Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures for Virginia

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JHONY HABBOUCHE, Ph.D., P.E.
Senior Research Scientist, Virginia Transportation Research Council

ILKER BOZ, Ph.D.
Research Scientist, Virginia Transportation Research Council

BENJAMIN SHANE UNDERWOOD, Ph.D.
Professor, North Carolina State University

CASSIE CASTORENA, Ph.D.
Professor, North Carolina State University

JAIME PRECIADO
Graduate Research Assistant, North Carolina State University

SAQIB GULZAR
Graduate Research Assistant, North Carolina State University

ANDREW FRIED
Graduate Research Assistant, North Carolina State University

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16. Abstract:

In recent years, several state highway agencies have introduced special provisions and specifications to allow the use of higher contents of reclaimed asphalt pavement (RAP) in asphalt surface mixtures. The challenges associated with high RAP mixtures can be addressed through the use of additives such as recycling agents (RAs) and/or softer binders. Currently, there are no specific guidelines or specifications available to evaluate the acceptability of RAs in Virginia. The purpose of this study was to evaluate the short- and long-term effectiveness of RAs in improving the performance of asphalt mixtures, particularly those with high RAP contents. Another objective of the study was to establish a performance-based framework to determine the acceptability of a specific RA product for inclusion in the Virginia Department of Transportation's Approved Product List. Both objectives were achieved by benchmarking recycled binder blends (Phase I) and mixtures (Phase II). These were then compared in terms of laboratory performance to commonly used virgin asphalt binders and mixtures in Virginia. Moreover, a comprehensive review of the literature and information from state departments of transportation and RA suppliers on the current state of the practice regarding the use of recycled materials and RAs in asphalt mixtures was summarized.

Component materials, including three virgin asphalt binders, RAP and aggregate materials from three different sources, and six RAs, were collected and tested. Phase I involved testing virgin and RAP binders; combinations of virgin binder and RAP binder; and combination of virgin binder, RAP binder, and RAs. A total of 26 binder blends were evaluated at various aging conditions through numerous rheology- and chemistry-based tests. In Phase II, 10 asphalt mixtures were designed and evaluated for durability, resistance to rutting, and resistance to cracking at various aging conditions. Cross-scale evaluation of asphalt binder and mixture testing data was established. Finally, preliminary verification was performed using data collected from various field trials constructed in Virginia.

Based on the binders and mixtures tested in this study, the effectiveness of RAs in improving the properties of asphalt binder blends is specific to the product being used and to the targeted temperatures or conditions. Moreover, RAs can enhance the performance and increase the use of recycled materials in asphalt mixtures provided that the correct and suitable dosage of RA product is determined through a performance-based testing framework.

The study recommends the following: (1) adopting the streamlined frameworks presented in this study to determine the acceptability of a given RA; (2) further validating the presented framework using different component materials; (3) employing balanced mix design tests to assess the performance characteristics of surface mixtures (with A and D designations) with RAs and drafting a roadmap; (4) collecting and further evaluating the field performance of all trials involving high RAP, RAs, and/or softer binders; (5) investigating the availability and activity of binders, especially with RAs, in RAP materials; (6) evaluating and establishing a protocol to assess the consistency of RAP materials; and (7) quantifying the environmental and economic impacts of using surface mixtures with high RAP contents and/or RAs.

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FINAL REPORT

ENGINEERED FRAMEWORKS FOR EVALUATING THE USE OF RECYCLING AGENTS IN SURFACE ASPHALT MIXTURES FOR VIRGINIA

Jhony Habbouche, Ph.D., P.E.
Senior Research Scientist
Virginia Transportation Research Council

Ilker Boz, Ph.D.
Research Scientist
Virginia Transportation Research Council

Benjamin Shane Underwood, Ph.D.
Professor
North Carolina State University

Cassie Castorena, Ph.D.
Professor
North Carolina State University

Jaime Preciado
Graduate Research Assistant
North Carolina State University

Saqib Gulzar
Graduate Research Assistant
North Carolina State University

Andrew Fried
Graduate Research Assistant
North Carolina State University

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ABSTRACT

In recent years, several state highway agencies have introduced special provisions and specifications to allow the use of higher contents of reclaimed asphalt pavement (RAP) in asphalt surface mixtures. The challenges associated with high RAP mixtures can be addressed through the use of additives such as recycling agents (RAs) and/or softer binders. Currently, there are no specific guidelines or specifications available to evaluate the acceptability of RAs in Virginia. The purpose of this study was to evaluate the short- and long-term effectiveness of RAs in improving the performance of asphalt mixtures, particularly those with high RAP contents. Another objective of the study was to establish a performance-based framework to determine the acceptability of a specific RA product for inclusion in the Virginia Department of Transportation's Approved Product List. Both objectives were achieved by benchmarking recycled binder blends (Phase I) and mixtures (Phase II). These were then compared in terms of laboratory performance to commonly used virgin asphalt binders and mixtures in Virginia. Moreover, a comprehensive review of the literature and information from state departments of transportation and RA suppliers on the current state of the practice regarding the use of recycled materials and RAs in asphalt mixtures was summarized.

Component materials, including three virgin asphalt binders, RAP and aggregate materials from three different sources, and six RAs, were collected and tested. Phase I involved testing virgin and RAP binders; combinations of virgin binder and RAP binder; and combination of virgin binder, RAP binder, and RAs. A total of 26 binder blends were evaluated at various aging conditions through numerous rheology- and chemistry-based tests. In Phase II, 10 asphalt mixtures were designed and evaluated for durability, resistance to rutting, and resistance to cracking at various aging conditions. Cross-scale evaluation of asphalt binder and mixture testing data was established. Finally, preliminary verification was performed using data collected from various field trials constructed in Virginia.

Based on the binders and mixtures tested in this study, the effectiveness of RAs in improving the properties of asphalt binder blends is specific to the product being used and to the targeted temperatures or conditions. Moreover, RAs can enhance the performance and increase the use of recycled materials in asphalt mixtures provided that the correct and suitable dosage of RA product is determined through a performance-based testing framework.

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Senior Research Scientist
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Benjamin Shane Underwood, Ph.D.
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Graduate Research Assistant
North Carolina State University

Saqib Gulzar
Graduate Research Assistant
North Carolina State University

Andrew Fried
Graduate Research Assistant
North Carolina State University

INTRODUCTION

Overview

Currently, a reclaimed asphalt pavement (RAP) material content of 15% to 20% is becoming a standard practice worldwide for the production of asphalt mixtures (Tarsi et al., 2020). This range of RAP contents has been largely exceeded in some countries such as the Netherlands and Japan (e.g., 50% to 70%) and relatively stagnant in other countries such as the United States (Tarsi et al., 2020; West and Copeland, 2015). In 2009, the National Asphalt Pavement Association conducted the first national survey on pavement recycling. The survey responses revealed that the average RAP content of asphalt mixtures has grown significantly. However, the year-after-year rate of growth plateaued at around 20% in 2014 (Copeland, 2011).

A 2019 survey on the use of recycled materials in the U.S. pavement industry reported that the average RAP content in asphalt mixtures was 21.1%, which was the same as the previous year's value (Habbouche et al., 2021; Williams et al., 2020). At that time, typical RAP contents were low enough that the asphalt mixtures containing recycled materials could be reliably designed using the same methods used to design mixtures not containing recycled materials without any substantial modifications. For example, in the early 2000s, it was recommended that the same virgin asphalt binder grade be used for up to 20% RAP content depending on the RAP binder stiffness (McDaniel et al., 2000).

In recent years, several state departments of transportation (DOTs) have introduced special provisions and specifications to allow the use of higher RAP contents in asphalt mixtures. It should be noted that the definition of "high RAP mixtures" is state-specific. The increased use of RAP was expected to offset the continuously rising cost of oil used to produce asphalt mixtures and fuel needed to transport and place them (Epps-Martin et al., 2020; Zaumanis et al., 2013). At these higher recycled material contents, the effect of the recycled material begins to affect the behavior of the resultant asphalt mixtures and alter the overall pavement performance. The use of recycled materials at these higher contents may result in diminishing returns at or beyond a certain content (Tarsi et al., 2020; Zaumanis et al., 2013). The primary concern with such mixtures has been that the use of a high percentage of RAP will overly stiffen mixtures, making them more brittle and prone to premature cracking. The use of a high RAP content, if not properly designed, can lead to numerous construction and performance issues such as the lack of compactability and workability in cool weather; low-temperature cracking with accumulation of thermally induced stresses; fatigue cracking with microdamage accumulation leading to crack initiation and propagation with repeated loading; reflection cracking with repeated loading and daily/seasonal thermal stresses; and raveling with subsequent aging or moisture damage (Epps-Martin et al., 2020).

The challenges arising from the use of high RAP mixtures can be addressed through the use of softer binders or additives such as RAs. These additives were used in asphalt mixtures in the early period of widespread recycling in the 1970s and 1980s for the purpose of realizing three types of benefits: environmental, economic, and engineering (Epps-Martin et al., 2020). The use of RAs holds promise as long as there is a proper understanding of how effectively they restore binder rheology and how that effectiveness evolves with laboratory mixture aging. In 2014, National Cooperative Highway Research Program (NCHRP) Project 09-58, The Effects of Recycling's Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios, was commissioned to study the effects of RAs on asphalt mixtures containing high amounts of recycled materials (Epps-Martin et al., 2020). Despite this research, the scientific knowledge on the selection and use of RAs in asphalt pavements is still limited, and there is a need to develop robust methodologies that establish threshold criteria and performance metrics to facilitate their use on a regular basis. Further, there are currently no specific guidelines or specifications available that provide a framework for evaluating the acceptability of RAs in Virginia.

Background on Virginia Efforts

With the changes in recycling streams over the last decade, the interest in using recycled materials (e.g., RAs) has been growing because of potential economic and environmental benefits, in addition to the performance gains. Like many other state DOTs, the Virginia Department of Transportation (VDOT) is working extensively to determine how best to incorporate recycled materials such as RAP, recycled crumb rubber, crushed concrete, and plastic waste into their roads. In 2007, VDOT introduced specifications to allow higher percentages of RAP (i.e., up to 30%) in surface mixtures (SMs). By 2013, VDOT had begun to consider the feasibility of allowing the use of SMs containing up to 45% RAP. Several trial sections were constructed containing mixtures with 20%, 30%, 40%, and 45% RAP for evaluation (Nair et al., 2019). In general, those trials showed that mixtures containing up to 45% RAP could be designed, produced, and constructed if specific procedures were followed. Whether those mixtures will perform satisfactorily remains to be determined.

In 2017, VDOT began to evaluate the feasibility of introducing performance requirements into mix design using the balanced mix design (BMD) method. VDOT has since committed to the implementation of the BMD method in an effort to improve the performance of asphalt mixtures (Diefenderfer et al., 2021a). Through a collaborative effort with the industry, VDOT developed two special provisions for use with field trials that used the BMD method to specify as-designed mixture performance: (1) Special Provision for Dense Graded Surface Mixtures Designed Using Performance Criteria, and (2) Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria.

In 2019 and 2020, field trials were constructed as the first applications of these specifications in Virginia. These trials incorporated combinations of different RAP contents, two binder grades, five RAs, and one fiber (Diefenderfer et al., 2021b; Diefenderfer et al., 2023a). Based on the test results, mixtures containing a softer binder and/or RAs could be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements. However, the long-term laboratory and field performance of these mixtures needed to be evaluated to verify these early findings. Therefore, the special provision for high RAP mixtures, with and without RAs, was put on hold until more information could become available. To gather more data and ensure a successful deployment of high RAP mixtures, three additional field trials were conducted in 2022 and 2023. These trials involved the use of high RAP contents with three different RAs. These mixtures are currently under evaluation as part of an ongoing research effort (Habbouche et al., 2025).

Simultaneously, efforts were undertaken to enhance and update the special provision for conventional dense-graded SMs with A and D designations that incorporate up to 30% RAP with unmodified asphalt binders. As an example, in 2021, about 72,000 tons of BMD mixtures were used for paving selected routes in 10 maintenance schedules across five of the nine VDOT districts. In 2022, approximately 222,000 tons of BMD mixtures were paved in 13 maintenance schedules, encompassing all nine VDOT districts (ensuring the execution of at least one BMD contract per district). The findings from the plant mix schedule pilots conducted in 2021 and 2022 are provided elsewhere (Diefenderfer et al., 2023b). In 2023, around 335,000 tons of BMD mixtures are being placed in 15 maintenance schedules across VDOT's nine districts, once again implementing at least one BMD contract per district.

PURPOSE AND SCOPE

The purpose of this study was to develop a framework to evaluate both the short- and long-term effectiveness of RAs in improving the performance of asphalt mixtures, especially those with high RAP contents. Another objective of the study was to establish a performance-based approach to facilitate the determination of acceptability of a specific RA product for inclusion in VDOT's Approved Product List (APL). Both objectives were achieved by benchmarking recycled binder blends and mixtures composed of typical virgin binders, RAP materials collected from representative sources, and selected RA products and comparing them against virgin PG 64S-22 asphalt binders and unmodified asphalt mixtures commonly used in Virginia.

METHODS

Seven tasks were performed to achieve the study objectives:

1. A literature review was conducted to summarize the state-of-the-art information regarding the selection and use of RAs in recycled asphalt mixtures.

2. Surveys were conducted to collect information reflecting multiple perspectives on the current state of the practice with regard to using recycled materials and RAs in asphalt mixtures in North America.

3. Component materials (asphalt binders, RAP materials, and RAs) were selected, collected, and tested for performance characteristics in the laboratory.

4. Extensive performance testing was conducted on virgin asphalt binders; asphalt binders extracted and recovered from RAP materials; blends of virgin binder and recovered RAP binder; and blends of virgin asphalt binder, recovered RAP binders, and RAs. Several analysis approaches were considered and performed on the data collected from testing these binders. This task comprised Phase I of the study.

5. Ten asphalt SMs that incorporated RAP and RA were created in the laboratory and verified in terms of aggregate gradation and volumetric properties based on previously approved VDOT asphalt mix designs. Laboratory performance tests with varying levels of complexity were performed on specimens fabricated from these laboratory-produced mixtures. Several analysis approaches were considered and performed on the data collected from these specimens. This task comprised Phase II of the study.

6. Two step-by-step performance-based frameworks related to RAs were developed. The first framework determines the acceptability of a specific RA product for inclusion in VDOT's APL. The second framework evaluates the short- and long-term effectiveness of RAs in improving the performance of asphalt mixtures, particularly those with high RAP contents.

7. A preliminary verification of the findings was performed using data collected from VDOT field trials constructed during the 2019, 2020, and 2022 paving seasons.

Review of the Literature

A comprehensive literature search was conducted to gather state-of-the-art information relevant to the objectives of this study. Various databases and search engines related to transportation engineering such as TRID, Transportation Research Information Services, Scopus, Catalog of Worldwide Libraries, Google Scholar, ProQuest, and Web of Science were searched for relevant literature. Notably, in 2014, a review of the literature assessing the use of RAs in asphalt mixtures with high recycled asphalt shingles (RAS) and RAP binder ratios was conducted as part of NCHRP Project 09-58 (Epps-Martin et al., 2020). Therefore, the focus of the literature review in this study was primarily built on the materials published after the completion of NCHRP Project 09-58. Approximately 315 additional publications were identified.

The research team summarized and synthesized findings from the laboratory and field studies that employed RAP and RAs to derive tangible lessons on their selection and use in recycling asphalt pavements. Performance concerns associated with the use of these products and shortcomings of the current specifications were highlighted. The review also discussed potential means of improving binder characterization to enable evaluation of RAs, and dosage selection procedures. Finally, the review identified the knowledge gaps that currently exist in the field. For the sake of brevity, a summary of the compiled literature is provided in this report. However, for further details, readers are referred to a publication by the research team (Gulzar et al., 2023).

State of the Practice

Information reflecting multiple perspectives on the current state of the practice with regard to using recycled materials (i.e., RAP and RAS) and RAs in asphalt mixtures was collected through surveys of all state DOTs and RA suppliers combined with a search of RA-related specifications and pilot projects previously constructed. The state DOT survey questionnaire (Appendix A) included questions related to permissibility and usage of RAP, RAS, and RAs; production-related attributes and quality assurance (QA); environmental restrictions; lessons learned; and ongoing research efforts. The RA supplier survey questionnaire (Appendix B) included questions related to classifications and types of various RAs available on the market; characterization of RAs and establishment of suitable dosage rates; blending protocols for laboratory mix designs and during production and field operations; establishment of an engineered framework to include RAs on APLs; and production-related attributes.

A case study describing VDOT's experience with RAs was also conducted to provide a tangible example of how at least one agency is approaching the potential implementation of these technologies. This practical review was achieved by conducting surveys to document the experience, lessons learned, and best practices of four experienced asphalt contractors and three asphalt binder suppliers in Virginia.

The contractor survey questionnaire (Appendix C) was primarily designed to collect information in relation to standard construction practices executed to handle asphalt mixtures with RAs. The RAP-related questions covered specific practices for characterizing, managing, processing, and stockpiling RAP material. The RA-related questions covered specific practices for selection of RAs in relation to types and brands, storage conditions of the RA-binder blend, and potential changes executed at the asphalt plant to incorporate RAs during production. Finally, the contractors were asked to provide any lessons learned based on their experience in placing asphalt mixtures containing RAs.

The asphalt binder supplier survey questionnaire (Appendix D) included questions covering specific practices for chemically characterizing the supplied asphalt binders; the potential impact of crude oil on the properties of the supplied binders; blending protocols in the laboratory and during plant production and field operations; the addition of RAs to APLs; and RA-related concerns and challenges.

The state-of-the-practice section of this study disseminated information collected through surveys similar to the ones conducted in 2014 as part of NCHRP Project 09-58. Therefore, it provided a second look at the use of RAs across North America. For the sake of brevity, a summary of the compiled information from the various surveys is provided in this report. However, for more comprehensive details, readers are referred to a publication by the research team (Habbouche et al., 2021).

Experimental Program

Selection of Component Materials

To fulfill the objectives of this study, component materials in terms of asphalt binders, RAP materials, and RAs were collected as follows:

- Virgin asphalt binders with performance grade (PG) PG 64S-22, typically used in Virginia, were sampled from two different sources (referred to herein as B1 and B2). In addition, a softer virgin asphalt binder, PG 58-28, was sampled from one source (referred to herein as B3). These selections covered both alternatives that could be used to address the challenges arising from the use of high RAP mixtures (i.e., the use of conventional typical binder + RA or the use of a softer binder). The binder blends and mixtures containing only the softer binder served as a reference.

- RAP materials were sampled from three representative sources in Virginia (referred to herein as R1, R2, and R3). Corresponding aggregate materials were sampled from the same source. The RAP sources for each of these materials varied with respect to their binder PG, binder content, and geographical location. The materials and compositions used in this study were based on three VDOT-approved asphalt mixtures.

- Six commonly used RAs (rejuvenators and softeners), identified from the literature and state of the practice reviews, were procured (referred to herein as RA1, RA2, RA3, RA4, RA5, and RA6). RA1 is a paraffinic oil (vacuum tower asphalt extender [VTAE]); RA2 is an aromatic extract; RA3 is derived from tall oils and fatty acids; and RA4, RA5, and RA6 are derived from triglycerides and fatty acids. These RAs were expected to cover a wide range of predicted performance, from relatively poor (e.g., softeners that stiffen substantially with long-term aging) to moderate and very good (e.g., true rejuvenators expected to perform well after long-term aging), based on the available information.

Laboratory Evaluation of Asphalt Binders and Asphalt Binder Blends

Phase I of this study involved testing three types of materials:

1. *Asphalt binders:* These included virgin binder (i.e., B1, B2, and B3) and binder extracted and recovered from RAP materials (i.e., R1, R2, and R3).

2. *Combinations of virgin binder and recovered RAP binder:* These combinations were mixed at relative ratios that matched specific asphalt mixtures, forming the base recycled system or what is referred to herein as the reference blend.

3. *Combinations of the base recycled system and different RAs:* The base recycled system was further modified by adding different RAs, creating the RA-modified systems or what is referred to herein as RA blends.

The term "blend" is used to refer collectively to base recycled systems (i.e., reference blends) and RA-modified systems (i.e., RA blends). A total of 26 binder blends containing various types of virgin binders, recovered RAP binders, and RAs were evaluated in this study. Figure 1 is a flowchart of the laboratory experimental program for Phase I of the study.

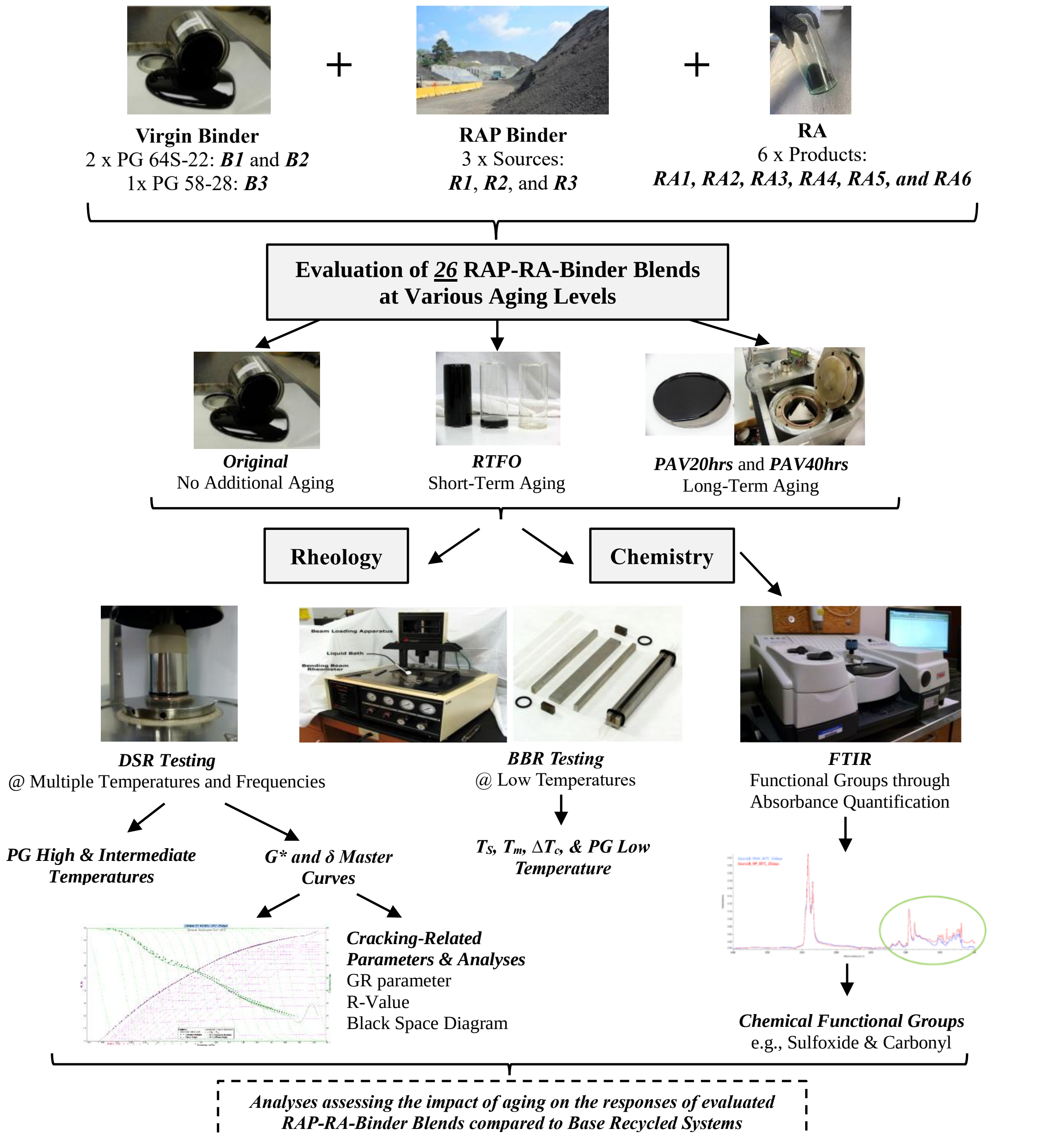

Figure 1. Flowchart of the Laboratory Experimental Program for Phase I of the Study. PG = performance grade; S = standard traffic; B = virgin asphalt binder; RAP = reclaimed asphalt pavement; R = extracted and recovered RAP binder; RA = recycling agent; RTFO = rolling thin film oven; PAV = pressure aging vessel; DSR = dynamic shear rheometer; G* = dynamic shear modulus; δ = phase angle; BB = bending beam rheometer; T_S = stiffness-critical low temperature; T_m = m-critical low temperature; $\Delta T_c = T_S - T_m$ = difference in critical low-temperature PG; GR = Glover-Rowe; FTIR = Fourier transform infrared spectroscopy.

Laboratory Evaluation of Asphalt Mixtures

In Phase II of the study, previously designed asphalt mixtures were replicated and/or mimicked using the collected materials, which included various binder-RAP-aggregate and binder-RAP-RA-aggregate combinations. A total of 10 mix designs were validated to ensure compliance with the volumetric properties and performance requirements specified in VDOT's BMD special provisions. In some cases, the asphalt binder contents of the replicated mixtures were adjusted to meet the VDOT BMD requirements, which included a maximum Cantabro mass loss (ML) threshold of 7.5%, a minimum cracking tolerance (CT) of 70 determined by the indirect tensile cracking test (IDT-CT), and a maximum rut depth of 8 mm determined by the Asphalt Pavement Analyzer (APA) rut test, all at short-term oven aging (STOA) conditions.

The mixtures were evaluated under STOA conditions in terms of volumetric properties, durability using the Cantabro test, engineering properties using the dynamic modulus |E*| test, resistance to cracking using the IDT-CT and direct tension cyclic fatigue (CF) test, and resistance to rutting using the APA rut test and stress sweep rutting (SSR) test. In addition, certain mixtures were subjected to long-term oven-aging (LTOA) and were further evaluated in terms of mechanical properties (|E*|) and resistance to cracking using the IDT-CT and direct tension CF test. Figure 2 is a flowchart of the laboratory experimental program for Phase II of the study.

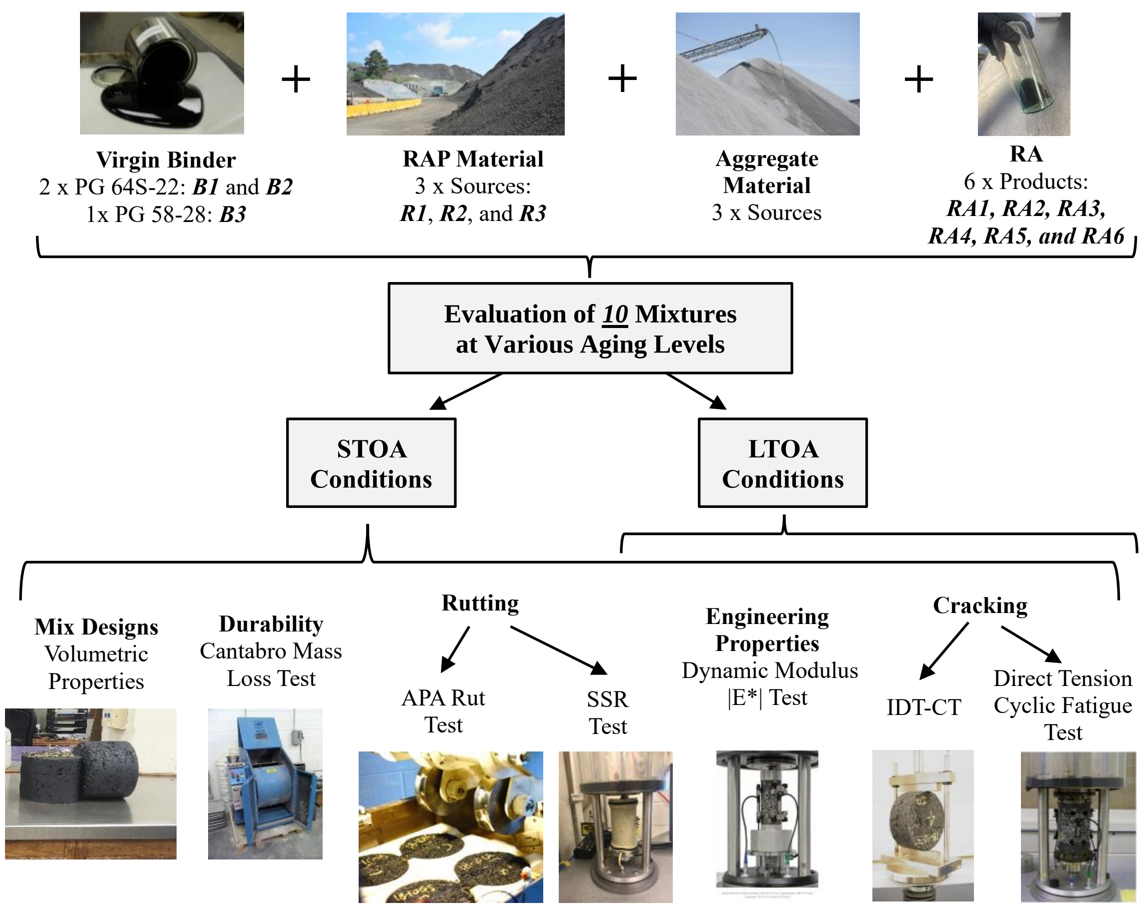

Figure 2. Flowchart of the Laboratory Experimental Program for Phase II of the Study. PG = performance grade; S = standard traffic; B = virgin asphalt binder; RAP = reclaimed asphalt pavement; R = RAP source; RA = recycling agent; STOA = short-term oven aged; LTOA = long-term oven aged; APA = Asphalt Pavement Analyzer; SSR = stress sweep rutting; IDT-CT = indirect tensile cracking test.

