binders. Adding recycling agents to recycled asphalt mixtures can significantly reduce the stiffness and improve the cracking performance by mitigating the brittleness of the recycled binder in the RAP and RAS. However, the reduction in stiffness and improvement in cracking resistance of recycled binder blends and corresponding recycled asphalt mixtures due to the addition of recycling agent is diminished with long-term aging, particularly when low recycling agent doses are utilized.

Despite previous research efforts, there are several aspects with respect to optimizing recycling agent usage in asphalt mixtures that have not been established. These aspects include selecting the appropriate dose of recycling agent; optimizing recycled materials type and content; evaluating the effect of various factors such as the type, source, and amount of recycled materials, and the source and grade of the base binder on the long-term performance of rejuvenated asphalt mixtures; and providing practice-ready guidelines for evaluation, materials selection/optimization, and design of mixtures with high recycled materials contents and recycling agent.

In this study, a summary of the current knowledge related to the use of recycling agents in the asphalt pavement industry was first provided, including recycling agent definition, advantages, and challenges; statistics on the use of recycling agents in the U.S.; rejuvenation mechanism of recycling agents; the effectiveness of recycling agents in improving the rheology of recycled binder blends and in improving the performance of recycled asphalt mixtures; and cost-effectiveness associated with the use of recycling agents. All the information was further used to identify current and future challenges that could prevent utilization of recycling agents and production of rejuvenated asphalt mixtures with adequate performance.

Next, different recycling agent dose selection methods were evaluated based on rheological parameters of the recycled binder blend. Three different methods were utilized to calculate the dose of the recycling agent to: (1) restore PGL of the recycled binder blend to that of the required target binder, (2) achieve a ΔT_c value of -5°C for the recycled binder blend, and (3) match the continuous PGH of the recycled binder blend to that of the required target binder. The rheological properties $|G^*|$ and δ at a specific temperature-frequency combination corresponds to the G-R parameter, was utilized to evaluate and compare the performance of the recycled and rejuvenated binder blends, and to evaluate their long-term durability.

Blending charts to balance recycled binder blend composition (as a tool to optimize the type and amount of recycled materials) and blending charts to select the appropriate dose of recycling agent to be added to an asphalt mixture during mix design were also established and verified. In addition, the improvement in the rheological, aging, and performance properties of the recycled binder blends and asphalt mixtures with the selected dose of recycling agent was verified.

Next, the performance of rejuvenated asphalt mixtures produced in five field projects in the U.S. that include a wide spectrum of materials (base binder PG; recycled materials content, source, and type; and recycling agent type and dose), mix designs, and climate was evaluated.

Finally, a proposed method to estimate the RAP Binder Availability Factor (BAF) which quantifies the available or effective RAP binder was introduced. The percentage of available or effective RAP binder in the asphalt mixture is usually less than 100% and difficult to quantify, which could yield a dry asphalt mixture with a high air void content; potentially leading to premature distress. BAF can be used to adjust the virgin binder content in RAP mixtures to ensure that the mix design optimum binder content is achieved.

The following key findings are based on the results of this study.

1. Recycling agent effectiveness needs be characterized in high RBR binder blends or asphalt mixtures initially and with long-term aging to capture the decrease in effectiveness with long-term aging.
2. 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 lower doses to restore PGL only sufficient with short-term aging.
3. Recycling agents are more effective in rejuvenating less aged recycled materials (RAP than RAS and MWAS than TOAS).
4. The total RBR should be controlled and a maximum RBR for RAS materials should be considered (to control the maximum PGH) to ensure adequate mixture performance at reasonable recycling agent doses. Mixtures with very high RBR (or high RAS contents) require very high recycling agent doses that can be detrimental to rutting resistance, and can be costly and may overcome the cost savings associated with increasing RBR. Utilizing blending charts to balance the proportions of RAP/MWAS/TOAS is beneficial to control the maximum recycling agent dose.
5. Use of high quality base binders (less negative or positive ΔT_c) improves the performance of high RBR binder blends and mixtures with and without recycling agents.

6. Rejuvenated mixtures at recycling agent doses to match the continuous PGH of the target climate showed significant reduction in stiffness and improved cracking resistance and facilitated the use of higher quantities of recycled materials, regardless of aging level, while maintaining the rutting resistance after short-term aging.
7. Some high RBR mixtures with recycling agent may be moisture susceptible, and thus, mixture modifications are needed to address this issue.
8. Recycled binder in RAP is not 100% available or effective in recycled asphalt mixtures. The RAP BAF ranged from 50% to 95% depending on RAP source (source climate and level of aging) and mixing temperature. Adding the recycling agent clearly increased the RAP BAF for most RAP sources at a lower mixing temperature (140°C), but did not significantly increase the RAP BAF at a higher mixing temperature (150°C).

Future Research

The following suggestions for future research are made based on the results of this study:

1. Rutting resistance for rejuvenated asphalt mixtures with the selected recycling agent dose to match continuous PGH for the target climate was verified in HWTT and APA testing. However, although test results suggest that adequate rutting resistance can be achieved, moisture susceptibility may be an issue when recycling agents are utilized, particularly at higher doses. Further research is necessary to address this issue.

2. The laboratory LTOA protocol used in this study (5 days at 85°C (185°F)) was based on AASHTO R30. Based on recent data from NCHRP Project 9-52, a more significant laboratory LTOA protocol is needed in order to simulate long-term aging during pavement service life, in which asphalt pavements are most vulnerable to cracking. Future research into the effectiveness of recycling agent at the selected dose, using different laboratory LTOA protocols, is necessary.
3. The focus in this study was on evaluation of the effect of recycling agent on recycled binder blends and asphalt mixtures through rheological and performance testing. However, chemical and physicochemical aspects of recycling and rejuvenation need to be evaluated through specialized testing such as FT-IR (Fourier Transform Infrared spectroscopy) and SAR-AD^{TM} (Saturates, Aromatics, Resins – Asphaltene Determinator fractions). These tests can help understand the rejuvenation mechanism, the possible diminished effectiveness of recycling agents with long-term aging, the chemical changes in rejuvenated binder blends typically observed when different recycling agent types are used, and the chemical compatibility of recycling agents with base and recycled binders. These aspects should be investigated in future research.
4. While test results indicated improved binder blend rheology and asphalt mixture performance due to recycling agent addition, as compared to recycled binder blends and asphalt mixtures without recycling agent, more research is needed with additional field projects to develop more refined rheological and performance thresholds, different from the current thresholds for use with virgin asphalt mixtures

without any recycled material. These thresholds should also consider different climates across the U.S.