Testing and Characterization of Asphalt Binders and Asphalt Binder Blends

Extraction and Recovery of RAP Materials

Extraction of the asphalt binder from the different RAP sources/materials was performed in accordance with AASHTO T 164, Standard Method of Test for Quantitative Extraction of Asphalt Binder From Hot Mix Asphalt (HMA), Method A, using trichloroethylene as the solvent (American Association of State Highway and Transportation Officials [AASHTO], 2018). The asphalt binder was then recovered from the solvent using the Rotavap recovery procedure specified in AASHTO T 319, Standard Method of Test for Quantitative Extraction and Recovery of Asphalt Binder From Asphalt Mixtures (AASHTO, 2019).

RA Dosing and Blending

In this study, the RA suppliers were asked to provide a dosage of RA that would restore the low-temperature PG of the recycled binder system to -22°C. This was aligned with the fact that typical virgin binders used for unmodified SMs with A and D designations in Virginia are PG 64S-22 binders. The suppliers were provided with information regarding the PG of virgin binders, PG of RAP binders, percentage of RAP in the corresponding asphalt mixture (i.e., 35%, 40%, or 45%), binder content of RAP stockpiles, and total binder content of the corresponding asphalt mixture. However, the specific method used by the RA suppliers to determine the required RA dosage was not disclosed to the research team.

The blends of virgin and recycled materials were prepared by preheating the virgin and RAP binders to temperatures of 140°C and 165°C, respectively. The RAP binders were preheated at 165°C, as they are stiffer than the virgin binder and require higher temperatures to achieve sufficient fluidity for blending. The component materials were blended together using a power drill equipped with a paddle attachment for a duration of 1 minute. The RA was then incorporated using a pre-weighted syringe. A detailed procedure describing the binder blend preparation is provided elsewhere (Fried et al., 2022).

Aging Methods

The binder materials were subjected to short-term aging in the rolling thin film oven (RTFO) in accordance with AASHTO T 240, Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test) (AASHTO, 2017). The standard long-term aging conditioning was performed in accordance with AASHTO R 28, Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV) (AASHTO, 2016). The standard long-term aging conditioning (20 hours) is referred to herein as PAV-20. The extended long-term aging conditioning (40 hours) is referred to herein as PAV-40. The same protocol was used for both, with the difference being that the total time in the PAV for the former was 20 hours and that for the latter was 40 hours.

PG Testing

Unaged and RTFO-aged samples of virgin binders, RAP binders, and blends containing virgin binder, RAP binder, and RAs were evaluated in accordance with AASHTO T 315, Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (AASHTO, 2020). High-temperature PG determination was performed in accordance with AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder (AASHTO, 2017). Testing was conducted at a minimum of two temperatures, one that met the AASHTO M 320 high-temperature PG criteria and the other that did not. The intermediate-temperature characterization was conducted on PAV-20 samples in the dynamic shear rheometer (DSR) in accordance with AASHTO T 315 (AASHTO, 2020) and the corresponding PG criteria specified in AASHTO M 320 (AASHTO, 2017). In all cases, a minimum of two replicate tests were conducted for each binder and aging condition combination.

Low-temperature characterization was conducted on PAV-aged samples using a bending beam rheometer (BBR) in accordance with AASHTO T 313, Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR) (AASHTO, 2019). Testing was carried out at two temperatures, one that met the AASHTO M 320 (AASHTO, 2017) low temperature PG criteria and the other that did not. The continuous-temperature grades were determined based on ASTM D7643, Standard Practice for Determining the Continuous Grading Temperatures and Continuous Grades for PG Graded Asphalt Binders (ASTM International [ASTM], 2022b). Two replicate tests were conducted for each temperature, binder, and aging condition combination.

In addition to the continuous PGs of the binders, two parameters obtained from the standard PG test methods were determined: (1) the difference in critical low-temperature PG limiting temperatures, and (2) the R-value.

Difference in Critical Low-Temperature PG Limiting Temperatures (ΔT_c)

The difference in critical low-temperature PG limiting temperatures, commonly referred to as ΔT_c, was calculated by subtracting the m-critical low temperature ($T_{c,m}$) from the S-critical low temperature ($T_{c,S}$), as shown in Equation 1 (Federal Highway Administration [FHWA], 2021a). Both temperatures were determined using the BBR in accordance with AASHTO T 313 (AASHTO, 2019). The m-critical low temperature ($T_{c,m}$) is the resulting low temperature at which the creep relaxation m-value at 60 seconds of loading is exactly equal to the specification value of 0.300. The S-critical low temperature ($T_{c,S}$) is the resulting low temperature at which the creep stiffness S-value at 60 seconds of loading is exactly equal to the specification value of 300 MPa.

$$\Delta T_c = T_{c,S} - T_{c,m} \qquad \text{[Eq. 1]}$$

R-Value

The R-value is a rheological index that can be related to binder fatigue properties and performance. One finding by Christensen and Tran (2022) in NCHRP Project 09-59 suggests that binders with lower R-values tend to exhibit higher failure strains compared to those with higher R-values. In addition, the researchers proposed an alternative method to calculate the R-value using properties derived from BBR testing. The R-value, referred to herein as R_{09-59}, can be calculated using the creep stiffness at 60 seconds of loading, S(60) and the relaxation rate at 60 seconds of loading, m(60), measured at the BBR testing temperature corresponding to the low-temperature PG of the evaluated binder or binder blend. In the case of this study, the temperature was -12°C; the calculation is represented by Equation 2.

$$R_{09-59} = \log(2) * \frac{\log\left(\frac{S(60)}{3{,}000}\right)}{\log\left(1-m(60)\right)} \qquad \text{[Eq. 2]}$$

Multiple Stress Creep Recovery (MSCR) Test

The MSCR test was conducted to evaluate the rutting susceptibility of the binders and binder blends. The MSCR test was performed on the RTFO-aged samples at the high-temperature PG in accordance with AASHTO T 350, Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR) (AASHTO, 2019). The MSCR test provides a key parameter known as the nonrecoverable creep compliance, J_{nr}, which represents the relationship between the strain response of the sample and the applied stress. A material exhibiting significant deformation under a specified load would have a higher J_{nr}, indicating higher compliance. The limits for J_{nr} are specified in AASHTO M 332, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test (AASHTO, 2020). In addition, the MSCR test characterizes the percentage of total strain recovered upon stress removal, denoted R. Higher R values indicate more elastic asphalt with a greater recovery of total strain, and lower R values indicate more viscous asphalt with less strain recovery. In this study, J_{nr} at a stress level of 3.2 kPa, referred to herein as $J_{nr3.2}$, was used as a parameter to evaluate the rutting susceptibility of the binders and binder blends.

Temperature-Frequency Sweep Test

The temperature-frequency sweep test was conducted using the 8-mm parallel plate geometry and 2-mm gap on the DSR. Testing at each temperature and frequency combination was done in accordance with AASHTO T 315 (AASHTO, 2020). A minimum of two replicate tests were conducted for each binder and aging condition combination. The test was conducted at 5°C, 20°C, 35°C, and 50°C over a frequency range of 0.1 to 10 Hz. A strain amplitude of 1.0% was applied at 35°C and 50°C; a lower strain of 0.1% was applied at 5°C and 20°C. These strain levels were verified to yield test results that fell within the linear viscoelastic (LVE) regime based on strain sweep testing conducted on a subset of binders from the study.

Analysis of Master Curves

The average test results for a given binder and aging condition combination were used to construct master curves of the dynamic shear modulus (G*) and phase angle (δ). A free-shifting approach, without predefined functional form, was used to determine the time-temperature shift factors. These shift factors were then fitted to the second-order polynomial function shown in

Equation 3. Subsequently, the Christenson-Anderson model was used to fit G* and δ master curves using Equations 4 and 5, respectively. More details regarding the construction of the master curves can be found elsewhere (Fried and Castorena, 2023).

$$\log a_T = a(T - T_{ref})^2 + b(T - T_{ref}) \quad \text{[Eq. 3]}$$

where

a and b = fitting parameters
T = temperature of interest, °F
T_{ref} = reference temperature, °F.

$$|G^*| = G_g[\,1 + \left(\frac{\omega_c}{\omega_{red}}\right)^{log2/R}]^{-R/log2} \quad \text{[Eq. 4]}$$

$$\delta = 90/[\,1 + \left(\frac{\omega_c}{\omega_{red}}\right)^{log2/R}] \quad \text{[Eq. 5]}$$

where

G_g = the glassy modulus of the asphalt binder, MPa
ω_c = crossover frequency, rad/sec
ω_{red} = reduced frequency, rad/sec
R = rheological index from the master curve.

Glover-Rowe (GR) Parameter

The GR parameter was calculated using Equation 6. This parameter has been used in numerous studies to quantify the brittleness of asphalt binders and indicate non-load associated cracking at 15°C and 0.005 rad/s (referred to herein as $GR_{15°C}$). Recently, Christensen and Tran (2022) in NCHRP Project 09-59 proposed using the GR parameter as a surrogate for the Superpave cracking parameter $|G^*|\sin\delta$ at a frequency of 10 rad/s and a temperature determined based on the low-temperature PG. The parameter was determined at 25°C based on a representative climatic low-temperature PG of -22°C, referred to herein as $GR_{25°C}$, as recommended by Christensen and Tran (2022). Both GR parameters, $GR_{15°C}$ and $GR_{25°C}$, were evaluated in this study.

$$GR = \frac{G^*(cos\delta)^2}{sin\delta} \quad \text{[Eq. 6]}$$

where

G^* = complex dynamic shear modulus, Pa
δ = phase angle, °.

Linear Amplitude Sweep (LAS) Test

The LAS test was performed in accordance with AASHTO TP 101, Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep, to investigate the fatigue damage characterization of the evaluated binders at an intermediate temperature of interest (AASHTO, 2018). The test included a frequency sweep test at 0.1% strain over a range of frequencies from 0.2 to 30 Hz followed by an amplitude sweep oscillatory shear in strain-control mode test at a frequency of 10 Hz over a range of induced strains from 0.1% to 30%. The test was conducted at a representative temperature of 16°C. This temperature was also selected such that the linear dynamic shear modulus G* fell within the range of 12 to 60 MPa at 10 Hz to mitigate any potential edge flow and/or adhesion loss (Safaei and Castorena, 2016). Following each test, the absence of adhesive failure between the binder and parallel plates, or material flow phenomenon, was verified visually. The test results were then used to calibrate a simplified viscoelastic continuum damage-based (S-VECD) model, which was employed to predict the fatigue life under constant strain amplitude conditions. The binder fatigue performance parameter N_f is calculated using Equation 7.

$$N_f = A * (\Upsilon_{max})^{-B} \quad \text{[Eq. 7]}$$

where

N_f = fatigue performance parameter, number of cycles to fatigue failure
Υ_{max} = maximum expected binder strain for a given pavement structure, %
A and B = modeling parameters associated with fatigue resistance of the binder.

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR was conducted to identify the chemical functional groups present in the recycled binder blends with RAs. FTIR was performed using a Bruker ALPHA spectrometer equipped with a diamond attenuated total reflectance sampling attachment. The absorbance spectra were obtained over a wave number range of 400 to 4000 cm^{-1}. In this study, the spectra were collected by averaging 64 scans with a spectral resolution of 4 cm^{-1}; a minimum of two replicates were tested. Baseline correction and normalization of the spectra were conducted using OPUS spectroscopy software.

Saturate, Aromatic, Resin, and Asphaltene Analysis

Saturate, Aromatic, Resin, and Asphaltene Analysis (SARA) fractionization testing was performed by an outside laboratory using the thin-film chromatography-flame ionization detection method (i.e., TLC-FID or Iatroscan analysis). The asphaltene content of each binder blend was first determined through precipitation of the binder in a solution of n-heptane. Subsequently, the maltene fraction that remained in solution was applied to rods for TLC-FID analysis. The Iatroscan analysis provided five replicates worth of fractionizations to examine for each blend containing the saturates, aromatics, and resins. The maltene fractions were used to determine the colloidal instability index (CII) (see Equation 8), which was used to examine the chemical compatibility of the binder blends.

$$CII = \frac{Saturates + Asphaltenes}{Aromatics + Resins} \quad \text{[Eq. 8]}$$

Testing and Characterization of Asphalt Mixtures

Volumetric Properties and Aggregate Gradations of Mixtures

The particle size distribution (gradation) of each stockpile (virgin aggregates and RAP) used to form the asphalt mixtures was determined in accordance with AASHTO T 27, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates (AASHTO, 2020), and AASHTO T 11, Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing (AASHTO, 2020). The binder content of the RAP materials was determined in accordance with AASHTO T 308, Standard Method of Test for Determining the Asphalt Binder Content of Asphalt Mixtures by the Ignition Method (AASHTO, 2018), and Virginia Test Method (VTM) 102, Determination of Asphalt Content From Asphalt Paving Mixtures by the Ignition Method (VDOT, 2013). The theoretical maximum specific gravity of each mixture was determined in accordance with AASHTO T 209, Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Asphalt Mixtures (AASHTO, 2019). Specimens were compacted in a Superpave gyratory compactor (SGC), and the bulk specific gravity of compacted asphalt mixtures was determined in accordance with AASHTO T 166, Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens (AASHTO, 2020). The air-void content of each specimen was determined in accordance with AASHTO T 269, Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures (AASHTO, 2018). Basic physical characteristics and volumetric parameters in terms of voids in total mixture, voids in mineral aggregate, voids filled with asphalt, fines to aggregate ratio, aggregate effective specific gravity, aggregate bulk specific gravity, absorbed asphalt binder content, effective asphalt binder content, and effective film thickness were determined at the optimum binder content (OBC).

Mix Design Verification

The mix designs were verified by determining the air-void contents of specimens compacted at the OBC specified in the job-mix formula (JMF) at an N_{design} of 50 gyrations (VDOT, 2020). Three specimens were compacted at each of the OBC-0.5%, OBC, and OBC+0.5% to obtain a relationship between air-void and binder content. A mix design was considered verified if the air-void content at the OBC fell within the range of 3.0% to 4.5% (Diefenderfer et al., 2023b). In cases where the OBC did not yield the air-void content within the acceptable range, the OBC was adjusted to achieve an air-void content within the range of 3.0% to 4.5%.

Mixture Aging Protocols

STOA and LTOA protocols were used in this study. The STOA protocol consisted of placing the loose asphalt mixtures in the oven at the compaction temperature. A duration of 2 hours was used for the mix design and specimens used for rutting performance characterization, and a duration of 4 hours was used for cracking characterization. The LTOA protocol followed the recommendations of Kim et al. (2021) (NCHRP Project 09-54). This protocol specifies conditioning the loose asphalt mixtures in the oven at a temperature of 95°C for 3 days (for Virginia) after completing the STOA, representing approximately 8 years of field aging in Virginia and intended for evaluation of asphalt mixtures for overall fatigue cracking. A deviation from the recommendations of Kim et al. (2021) was that the STOA was initially conducted in accordance with VDOT's BMD specification and not in accordance with AASHTO R 30, Standard Practice for Laboratory Conditioning of Asphalt Mixtures (AASHTO, 2019). As part of the LTOA protocol, the loose mixtures were placed into several pans with thin layers of material with a thickness approximately equal to the nominal maximum aggregate size (NMAS) of the mixture. After LTOA conditioning, the mixtures were allowed to cool to room temperature and then reheated to the compaction temperature. Finally, the mixtures were compacted using the SGC. In addition, in some cases, another LTOA protocol was considered in this study. This protocol involved aging the loose mixtures for 1 day at 95°C after STOA was performed, representing approximately 4 years of field aging in Virginia.

Cantabro Mass Loss (ML)

The Cantabro ML was determined to evaluate the durability of asphalt mixtures in accordance with AASHTO TP 108, Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens (AASHTO, 2021). The test was performed on specimens fabricated using a SGC that were compacted from loose mixtures produced in the laboratory. The loose mixtures were conditioned at the design compaction temperature prior to compaction to N_{design} gyrations. The Cantabro test specimens were 150 mm in diameter by 115 ± 5 mm in height. The test was performed at a temperature of 25°C. The test was performed by placing the specimen into an uncharged Los Angeles abrasion machine and rotating it for 300 rotations at a speed of approximately 30 rotations per minute. For each mixture, three replicates were tested for each binder content, and three binder contents (OBC, OBC-0.5%, and OBC+0.5%) were evaluated. An average ML was reported for each binder content. The ML was calculated using Equation 9. A lower ML indicates higher durability.

$$ML = (A - B) * 100\%/A \quad \text{[Eq. 9]}$$

where

A = initial mass of the specimen before the test, g
B = final mass of the specimen after the test, g.

LVE Test Method: Dynamic Modulus |E*|

The dynamic modulus test was conducted using an Asphalt Mixture Performance Tester (AMPT) in accordance with AASHTO T 132, Standard Method of Test for Determining Dynamic Modulus for Asphalt Mixtures Using Small Specimens in the Asphalt Mixture Performance Tester (AASHTO, 2021). The test was conducted on 38-mm-diameter by 110-mm-tall specimens at temperatures of 4°C, 20°C, and 40°C. The test frequencies were 10 Hz, 1 Hz, and 0.1 Hz at the three selected temperatures. In addition, a frequency of 0.01 Hz was used only at 40°C. An on-specimen strain level between 50 and 75 microstrain was maintained for all temperature-frequency combinations to ensure measurement of a LVE response. Three replicates were tested for each mixture and aging condition. FlexMAT Cracking, Version 2.1.3b, was used as the analysis software to process the dynamic modulus data.

Cracking Performance Tests

IDT-CT

The IDT-CT was conducted at a temperature of 25°C in accordance with ASTM D8225-19, Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature (ASTM, 2019). Tests were performed at a loading rate of 50 ± 3 mm/min on specimens 150 mm in diameter by 62 mm in height compacted with a SGC to 7 ± 0.5% air-void content. The CT index (CT_{index}) was then calculated from the test load-displacement curve using Equation 10. A higher CT_{index} value for the asphalt mixture indicates a better resistance to cracking.

$$CT\ index = \frac{G_f}{|m_{75}|} * \left(\frac{l_{75}}{D}\right) * \left(\frac{t}{62}\right) \qquad \text{[Eq. 10]}$$

$$m_{75} = \left|\frac{p_{85}-p_{65}}{l_{85}-l_{65}}\right| \qquad \text{[Eq. 11]}$$

where

CT index = cracking tolerance index expressed in Equation 10
G_f = total area under the load-displacement curve divided by the product of the specimen thickness [t] and diameter [D], kN/mm
m_{75} = slope of interest expressed in Equation 11
p_{85}= 85% of the peak load (P_{max}) at the post-peak stage, kN
p_{75}= 75% of P_{max} at the post-peak stage, kN
p_{65}= 65% of P_{max} at the post-peak stage, kN
l_{85} = displacement corresponding to p_{85}, mm
l_{75} = displacement corresponding to p_{75}, mm
l_{65} = displacement corresponding to p_{65}, mm
D = specimen diameter, mm
t = specimen thickness, mm.

Direct Tension Cyclic Fatigue (CF) Test

The uniaxial CF test was conducted using the AMPT on cylindrical specimens in accordance with AASHTP TP 133, Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using Small Specimens in the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test (AASHTO, 2021). The CF test was conducted on a 38-mm-diameter by 110-mm-tall specimen at a temperature of 18°C using a tension-only actuator-controlled sinusoidal displacement at 10 Hz. All test specimens were compacted to an air-void level of 5.0 ± 0.5%. The CF test data were analyzed using the S-VECD model with FlexMAT Cracking, Version 2.1.3b (FHWA, 2019). Three key test outcomes were obtained from the CF tests: (1) the damage characteristic curve, also referred to as the material integrity (C) versus damage (S) curve; (2) the pseudo-energy-based failure criterion D^R (see Equation 12); and (3) the apparent damage capacity, S_{app} (see Equation 13). The last parameter measures the amount of fatigue damage the material can tolerate considering the effect of the material's toughness and modulus. A higher S_{app} indicates higher fatigue cracking resistance.

$$D^R = \frac{Sum(1-C)}{N_f} \quad \text{[Eq. 12]}$$

$$S_{app} = 1000^{\frac{\alpha}{2}-1} * \frac{\alpha_{T(Sapp)}^{\frac{1}{\alpha+1}} * \left(\frac{D^R}{C_{11}}\right)^{\frac{1}{C_{12}}}}{\left|E^*_{LVE,Sapp}\right|^{\frac{\alpha}{4}}} \quad \text{[Eq. 13]}$$

where

C_{11} and C_{12} = fitting coefficients of the power model
Sum(1 − C) = integral area below the curve of (1 − C) versus cycle number until the failure cycle
N_f = number of cycles to failure
α_T = time-temperature shift factor at a given temperature
$|E^*_{LVE,Sapp}|$ = average representative dynamic modulus, kPa.

Rutting Performance Tests

Asphalt Pavement Analyzer (APA) Rut Test

The APA rut test was performed in accordance with AASHTO T 340, Standard Method of Test for Determining the Rutting Susceptibility of Hot Mix Asphalt Using the Asphalt Pavement Analyzer (APA) (AASHTO, 2019). The APA rut test was performed on specimens 150 mm in diameter by 75 ± 2 mm in height compacted using an SGC to 7 ± 0.5% air voids. This test simulates rutting in the laboratory by applying a loaded wheel back and forth over a pressurized rubber tube located along the surface of the test specimen at a temperature of 64°C. The rut depth was measured at the end of the 8,000th cycle. A larger rut depth value indicates a higher susceptibility to rutting.

SSR Test

The SSR test was used to characterize the resistance to permanent deformation of the asphalt mixture in accordance with AASHTO TP 134, Standard Method of Test for Stress Sweep Rutting (SSR) Test Using Asphalt Mixture Performance Tester (AMPT) (AASHTO, 2021). The test was conducted using 100-mm-diameter and 150-mm-high specimens cored and cut from a 150-mm-diameter and 180-mm-high SGC specimens. The low temperature and high temperature (T_L and T_H) were determined using the long-term pavement performance bind (LTPPBind) online web-based tool. Three deviatoric stress levels, with 200 cycles each, were applied at each temperature in the following pattern: 483 kPa, 689 kPa, and 895 kPa for T_L and 689 kPa, 483 kPa, and 895 kPa for T_H. The loading pulses had a duration of 0.4 s and were followed by a rest time of 3.6 s at T_H and 1.6 s at T_L. The test specimens were subjected to a confining pressure of 69 kPa.

The results of the SSR test were coupled with the viscoplastic shift model to capture the effects of deviatoric stress, load time, and temperature on the permanent strain of the asphalt mixture using time-temperature-stress superposition (see Equation 14). FlexMAT Rutting, Version 2.1.4, was used to analyze the SSR test data and calculate the rutting strain index (RSI) (FHWA, 2021b; Ghanbari et al., 2022). The RSI is defined as the ratio of the permanent deformation in the asphalt layer to the thickness of that layer at the end of 30 million 18-kip single-axle-load repetitions. These repetitions are spaced evenly over a 20-year period. The RSI is obtained using a simplified rutting performance model. A higher RSI indicates relatively less resistance to permanent deformation.

$$\varepsilon_{vp} = \frac{\varepsilon_0 * N_{red}}{(N_1 + N_{red})^{\beta}} \qquad \text{[Eq. 14]}$$

where

ε_{vp} = viscoplastic strain
ε_0, N_1, and β = model coefficients
N_{red} = reduced number of cycles.

Description of Analyses and Approaches

Asphalt Binders and Asphalt Binder Blends

Performance Grading

The Superpave PG test results were used to compare the binder blends (i.e., reference and RA blends) with the reference binders and among themselves in terms of high-, intermediate-, and low-temperature properties. These comparisons were carried out in four ways. First, direct comparisons were made based on the resulting PG grades. Second, a statistical analysis was conducted using the rheological properties obtained from PG tests to establish a benchmark for evaluating the binder blends. Third, a similarity analysis was performed using the same dataset to assess the rheological similarities between the binder blends and reference binders across high, intermediate, and low temperatures. Fourth, Superpave parameters such as $|G^*|/\sin(\delta)$ at high temperature and $|G^*|\sin(\delta)$ along with the $GR_{25°C}$ parameter determined at intermediate temperature by Christensen and Tran (2022) in NCHRP Project 09-59 were used to assess further the rutting and cracking performance of these blends, respectively.

Balance of Rheological Parameters

Benchmarking Analysis. The recycled binder blends (i.e., reference and RA blends) evaluated in this study were compared against typical Virginia virgin PG 64S-22 binders. QA data collected by VDOT's Materials Division from 2016 to 2021 served as the benchmark for evaluating the recycled binder blends based on the rheological properties specified in AASHTO M 332. Typical asphalt mixtures with A and D designations were evaluated in this study. According to VDOT specifications, PG 64S-22 binders are commonly used in these types of mixtures. Thus, a dataset composed of 435 PG 64S-22 binder records that had been supplied to

VDOT since 2016 was used. These binders were predominantly sourced from the East-South, Central, and South-Atlantic regions of the United States.

Similarity Analysis. A multivariate statistical analysis was used to quantify the similarities between the recycled binder blends (i.e., reference and RA blends) and a reference binder that was created based on the QA data in terms of high-, intermediate-, and low-temperature properties and overall characteristics (referred to herein as "global"). In this study, the Mahalanobis distance (MD) was used to calculate the statistical distance between the RA blends and the reference QA binder (Mason and Young, 2022). The choice of MD over the commonly used Euclidean distance was motivated by its ability to provide a unitless measure of statistical distance that takes into account data variability and correlation. The MD calculations were conducted using the command *mahalanobis* from the statistical package *{stats}* in the programming language R. This command returns the squared MD, i.e., MD^2, for a given vector using the mean value and covariance of the distribution as main key arguments (R Core Team, 2021). Further details regarding the analysis procedure can be found in Preciado et al. (2023a).

Creep Stiffness—Relaxation Balance Analysis. In recent years, the ΔT_c and other black space–based parameters have highlighted the importance of balance between the creep stiffness (S[60]) and relaxation ability (m[60]) of non–polymer-modified asphalt binders in predicting the thermal cracking resistance of asphalt mixtures (Rowe, 2019). These findings have shifted the focus from simply meeting a specific low-temperature grade to obtaining an adequate/appropriate relationship between creep stiffness and relaxation. An analysis was conducted to evaluate the relationships between RA type and dosage, virgin binder, RAP binder, and the balance between the creep stiffness and m-value obtained at 60 seconds of loading. The analysis consisted of evaluating the relationship between S(60) and m(60) with respect to RA dosage. Subsequently, the effect of the different RAs on S(60) and m(60) at different dosages was explored using the pseudo-black space diagram (Marasteanu and Anderson, 2001), and a parameter that characterizes the balance between the creep stiffness and relaxation was identified. Finally, two approaches that illustrate how the new parameter can be used as a product-dependent parameter were provided.

Targeting of a ΔT_c Value. Many studies have highlighted the potential of the ΔT_c parameter to predict cracking performance and screen potentially deleterious asphalt binders (Anderson et al., 2011; Asphalt Institute Technical Advisory Committee, 2019). In light of the complexity of the recycled binder system and the modification through RAs, it is important to target a defined area where log S(60) and m(60) have proven to yield adequate ΔT_c values. Komaragiri et al. (2021) proposed a predictive model for ΔT_c based on the correlation between this parameter and S(60) and m(60) of the binder measured at the low-grade test temperature. In their work, a power-law model, with the form shown in Equation 15, was found to describe the response variable best. The advantage of using a calibrated power-law model is that it allows for the prediction of ΔT_c using only one test temperature, increasing the efficiency of routine binder characterization.

$$\Delta T_c = \alpha + \beta S(60)^{\Upsilon} + \mu m(60)^{\varphi} \qquad \text{[Eq. 15]}$$

where

S = creep stiffness, MPa
m = coefficient of relaxation (m-value)
α, β, μ, φ, and Υ = fitting coefficients.

Although the intended use of Equation 15 is to predict ΔT_c from the measured S(60) and m(60), it can also be used to define the functional relationship between S(60) and m(60) for predefined ΔT_c values for plotting in the pseudo-black space. Equation 16 shows this rearranged relationship, which can then be used to evaluate the rejuvenation of the low-temperature properties of recycled binder systems.

$$\log S(60) = \log\left(\frac{\Delta T_c - \alpha - \mu m(60)^{\varphi}}{\beta}\right)^{1/\Upsilon} \quad \text{[Eq. 16]}$$

Ranking Analysis for PAV-20 and PAV-40 Data. Ranking analysis was performed on several alternative master curve–based parameters including $GR_{15°C}$, crossover temperature (T_{45}), crossover frequency (ω_c), and rheological index R-value (referred to herein as R_{MC}). These parameters were calculated using the resultant time-temperature shift factor and Christenson-Anderson model coefficients for the master curves. T_{45} was calculated as the temperature where the phase angle is equal to 45° at a frequency of 10 rad/s based on the recommendations of Garcia-Cucalon et al. (2019). The crossover frequency (ω_c) was calculated at a reference temperature of 20°C and is the point at which the phase angle is 45°. The R_{MC} parameter was calculated as the log of the difference between a glassy modulus of 1.0 GPa and the modulus at the crossover frequency. Also examined in this study were parameters calculated from |G*| and δ at 25°C intermediate grading to calculate $GR_{25°C}$ and |G*|sin(δ) at 25°C and 10 rad/s, and BBR-derived parameters such as S(60) at -12°C, m(60) at -12°C, ΔT_c, and $R_{09\text{-}59}$.

A ranking analysis was performed by conducting a Spearman's rank correlation analysis on each parameter and comparing each parameter to determine if a correlation existed between the two. The Spearman analysis was performed instead of the Pearson correlation analysis because the relationship between the two parameters of interest were non-linear. Spearman's rank correlation analysis was performed by assigning a rank from one to the total number of samples examined for each parameter. The ranks for each blend were then compared using Equation 17. The Spearman's rank correlation coefficient ranges from negative 1 to plus 1 with negative 1 indicating a negative relationship, plus 1 indicating a positive relationship, and values closer to zero indicating no correlation. This ranking analysis was performed to determine which parameters provided similar information and indicated a test was potentially redundant while also providing several potential tests to determine how additives are affecting the performance of a given binder blend.

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \quad \text{[Eq. 17]}$$

where

ρ = Spearman's rank correlation coefficient
d_i = difference between the two ranks of each observation
n = number of observations.

Statistical Grouping Analysis. The grouping analysis for the durability indices was completed by using Dunnett's test for parameters. The data for each parameter were assumed to be normally distributed as the sample size exceeded 30. An assumption of equal variance was confirmed by performing Bartlett's test on each parameter at a given aging condition. If the corresponding p-value was greater than 0.05, then the variance could be assumed as equal and Dunnett's test was used. If the corresponding p-value was less than 0.05, then the standard deviations were compared for each blend of a specific parameter and the blends with the highest standard deviation were removed. This improved Bartlett's test score to above 0.05. Figure 3 is a flowchart for the statistical grouping analysis.

Dunnet's test (t-test comparison of multiple groups) was performed to determine if a binder blend was statistically equal to the target binders of B1 and B2 at its respective aging condition. Dunnet's test indicated which binder blends had a similar level of performance when compared to its target. Based on the means for each binder blend determined in this step, the binders were classified as equal, better, or worse performing with respect to its target binder for each parameter examined.

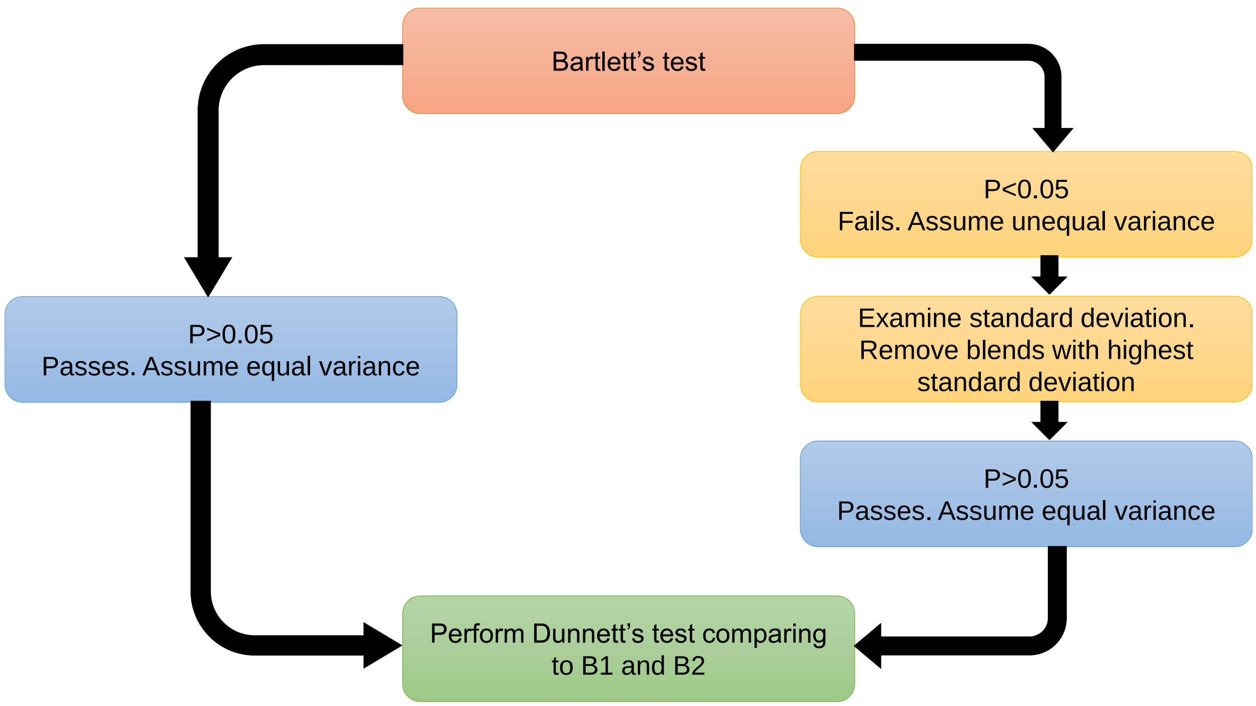

Figure 3. Flowchart of the Statistical Grouping Analysis. P = p-value; B = virgin asphalt binder.

Aging Assessment

LVE Parameters. Several studies have suggested that the restoration capacity of RAs does not ensure the durability of the recycled binder blends (Rajib et al., 2020; Yin et al., 2017). In this study, the long-term aging susceptibility of the recycled binder blends (i.e., reference and RA blends) was assessed by quantifying the changes in LVE properties between binder/binder blends subjected to PAV-20 conditioning and binder/binder blends subjected to PAV-40 conditioning. LVE properties such as the $GR_{25°C}$ and R_{MC} were used with the purpose of evaluating the durability of the binder and potentially discriminating tendencies that do not occur at the standard PAV level.

LAS Test Results. The LAS test was conducted at both the PAV-20 and PAV-40 aging conditions. The fatigue life (N_f) at different strain levels was compared for both aging conditions. In most cases, the N_f at a given strain level was found to be higher at the PAV-40 aging condition compared to the PAV-20 aging condition, which implies better fatigue resistance at the higher aging condition. This outcome is counterintuitive and therefore further research was needed to understand better the reasons for the results and possibly revise the interpretation of fatigue resistance from the test. Therefore, the research team looked at the index parameters derived from the LAS test and assessed the changes in fatigue resistance with aging through these parameters.

Aging Correlation Analysis of PAV-20 vs. PAV-40. Aging analysis was conducted by performing a correlation analysis between parameters at the PAV-20 and PAV-40 aging conditions. This analysis involved determining both Spearman's rank correlation and Pearson's correlation between the same parameter at the two aging conditions (PAV-20 and PAV-40). When the Pearson's and Spearman's rank correlation coefficients are compared, it should be noted that Pearson's correlation measures linear relationships whereas Spearman's correlation can capture both linear and non-linear relationships. Given this, greater emphasis was placed on the Spearman's rank correlation coefficient during the analysis.

Ranking Analysis of PAV-20 vs. PAV-40. Ranking the performance of the PAV-20 and PAV-40 aging was another criterion considered when analysis was performed on the parameters. The purpose of ranking the performance of the PAV-20 and PAV-40 aging was to assess whether the aging conditions had the potential to capture distinctive information and determine if there were advantages to running/using PAV-40 instead of PAV-20 in certain cases. PAV-40–aged materials could be valuable for identifying problematic additives in binder blends that might not be apparent in parameters based on a shorter aging duration.

Asphalt Mixtures

Durability Assessment

The ML from the Cantabro test was used to assess the durability and resistance to abrasion of the recycled asphalt mixtures containing RAs in comparison to the refence mixture. A statistical analysis of ML was conducted to capture any significant differences at a confidence level of 95%. The results were then compared to the VDOT BMD Cantabro threshold of 7.5% (Diefenderfer and Bowers, 2019; Diefenderfer et al., 2021a).

Use of LVE Properties

The results from the dynamic modulus test ($|E^*|$ and δ) were used to examine the impact of RAs on the LVE properties of the recycled asphalt mixtures containing RAs. The $|E^*|$ and δ master curves were constructed using the 2S2P1D model where S stands for spring, P stands for parabola, and D stands for dashpot. These master curves were used to compare the LVE responses of recycled asphalt mixtures with RAs against the reference and/or control mixture. The objective of this analysis was to evaluate whether the RA dosage provided by the manufacturer to achieve a low temperature grade of -22°C resulted in an asphalt mixture that exhibited stiffness and viscoelastic behavior similar to that of the control/reference mixture. A statistical analysis was performed at a 95% confidence level to identify any significant differences. Further, the results of the dynamic modulus test were used to obtain $|E^*|_{LVE,Sapp}$ and the relaxation modulus, E(t), using the S-VECD model as specified in AASHTO TP 133 (AASHTO, 2021). A supplementary analysis was conducted using VDOT's spreadsheet to construct master curves for compatibility with other ongoing VDOT projects and to facilitate mixture comparisons. However, the outputs of this analysis were not used for modeling purposes.

Cracking Assessment

Using IDT-CT Data. The results of the IDT-CT (in terms of the CT_{index}) were used to analyze the impact of RAs on the cracking resistance of recycled asphalt mixtures containing RAs when compared against the reference mixture. The CT_{index} results of the mixtures were also compared against VDOT's BMD criterion of 70 established for SMs, 9.5 mm and 12.5 mm NMAS, with A and D designations (Diefenderfer and Bowers, 2019; Diefenderfer et al., 2021). The results were further assessed by plotting the average G_f against the average l_{75} over $|m_{75}|$ ($l_{75}/|m_{75}|$). This plot is commonly referred to as the CT_{index} interaction diagram (Alfalah et al., 2023). This analysis was conducted with the objective of gaining a more robust understanding of the effect of the RAs on the toughness (represented by G_f) and the ductile versus brittle behavior (represented by $l_{75}/|m_{75}|$) of the recycled asphalt mixture.

Using CF Test Data. The damage characteristic curve, D^R failure criterion, and S_{app} were calculated from the CF test results to compare the effect of the RAs on the position of the C versus S curve, toughness, and apparent damage capacity of the recycled asphalt mixture with RAs in comparison to the reference mixture. A statistical analysis of S_{app} was conducted to identify significant differences using a 95% confidence level. Two sets of S_{app} values were determined. The first set was calculated at 15°C, representing the intermediate-temperature climatic condition in Charlottesville. The second set was determined using the climatic data from the regions/areas from which RAP materials were sampled. The climatic database is populated beforehand using simulations based on hourly climatic data including temperature, precipitation, wind speed, and percentage of sunshine, obtained from the Enhanced Integrated Climate Model (EICM). Further, the S_{app} values were evaluated against the recommended criteria for standard traffic conditions (FHWA, 2019).

Rutting Assessment

Using APA Rut Depth Data. The APA rut depth after 8,000 cycles was used to evaluate the potential rutting susceptibility of the recycled asphalt mixtures with RAs and compare it against the rut depth of the reference mixture. A statistical analysis was conducted on the APA rut depth data to identify any significant differences between the mixtures with RAs and reference mixtures, using a 95% confidence level. The results were also contrasted against VDOT's BMD rut depth criterion of 8.0 mm at 64°C (Diefenderfer and Bowers, 2019;

Diefenderfer et al., 2021a). This analysis was conducted to determine if there was any over-softening of the mixture due to the RAs that could potentially compromise the rutting resistance of the asphalt mixture.

Using SSR Test Data. The SSR test results were used to calculate the RSI and compare the resistance to permanent deformation of the recycled asphalt mixtures with RAs against the reference mixtures. The first set of RSI values was calculated using the climatic data of Charlottesville as a common location. The second set of RSI values was calculated using the climatic data from the regions/areas from which RAP materials were sampled. The RSI values were then compared to the recommended criteria for standard traffic conditions (FHWA, 2021b).

Aging Assessment by Means of Correlations

The IDT-CT, |E*|, and CF test results were assessed across STOA and LTOA conditions for all evaluated recycled asphalt mixtures with RAs in comparison to the reference mixtures. Insights were derived from analyzing the sensitivity of LVE and cracking parameters to assess the effect of RAs.

Asphalt Binders and Mixtures Cross-Scale Evaluation

The results from binder and mixture testing were compared through a cross-scale investigation. The research team established cross-scale models and correlations to analyze the relationship between binder and mixture properties, taking into consideration the use of RAs.

Preliminary Verification of Results

Preliminary verification of the results of this study was performed using data collected from conventional and high RAP field trials constructed during VDOT's 2019, 2020, and 2022 paving seasons and the accelerated pavement testing BMD experiment carried out during the 2020 paving season. These trials featured the use of various RA products and/or softer binders. The collected data primarily focused on the design and production aspects, comparing them to control mixtures commonly produced in Virginia.

RESULTS AND DISCUSSION

Review of the Literature

Overview

Asphalt mixtures containing RAP and RAS have been used for more than 50 years (Al-Qadi et al., 2007). However, in recent years, RAP contents have increased and now it is common to design mixtures with 30% or higher RAP contents (McDaniel et al., 2000). At these higher recycled material contents, the effect of the recycled material begins to affect the behaviors of these asphalt mixtures and alter the pavement performance. The use of recycled materials in asphalt mixtures at these contents may result in diminishing returns at or beyond a certain incorporation dosage level (Tarsi et al., 2020; Zaumanis et al., 2013). To overcome this barrier, RAs are used to extend the break-even point and/or provide savings, both in terms of cost-effectiveness and environmental impacts. This review focuses exclusively on the use of RAs as they are the focus of this research project.

Fundamentally, RAs act to restore the rheological properties of recycled aged binders by either (1) improving the asphaltene to maltene ratio; (2) reducing the size of asphaltene clusters; (3) enhancing the dispersive power of the maltene phase; and/or (4) amplifying the molecular mobility. All four of these mechanisms will result in a reduction in the viscosity, modulus, and brittleness of the asphalt binder but will vary in terms of their effectiveness, compatibility with asphalt binders of different origins, and long-term efficacy (Al-Saffar et al., 2021; Hassanpour-Kasanagh et al., 2020; Kaseer et al., 2019b; Mazzoni et al., 2018; Mohammadafzali et al., 2015; Shen et al., 2007a; Shen at al., 2007b; Tarsi et al., 2020; Xu et al., 2020; Zaumanis et al., 2014a; Zhou et al., 2020; Ziari et al., 2019). The specific reported benefits of using RAs at the right dosage include the following:

- improving workability by reducing the stiffness of recycled asphalt mixtures (Im et al., 2014; Kaseer et al., 2017; Munoz et al., 2015; Tran et al., 2012)

- improving cracking performance by reducing the embrittlement of recycled asphalt mixtures (Chen et al., 2021a; Kaseer et al., 2018a; Mogawer et al., 2013b; Yin et al., 2017)

- reducing production costs, emissions, and landfill space requirements (Haghshenas et al., 2019; Robinette and Epps, 2010; Zaumanis et al., 2016).

Despite the widespread understanding of the need and mechanisms of RAs, there is still a very limited understanding about the effectiveness of RAs, both short term and long term, and their overall cost-to-benefit ratio. The research gaps concerning the use of RAs, which have limited their use by state DOTs, can be broadly divided into six categories, as shown in Figure 4 (Epps-Martin et al., 2020; Kaseer et al., 2019a; Tarsi et al., 2020; Zaumanis et al., 2014b). The lack of expertise and comprehensive studies in these six categories need to be addressed before RAs are used on a regular basis.

The scientific knowledge on the selection and use of RAs in asphalt pavements is limited, and there is a need to develop robust methodologies that establish threshold criteria and performance metrics to facilitate their use on a regular basis. In 2014, NCHRP Project 09-58 was commissioned to study the effects of RAs on asphalt mixtures containing high contents of recycled materials (RAP and RAS). A draft AASHTO "Standard Practice to Characterize Asphalt Mixtures With High Recycled Materials Contents Incorporating Recycling Agents Using Recycled Binder Blend and Asphalt Mixture Testing" was recommended in the project (Epps-Martin et al., 2020). In the review of this current study, the findings of Epps-Martin et al. (2020) in NCHRP Project 09-58 are treated as the state of the art at the time the project was completed, and the advances made since the completion of the project are enumerated.

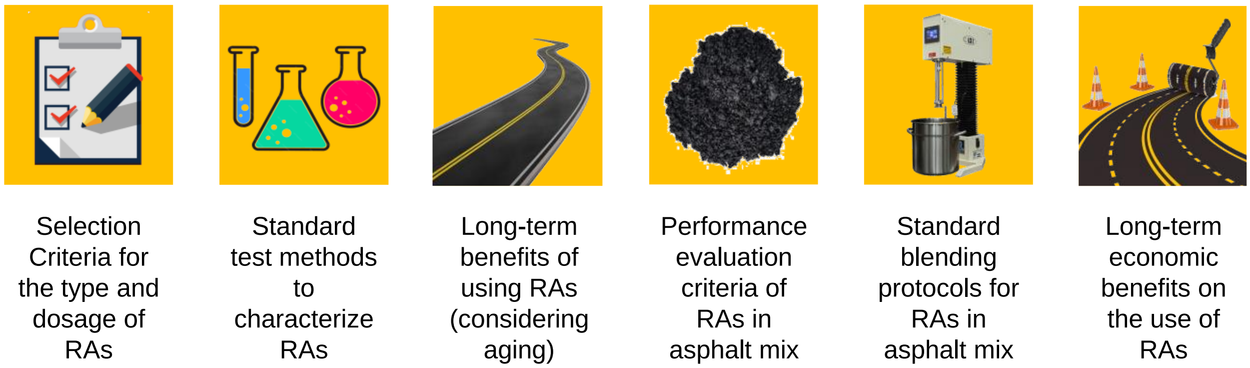

Figure 4. Six Areas of Further Research for Recycling Agents (RAs)

Recycling Agents

Rejuvenation Mechanism

It must first be understood that RAs do not restore the chemistry of an aged asphalt binder. In other words, they do not reverse the oxidation process. Rather their purpose is to reverse the impacts of oxidation on the rheology and performance characteristics of the binder (Al-Saffar et al., 2021; Hassanpour-Kasamagh et al., 2020; Kaseer et al., 2019b; Mazzoni et al., 2018; Mohammadafzali et al., 2015; Shen et al., 2007a; Shen et al., 2007b; Tarsi et al., 2020; Xu et al., 2020; Zaumanis et al., 2014b; Zhou et al., 2020; Ziari et al., 2019). This rejuvenation mechanism operates through three processes: dispersion, diffusion, and compatibility. The main points about each process are summarized in Table 1 (Bressi et al., 2016; Epps-Martin et al., 2020; Kleiziene et al., 2019; Oliver, 1974; Xu et al., 2019; Yang et al., 2017).

Table 1. Details on the Three Processes of the Rejuvenation Mechanism

Process	Dispersion	Diffusion	Compatibility
Description	RA is mechanically mixed with recycled binder	RA diffuses into recycled binder	RA affects the extent of microstructure in the recycled binder
Desirable Properties	Uniform dispersion of RA throughout aged and virgin binder	Absorption of maltene-type phase from the RA by the recycled binder	Homogeneity of RA, aged, and virgin binder
Governing Factors	Mixing characteristics such as time and temperature	Temperature, time, dosage, mixing method, etc.	Proportion of SARA phases, dispersive power of maltene phase, etc.
Problems If Inadequate	Rutting, cracking, moisture susceptibility, etc.	Cracking and/or rutting	Phase separation
Measures/Tests	Visual observation, image analysis	Viscosity for diffusion rate	Exudation droplet test, automated flocculation titrimeter, Gaestel index, etc.

RA = recycling agent; SARA = Saturate, Aromatic, Resin, and Asphaltene Analysis.

Classification of RAs

There have been many attempts to classify RAs over the years due to their increased usage. Currently, four classification systems for RAs have been proposed based on different criteria, as illustrated in Figure 5.

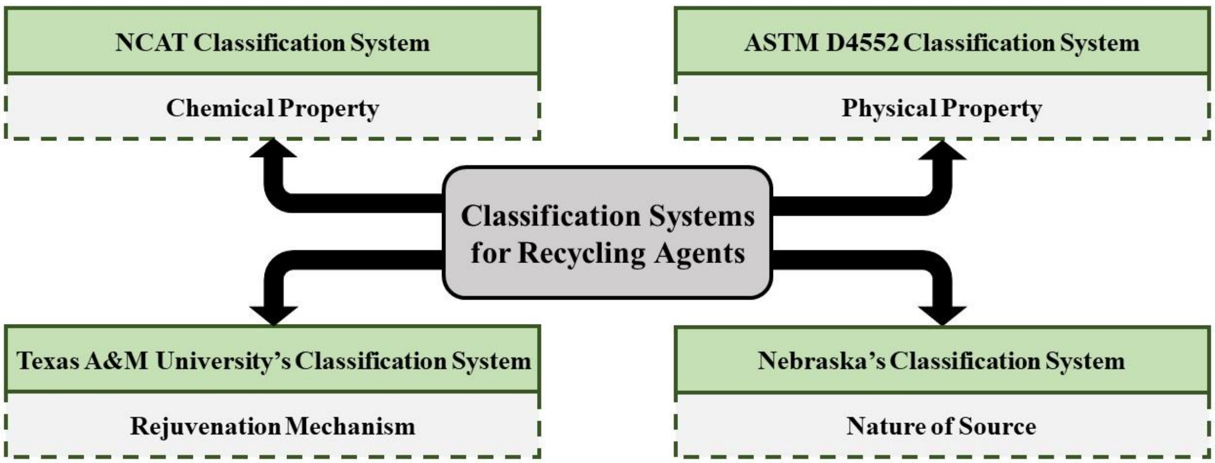

Figure 5. Basis of Different Classification Systems for Recycling Agents. NCAT = National Center for Asphalt Technology; ASTM = American Society for Testing and Materials.

The foremost system among these is the National Center for Asphalt Technology (NCAT) classification system, which differentiates RAs based on their chemical origins (NCAT, 2014). It categorizes RAs into petroleum-based, organic or non–petroleum-based, and emulsion-based, with sub-categories under each type. A specification system purely based on chemical properties has drawbacks, as it does not directly address or elucidate the rejuvenation mechanism for each category. Despite these limitations, researchers have used the NCAT classification system as a foundation to develop additional classification systems (ASTM, 1999; ASTM, 2020a; Bajaj et al., 2020; Haghshenas et al., 2018; Haghshenas et al., 2019; Puchalski, 2021). For instance, subsequent research has shown that organic-based oils are more effective than petroleum-based oils (Ali and Mohammadafzali, 2015; Kaseer et al., 2018a; Osmari et al., 2017; Zaumanis et al., 2014b), leading recent NCAT efforts to focus on a more specific classification of bio-based RAs (Puchalski and Tabatabaee, 2021; Tran, 2021).

Nebraska's classification system draws inspiration from the NCAT classification system but incorporates an additional layer of information regarding the effectiveness of RAs based on changes in the low-temperature and high-temperature PG and cracking resistance (Haghshenas, 2021; Haghshenas et al., 2021b). The system also includes typical dosage levels for each class of RA and provides advisories and cautions regarding the use of each class. Although this classification is still in its draft stage, several scientific articles and reports have already been published (Haghshenas et al., 2018; Haghshenas et al., 2019; Haghshenas et al., 2020; Haghshenas et al., 2021a; Nabizadeh et al., 2017; Nsengiyumva et al., 2020).

ASTM D4552, published in 1999, was one of the first classification systems developed for petroleum-based RAs (ASTM, 1999). In 2018, an ASTM task force was formed to revise the classification system to include the non–petroleum-based RAs. This classification system is used only to assess the suitability of RAs for use in hot mix asphalt and does not consider any impacts on performance. In July 2020, a revised version of ASTM D4552 was published incorporating updated thresholds and revised test methods to accommodate RAs irrespective of their sources (ASTM, 2020a). This classification is based on the physical properties of RAs and mainly uses viscosity at 60°C. Other relevant properties such as saturates content, flash point, specific gravity, and weight change are evaluated in accordance with ASTM D2872 (ASTM, 2022a). This classification system serves as a screening tool to ensure the safety, handling, and durability of RAs in asphalt plants (ASTM, 2020a). In general, it has been reported that organic-based RAs require a lower dosage to achieve the same effect on the viscosity and/or high-temperature PG of the recycled binder blend compared to petroleum-based RAs (Ali and Mohammadafzali, 2015; Kaseer et al., 2018a; Osmari et al., 2017; Zaumanis et al., 2014c). However, contrary observations have also been reported (Nabizadeh et al., 2017).

Texas A&M University's new classification system is the most recent effort to classify RAs. The proposed classification system incorporates the rejuvenation mechanism as a basis to classify RAs (Bajaj et al., 2020). Based on a collection of RA studies at Texas A&M University, the researchers there proposed classifying RAs into three main categories: (1) softeners, (2) replenishers, and (3) emulsifiers (Epps-Martin, 2021). In this system, paraffinic oil, which lacks polar components, is classified as a softener. Despite having a low carbonyl growth (CA_g), it exhibits poor compatibility and high aging sensitivity. Aromatic extracts, which contain polar components that replace some maltenes, act as replenishers at higher doses for most binder blend combinations. Finally, vegetable oils, bio-oils, and tall oils are classified as emulsifiers. They enhance chemical compatibility by facilitating the dispersion of asphaltene agglomerations and result in more effective binder blends. Although these oils are sensitive to aging, the rheological impact of such aging is minimal (Bajaj et al., 2020; Epps-Martin, 2021; Kaseer et al., 2019a). Epps-Martin et al. (2020), in NCHRP Project 09-58, highlighted the need for specifications for both binder blends and RAs to better characterize and rank the effectiveness of different RAs (Epps-Martin et al., 2020).

Performance Testing and Evaluation of Recycled Asphalt Binder Blends

Rutting

Since the addition of RAs aims to restore binder rheology and enhance the cracking resistance of the recycled binder blends, it becomes crucial to address the potential impact on rutting resistance of the resultant mixtures. Proper consideration should be given to the selection of RA dosage and blending protocols to mitigate this concern. Previous research indicates that recycled binder blends generally exhibit reduced rutting potential, as evidenced by a decrease in $|G^*|$ and an increase in δ (Ali et al., 2016; Karki and Zhou, 2016; Oliveira et al., 2013; Osmari et al., 2017). In NCHRP Project 09-58, the rutting resistance of binder blends was evaluated based on the high-temperature PG after short-term aging, as specified in AASHTO T 315 and AASHTO M 320. As long as the rejuvenated binder blend achieved the target high-temperature PG grade according to these specifications, it was assumed to possess acceptable rutting resistance at the binder level (Epps-Martin et al., 2020).

Fatigue Cracking

In general, the primary testing method used to study the fatigue performance of recycled asphalt binder blends is AASHTO T 315, which involves evaluating PAV-aged binder at intermediate temperature using the DSR (AASHTO, 2020). These tests provide valuable insights into the fundamental material properties, such as the norm of G^* and δ, which are determined through oscillatory shear. It is commonly observed that the addition of RAP tends to increase |G*| and decrease δ (Abdelaziz et al., 2021; Ansari et al., 2021; Arabzadeh et al., 2021; Kaseer et al., 2018b; Yang et al., 2022a; Yang et al., 2022b; Zhu et al., 2021) whereas the incorporation of RA often produces the opposite effect (Grilli et al., 2017; Karki and Zhou, 2016; Kaseer et al., 2018b; Oliveira et al., 2013; Osmari et al., 2017; Yin et al., 2017; Yu et al., 2014). The GR parameter at 15°C and 0.005 rad/sec has been extensively used to assess the effectiveness of RAs in improving the non-load related cracking resistance of recycled binder blends and monitoring rheological changes with aging (Ansari et al., 2021; Arámbula-Mercado et al., 2018; Garcia-Cucalon et al., 2017; Haghshenas et al., 2021a; Karki and Zhou, 2016; Kaseer et al., 2018b; Kaseer et al., 2021; Yin et al., 2017; Zhang et al., 2021a; Zhu et al., 2021).

Thermal Cracking

Thermal cracking potential has been typically assessed using the BBR, where two parameters, S(60) and m(60), are used to characterize the modulus and relaxation characteristics of the binder blends. When recycled materials are introduced to the asphalt binder, S(60) generally increases and the m(60) decreases. In the case of RAs, it is generally observed that their addition to recycled binder blends reduces S(60) and increases m(60) (Epps-Martin et al., 2020). Another parameter obtained from the BBR test was ΔT_c, which represents the difference in critical temperature between S(60) and m(60). In addition to the BBR test, other tests such as the crack tip opening displacement test (Paliukaite et al., 2016; Qiu et al., 2018), asphalt binder cracking device test (Zhang et al., 2019), and single-edge notched beam test (Moraes and Bahia, 2018; Swiertz et al., 2011) have been reported in the literature for determining the effects of RAs on thermal cracking in recycled binder blends.

Long-Term Aging and Changes in Chemical Composition

In NCHRP Project 09-58, Epps-Martin et al. (2020) conducted a study on the long-term aging of recycled binder blends using various analytical techniques. They employed FTIR to examine different chemical peaks related by sulfoxide and carbonyl for PAV-20 and PAV-40 aging conditions. The carbonyl area and its changes with aging conditions were tracked. The researchers also used the saturates, aromatics, resins–asphaltene determinator fractions and modulated differential scanning calorimetry tests to track changes in chemical composition and compatibility with aging. Finally, the researchers supplemented their analytical studies with DSR testing to evaluate the effectiveness of RAs initially and with aging. The rheological measurements with the DSR and physiochemical measurements from modulated differential scanning calorimetry showed the occurrence of rejuvenation upon the addition of RAs. Further, the effectiveness of rejuvenation from RAs decreased even though all blends showed improved performance over the control blend without RA. Although the saturates, aromatics, resins–asphaltene determinator fractions analysis was also conducted on the aged samples, it did not show any difference in the asphaltene content between binder blends containing RAs and the control.

It is important to note that Epps-Martin et al. (2020) could not confirm whether the addition of RAs resulted in a reduction in asphalt agglomerates. Nonetheless, they observed that strong polar interactions between RAs and asphaltenes might enhance molecular mobility, contributing to the restoration of rheological properties (Epps-Martin et al., 2020). Previous studies have indicated that the carbonyl and sulfoxide indices decrease when RAs are added (Cao et al., 2018; Liu et al., 2018; Zhu et al., 2017). It has been argued that although these indices can track changes in functional groups during aging and rejuvenation, they should not be solely relied upon to evaluate the effectiveness and efficacy of RAs (Fini et al., 2020b).

Another method to quantify long-term aging is to use gel permeation chromatography to analyze chemical changes. With aging, binders usually show an increase in the amount of large sized molecules in this test. Several studies have reported an increase in large sized molecules upon aging, which decreases after the addition of RAs, though it may not fully return to the original state (Cao et al., 2018; Cong et al., 2020; Osmari et al., 2017; Siddiqui and Ali, 1999; Zadshir et al., 2018).

Performance Testing and Evaluation of Recycled Asphalt Mixtures

Stiffness

The stiffness of asphalt mixtures is an important property used in the mechanistic-empirical design of asphalt pavement structures. Historically, the stiffness characterization of asphalt mixtures was defined by the use of the resilient modulus, M_R (ASTM, 2020b) and, more recently, the dynamic modulus, $|E^*|$ (AASHTO, 2019; Loulizi et al., 2006). When RAP is included in asphalt mixtures, it is commonly believed that the stiffness of asphalt mixtures will increase, resulting in a higher potential for cracking (Baek et al., 2012). As a consequence, numerous research studies have been conducted on the use of RAs to mitigate this effect. The general trend observed in these studies is that the use of RAs promotes the softening of recycled asphalt mixtures and reduces the stiffness that already increased due to the incorporation of RAP (Bonicelli et al., 2017; Mogawer et al., 2013a; Munoz et al., 2015; Pradhan and Sahoo, 2022; Rodríguez-Fernández et al., 2019; Tran et al., 2012; Vackova et al., 2022; Wróbel et al., 2021; Yan et al., 2021; Zhang et al., 2020). However, it is crucial to ensure a balance because excessive softening of recycled asphalt mixtures can lead to pavement rutting (Meroni et al., 2021).

Rutting

In the context of high RAP or high recycled binder ratio (RBR) mixtures and RAs, significant attention has been given to understanding the impact on the cracking resistance of these mixtures. However, it is equally important to consider their rutting behavior for ensuring the long-term performance of asphalt pavements. In NCHRP Project 09-58, Epps-Martin et al. (2020) evaluated rutting using the Hamburg Wheel Track Test (HWTT) and the APA rut test. The results demonstrated that the rutting performance was dependent on the specific RA used, with some performing better than others. Overall, the findings from the HWTT and APA rut test conducted in NCHRP Project 09-58 indicated that the approach of selecting RA doses to restore the continuous climatic high-temperature grade does not excessively increase the rutting potential of the asphalt mixtures (Epps-Martin et al., 2020). Other tests such as the high-temperature IDT, APA rut test, flow number test, and SSR test have been used, and the results suggested that mixtures with RAs perform better than those without RAs (Meroni et al., 2021). In contrast, the rutting tolerance index from the IDEAL rutting test and a new rutting resistance index from the HWTT suggested otherwise (Zhou et al., 2021). Although not explicitly evaluated in the literature, the substantial variation in conclusions across researchers may also imply that laboratory handling and testing procedures play a major role.

Fatigue Cracking

The fatigue cracking of recycled asphalt mixtures has been reported to improve with the addition of RAs (Espinoza-Luque et al., 2018; Im et al., 2014; Mogawer et al., 2013b; Mogawer et al., 2015; Mogawer et al., 2016; Yan et al., 2014; Yin et al., 2017). The identified studies suggested that the factors influencing the intermediate cracking performance of recycled asphalt mixtures include the RA type, but more important, the dosage level plays a vital role. Further, the effectiveness of the RA in improving fatigue resistance is dependent on the aging condition (Epps-Martin, 2021). Several studies have reported a decrease in the effectiveness of RAs with long-term aging (Arámbula-Mercado et al., 2018; Yin et al., 2017). In NCHRP Project 09-58, Epps-Martin et al. (2020) showed that the long-term effectiveness of RAs can be ensured through the proper selection of the dosage method, which in their case was chosen to match the continuous high-temperature PG of the binder blends based on climate and traffic requirements. Given the variety of tests available, it must be noted that the selection of a test method and its parameters may also affect the ranking of recycled asphalt mixtures for fatigue and rutting performance. These tests included the IDT-CT, CF test, and Illinois semi-circular bending test (Meroni et al., 2021).

Thermal Cracking

The addition of RAP increases the modulus and brittleness of asphalt mixtures, thereby increasing their susceptibility to low-temperature cracking. On the other hand, the addition of RAs is reported to decrease the stiffness characteristics at low temperatures and improve the relaxation properties of recycled asphalt mixtures (Chen et al., 2021b; Shen et al., 2007a; Song et al., 2021; Tran et al., 2012; Wielinski et al., 2017; Wu et al., 2021; Yan et al., 2014; Zaumanis et al., 2013). Thus, the addition of RAs likely has a positive effect on the potential for thermal cracking. Traditionally, the thermal stress restrained specimen tensile strength test has been used to assess the low-temperature cracking behavior of recycled asphalt mixtures. Most studies have found that the addition of RAs improves the low-temperature properties, with the extent of the improvement dependent on the type of RAs used (Hajj et al., 2013; Mogawer et al., 2013b; Shen et al., 2004). However, some studies reported that RAs may worsen the low-temperature performance (Cooper et al., 2015).

Moisture Damage

It has been shown that the molecular composition of the asphalt binder and the chemistry of the aggregate are key factors in the loss of adhesive bonding between the asphalt binder and aggregate interface (Cala and Caro, 2022; Caro et al., 2008; Kim et al., 2008). Therefore, the increasing use of RAs in asphalt mixtures provides an opportunity to enhance moisture damage resistance by incorporating suitable components that improve interfacial bonding, commonly found in anti-stripping agents, into the RA formulations (Fini et al., 2020a). In NCHRP Project 09-58, Epps-Martin et al. (2020) acknowledged the challenge of separating rutting resistance from moisture susceptibility in the HWTT. They noted instances where some recycled asphalt mixtures failed the HWTT criteria; however, upon additional dry HWTT testing, the same mixtures exhibited satisfactory rutting resistance. They highlighted that the addition of RAs could ensure adequate rutting resistance but moisture susceptibility might still be a concern, necessitating further research (Epps-Martin et al., 2020). A recent study by Zhang et al. (2021b) indicated that rejuvenated blends had a higher potential for stripping compared to virgin blends whereas the opposite was observed for rutting potential.

Blending Studies

The degree of blending between the recycled binder and virgin binders affects the overall performance of the recycled asphalt mixtures. The extent of this blending depends on several factors, including the material properties of the RAP, virgin binder, and aggregates and the mixing parameters such as time and temperature. The use of RAs typically enhances the degree of blending and allows for a greater binder contribution from RAP in the recycled asphalt mixtures. Theoretically, the addition of RAs does not affect the amount of active binder from RAP. However, it does influence the availability of binder from RAP, which in turn affects the performance properties of both recycled binder blends and recycled asphalt mixtures. Epps-Martin et al. (2020), in NCHRP Project 09-58, proposed a framework for calculating the availability of recycled binder using a method known as the size-exclusion method. This method involves preparing two loose mixtures, one with RAP and one without. They assumed 0% RAP binder availability for the virgin mixture and 100% for the RAP mixture. By interpolating between these two extremes, they calculated a binder availability factor (Kaseer et al., 2019a). To enhance the practical application of this method, they also proposed a set of equations based on the high-temperature PG of the extracted and recovered RAP binder and the mixing temperature. Although other methods, such as degree of binder availability and activity, have been used to estimate blending parameters, there is currently no standardized test available (Lo Presti et al., 2020). It is worth noting that an effort by the NCHRP (NCHRP Project 09-68) to address this issue is ongoing.

Knowledge Gaps and Scope for Future Work

There have been many efforts to study the positive reuse of asphalt mixtures. More recently, RAs have emerged as a widely available tool for engineers to increase the use of recycled materials (RAP and RAS) while ensuring the good performance of pavements. Despite a significant increase in the number of published reports in recent years, very little new knowledge has been generated. However, some recent advances have proposed novel methods for understanding the chemical nature of RAs; the interaction among RAP, virgin binder, and RAs; and how acceptable performance of recycled asphalt binder blends and mixtures can be achieved through dosage selection. Nonetheless, many issues remain:

- First and foremost, a robust classification system that is blind to the origin or source of RAs does not currently exist. The closest method to achieving this goal is the Texas A&M University classification system; however, it is based purely on a rejuvenation mechanism. This approach oversimplifies the complex interactions among virgin binder, RAP binder, and RAs. A comprehensive chemical, rheological, and microstructural classification system that reflects the underlying mechanisms would enable better selection and screening of RAs.

- Existing dosage selection methods focus on an individual property at a time while aiming to ensure acceptable performance across various temperatures or conditions. However, a unified dosage selection method that guarantees optimal performance across all conditions including low, intermediate, and high temperatures and chemical compatibility has yet to be developed.

- Considerable efforts have been made to investigate the impact of RAs on the performance properties of recycled asphalt binder blends and mixtures through conducting systematic studies, varying multiple variables, altering mixing or testing conditions, and incorporating additional additives. Although cross-verification and repeatability of studies are essential parts of the scientific process, most studies have not contributed significantly to the collective knowledge since Epps-Martin et al. (2020), in NCHRP Project 09-58. Therefore, a meta-analysis of these studies is necessary to identify critical aspects regarding the use of RAs.

- Limited modeling efforts have been devoted to capturing the effect of RAs on the rheology and performance of both recycled binder blends and mixtures. Further work in this direction is required.

- The cost of using RAs depends on the type of agent and the amount of RA being used. Therefore, considering cost in the selection and evaluation of RAs can be of prime importance. However, very few studies have proposed methodologies to incorporate the cost of RAs in their selection or evaluation for use in recycled pavements.

- Since most RAs are chemically active, it is essential to study their environmental impacts in both the short term and long term. In addition, as these RAs are or will be used extensively during production, mixing, and compaction, the emissions from recycled asphalt mixtures employing RAs need to be explored.

In addition to these knowledge gaps, the literature review revealed a lack of clear, definitive, and universally accepted metrics for evaluating the effectiveness of RAs, other than those obtained from dosage selection methods. In practice, contractors propose the RA dosage, and the DOT needs to determine if a particular dosage will ensure long-term performance. Therefore, methods, metrics, and frameworks that enable screening and selection of RAs based on their effectiveness in recycled asphalt binder blends and mixtures are needed. Further, the literature review showed that although there are trends regarding RA effectiveness, the specific benefits and limitations reported in individual studies vary greatly. As a consequence, given the current state of knowledge, RAs should be evaluated on a material-by-material basis using asphalt mixtures designed and delivered in accordance with local practices.

State of the Practice

Survey of State DOTs

Of the surveys sent to all state DOTs (hereinafter "agencies"), 34 responses were received, with an overall response rate of nearly 68%, as shown in Figure 6.

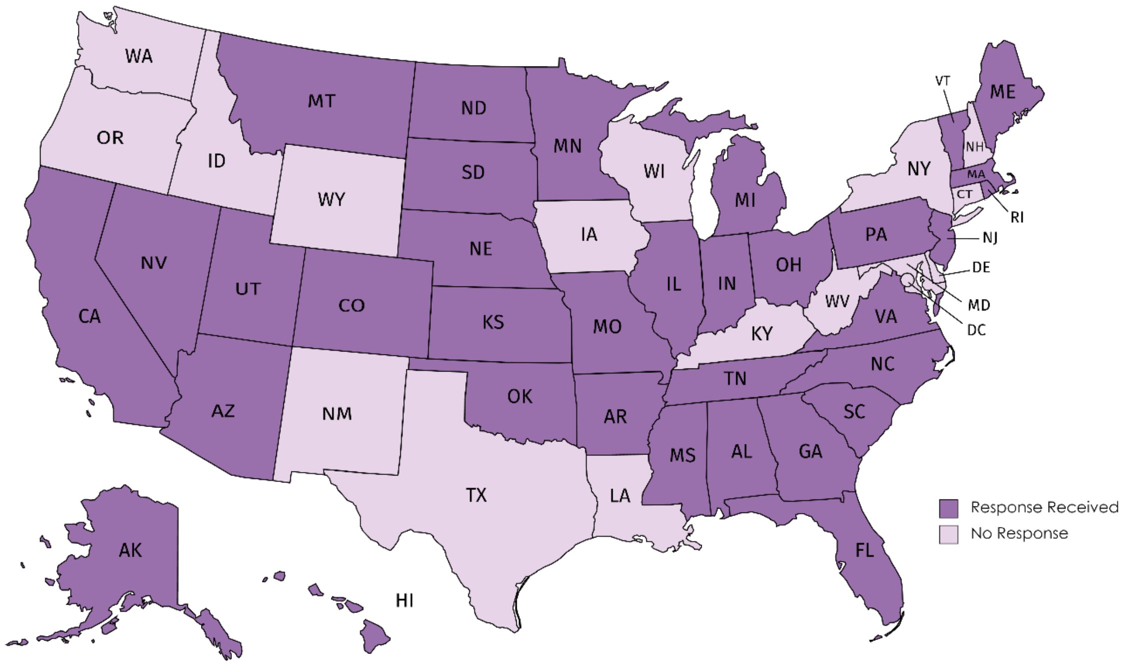

Figure 6. U.S. Map Indicating Survey Response Status of U.S. Transportation Agencies. Source: Habbouche et al., 2022.

Permissibility and Usage of RAP

Of the 34 agencies that responded to the survey, 88% (30 agencies) allow the use of RAP in asphalt SMs. This rate represents a 10% increase in the number of agencies when compared to the responses reported as part of NCHRP Project 09-58 (Epps-Martin et al., 2020). The remaining 4 agencies (12%) (i.e., Arizona, Oklahoma, Rhode Island, and Utah) reported numerous reasons to prohibit the use of RAP in SMs such as previous non-promising contractor experience and hurdles related to the quality, quantity, and source of RAP material.

Of the respondents, 14 (41%) allow the use of high RAP contents in asphalt SMs as an option. The majority of responses conveyed that the definition of "high RAP mixtures" is state specific and the minimum RAP content for a mixture to be considered a high RAP mixture can vary among states, as summarized in Table 2. From this table it is seen that some states (Pennsylvania, for example) define "high RAP" at a content as low as 15%; however, a more common threshold is approximately 30%.

Table 2. Summary of Agency-Specific Definitions for "High RAP" Mixture

State	Definition of "High RAP Mixture"	Key Findings and Comments
California	25%-40% RAP content	• Allowed in mixtures to be produced for special pilots
Georgia	Greater than 30% RAP content	• Maximum RAP content of 40% in surface mixtures if corresponding RAP stockpile is approved in accordance with Georgia specifications
Illinois	Does not have a specific definition	• When more than 20% RBR is used, the mixtures will be treated as high RAP mixtures and both the high and low performance grades of the asphalt binder must be reduced by one grade each
Kansas	26%-40% RAP content	• Up to 40% RAP content allowed if the millings used correspond to the same field site where the mixture is to be placed
Missouri	Greater than 30% RAP content	• No upper limit to RAP content as long as the final performance grade of the resultant mixture is proven and verified through extraction, recovery, and grading/testing
Nebraska	Greater than 25% RAP content	• Up to 50% RAP content allowed
New Jersey	Greater than 20% RAP content	• No upper limit to RAP content defined as long as resultant mixture meets the performance requirements in the corresponding specifications
North Carolina	Greater than 30% RAP content	• Up to 40% total RBR (maximum 20% RBR from RAS) allowed in conventional surface mixtures when virgin asphalt binder is PG 58-28 • Up to 18% RAP and RAS content allowed in mixtures produced using a PG 76-22 asphalt binder.
Pennsylvania	Greater than 15% RAP content	• Additional testing and processing required according to the specifications, Tier 2 • No prescribed maximum %RAP
South Carolina	Greater than 30% RAP content	• Allowed in some mixtures to be placed on roads subjected to relatively lower traffic and where higher risk is tangible
South Dakota	30%-50% RAP content	• 20 ± 5% RAP required in most surface courses • 30%-50% RAP in surface shoulder courses
Vermont	Greater than 25% RAP content	• Not specifically defined in specifications • Up to 50% RAP usually allowed in surface mixtures; however, majority of mixtures use no more than 20% RAP
Virginia	Greater than 30% RAP content	• Allowed in mixtures to be produced for special pilots in accordance with balanced mix design high RAP special provisions

RAP = reclaimed asphalt pavement; RAS = recycled asphalt shingles; RBR = recycled binder ratio.

The main roadblocks and barriers to a greater usage of RAP are shown in Figure 7. Multiple agencies included "Others" (11%) as part of their response. For example, Alabama reported premature cracking at around 25% RAP usage. Colorado, Massachusetts, and South Carolina confirmed the need for performance-related test criteria to design high RAP mixtures appropriately; they currently do not have such criteria, which triggers their concern that high RAP mixtures could lead to further premature distresses. Hawaii reported concerns about the capabilities of asphalt plants to operate effectively with high percentages of recycled materials in general. Indiana and Mississippi reported that high RAP mixtures tend to be dry, which may lead to premature fatigue cracking within the first few years of pavement service life. Kansas reported concerns related to the characterization of bulk and effective specific gravities (G_{sb} and G_{se}) for the RAP material. Virginia reported concerns related to contractor practices in terms of management and quality control (QC) of RAP stockpiles. Multiple agencies reported "No

Roadblocks” (10%) as part of their response. Upon further examination and referring to the literature review, these agencies have made major progress in adopting the BMD approach.

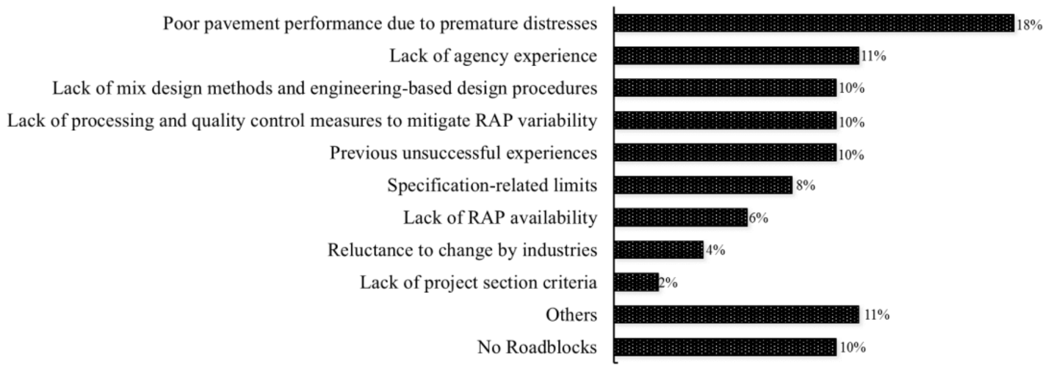

Figure 7. Percentages of the 34 Survey Responses With Regard to Particular Roadblocks and Barriers to a Greater Usage of Reclaimed Asphalt Pavement (RAP) in Asphalt Mixtures. Source: Habbouche et al., 2022.

Permissibility and Usage of RAs

Of the 34 respondents to the survey, 7 agencies reported experience with RAs in asphalt mixtures and 1 agency allows the use of RAs only in asphalt mixtures with high RAP/RAS contents. This group is referred to as Group A, and it included Arkansas, California, Kansas, Minnesota, Missouri, New Jersey, and Pennsylvania.

An online search of specifications, special provisions, and field trial or pilot projects identified another 10 agencies as having experience with RAs in SMs. Of these 10 agencies, 7 do not specify or allow the use of RAs in asphalt mixtures. This group is referred to as Group B, and it included Alabama, Colorado, Florida, Michigan, North Carolina, Oklahoma, and Virginia. The remaining 3 of these 10 agencies did not submit their responses to the survey. This group is referred to as Group C, and it included New York, Texas, and Washington. From Groups A, B, and C, a total of 17 agencies uses or has constructed field trials and pilot projects using asphalt mixtures with RAs, as shown in Figure 8. This outcome represents a 4-fold increase in the number of agencies when compared to the responses reported as part of NCHRP Project 09-58 by Epps-Martin et al. (2020) (only 4 agencies).

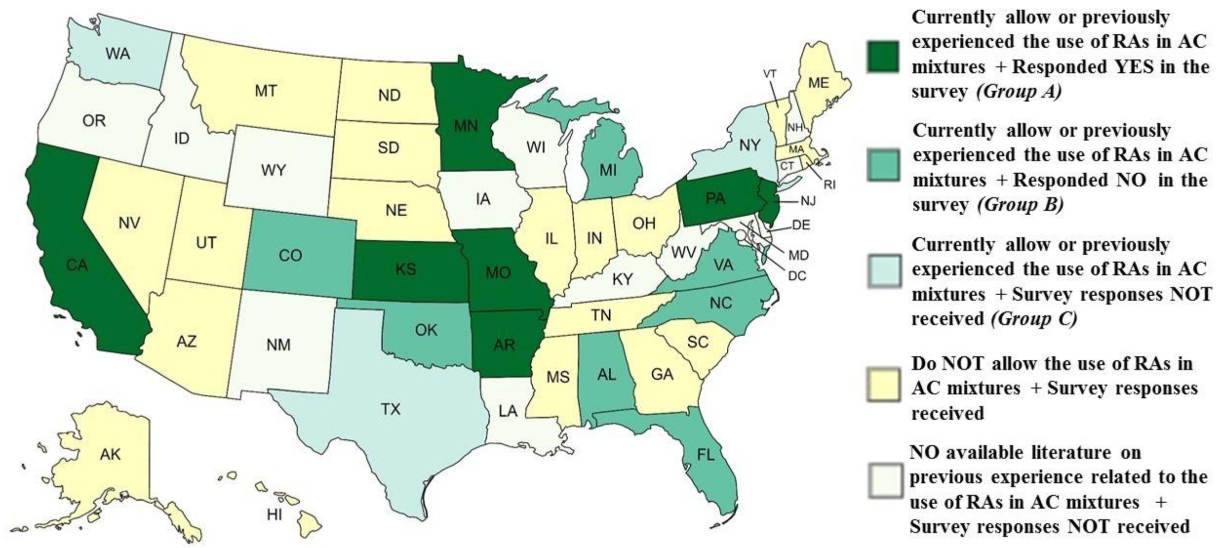

Figure 8. U.S. Map Indicating Agencies' Experience Status With Recycling Agents (RAs) in Asphalt Mixtures. Source: Habbouche et al., 2022.

The main roadblocks to using RAs included lack of tests and criteria to determine dosage rate and/or performance (22%), lack of agency experience (21%), lack of mix design methods and engineering-based design procedures (20%), lack of contractors' expertise in using RAs (16%), distrust of actual RA effectiveness (15%), specifications-related limits (6%), cost of RAs (3%), reluctance to changes by industries (3%), lack of project selection criteria (2%), and poor pavement performance associated with premature distresses and/or failures (2%). For instance, previous issues were reported with the use of refined engine oil bottoms. Five agencies included "Others" as part of their response. For example, Florida frequently specifies the use of softer grades of binder instead of RAs when using higher amounts of RAP to avoid jeopardizing the resistance of the produced mixtures to rutting. Georgia uses the corrected optimum asphalt content approach for asphalt mixtures incorporating recycled materials that, as they report, seems to work better than incorporating RAs. Illinois reported that the information on the long-term performance of mixtures with RAs is very limited. Further, Illinois reported that RAs might initially improve the properties of a mixture, but they may tend to stiffen excessively the mixture over time. Further, there are very limited data to identify and distinguish when this is or is not the case. Pennsylvania is sponsoring a research project to evaluate the use of RAs and to determine a handy and practical method to test the effectiveness of RAs in both the short term and the long term. Finally, South Carolina reported the inaccurate dosage of RAs because of replenishment and non-consistency of RAP and/or RAS piles.

At the time of the survey, no agency included RAs on their APL. However, Nebraska reported positive feedback about their research efforts on the use of RAs in asphalt mixtures and that they expect the RAs being evaluated as part of their studies to be added to their APL and to be used solely. Moreover, Virginia is in the midst of establishing an engineered framework and testing guidelines to add RA products to their APL as part of an ongoing comprehensive research effort.

Agencies were asked to elaborate on how they select and characterize RAs in terms of type, brand, and appropriate dosage when used in asphalt mixtures. The majority of responses conveyed that the agency relies on the efforts of contractors to select an appropriate type and brand of RA to be used when needed and on the contractor / RA suppliers to characterize the needed dosage of RAs.

No agency reported any special practice or enforcement of specific safety, health, or environmental restrictions when RAs were used in asphalt mixtures.

Lessons Learned and Best Practices

There was an extreme lack of lessons learned and best practices, as these agencies reported using little to no RAs as part of their paving projects. Some of the lessons learned, experiences, and thoughts for future consideration are summarized as follows:

- Determining a correct and suitable dosage of RA product is a crucial factor and must be done on a project-by-project basis. For example, Nebraska reported the use of an RA as a warm mix asphalt additive on one of their test sections. This resulted in major rutting potentially because of a possible high dosage provided by the manufacturer.

- The findings from NCHRP Project 09-58 (Epps-Martin et al., 2020) and a general lack of interest in RAs by the industry have not made them a high priority in some states. In general, the findings seemed to indicate rather high dosage rates for RAs in order to approach the performance of control mixtures (Epps-Martin et al., 2020). Combining those elevated levels with limited permissible RAP percentages has not made RAs a topic of high interest.

- Developing a performance-based testing framework is mandatory for the successful use of RAs in asphalt mixtures.

Survey of RA Suppliers

Thirteen RA suppliers responded to the survey including American Refining Group Inc., Arkema Road Science, Asphalt & Wax Innovations LLC, Blacklidge Emulsions Inc., Cargill, Engineered Additives LLC, Georgia-Pacific Chemicals LLC, HollyFrontier, Ingevity Corp, POET Live, Safety-Kleen Oil Inc., Sripath Technologies, and Universal Environmental Services (Avista Oil).

Characterization, Dosage, and Blending Protocols

In the survey (see Appendix B), the RA suppliers were asked to elaborate on their current state of practice with regard to characterizing RAs. Of the13 respondents, 2 suppliers follow standard test methods/procedures. These include the requirements of ASTM D8125-18, ASTM D4552-20, and SARA testing, mainly for QC purposes. The other 11 suppliers follow a combination of standard methods and best/typical/special practices of the company. Some of these practices focus on the analytical characterization of the RA itself. This includes the viscosity-aging index before and after short-term aging of the RA product and testing using

Iatroscan, SARA, gel permeation chromatography, differential scanning calorimetry, FTIR, near infrared, and other tests. Other reported practices focus on the properties of the resultant binder blend: RA + virgin asphalt binder + aged asphalt binder recovered from RAP/RAS material. These blends are then characterized in several ways such as the following: AASHTO M 320 and AASHTO M 322, master curve testing (e.g., the GR parameter), and critical low-temperature difference after 20 and 40 hours of long-term aging using PAV (PAV-20 and PAV-40), which might provide a more complete understanding of the RA impact on the long-term performance of the binder blend.

With regard to establishing a suitable dosage rate of the RA for a given asphalt mixture, the majority of responses highlighted the importance of testing the resultant binder blend (e.g., to meet a target PG) and the physical performance of the evaluated mixture. Some of the respondents use internally developed performance database and correlation models with cracking tests to calculate and recommend appropriate dosages based on application requirements and agency specifications. Few suppliers provide a single dosage typically used for mixtures with a known range of RAP content. Few of the respondents reported that they sell their product/components to laboratories that define the appropriate blending rates.

The suppliers were also asked to elaborate on what blending protocol they recommend for laboratory mix design and during plant production and field operations of mixtures with RAs. The majority of responding suppliers conveyed that blending with the virgin binder is the most typical and consistent way. In the laboratory, pre-blending with RAP is possible if that would better represent the intended field implementation method; however, extra care is necessary for full and consistent blending because of the small sample size and risk of losing material at the edge of the mixing bowl. In the field, in-line blending with the virgin binder via an additive pump was reported to be the most common and flexible blending field protocol by far, especially for drum plants. Facilities that pre-blend have the advantage of being able to provide a record that demonstrates the dosage rate added to the base asphalt, which can then be used easily to calculate and verify the amount of RA in the final mixture. The shipped asphalt binder blend can be tested and certified to meet project specifications. For batch plants, RAs may be added directly to the binder tank, to the RAP via spray bar, or directly into the pug mill during final mixing. Some suppliers reported no differences in results using any of the provided methods.

Suppliers were also asked to elaborate on the shelf life of their RA product and its stability in the resultant binder blend. Some of the suppliers reported a shelf life of 2 years when the RA is stored properly at room temperature in a closed container and with no interaction with moisture/water. However, this does not mean that any loss of quality is expected with time if the product is being stored in a reasonable condition. For example, some suppliers reported that upon 2 years, they have the option to sample, test, and recertify products if they still meet the QC requirements. Other suppliers reported a shelf life of up to 1 year for their products. It is worthwhile to note that some suppliers attributed the successful shelf life and stability of their product to the shelf life and stability of the virgin asphalt binder used to produce the asphalt mixtures.

Acceptance and Usage of RAs

Several state DOTs are attempting to develop methods to evaluate and accept/reject adding RA products to their official APL. This will enhance and facilitate the incorporation of innovative materials as part of the BMD concept in general. Within these lines, the RA suppliers were asked to elaborate on whether they support the inclusion of their products on the APLs of state DOTs. All suppliers conveyed their support. In general, states have better control over what is included in their mixtures by putting the corresponding components (i.e., aggregate, binder, additives, etc.) on their APL. Some suppliers reported that too many inefficient additives can be slipped into a mixture if the products were not previously tested and thoroughly evaluated. Other suppliers emphasized the need to include long-term binder and mixture performance evaluation as part of the process. In other words, if the evaluation comprises a mere RA composition–based specification, it defeats the purpose of producing performance-based mixtures. This will also help differentiate between true long-term rejuvenation and short-term softening.

In the survey, the suppliers were asked to elaborate on how the framework to add RAs to a state's official APL should be established. The following summarizes some of their insights:

- The framework should be established based on a proven history of use and compliance with safety, stability, and handling requirements in accordance with ASTM D4552-20. Moreover, the product should demonstrate proper QC and batch traceability protocols during its production. Finally, the resultant mixture should still be required to pass performance requirements.

- Determining acceptable additives, their acceptable applications, and their dosages can be assessed by peer-reviewed scientific publications.

- The framework should be established based on demonstrated success and field performance associated with credible comparison research results.

- The framework should be based on parameters related to the virgin binder–RA blend parameters and threshold criteria, for example:

    a. Measure the long-term properties of the virgin binder (preferably up to two PAV cycles) and the virgin-RAP binder using preferred test methods (e.g., AASHTO M 320 and AASHTO M 322, the GR parameter, ΔT_c, etc.). These will act as controls.

    b. Determine the optimum RA dosage based on the target PG of the resulting binder blend (at known/target %RAP and the virgin binder to be used for the job).

    c. Measure the long-term performance of the resulting binder blend to determine if the blend performs to the satisfactory level relative to the controls established in (a). This will also help cap the maximum %RAP for a given RA in order to achieve satisfactory performance in comparison to the controls.

d. Lower the %RAP or increase the RA dosage (if the high-temperature PG grade and the low-temperature PG grade of the blends are still within the acceptable ranges) if the resulting blend is not satisfactory in (c).

e. Determine the mix design with the binder blend and evaluate the corresponding rutting and cracking performance using preferred test methods.

f. Measure the cracking performance on long-term oven-aged mixtures to compare with historic data of the virgin mixtures and possibly RAP mixtures with no RAs; thresholds for specifications could be established here. This will help with maintaining the performance regardless of the amount of RAP replaced.

- For long-term usage, specific binder grades should be specified with a known range of RAP contents; for example, PG 64-22 for <20% RBR; PG 58-28 for 20% to 30% RBR; and PG 52-34 for 30% to 50% RBR. Any approved RA could then be used.

Case Study: Virginia

Four Virginia contractors with experience with RAs were asked to provide any lessons learned based on their experience in placing asphalt mixtures containing RAs. All four contractors responded.

RA-Related Attributes at the Asphalt Plant

The contractors reported the need to pursue reputable partner suppliers with strong technical support and proven experience who can recommend suitable dosages based on laboratory testing results from the contractor / project-specific materials. Other factors for consideration included the selection of environmentally friendly products, any modifications needed at the plant, availability of past test results, and cost.

As for specific changes or modifications required at the plant when producing asphalt mixtures with RAs, the contractors conveyed that the only modifications, if any, are the ones recommended by the RA supplier. RA-binder blends are usually stored in tanks with agitators to lessen any risk of separation. RAs and other additives are typically added at the plant as opposed to at the terminal. According to the contractors, this helps control the dosage as needed depending on the weather, haul, and production performance data. Asphalt contractors also reported the use of warm mix additives in addition to RAs at all locations in an attempt to make the produced RA mixture (typically with high RAP) more workable.

Field-Related Attributes

No contractors reported changes from routine established practices in terms of surface preparation or paving operations. They reported that the roller pattern for mixtures with RAs was the same as for conventional mixtures. No contractors reported significant changes to their QC program; however, one contractor recommended/executed QC testing of all materials (i.e., aggregate and RAP) on a weekly basis. The contractors did not encounter any safety, health, or environmental considerations specific to binders/mixtures with RAs that did not apply to standard conventional asphalt binders/mixtures.

Lessons Learned and Best Practices

The asphalt contractors surveyed reported many lessons learned and best practices based on their experience with mixtures that contain RAs. These are summarized as follows:

- The technical help provided by the RA supplier was very beneficial; the contractors learned a lot about how to handle and store the RA and RA-binder blend.

- The industry must have a strong QC/QA testing program to ensure materials have the properties needed to produce a good-performing mixture.

- Good and frequent communication with the RA supplier is critical and necessary during the early planning stages, the production of mixtures, the continuous QC by the supplier, and the teamwork to resolve issues when they arise. Good communication with all project stakeholders (supplier, producer, contractor, and owner) to predict changes and respond in a timely manner is very important. Good unloading, storage, and production practices at the plant are critical for success with RA-based mixtures. A strong focus on QC will yield success with RA-based mixtures.

- The quality of RA-based mixtures should always be checked with respect to required specifications.

Insights From Asphalt Binder Suppliers in Virginia

As mentioned previously, RA suppliers attributed the successful shelf life and stability of their products to the shelf life and stability of the virgin asphalt binder used to produce the asphalt mixtures. To address this aspect of RAs, an email-based survey was distributed to all three asphalt binder suppliers in Virginia. A total of three responses were received.

To characterize their asphalt binders chemically, the suppliers perform testing such as SARA analysis on new sources/refineries and FTIR on a regular basis. The suppliers reported that the crude oil sources do not have a significant impact on the PG of unmodified asphalt binders because refineries are producing these binders to meet the respective state specifications. However, as crude oil sources have an impact on the formulation and optimization of polymer modified asphalt binders and asphalt emulsions, this change may have a major impact on the effectiveness and dosage optimization of RAs.

The suppliers consider any mix design protocols they follow to be strategic in their formulation and cost. They suggest blending RAs in asphalt binder at the terminal (terminal blending) to ensure that the correct testing equipment is available and that the proper QA/QC parameters can be achieved. Then, the RA and virgin binder can be blended at the plant and monitored successfully using current guidelines.

The suppliers tend not to support including RAs on APLs of state DOTs. For them, if RAs are being used to improve performance as part of the BMD approach, their addition to APLs would limit innovation and product formulation and "handcuff" the creativity of mix designers. No major concerns were reported by the suppliers about using RAs more frequently in the production of asphalt mixtures in Virginia.

Laboratory Evaluation of Component Materials

Virgin Asphalt Binders and Recovered RAP Binders

The PG grading was performed on all virgin asphalt binders, RAP binders, and recycled binder blends under both aging conditions (PAV-20 and PAV-40). The two base binders, B1 and B2, were PG 64S-22 binders and were obtained from different sources in Virginia. The first one, from the Hopewell area, represents the eastern side of Virginia and is typically delivered via waterborne vessels from offshore locations such as Canada, Europe, Caribbean, and the Mediterranean. The second one, from the Roanoke area, represents the western side of Virginia and is transported by rail barrels from the midcontinent. The third source, B3, is a PG 58-28 binder sampled from Greensboro, North Carolina.

For this study, three RAP sources representative of Virginia were selected. These selections were based on various factors, including the expected PG of the RAP extracted and recovered binder typically found in the considered area, asphalt content, age, geographical location, aggregate mineralogy and gradation, clustering of RAP, and the availability of field trials and projects where the chosen RAP stockpiles were used. The first RAP material (R1) was sampled from the Salem area (western area); the second RAP material (R2) was sampled from the Burkeville area (central area), and the third RAP material (R3) was sampled from the Chesapeake area (coastal area) in Virginia. Figure 9 shows a sample of each of the three selected RAP stockpiles/sources. These three RAP materials (R1, R2, and R3) were incorporated into typical mixtures at contents of 45%, 35%, and 40% by total weight, respectively. Therefore, these contents were considered in this study to replicate some real-world conditions.

(a) (b) (c)

Figure 9. RAP Materials Sampled for This Study: (a) R1 from Salem; (b) R2 from Burkeville; (c) R3 from Chesapeake. RAP = reclaimed asphalt pavement.

Table 3 presents a summary of the PG grading for both the virgin and RAP binders. Binders B1 and B2 met a high-temperature PG of 64°C and a low-temperature PG of -22°C, with a similar intermediate-temperature PG (~22°C). Binder grading for virgin binders was also performed in accordance with AASHTO M 320, which incorporates the J_{nr} and percent recovery at 3.2 kPa determined using the MSCR test. The MSCR test was conducted at 64°C, the average 7-day maximum pavement design temperature for Virginia. AASHTO M 332 specifies a maximum J_{nr} requirement for standard (S), heavy (H), very heavy (V), and extremely heavy (E) traffic of 4.5 kPa^{-1}, 2.0 kPa^{-1}, 1.0 kPa^{-1}, and 0.5 kPa^{-1}, respectively. VDOT specifications call for a minimum of PG 64S-16 and PG 64H-16 "virgin" asphalt binders for SMs with A and D designations, respectively (VDOT, 2020). Binders B1 and B2 exhibited J_{nr} values of 2.3 kPa^{-1} and 2.1 kPa^{-1}, respectively, placing them in the "S" category.

Table 3 also presents the ΔT_c values for all evaluated virgin and RAP binders. All virgin binders had ΔT_c values ranging from −3.0°C to +1.0°C, with none exceeding the traditional cracking zone of -5.0°C. However, one binder (B1) surpassed the cracking warning limit of -2.5°C (Yang et al., 2022a). The ΔT_c values significantly decreased with the longer duration of aging (PAV-40 vs. PAV-20). The RAP binders had much more negative ΔT_c values compared to the virgin binders, ranging from -9.4°C to -4.7°C. The RAP binders R1 and R3 from Source 1 and Source 3, respectively, had a high-temperature PG of 94°C, and the RAP binder R2 from Source 2 had a high-temperature PG of 106°C. Moreover, RAP binders R1 and R2 had a low-temperature PG of -4°C and -10°C, respectively, and RAP binder R2 had a low-temperature PG of +2°C. This indicated that R2 originated from a stiff and brittle RAP stockpile, making it the most difficult RAP binder to address in this study.

Table 3. Summary of Performance Grading for Virgin and RAP Binders

Binder ID	PAV-20					PAV-40			
	PGH_c (°C)	PGI_c (°C)	PGL_c (°C)	ΔT_c (°C)	PG	PGI_c (°C)	PGL_c (°C)	ΔT_c (°C)	PG
B1	68.1	21.6	22.4	3.0	PG 64-22	25.6	17.0	10.5	PG 64-16
B2	67.0	22.1	24.6	1.2	PG 64-22	27.0	19.8	10.2	PG 64-16
B3	60.6	15.1	30.3	+1.0	PG 58-28	19.7	25.8	5.9	PG 58-22
R1	95.5	36.2	7.9	8.6	PG 94-04	--	--	--	--
R2	107.1	46.0	3.8	4.7	PG 106+02	--	--	--	--
R3	94.5	34.7	10.3	9.4	PG 94-10	--	--	--	--

RAP = reclaimed asphalt pavement; PAV = pressure aging vessel; PAV-20 = PAV for 20 hours; PAV-40 = PAV for 40 hours; PG = performance grade; PGH_c = continuous high-temperature PG; PGI_c = continuous intermediate-temperature PG; PGL_c = continuous low-temperature PG; B = virgin asphalt binder; R = RAP binder; -- = data not available.

Aggregate and RAP Stockpiles

The gradations of each individual aggregate and RAP stockpile were determined for representative samples from each source and compared with the mix design gradation for verification purposes. The verified gradations of the individual aggregates and RAP stockpiles for each source are provided in Appendix E, along with the job-mix formulae.

Laboratory Evaluation of Asphalt Binder Blends

RA Dosing

In this study, the RA manufacturer was asked to supply an RA dosage that would restore the low-temperature PG (PGL) of the recycled binder blend to -22°C. However, the supplier of RA1 did not provide a recommended dosage. Therefore, 10% by weight of total binder was considered for the blends fabricated with this product, following the guidelines provided by the Asphalt Institute Technical Advisory Committee (2016). Table 4 summarizes the dosage levels used in the study. A total of 26 binder blends (i.e., reference and RA blends) containing various types of virgin binders, extracted and recovered RAP binders, and RAs were evaluated in this study. As for the nomenclature, B1R1RA1, for instance, is a blend produced using virgin binder B1, RAP binder from Source 1 (R1), and RA1.

Table 4. Summary of RA Dosages to Achieve a Low-Temperature Performance Grade of −22°C

Binder Source	RAP Source	RA1	RA2	RA3	RA4	RA5	RA6	No RA
Hopewell, VA (B1)	Source 1 Salem, VA (R1)	B1R1RA1 15.4% (10.0%)	B1R1RA2 4.3% (2.8%)	B1R1RA3 5.9% (3.8%)	B1R1RA4 6.2% (4.1%)	--	B1R1RA6 5.7% (3.7%)	--
	Source 2 Burkeville, VA (R2)	--	B1R2RA2 5.3% (3.8%)	B1R2RA3 5.7% (4.0%)	B1R2RA4 5.8% (4.1%)	B1R2RA5 8.5% (6.0%)	B1R2RA6 5.2% (3.7%)	--
	Source 3 Chesapeake, VA (R3)	--	B1R3RA2 3.8% (2.6%)	B1R3RA3 4.1% (2.9%)	B1R3RA4 4.5% (3.1%)	B1R3RA5 8.6% (6.0%)	B1R3RA6 3.9% (2.7%)	--
Roanoke, VA (B2)	Source 1 Salem, VA (R1)	--	--	B2R1RA3 4.4% (2.9%)	--	B2R1RA5 9.2% (6.0%)	B2R1RA6 4.6% (3.0%)	--
	Source 2 Burkeville, VA (R2)	--	--	--	B2R2RA4 4.5% (3.2%)	B2R2RA5 8.5% (6.0%)	--	--
	Source 3 Chesapeake, VA (R3)	B2R3RA1 14.4% (10.0%)	B2R3RA2 3.5% (2.4%)	B2R3RA3 2.60% (1.8%)	--	--	--	--
Greensboro, NC (B3)	Source 1 Salem, VA (R1)	--	--	--	--	--	--	B3R1 0.0% (0.0%)
	Source 2 Burkeville, VA (R2)	--	--	--	B3R2RA4 1.2% (0.90%)	--	--	--
	Source 3 Chesapeake, VA (R3)	--	--	--	--	--	--	B3R3 0.0% (0.0%)

RA = recycling agent; RAP = reclaimed asphalt pavement; VA = Virginia; B = virgin binder; R = RAP binder; NC = North Carolina; -- = blends not evaluated in this study. The percentage outside the parentheses indicates the RA dosage by weight of virgin asphalt binder; the percentage inside the parentheses indicates the RA dosage by weight of total binder.

Performance Grading Results

The detailed PG grading results are presented in Table 5, Table 6, and Table 7 for all evaluated binder blends (i.e., reference and RA blends) produced using B1, B2, and B3, respectively. All B1, B2, and B3 blends had a PGH of either 64°C or 70°C except B1R2RA2, which had a PGH of 76°C. Similarly, all these blends had a PGL of either -22°C or -28°C except B1R1RA1, B1R1RA2, B1R2RA2, and B1R1RA3, which had a PGL of -16°C for the PAV-20 aging condition. The PGL for the PAV-40 aging condition either remained at or increased to -16°C or -22°C in most cases except B2R1RA5, where it stayed at -28°C. This can be attributed to the high dosage of RA5 compared to that of all other RAs.

As for the ΔTc, similar or lower values were observed under PAV-40 aging conditions compared to PAV-20 aging conditions, regardless of the evaluated binder blend. However, no specific trend was observed in relation to the source of virgin binder, RAP binder, and/or RA.

Table 8 summarizes the continuous PG results for all evaluated binder blends at the PAV-20 aging condition. Three categories of binder blends were identified: a category where the PGL of -22°C was never restored, regardless of the increase in the dosage of RA; a category where the PGL of -22°C was restored; and a category where the PGL was improved from -22°C to -28°C with the provided RA dosage.

Table 5. Summary of PG Results for B1 Binder Blends

	PAV-20					PAV-40			
Binder Blend ID	PGH_c (°C)	PGI_c (°C)	PGL_c (°C)	ΔT_c (°C)	PG	PGI_c (°C)	PGL_c (°C)	ΔT_c (°C)	PG
B1R1RA1	73.6	19.2	-19.5	-14.5	PG 70-16	22.4	-17.4	-11.5	PG 70-16
B1R1RA2	75.3	25.3	-18.6	-5.6	PG 70-16	27.3	-18.0	-5.7	PG 70-16
B1R2RA2	76.1	26.6	-20.2	-2.9	PG 76-16	28.6	-19.6	-2.1	PG 76-16
B1R3RA2	73.2	24.2	-22.9	-4.5	PG 70-22	26.7	-20.6	+10.6	PG-70-16
B1R1RA3	69.6	21.5	-20.7	-8.5	PG 64-16	24.5	-23.3	-4.2	PG 64-22
B1R2RA3	71.8	23.4	-23.7	-3.9	PG 70-22	26.6	-21.9	-4.3	PG 70-16
B1R3RA3	69.6	21.4	-23.3	-4.3	PG 64-22	24.1	-22.7	-3.2	PG 64-22
B1R1RA4	71.5	20.4	-27.5	-1.8	PG 70-22	22.5	-22.0	-5.8	PG 70-22
B1R2RA4	73.2	20.2	-24.1	-4.6	PG 70-22	24.4	-20.4	-6.8	PG 70-22
B1R3RA4	71.9	21.2	-27.9	-0.8	PG 70-22	22.8	-23.1	-5.4	PG 70-22
B1R2RA5	70.2	17.7	29.4	+2.1	PG 70-28	22.6	-20.7	-8.7	PG 70-16
B1R3RA5	64.5	16.4	-30.9	-1.9	PG 64-28	19.2	-27.8	-3.4	PG 64-22
B1R1RA6	71.1	20.8	-25.5	-5.0	PG 70-22	22.9	-22.4	-5.8	PG 70-22
B1R2RA6	73.3	24.2	-23.0	-5.8	PG 70-22	23.9	-21.4	-6.0	PG 70-16
B1R3RA6	70.4	21.7	-23.9	-5.0	PG 70-22	24.1	-22.7	-5.2	PG 70-22

PG = performance grade; PAV = pressure aging vessel; PAV-20 = PAV for 20 hours; PAV-40 = PAV for 40 hours; PGH_c = continuous high-temperature PG; PGI_c = continuous intermediate-temperature PG; PGL_c = continuous low-temperature PG; B = virgin binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; -- = data not available.

Table 6. Summary of PG Results for B2 Binder Blends

Binder Blend ID	PAV-20 PGH$_c$ (°C)	PAV-20 PGI$_c$ (°C)	PAV-20 PGL$_c$ (°C)	PAV-20 ΔT$_c$ (°C)	PAV-20 PG	PAV-40 PGI$_c$ (°C)	PAV-40 PGL$_c$ (°C)	PAV-40 ΔT$_c$ (°C)	PAV-40 PG
B2R1RA3	71.7	22.6	-22.7	-6.9	PG 70-22	25.4	-22.0	-4.3	PG 70-22
B2R3RA1	69.0	17.2	-24.9	-7.3	PG 64-22	20.4	-20.2	-8.4	PG 64-16
B2R3RA2	72.6	22.1	-24.9	-2.1	PG 70-22	23.9	-22.1	-2.3	PG 64-22
B2R3RA3	70.4	22.6	-26.3	-0.8	PG 70-22	24.3	-22.0	-5.4	PG 70-22
B2R2RA4	74.5	22.9	-23.6	-2.8	PG 70-22	26.5	-22.7	-4.7	PG 70-22
B2R1RA5	66.7	16.9	-30.3	-2.1	PG 64-28	20.1	-29.6	-0.8	PG 64-28
B2R2RA5	67.7	16.3	-30.1	+1.4	PG 64-28	21.9	-24.1	-6.2	PG 64-22
B2R1RA6	71.8	21.2	-28.4	-0.5	PG 70-28	23.9	-19.7	-7.2	PG 70-16

PG = performance grade; PAV = pressure aging vessel; PAV-20 = PAV for 20 hours; PAV-40 = PAV for 40 hours; PGH$_c$ = continuous high-temperature PG; PGI$_c$ = continuous intermediate-temperature PG; PGL$_c$ = continuous low-temperature PG; B = virgin binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; -- = data not available.

Table 7. Summary of PG Results for B3 Binder Blends

Binder Blend ID	PAV-20 PGH$_c$ (°C)	PAV-20 PGI$_c$ (°C)	PAV-20 PGL$_c$ (°C)	PAV-20 ΔT$_c$ (°C)	PAV-20 PG	PAV-40 PGI$_c$ (°C)	PAV-40 PGL$_c$ (°C)	PAV-40 ΔT$_c$ (°C)	PAV-40 PG
B3R2RA4	72.8	23.1	-24.1	-3.0	PG 70-22	25.5	-20.2	-7.6	PG 70-16
B3R1	72.9	23.2	-23.1	-5.1	PG 70-22	26.3	-20.7	-5.4	PG 70-16
B3R3	70.5	20.1	-26.2	-1.4	PG 70-22	24.2	-19.6	-10.3	PG 70-16

PG = performance grade; PAV = pressure aging vessel; PAV-20 = PAV for 20 hours; PAV-40 = PAV for 40 hours; PGH$_c$ = continuous high-temperature PG; PGI$_c$ = continuous intermediate-temperature PG; PGL$_c$ = continuous low-temperature PG; B = virgin binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; -- = data not available.

Table 8. Summary of Continous PG Results for All Evaluated Binder Blends at the PAV-20 Condition

Binder Source	RAP Source	RA1	RA2	RA3	RA4	RA5	RA6	No RA
B1	R1	73.6-19.5	75.3-18.6	69.6-20.7	71.5-27.5	--	71.1-25.5	--
	R2	--	76.2-20.2	71.8-23.7	73.0-24.1	70.2-30.2	73.3-23.3	--
	R3	--	73.2-22.9	69.6-23.3	71.9-27.9	64.5-30.9	70.4-23.9	--
B2	R1	--	--	71.7-22.7	--	66.7-30.3	71.8-28.6	--
	R2	--	--	--	74.5-23.6	67.7-31.6	--	--
	R3	69.0-24.9	72.6-24.9	70.4-26.3	--	--	--	--
B3	R1	--	--	--	--	--	--	72.9-23.1
	R2	--	--	--	72.8-24.1	--	--	--
	R3	--	--	--	--	--	--	70.5-26.2

PG = performance grade; PAV = pressure aging vessel; PAV-20 = PAV for 20 hours; RAP = reclaimed asphalt pavement; RA = recycling agent; B = virgin binder; R = RAP binder; -- = blend not evaluated in this study. Orange cells indicate that the low-temperature PG of -22°C was not restored. Blue cells indicate that the low-temperature PG of -22°C was restored. Green cells indicate that the low-temperature PG was improved.

Balance of Rheological Parameters

Benchmarking Analysis

Figure 10 shows histograms depicting the distribution of main rheological properties included in VDOT's QA program, along with individual data points representing a subset of the binders in this study. Only a subset of binders were selected for this plot since not all binders had a J_{nr} at 64°C, which is necessary for the further analyses presented. In these graphs, the vertical position of the blends, both reference and RA blends, is aligned with the reference QA binder histogram at the corresponding rheological quantity. For example, in Figure 10a, B1R3RA5 exhibits a $|G^*|/\sin\delta$ value of approximately 1.16 kPa. Since 21 binders of the 435 QA data points fell within the $|G^*|/\sin\delta$ range of 1.15 to 1.20 kPa (the defined bin size for constructing the histogram), the vertical position of the data point for B1R3RA5 is approximately 0.05, which is equivalent to 21 divided by 435. This approach was employed to facilitate easy differentiation among the individual blends.

Figure 10a displays the distribution of $|G^*|/\sin\delta$ at 64°C, which is the Superpave rutting specification parameter, for Virginia's PG 64S-22 binders and for the unaged (original) blends. It is evident that most of the RA blends, prepared with the dosage level recommended by the manufacturer to restore the low-temperature PG, have a $G^*|/\sin\delta$ at 64°C higher than the mean value of the distribution. In Figure 10b, an opposite but expected trend is observed with the distribution of J_{nr} at 64°C for Virginia's PG 64S-22 binders and the blends. The blends prepared with RA5 exhibit high-temperature properties that fall within the distribution of typical values of Virginia's virgin binders.

Figures 10c and 10d depict the low-temperature properties of Virginia's PG 64S-22 binders and the blends. In general, RA blends are positioned to the left of the S(60) distribution, exhibiting values lower than the mean. Figure 10d displays the distribution of m(60), and it is observed that the RA blends with a high-temperature performance similar to that of Virginia's PG 64S-22 binders (RA5-modified blends) fall outside the distribution of this rheological property. This finding suggests that the manufacturer may have recommended an RA dosage to restore the intended PGH, which Epps-Martin et al. (2020) in NCHRP Project 09-58 showed met or exceeded the target PGL. Selecting a dosage that restores the PGH yields a higher dosage than that required to meet the maximum specified PGL, as evidenced by the relatively high dosage levels specified for these blends in Table 4. Further, a distinct behavior is observed with B1R1RA1 where the blend exhibited a low S(60) but also a low m(60). This indicates that the predominant effect of the additive is that the RA blend is softening without improvement in the relaxation behavior of the material, as documented in other studies. More discussion regarding the balance between creep stiffness and relaxation is presented in the following section.

Figure 10e shows the distribution of the Superpave intermediate-temperature cracking parameter $|G^*|\sin\delta$ at 25°C. In this case, the values for most of the RA blends fall within the range of values for the virgin binders, suggesting that the intermediate-temperature performance of the RA blends in terms of $|G^*|\sin\delta$ at 25°C is similar to that of Virginia's PG 64S-22 binders. This indicates a potential similarity in intermediate-temperature cracking performance.

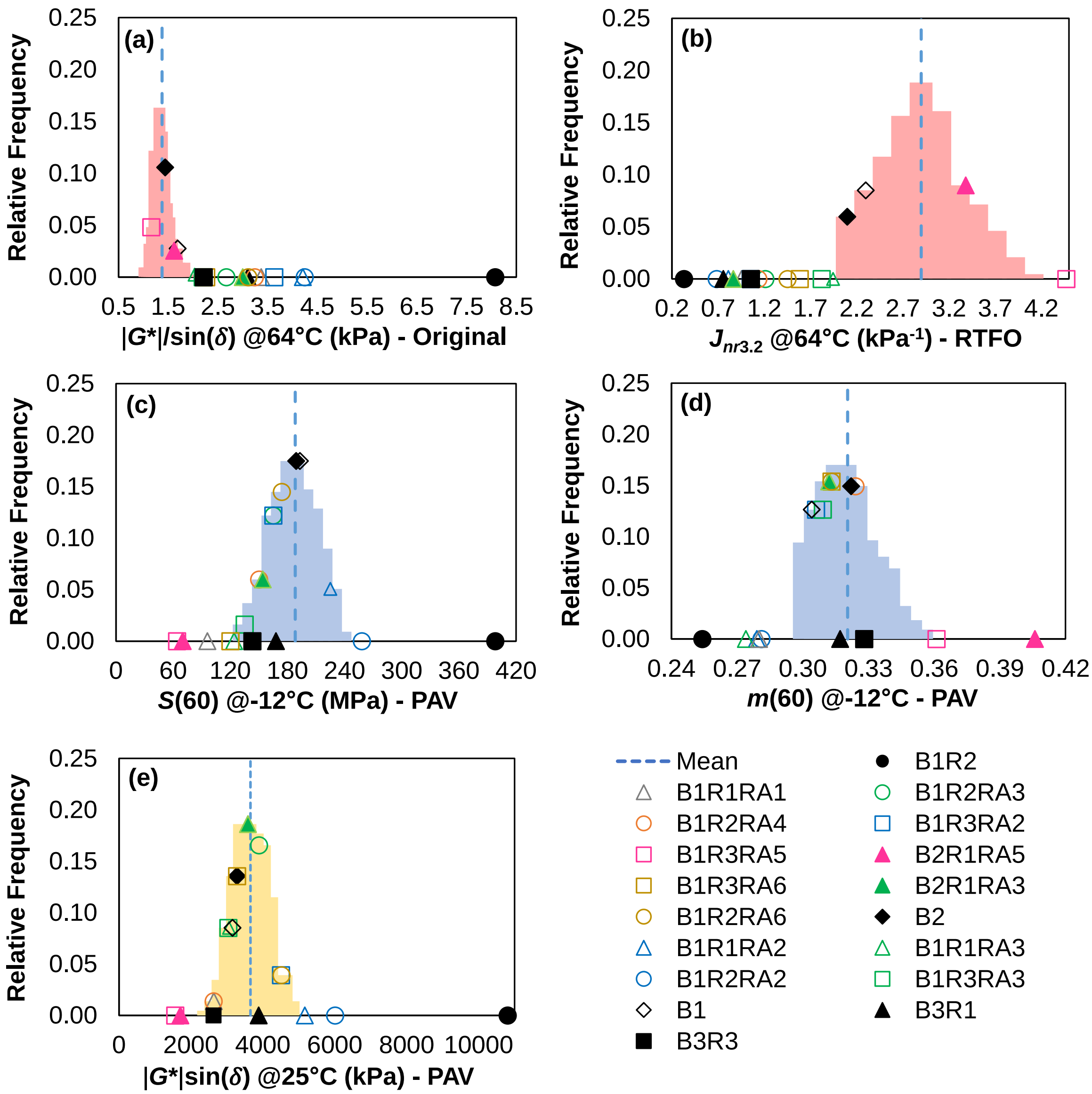

Figure 10. Distribution of Superpave Binder Properties of Virginia PG 64S-22 Binders and Recycled Binder Blends: (a) |G*|/sinδ at 64°C - original; (b) J_{nr} at 64°C – RTFO; S(60) at -12°C - PAV-20; (d) m(60) at -12°C – PAV-20; (e) |G*|sinδ at 25°C – PAV-20. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; PG = performance grade; S = standard traffic; RTFO = rolling thin film oven.

Figure 11 shows the high- and low-temperature rheological properties of Virginia's materials as bivariate distributions of different rheological properties. The B2R1RA5 RA-modified blend highlights the importance of examining the multivariate distribution of rheological properties. Although Figures 10a and 10b show that this blend falls within the univariate distribution of G*|/sinδ at 64°C and J_{nr} at 64°C, Figure 11a reveals that B2R1RA5 lies outside the bivariate distribution of high-temperature properties defined by the dataset of reference QA binders.

Further, the results suggest that RA blends can be similar with respect to log S(60) and m(60) at -12°C, as shown in Figure 11b, but this does not necessarily imply similarity to typical binders since other rheological parameters may significantly differ from the benchmark. Generally, Figure 11 shows that modifying the reference blend (base recycled blends) with RAs to restore the low-temperature performance reduces the similarity between the RA blends and the reference QA binders in terms of high-temperature performance. Therefore, a statistical-based approach is desirable to quantify the similarity of RA blends and typical binder blends and identify RA dosages that result in modified blends with rheological combinations outside typical patterns.

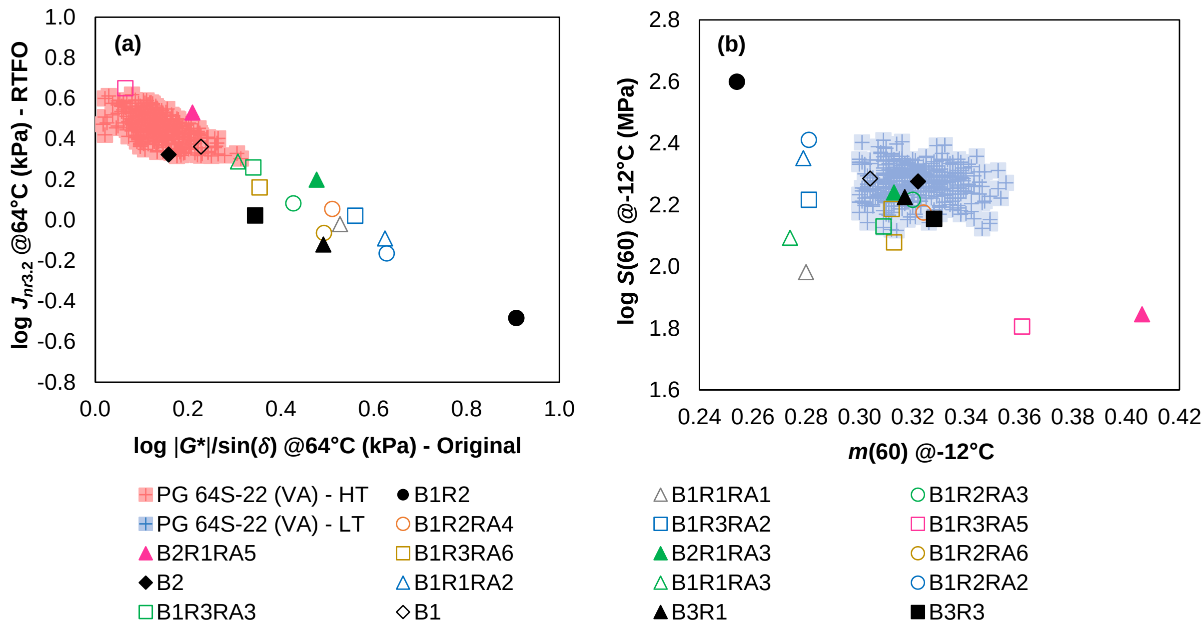

Figure 11. Bivariate Distribution of High- and Low-Temperature Rheological Properties of Virginia's Materials: (a) AASHTO M 322 high-temperature rheological space; (b) AASHTO M 332 low-temperature rheological space. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; PG = performance grade; S = standard traffic.

Similarity Analysis

Concepts and methods of multivariate statistical analysis and control theory were used to examine the rheology of reference and RA blends, considering the different Superpave rheological properties measured in routine binder characterization. Details of the analysis procedure are provided in Preciado et al. (2023a).

As detailed in Preciado et al. (2023a), the similarity in any of the spaces is dependent on the rheological properties of the RA blend, which in turn are influenced by the dosage of RA used in the blend. As a consequence, it is expected that the MD^2 is a function of the RA dosage. As observed elsewhere (and not shown here for brevity), the logarithms of the G*, S(60), and m(60) all exhibit a linear trend in relation to the RA dosage. In this section, a linear relationship between RA dosage and the rheological properties is assumed to determine the MD^2 as a function of dosage. Although this analysis focuses on a subset of the RA blends, the same analysis can be conducted for other blends.

Figure 12 shows the rheological properties of B1R2 in the high- and low-temperature rheological domains as a function of the dosage of RA2 and RA3. The elliptical-shaped dashed lines in Figure 12 represent all points having a fixed MD^2 value, as indicated on the lines themselves. These lines visually represent the MD in two dimensions. As observed, the similarity in the high-temperature domain increases with the additive content until the blend closely matches the high-temperature rheological characteristics of Virginia's PG 64S-22 binders to the greatest extent possible. Once this point is reached, further increases in the RA dosage reduce the similarity of the blend with respect to Virginia's PG 64S-22 binders. This effect is shown in Figures 13a and 13b for the blends modified with RA2 and RA3, respectively. These observations suggest that for B1R2, there exists an optimum content of a particular RA that maximizes the similarity of the RA blend and Virginia's PG 64S-22 binders in terms of high-temperature performance. Further, this optimum content is influenced by the effectiveness of each RA in altering $|G^*|/\sin\delta$ and J_{nr} with respect to additive dosages.

In Figure 12b, the low-temperature rheological space, B1R2 is positioned at the upper left side of the reference binder for Virginia. As the RA dosage increases, the low-temperature similarity also increases, reaching a point where the RA blend closely matches the low-temperature properties of the reference binder to the best extent possible. Once the maximum similarity point is achieved, the similarity starts to decrease with further increases in RA dosage. This trend is demonstrated in Figures 13a and 13b. More details related to the low-temperature performance are provided in the next section. A similar behavior was observed in the intermediate-temperature rheological space, which is not discussed here for brevity.

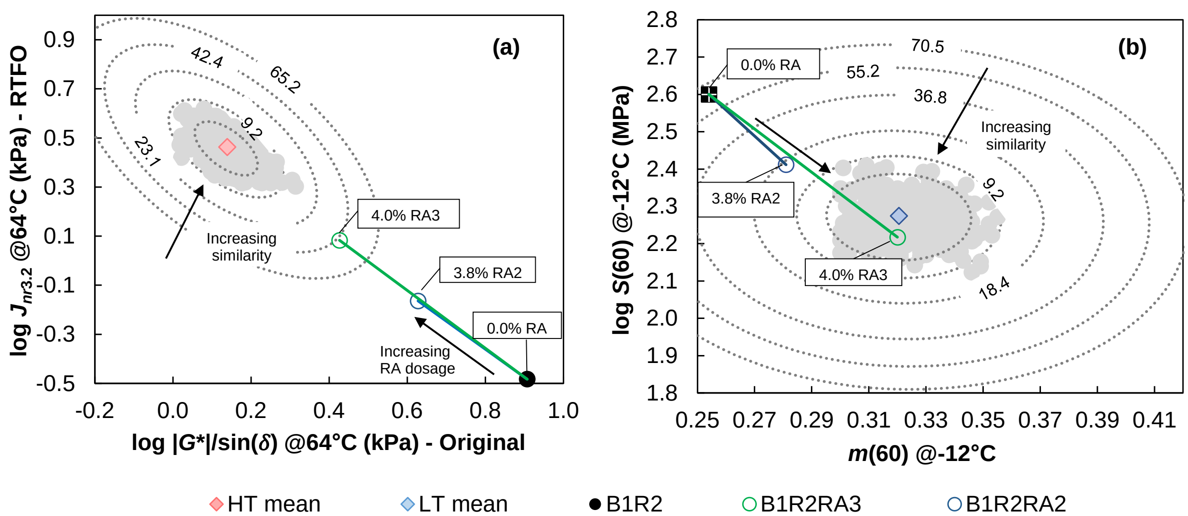

Figure 12. Relationship Between RA Dosage and Similarity for B1R2RA3 and B1R2RA2: (a) high-temperature rheological space; (b) low-temperature rheological space. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven; HT = high temperature; LT = low temperature.

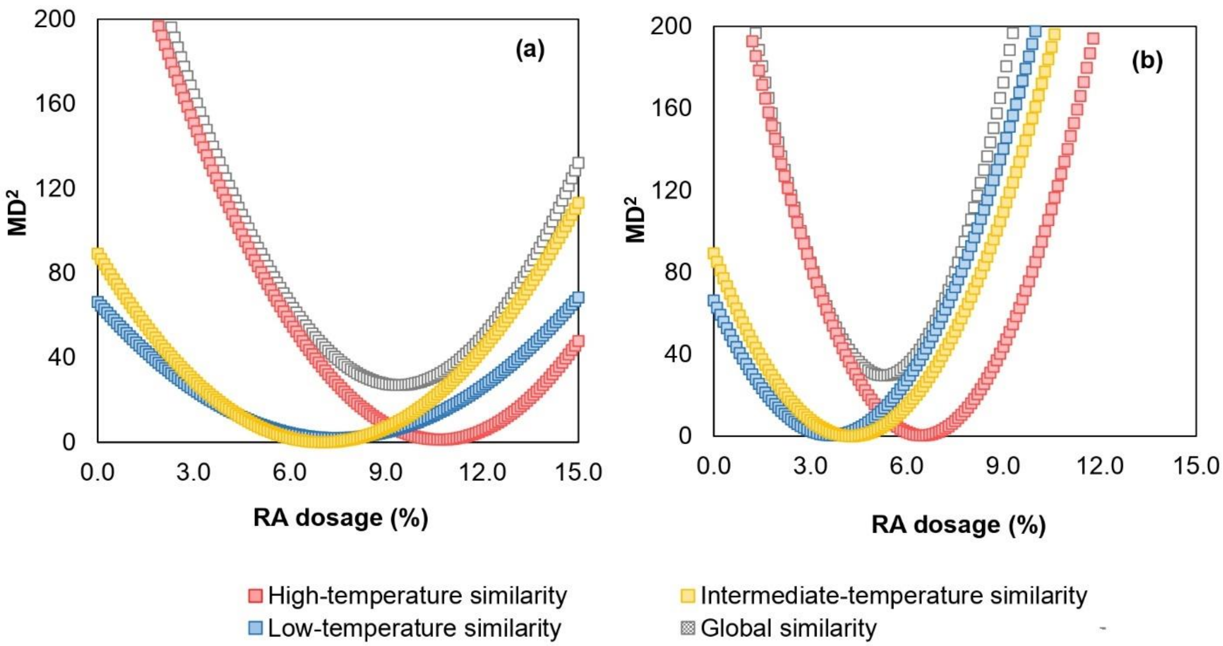

Figure 13. Statistical Similarity of Recycled Asphalt Blends With RAs to Virginia PG 64S-22 Binders: (a) B1R2RA2; (b) B1R2RA3. MD = Mahalanobis distance; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Further, Figures 13a and 13b suggest that, in general, a higher dosage is needed to modify the high-, intermediate-, and low- temperature rheological properties to achieve the highest similarity with the reference virgin binders of B1R2 with RA2 compared to RA3. It can be observed that the minimum MD^2 values for each rheological space are attained at lower dosages with RA3 when compared to dosages with RA2. Of interest, similar minimum global MD^2 values can be achieved with RA2 and RA3, but at different dosage levels. This indicates that although a greater amount of RA2 is needed to alter the rheological properties of B1R2, the relationship between the rheological properties at different aging and temperature conditions as a function of additive content is comparable to the RA3-modified blend, resulting in similar rheological combinations. An application of this approach using other component materials is presented in Preciado et al. (2023a).

Figure 14 shows the global, high-, intermediate-, and low-temperature similarity results for the binders and binder blends presented in Figure 10. It should be noted that the RA blends presented in Figure 10 were prepared with the dosage recommended by the manufacturer to restore the PGL to -22°C. For the binders where J_{nr} at 64°C was not available, it was not possible to compute the global and high-temperature similarity. However, the intermediate- and low-temperature similarity results are presented in Appendix F. Figure 14 shows that the base recycled blend exhibited the lowest similarity with respect to Virginia's PG 64S-22 binders in terms of high- and intermediate-temperature properties and global/overall similarity. Regarding the low-temperature similarity, the blends with RA5 showed less similarity compared to the base recycled blend. In addition, these blends were the only systems where the high-temperature similarity is higher than the low-temperature similarity. In general, the incorporation of RAs in

B1R2 increased the similarity globally, with the highest global similarity to Virginia's PG 64S-22 binders achieved with the modification of B1R2 with RA3. An important observation is that B1R1RA1 has a high-temperature MD^2 similar to B1R2RA6 but a different low-temperature MD^2. This suggests that the modification mechanisms of the RAs are different, and although both modifications yielded similar high-temperature performance, the RA blend with RA6 appeared to exhibit a more typical relationship between stiffness and relaxation characteristics compared to the blend modified with RA1.

The similarity analysis, as presented, does not provide information on whether the blends met the Superpave grading criteria. For example, B1R2 showed a higher low-temperature rheological similarity with Virginia's PG 64S-22 binders compared to B2R1RA5; however, B2R1RA5 met the Superpave grading criteria at -22°C and the former did not. Nonetheless, the similarity analysis can provide insights into the degree of similarity in the various rheological spaces evaluated after RA modification.

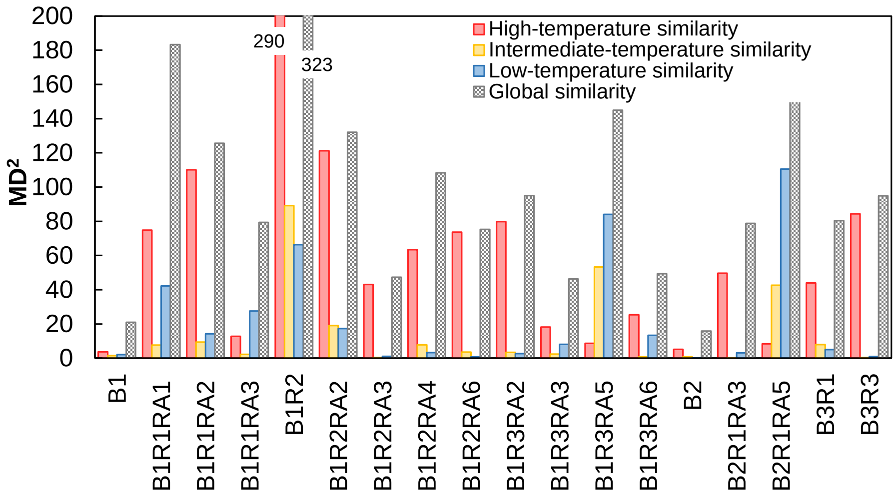

Figure 14. Similarity Analysis Results for Virginia's Binder Blends. MD = Mahalanobis distance; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Creep Stiffness and Relaxation Analysis

The previous section presented the results regarding the similarity of the RA blends to the typical properties of Virginia's virgin binder. This section further examines the effects of RA modification on the rheological properties that define the low-temperature rheological space discussed earlier. More detailed information on this analysis is provided in Preciado et al. (2023b).

Figure 15 shows the relationship between the log S(60) and RA dosage for the B1R2 blend modified with RA1, RA2, RA3, and RA4. It is important to note that each of the blends presented in Figure 14 contains an RA with a distinct classification in accordance with the NCAT classification system. As shown, log S(60) follows a clear linear trend in relation to RA dosage, supported by the high coefficient of determination (R^2) values for each model. However, the rate of change of log S(60) with respect to RA dosage is unique for each RA. In this case, the highest rate of change was observed with RA4, followed by RA3, RA2, and RA1.

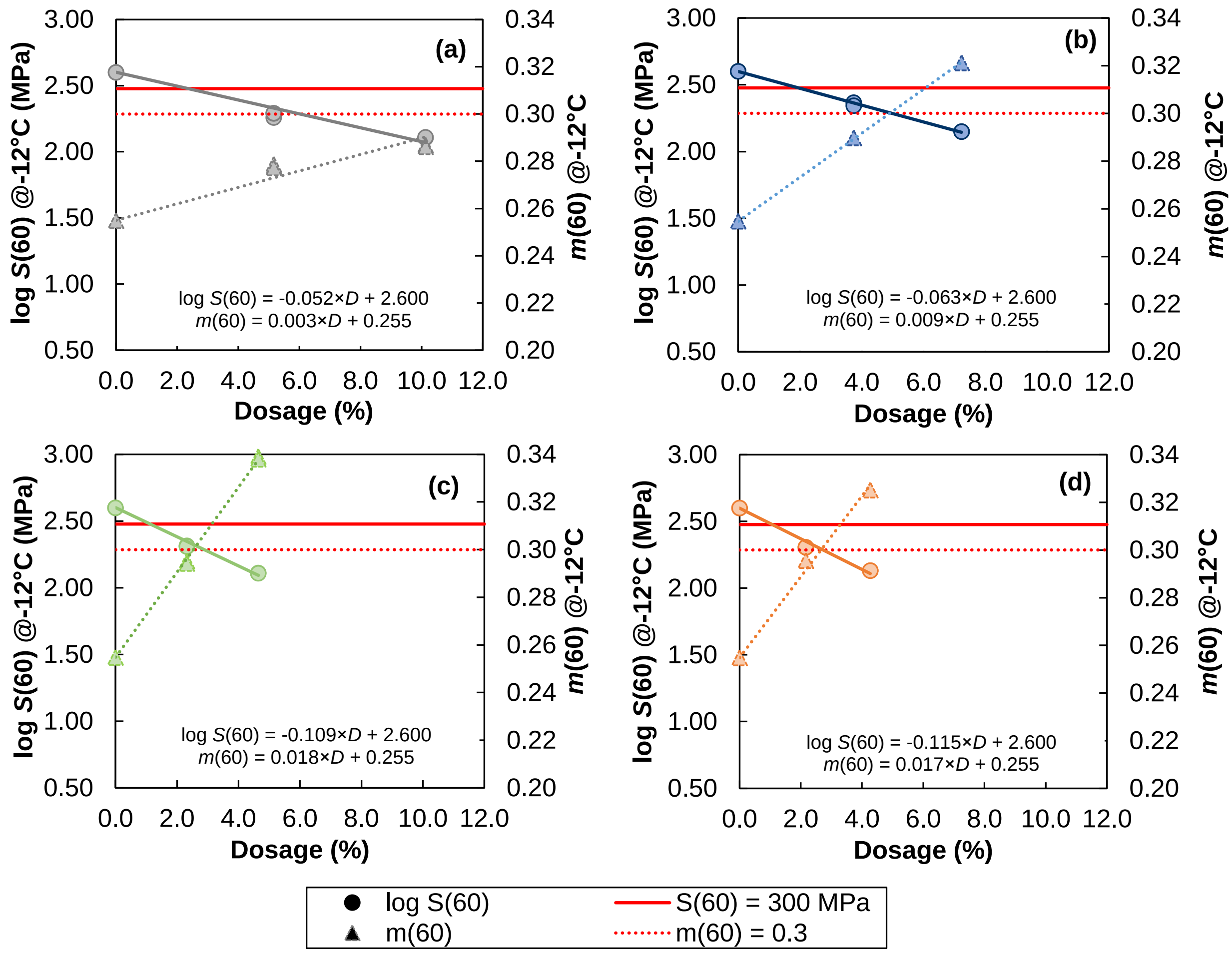

Figure 15. Relationship Between log S(60) and m(6) With RA Dosage: (a) B1R2RA1; (b) B1R2RA2; (c) B1R2RA3; (d) B1R2RA4. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

These results suggest that achieving a target creep stiffness (S[60] = 300 MPa) for the B1R2 system would require the highest RA dosage with RA1 and the lowest RA dosage with RA4. It is believed that the rate of change of log S(60) with respect to RA dosage is a function of the inherent characteristics of each RA such as chemical composition, rheology, etc., and the interaction with the recycled blend including RAP and virgin binder. Similar qualitative trends were observed with the m-value and RA dosage.

The observed linear relationships between the low-temperature properties and RA dosage imply that only two dosage levels, including 0%, need to be evaluated in order to determine the coefficients of the linear function that relates the RA dosage to low-temperature properties. Interpolations can then be performed to find a dosage level that yields low-temperature properties that meet both Superpave criteria (S[60] ≤ 300 MPa and m[60] ≥ 0.300). This simplification expedites the low-temperature characterization of recycled binders with RAs for state DOTs and contractors. In the following analysis, an additional set of blends was analyzed to propose a framework for evaluating the acceptance of RAs using pseudo-black space diagrams, considering the existence of a linear relationship between low-temperature properties and RA dosage. More detailed information on this analysis is provided in Preciado et al. (2023b).

Figure 16 shows the relationship between log S(60) and m(60) for a binder blend modified with an RA based on the linear relationships observed in Figure 15. The first point for each binder blend corresponds to the log S(60) and m(60) of the virgin binder plus RAP combination (without any RA). The second point corresponds to the recycled blend plus the RA at a specific dosage level. The length of the black line in Figure 16, termed the low-temperature rejuvenation path (referred to herein as SR_D), depends on the dosage level recommended by the manufacturer and the effectiveness of the RA in modifying the properties of the recycled binder blend. Higher dosage levels or greater effectiveness in altering the low-temperature properties of the recycled blend with dosage will yield longer rejuvenation paths. This aspect is essential for a dosage selection procedure given that the length of the rejuvenation path should be sufficient to ensure that the recycled binder blend with RA has a creep stiffness S(60) of less than 300 MPa and an m(60) greater than 0.300. However, for the acceptance of an RA, the rate of SR_D holds greater significance, as it provides information about the ability of the RA to achieve a specific balance between stiffness and relaxation capacity.

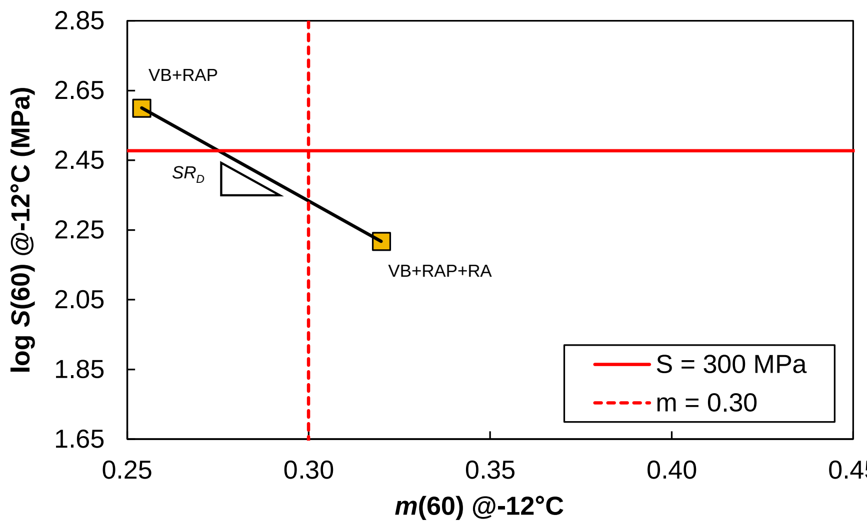

Figure 16. Graphical Representation of the SR_D Parameter. VB = virgin binder; RAP = reclaimed asphalt pavement; RA = recycling agent.

Table 9 presents the SR_D values of the different blends evaluated. As observed, the SR_D values for RA1 blends were higher than those of blends with other RAs. This finding suggests that the RA1 leads to a greater reduction in creep stiffness relative to the increase in m-value compared to RA2, RA3, RA4, RA5, and RA6. Further, the results for RA1 indicate that this parameter is a function of the combination of virgin binder and RAP, emphasizing the complexity of recycled binder blends. Apart from the RA1 products, the SR_D parameter appears to be approximately uniform and relatively consistent for each set of recycled blends modified with a specific non-extender product, meaning that the parameter may be independent of RAP, the virgin binder source, and the RBR used to constitute the recycled binder blend in this study.

Table 9. Summary of SR_D Results for the Evaluated RAs

RAP Source	Virgin Binder Source	Recycling Agent					
		RA1	RA2	RA3	RA4	RA5	RA6
R1	B1	26.6	5.9	5.4	6.3	-	6.5
	B2	-	-	5.4	-	6.8	6.5
	B3	-	-	-	-	-	-
R2	B1	15.1	6.8	5.8	6.5	6.6	6.2
	B2	-	-	-	6.1	6.6	-
	B3	-	-	-	-	-	-
R3	B1	-	6.2	5.1	6.0	6.7	6.3
	B2	21.4	5.7	5.2	-	-	-
	B3	-	-	-	-	-	-
Average		21.0	6.1	5.4	6.2	6.7	6.4
Standard deviation		5.8	0.4	0.3	0.2	0.1	0.2

RA = recycling agent; RAP = reclaimed asphalt pavement; R = RAP binder; B = virgin asphalt binder; - = data not available.

It should also be noted that, by definition, SR_D is independent of RA dosage; the SR_D value depends on the ratio between the rate of change of log S(60) with respect to dosage and the rate of change of m(60) with respect to dosage. The results in Table 9 suggest that for a particular RA, the rate of change of log S(60) and m(60) with dosage may vary based on the combination of virgin and RAP binder. However, the findings of this study indicate that the ratio of the rates of change is approximately the same for each product, excluding extenders.

The fact that SR_D is independent of RA dosage, RAP binder, virgin binder, and RBR for non-extender products indicates that this rheological parameter can be used for the acceptance of RAs. If the low-temperature characteristics of the virgin and RAP binder combination are known a priori as part of the standard routine characterization for the mix design of recycled asphalt mixtures, and if SR_D is provided by the RA manufacturer, then it is possible to determine whether the RA can potentially be used to achieve a low-temperature rheological target such as the desired location of the recycled blend in the pseudo-black space diagram.

This desired location can be selected based on different approaches. The recycled binder blend present in a recycled asphalt mixture consists of virgin binder plus the binder contribution of the RAP plus the RA. The recycled asphalt binder serves as a surrogate for the virgin asphalt binder, aiming to achieve comparable performance while being a sustainable pavement material. Therefore, it is reasonable to expect that the recycled binder blend exhibits approximately the same rheological behavior as a binder that meets or exceeds the low-temperature properties specified in AASHTO M 320 or AASHTO M 332 for the specific location of interest.

One approach consists of selecting a single representative binder (which could be the virgin binder used to constitute the recycled binder blend) and attempting to replicate its low-temperature properties. However, the coordinates of the virgin binder's log S(60) and m(60) represent only one point in the pseudo-black space diagram. This approach is likely to be impractical and unnecessarily restrictive since it is not clear if the use of a single blend is the only way to achieve acceptable performance. As a result, a more reasonable alternative is to target an arbitrary point within a region in the stiffness-relaxation space that encompasses a set of points of virgin binders known for their acceptance and use in asphalt mixtures, where reasonably good low-temperature performance has been observed. An example of such a region is the one specified for Virginia's virgin binder specified in Figure 12b. At this point, it becomes intuitive that the SR_D parameter controls the minimum low-temperature MD^2 (maximum similarity) that a recycled binder blend can achieve through the modification with a specific RA product.

Targeting of a ΔTc Value Analysis

A second approach to determine the desired location in the pseudo-black space diagram is based on the relationship between log S(60) and m(60) and the well-known ΔT_c parameter. Details of this approach are presented in Preciado et al. (2023b). Komaragiri et al. (2021) proposed values for α, β, μ, φ, and γ equal to 41.77, 0.707, 0.5963, -30.92, and -0.5769, respectively, based on an experimental program involving 202 different binders produced in Texas and neighboring states (see Equation 16). For this study, the measured ΔT_c and known S(60) and m(60) were used to recalibrate the model.

Figure 17 shows ΔT_c prediction using the power-law model calibrated with the dataset used in this study. It should be noted that the fitting coefficients reported by Komaragiri et al. (2021) yielded an R^2 of 0.68 for the measured ΔT_c in Figure 17.

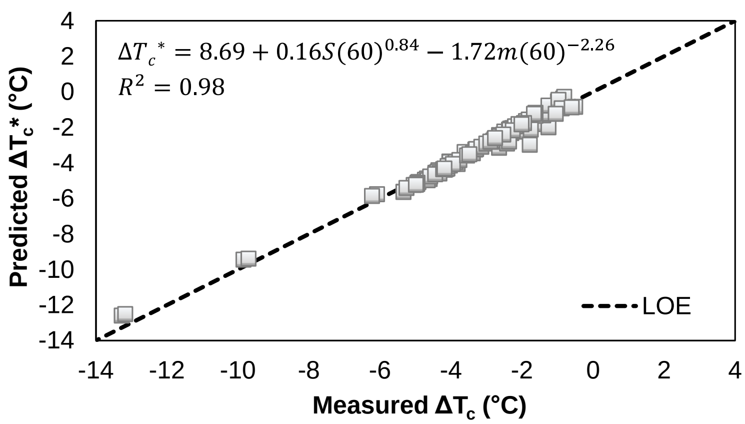

Figure 17. Regression Model to Predict ΔT_c Based on S and m-value at -12°C. LOE = line of equality; S(60) = creep stiffness; m(60) = coefficient of relaxation; ΔT_c = difference between the continuous grade based on S(60) and m(60) parameters.

Figure 18 shows the ΔT_c prediction curves from 2°C to -10°C portrayed in a black space diagram. In this space, the relationship between S(60) and m(60) for any given ΔT_c is found to be linear with ΔT_c-dependent slopes and the intercept. Since SR_D defines the trajectory that a recycled binder blend would take in the pseudo-black space, it also can be used to estimate the potential ΔT_c values that can be achieved upon rejuvenation of the recycled binder system. As expected, high SR_D values yielded to a more negative ΔT_c than did low SR_D values for a given virgin and recycled binder combination. It is observed that depending on the SR_D of the RA, the trends of ΔT_c with dosage can be either positive, negative, or zero.

In the example presented in Figure 18, the SR_D of the yellow system is such that ΔT_c is roughly -2°C throughout the rejuvenation path. A higher SR_D, such as the SR_D of the blue system, would make the ΔT_c of the recycled system more sensitive to dosage level, as more ΔT_c

curves would be interested by the rejuvenation line. In this scenario, ΔT_c would become more negative with dosage. Similarly, an SR_D such as the one of the pink system would also make the ΔT_c of the recycled system more sensitive to dosage level; however, in this scenario, ΔT_c would become less negative with RA dosage.

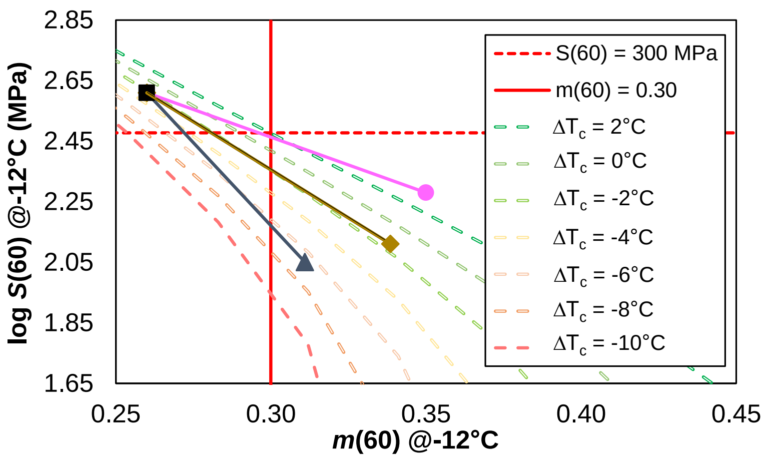

Figure 18. Black Space Diagram Considering ΔT_c Prediction Curves. Filled squares indicate possible rejuvenation paths. S(60) = creep stiffness; m(60) = coefficient of relaxation; ΔT_c = difference between the continuous grade based on S(60) and m(60) parameters.

Assessment of Durability

Overview. Additional analysis of the durability of the recycled binder blends was conducted using standard PG and alternative parameters identified in the literature. This section presents the results of the alternative durability parameters at PAV-20 and PAV-40 aging conditions. The binder parameters evaluated are divided into three groups: intermediate-temperature point parameters, low-temperature point parameters, and parameters that measure the rheological balance of stiffness (modulus) and relaxation (phase angle) characteristics. Table 10 provides a summary of the durability-related asphalt binder parameters evaluated along with suggested limits (if available in the literature and/or specifications) and whether a higher or lower value is generally desired.

The recycled binder blends were benchmarked against the suggested limits and compared to the PG 64S-22 virgin binder in the blend. The PG 64S-22 virgin binder in a given RA blend was considered a control that reflects the target binder properties since VDOT uses PG 64S-22 asphalt binder in the absence of RAP. For example, blend B1R2RA5 was compared to B1. The reference blends that constitute the typical practice in Virginia, including a PG 58-28 virgin binder and recycled binder with no RA, were also compared to the PG 64S-22 virgin binders (B1 and B2). To compare the binder blend results to those for a PG 64S-22 virgin binder, Bartlett's test was first performed to determine if equal variance could be assumed. Then, Dunnett's test was used to compare the mean results of each blend to the control mean result of the respective PG 64S-22 virgin binder for all blends that satisfied the equal variance criterion. The significance level for all statistical tests was 0.05.

Table 10. Summary of Durability-Related Binder Paramters Evaluated in This Study

Parameter	Suggested Limit(s)	Higher or Lower Desired?	Reference
Low-Temperature Point Parameters			
S(60) (MPa)	Max. 300 MPa @ PAV-20	Lower	AASHTO M 320-21
m(60)	Min. 0.300 @ PAV-20	Higher	AASHTO M 320-21
Intermediate-Temperature Point Parameters			
$\|G^*\|\sin(\delta)$ (kPa)	Max. 6,000 kPa$^+$ @ PAV-20	Lower	AASHTO M 320-21
$GR_{25°C}$ (kPa)	Max. 5,000 kPa @ PAV-20 Max. 8,000 kPa @ PAV-40	Lower	Christensen and Tran, 2022
$GR_{15°C}$ (kPa)	Max. 180 kPa for crack onset Max. 450 kPa for significant cracking	Lower	Anderson et al., 2011
Rheological Balance Parameters			
T_{45} (°C)	Warning 32°C Max. 45°C	Lower	Garcia-Cucalon et al., 2017
R_{MC}	NA	Lower	Christensen and Tran, 2022
$R_{09\text{-}59}$	Max. 2.50 @ PAV-20 Max. 3.20 @ PAV-40	Lower	Christensen and Tran, 2022
ΔT_c (°C)	Min. -5°C	Higher	Asphalt Institute Technical Advisory Committee, 2019

PAV-20 = 20 hours of pressure aging vessel (PAV) aging; PAV-40 = 40 hours of PAV aging.

The results for the B2 blends are presented graphically. The results for the B1 blends are presented in Appendix G. The results for the B1 and B2 blends with respect to a given RA and RAP source were generally consistent. However, differences between the B1 and B2 blend results were notable and are discussed.

Figure 19, Figure 20, and Figure 21 show the results for the PAV-20 and PAV-40 blends for the low-temperature point parameter, intermediate-temperature point parameter, and rheological balance parameter results, respectively. Color coding in the figure is used to convey Dunnett's test results, as indicated. A result was considered better if it had a statistically different result based on Dunnett's test and if the blend result was desirable relative to the control according to Table 5. For example, if the blend S(60) result was statistically distinct and lower than B2, it was considered better than the control. Detailed discussions of the results are provided with respect to the reference blends and RA blends in the subsequent sections.

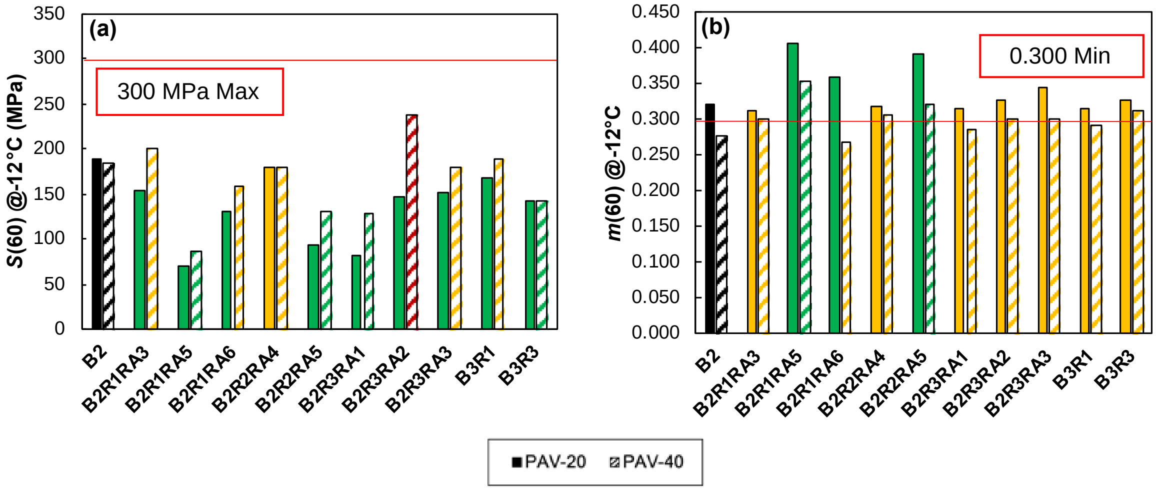

Figure 19. Low-Temperature Point Parameters: (a) stiffness S(60); (b) coefficient of relaxation m(60). Colors convey Dunnett's test results: green, yellow, and red indicate better, equal, and worse results relative to B2, respectively. Gray indicates that the blend could not be compared statistically to B2 using Dunnett's test because its variance differed from B2 and thus failed. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

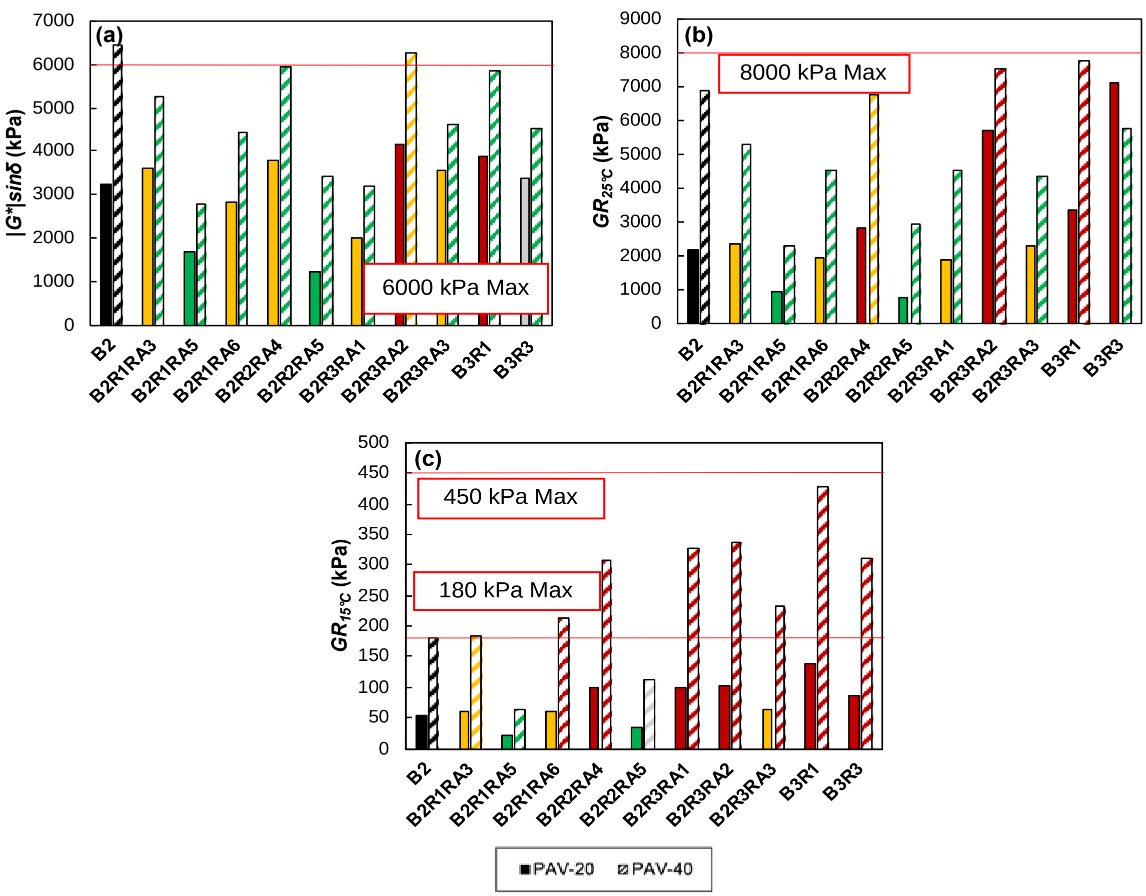

Figure 20. Intermediate-Temperature Point Parameters: (a) |G*|sin(δ); (b) $GR_{25°C}$; (c) $GR_{15°C}$. Colors convey Dunnett's test results: green, yellow, and red indicate better, equal, and worse results relative to B2, respectively. Gray indicates that the blend could not be compared statistically to B2 using Dunnett's test because its variance differed from B2 and thus failed. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

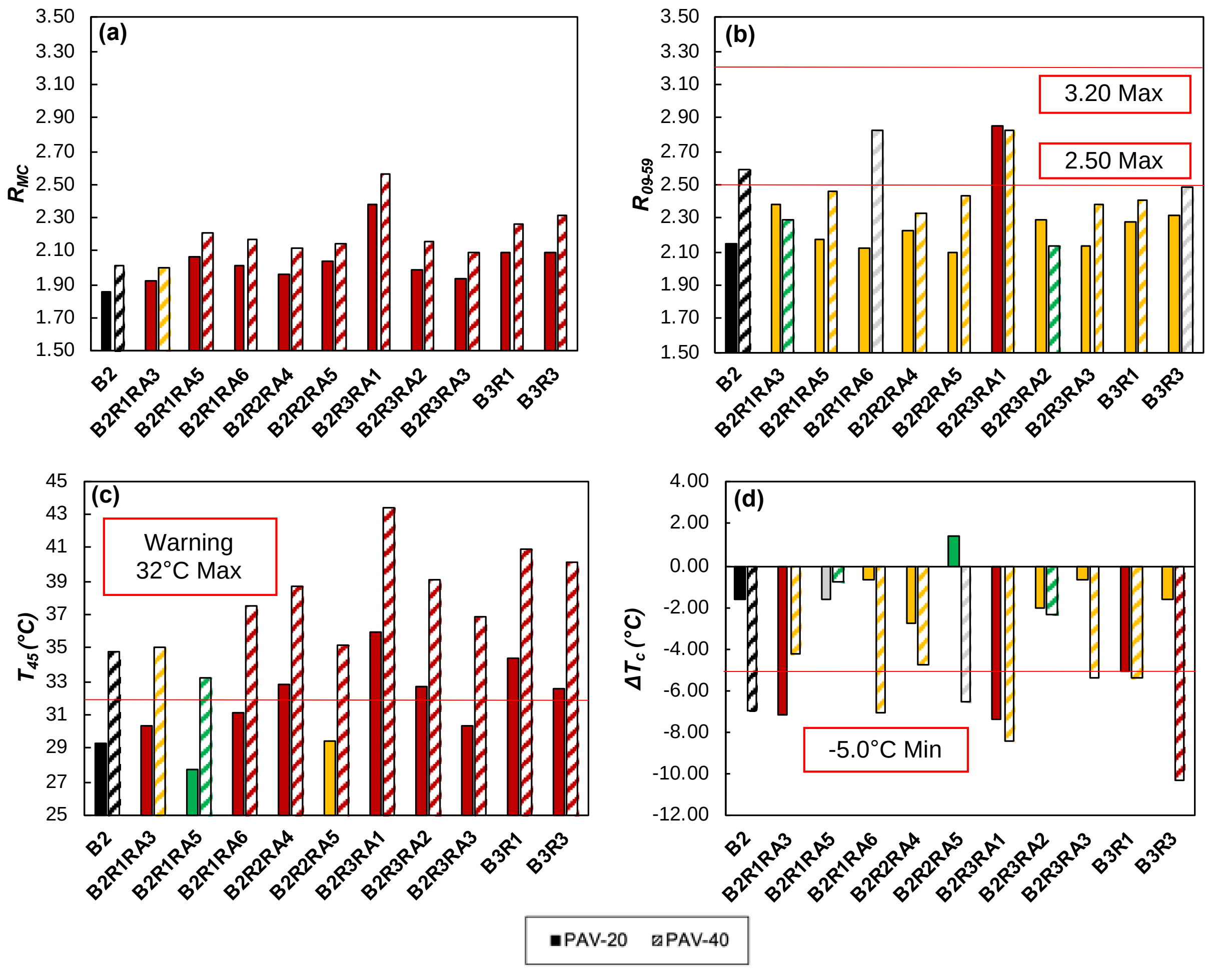

Figure 21. Rheological Balance Parameters (a) R_{MC}; (b) $R_{09\text{-}59}$; (c) T_{45}; (d) ΔT_c. Colors correspond to performance; black is target, green is better performance, yellow is equal performance, red is worse performance, and gray is removed. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Evaluation of the Reference Blends. Figure 19 shows that the reference blends generally has lower S(60) values and equal or higher m(60) values compared to the control PG 64S-22 binder (B2). This indicates that the use of PG 58-28 virgin binder to restore RAP binder characteristics softens to a greater extent rather than enhances relaxation characteristics. Figure 20 shows that the reference blends generally had poorer intermediate-temperature properties than the control PG 64S-22 virgin binder, with one blend (B3R1) failing the $GR_{25°C}$ limit. Figures 21a and 21c show that the reference blends exhibited inferior R_{MC} and T_{45} values compared to the control binder (B2), with T_{45} values that surpassed the warning limit, indicating a potential imbalance in stiffness and relaxation characteristics. In contrast, Figure 21b shows that the reference blends exhibited similar $R_{09\text{-}59}$ values to the control binder. Figure 21d reveals that the reference blends also had ΔT_c values consistent with those of the control binder in most cases. However, one reference blend exhibited a poorer ΔT_c than the PG 64S-22 virgin binder, which also fell below -5°C, which further indicates a potential imbalance in rheological characteristics. With respect to aging, the low-temperature parameters changed little with aging. B3R1 went from better to equal performance with the control; however, other blends remained unchanged. The intermediate-temperature parameters had more mixed changes with aging. For $GR_{15°C}$, the reference performance remained the same and increased more than the control. The |G*|sinδ values of the reference blends generally compared more favorably to the control B2 binder at the PAV-40 compared to the PAV-20 aging condition. With respect to B1, the reference blends did not improve, and they exhibited a worse performance than B1 at the PAV-40 aging condition. For $GR_{25°C}$, the performance of the reference blend B3R1 compared to the control was unaffected by aging and remained worse than both controls irrespective of the aging condition. B3R3 performed better than the control B2 at the PAV-40 aging condition by. Comparison of the rheological parameters R_{MC}, R_{09-59}, and T_{45} between the reference blends and controls showed that all had the same statistical test result at the PAV-20 and PAV-40 aging conditions. The ΔT_c showed mixed results when the reference blends were compared to the control at the PAV-40 aging condition, with B3R1 having slightly better results than B2 and B3R3 performing significantly worse and exceeding the threshold of -5.0°C.

Evaluation of the RA Blends. Figure 19 shows that the RA blends generally had better S(60) and equal or better m(60) results compared to the control virgin binder. As discussed previously, the manufacturers were asked to provide RA dosages to restore the low temperature to -22°C. The results suggest that the required dosage was controlled by restoration of the relaxation characteristics (i.e., m(60)), indicating that the additives generally soften to a greater extent rather than restore relaxation characteristics. Also noteworthy, there were a few cases where the B1 blends with RAs did not meet the minimum m(60) specified in AASHTO M 320-21 (B1R1RA1, B1R1RA2, B1R1RA3, and B1R2RA2). It can also be seen in Figure 19 that from PAV-20 to PAV-40 for m(60), there is generally not a change in how the reference blends compare to the control whereas for S(60), there are a few blends that have worse performance going from better to equal from PAV-20 to PAV-40, or in one case changing from better at PAV-20 to worse at PAV-40compared to the control. However, the overall change in findings across the two aging conditions is low across most blends.

Figure 20 shows that in the majority of cases evaluated, the RA blends have equal or better intermediate-temperature properties than the control virgin binder, with the blends containing RA5 having the most instances of better values. The primary exception is that the blends containing RA2 (tall oil) consistently exhibited inferior intermediate-temperature properties compared to the control virgin binder and tended to fail established limits. There are also select blends containing RA1, RA4, and RA6 that display inferior intermediate-temperature characteristics compared to the control binder. More of these cases are identified through the $GR_{25°C}$ and $GR_{15°C}$ parameters than through the standard |G*|sin(δ) parameter, with the $GR_{15°C}$ parameter indicating the most cases of potentially inferior performance in the blends. However, these blends generally passed established limits, and it is important to recognize that the control binders constituted only two PG 64S-22 virgin binders. As previously discussed, Figure 10e indicates that |G*|sin(δ) values of the RA-modified blends generally fall within the distribution of PG 64S-22 virgin binders in Virginia. When the effect aging had on the RA blends was examined, each of the three parameters had different results. |G*|sinδ exhibited an improvement in performance compared to the control for most blends at the PAV-40 compared to the PAV-20 aging condition. In most cases, the $GR_{15°C}$ values had the same Dunnett's test results at the two aging conditions, with a few additives such as RA1 and RA2 surpassing the allowable limit of 450 kPa at PAV-40. For $GR_{25°C}$, most blends compared more favorably to the control at PAV-40 than at PAV-20 for both B1 and B2 and a few blends retained the same comparative performance at the two aging conditions.

Figures 21a and 21c show that in most cases the RA blends exhibited inferior R_{MC} and T_{45} values compared to the control binder, consistent with the reference blends. Several cases failed the T_{45} warning limit. In contrast, Figures 21b and 21d show that the majority of the blends containing RAs had $R_{09\text{-}59}$ and ΔT_c values equal to the control binder. However, RA1 (VTAE) blends tended to have inferior ΔT_c values and $R_{09\text{-}59}$ values that in some cases failed established limits. This matches expectations because VTAE is known to contribute to poor relaxation characteristics that are captured through ΔT_c. Several RA3 blends exhibited inferior ΔT_c compared to the control binder that were not identified through $R_{09\text{-}59}$. Also noteworthy, several blends containing RA3 and RA5 had better ΔT_c values than the PG 64-22 virgin binders. With respect to aging (PAV-20 and PAV-40), most of the rheological parameters exhibited little change comparing the control binders. For R_{MC}, $R_{09\text{-}59}$, and T_{45}, there no substantial change in comparative performance of the blends to the control binders; blends that were worse than the control at the PAV-20 aging condition remained worse than the control after further aging (i.e., PAV-40). The results for ΔT_c were more mixed; however, the majority of blends did not experience large changes in the statistical test results with respect to the control.

Figure 22 shows the black space graphs for the binder blends containing B2. This graph shows that the virgin binder is located at the highest point on the graph and that the blends containing no additive have some of the lowest values. The values of a few blends do fall below the reference blends of B3R1 and B3R3; however, the values of most additives fall between the virgin binder and the reference blends. For the B2 graphs, the blends containing RA5 seem to be more similar to the B3R1 and B3R3 points. However, for the B1 blend, the lowest value is not for B3R1 or B3R3 but instead for a blend of B1R1RA1. It should be noted that this blend had worse performance compared to B1 for seven of the nine parameters examined.

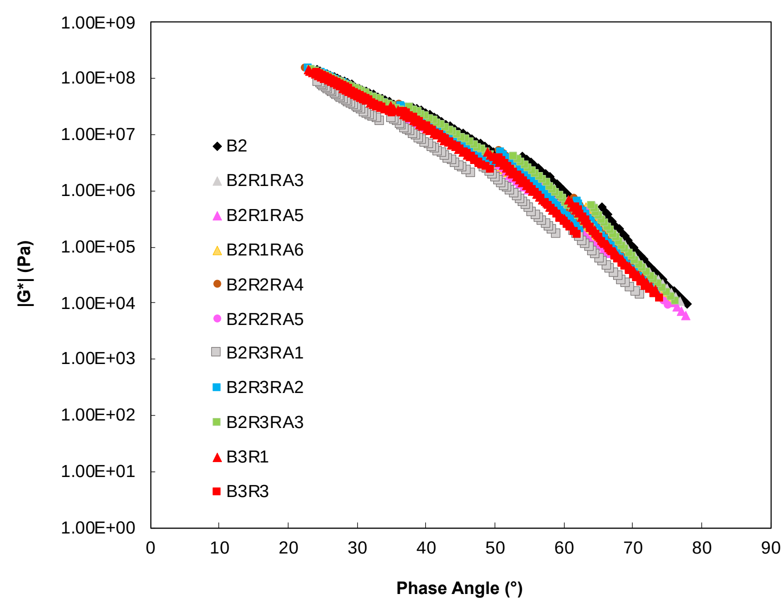

Figure 22. Black Space Graph for B2 Binder Blends and Reference Blends. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

An important aspect of the comparison between the PAV-20 and PAV-40 aging conditions was examining if the two aging conditions provided similar or distinct insight regarding the relative performance of the study binders and blends. The results in Table 11 show that most parameter results were positively correlated at the two aging conditions, indicating that the two conditions generally provide similar insights regarding the relative performance of the study binders and blends. The results of three parameters were not correlated at the two conditions: m(60), $R_{09\text{-}59}$, and ΔT_c. This could be related to the variability of some of the BBR results for blends containing additives and could have been affected by parameters directly calculated from m(60).

Table 11. Spearman's Correlation Coefficients Comparing PAV-20 and PAV-40

Parameter	Spearman's Rank Correlation
S(60)	0.77
m(60)	0.37
$\lvert G^*\rvert \sin(\delta)$	0.85
$GR_{25°C}$	0.84
$GR_{15°C}$	0.96
R_{MC}	0.94
$R_{09\text{-}59}$	0.08
T_{45}	0.96
ΔT_c	0.03

PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours.

Summary of Rheological Balance Outcomes

Collectively, the results demonstrate that the reference blends and blends containing RAs generally have S(60) and m(60) results similar to those of the PG 64S-22 virgin binders evaluated. This finding was expected because the manufacturers were asked to provide RA dosages to restore the low temperature to -22°C. However, there were a few exceptions where the blends with RAs did not meet the minimum m(60) specified in AASHTO M 320. Although the blends tended to have low-temperature properties similar to the PG 64S-22 virgin binders, the findings with respect to intermediate-temperature properties were mixed, with many cases of inferior performance in the recycled binder blends identified. Notably, the blends containing RA2 (tall oil) consistently exhibited inferior intermediate-temperature properties compared to the PG 64S-22 virgin binders. Also, although the intermediate-temperature parameters evaluated were all correlated, the $GR_{25°C}$ and $GR_{15°C}$ parameters identified more cases of potentially inferior performance in the recycled binder blends compared to the standard $\lvert G^*\rvert \sin(\delta)$ parameter, particularly in the case of blends containing RA1. Notably, RA1 failed to restore the phase angle to the same extent as the modulus of the recycled binder blends. The majority of the RA3, RA4, RA5, and RA6 blends (all derived from fatty acids and triglycerides) exhibited equal or better intermediate-temperature parameters compared to the PG 64S-22 virgin binders, with the blends containing RA5 having the most instances of better values.

In a final evaluation of the impact of the rheological balance testing parameters on RAs, it was seen that most additives did not improve performance and that aging had little impact on performance compared to virgin binders B1 or B2. R_{MC} and $R_{09\text{-}59}$ had no blends that performed better than the initial target of virgin binders B1 or B2. The majority of blends containing additives performed worse with respect to T_{45} and the control. Two additives that had better T_{45}

performance were RA3 and RA5. RA5 consistently showed better performance when compared to the target, regardless of aging condition. For ΔT_c, the only blends that had improved performance contained the additive RA5. All other blends were either worse or equal to the ΔT_c of the target, and blends containing RA1 and RA3 typically exceeded the threshold limit of -5.0°C, indicating poor performance (Asphalt Institute Technical Advisory Committee, 2019).

Overall, the rheological balance test parameters provided unique insight into the additives by indicating that RA1 and RA3 lead to worse performance whereas RA5 improves the performance of the blend compared to Virginia's PG 64S-22 binder. It should be remembered that a relatively high dosage of RA5 was specified by the corresponding manufacturer. The effect that aging had on the rheological balance testing parameters with respect to the target from PAV-20 to PAV-40 was minimal, which made sense given how strongly correlated most of the parameters were between the two aging conditions.

LAS Test Results

Overview

The fatigue life (i.e., N_f) at different strain levels for each binder blend was compared across the two aging conditions (PAV-20 and PAV-40). Although the recycled binder blends showed an either similar or better fatigue life compared to the corresponding virgin binders, the N_f at a given strain level (such as 5% or 15%) was found to be higher at PAV-40 compared to PAV-20 for most cases. This observation implies better fatigue resistance at the higher aging condition, which is counterintuitive and averse to the collective understanding of the pavement community. However, if a higher strain level such as 35% was chosen, the expected trend was observed. Chen and Bahia (2021) observed the same in their study and recommended using higher strains to evaluate changes in fatigue properties with aging. Table 12 shows the fatigue life estimations at different strain levels for both aging conditions.

Several indices derived from the LAS test were evaluated and are discussed in detail in Appendix H. Most of these indices consider different aspects of the stress-strain behavior response under a strain-controlled linear amplitude sweep. One thing that stays consistent across all these indices is that failure is considered at the occurrence of peak stress. However, in proposing a unified failure criterion for asphalt binders, Wang et al. (2015) showed that an analysis approach that incorporates the inherent viscoelasticity of the asphalt binder (the so-called pseudo-strain energy [PSE] approach) yields more consistent fatigue failure across binders and mixtures and can yield a fundamental relationship for full fatigue characterization of an asphalt binder. The evidence for this was further provided by Wang and Kim (2019), who proposed a PSE-based fatigue failure criterion for asphalt mixtures that required less testing for full characterization. In Appendix H, PSE-based analysis was explored to evaluate novel indices that can capture fatigue performance across different binders for different aging conditions. Figure 23 shows the PSE definitions employed in an LAS test. The undamaged line presents the LVE response of the binder to serve as a reference as if no damage took place with increasing loading. The blue dotted line represents the measured response, which shows deviation from the undamaged line as loading progresses, indicating the occurrence of damage.

Table 12. Fatigue Life Estimation for All Evaluated Binders at Different Strain Levels

Binder	N_f at 5%		N_f at 15%		N_f at 35%	
	PAV-20	PAV-40	PAV-20	PAV-40	PAV-20	PAV-40
B1	14,189	35,165	13.29	18.97	0.06	0.06
B1R1RA1	1,634,934	4,065,023	606.04	794.86	1.37	1.10
B1R1RA2	49,371	81,034	31.15	26.93	0.11	0.06
B1R1RA3	38,625	55,356	47.15	34.71	0.27	0.12
B1R1RA4	39,627	120,165	41.45	66.67	0.21	0.21
B1R2RA2	14,025	7,203	7.96	2.42	0.02	0.01
B1R2RA3	24,737	16,623	27.40	7.38	0.14	0.02
B1R2RA4	32,009	7,695	31.77	5.32	0.15	0.02
B1R2RA5	19,560	62,333	23.23	46.06	0.13	0.18
B1R2RA6	27,733	30,813	21.96	13.61	0.09	0.04
B1R3RA2	40,539	86,831	28.62	33.12	0.11	0.08
B1R3RA3	31,484	51,305	35.50	31.46	0.19	0.10
B1R3RA4	39,545	104,901	42.01	63.67	0.21	0.21
B1R3RA5	83,360	108,444	144.02	109.51	1.07	0.54
B1R3RA6	54,924	74,523	56.91	42.40	0.28	0.13
B2	14,893	19,120	21.28	13.78	0.14	0.05
B2R1RA3	14,077	41,492	19.49	29.32	0.12	0.11
B2R1RA5	30,088	110,274	44.32	119.10	0.29	0.61
B2R1RA6	34,967	81,916	42.42	48.20	0.24	0.16
B2R2RA4	22,948	16,602	24.11	9.09	0.12	0.03
B2R2RA5	16,722	87,045	26.49	82.98	0.18	0.39
B2R3RA1	248,431	1,408,892	184.94	498.05	0.72	1.08
B2R3RA2	27,698	28,191	29.24	15.00	0.15	0.04
B2R3RA3	11,528	18,944	12.06	11.42	0.06	0.04
B3	53,825	152,375	105.90	154.32	0.87	0.76
B3R1	53,981	191,977	42.64	73.66	0.17	0.17
B3R2RA4	32,678	31,194	27.24	14.67	0.11	0.04
B3R3	62,950	170,776	64.43	81.34	0.32	0.22

N_f = fatigue parameter; PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

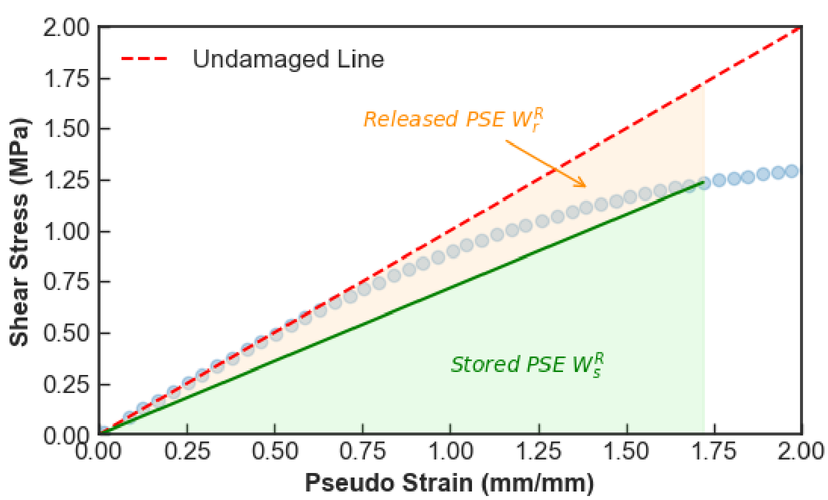

Figure 23. Liner Amplitude Sweep-Based Pseudo-Strain Energy Definitions. The undamaged line presents the LVE response of the binder to serve as a reference as if no damage took place with increasing loading. The blue dotted line represents the measured response, which shows deviation from the undamaged line as loading progresses, indicating the occurrence of damage. LVE = linear viscoelastic.

Wang et al. (2015) proposed peak stored PSE as the occurrence of failure in an LAS test instead of peak stress. They verified the fatigue life based on this failure definition and a drop in phase angle data and found good agreement, indicating that peak stored PSE is a reliable definition of fatigue failure in an LAS test. The current study built on this energy-based failure definition to propose a novel index that captures the ability of binders to withstand fatigue cracking in terms of stress level and strain tolerance at peak PSE.

Stress Level at Peak Stored PSE (S_L)

The experimental results demonstrated that the stored PSE shows a peak within the current LAS test framework in accordance with AASHTO TP 391-20. This peak generally occurs after the peak stress has occurred, as shown in Figure 24, indicating that the binder continues to retain its ability to store additional energy after the peak stress condition.

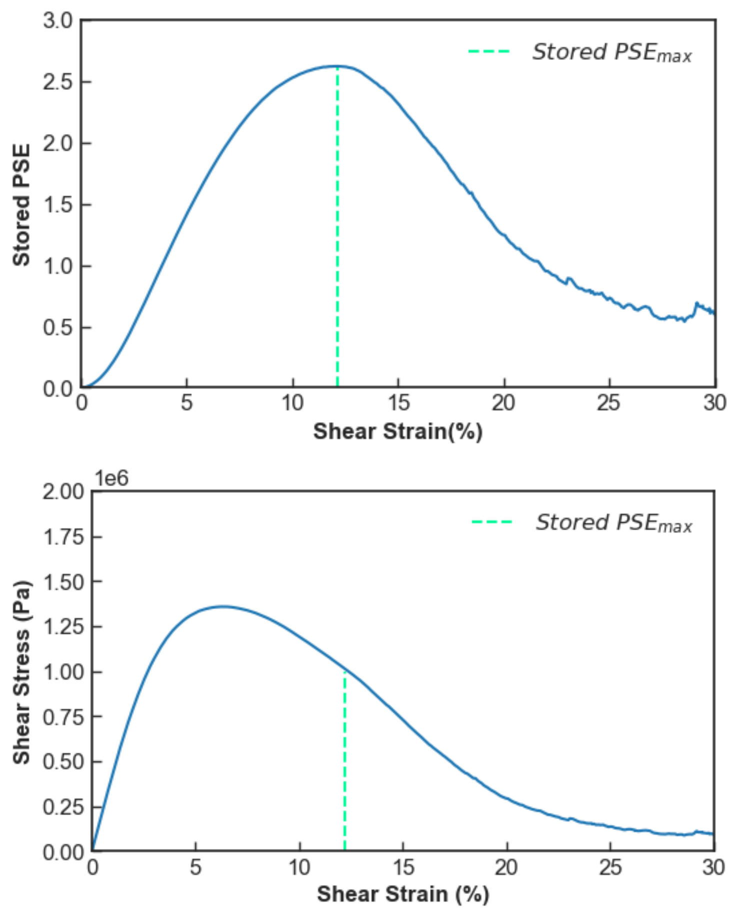

Figure 24. Schematic for Peak Stored Pseudo-Strain Energy (PSE) and the Corresponding Shear Stress

The shear stress at the peak stored PSE can be considered a metric to compare the shear capacity until failure. In other words, this refers to the ability of the binder to continue resisting fatigue failure even after the peak stress is reached. In order to obtain a normalized parameter, the ratio of stress at peak stored PSE to the peak stress termed as stress level at peak stored PSE (S_L) is taken as an index parameter to characterize the fatigue resistance of asphalt binders and is calculated using Equation 18. A higher value of S_L indicates higher fatigue resistance capacity. It is expected to decrease with aging.

$$S_L = \left(\frac{\tau_{peak\ stored\ PSE}}{\tau_{peak\ stress}}\right) * 100 \quad \text{[Eq. 18]}$$

The studied binders were evaluated using S_L for both aging conditions (PAV-20 and PAV-40), and it was found that S_L for binders B1, B2, and B3 was higher for most of the corresponding binder blends containing RAs. The RA5 blends, which generally have a higher RA dosage, showed a higher S_L as compared to other binder blends. RA1, which is observed to have a negative impact on cracking performance, showed a low S_L across aging conditions. S_L seems to capture the impact of aging consistently across all studied binders and decreases with aging, as shown in Figure 25. Among the RA blends, RA1 blends showed the highest sensitivity to aging, with S_L decreasing by about 14% and 28% for B1R1RA1 and B2R3RA1, respectively.

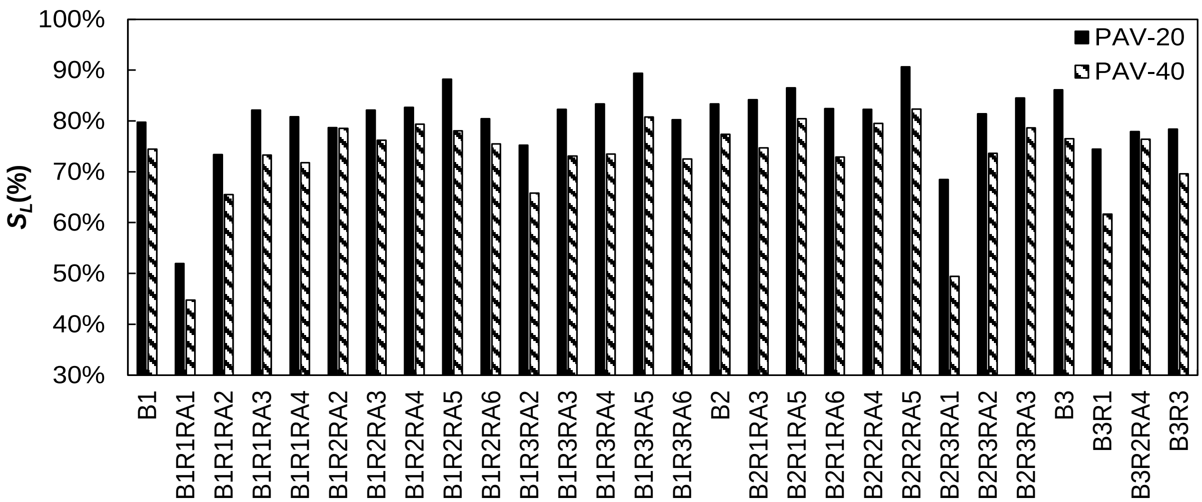

Figure 25. S_L for All Evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours.

In terms of ranking the binders at the PAV-20 and PAV-40 aging conditions, RA1 blends showed the worst fatigue performance for both whereas most RA5 blends showed the best fatigue performance for both in terms of S_L. Binder B3, which is a PG58-28 binder and was expected to show better fatigue performance owing to a softer grade, ranked high in terms of S_L. The relative ranking of the studied binders in terms of S_L is shown in Table 13 for both aging conditions. It can be seen that the relative ranking changes from PAV-20 to PAV-40; however, as discussed, most of the best and the worst binder blends in terms of fatigue performance retained the same or similar relative rankings. The change in rankings can be attributed to varying sensitivity to aging of the base binders, RAP binders, RA types, source of respective binders, the interaction of these three constituents in the binder blends, RA dosage, etc., among several other factors.

An important aspect of the comparison between the PAV-20 and PAV-40 aging conditions was examining if the two aging conditions provided similar or distinct insight regarding the relative performance of the study binders and blends in terms of S_L. The results presented in Table 13 were used to calculate Spearman's rank correlation coefficient, which was found to be 0.76, indicating that the S_L results were positively correlated at the two aging conditions. This essentially means that the two aging conditions generally provide similar insight regarding the relative performance of the study binders and blends in terms of S_L.

Table 13. Relative Ranking of Binder Blends Based on S_L for PAV-20 and PAV-40 Aging Conditions

Binder	Relative Ranking	
	PAV-20	PAV-40
B1	20	15
B1R1RA1	28	28
B1R1RA2	26	25
B1R1RA3	14	18
B1R1RA4	17	22
B1R2RA2	21	7
B1R2RA3	15	12
B1R2RA4	10	5
B1R2RA5	3	8
B1R2RA6	18	13
B1R3RA2	24	24
B1R3RA3	12	19
B1R3RA4	8	17
B1R3RA5	2	2
B1R3RA6	19	21
B2	9	9
B2R1RA3	7	14
B2R1RA5	4	3
B2R1RA6	11	20
B2R2RA4	13	4
B2R2RA5	1	1
B2R3RA1	27	27
B2R3RA2	16	16
B2R3RA3	6	6
B3	5	10
B3R1	25	26
B3R2RA4	23	11
B3R3	22	23

SL = stress level at peak stored PSE; PSE = pseudo-strain energy; PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent. The color palette corresponds to the relative ranking of the binder blends based on S_L, with green corresponding to the highest rank (1) and red corresponding to the lowest rank (28). The color of each cell corresponds to the rank entry in that cell.

Fourier Transform Infrared Spectroscopy (FTIR) Results

The FTIR spectra for some of the blends evaluated in this study are presented in Figures 26 through 28. The remaining FTIR spectra for all virgin binders and binder blends evaluated in this study are presented in Appendix I. Each subfigure contains the spectra for RTFO and the PAV-20 and PAV-40 aging conditions.

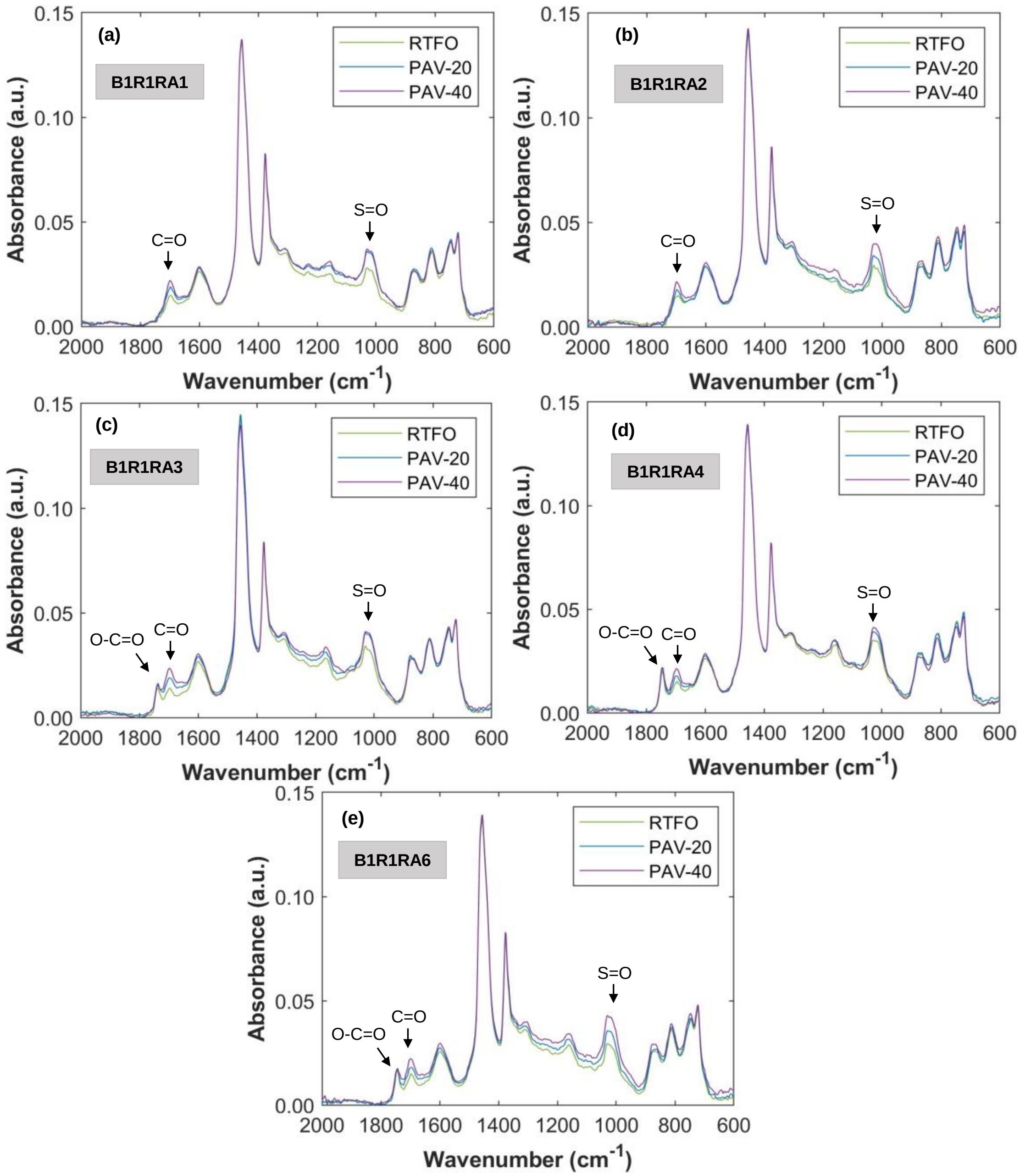

Figure 26. FTIR Spectra for B1R1 Blends: (a) B1R1RA1; (b) B1R1RA2; (c) B1R1RA3; (d) B1R1RA4; (e) B1R1RA6. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

As mentioned previously, the experimental data were recorded in the 600 to 4000 cm^{-1} range. However, since no changes were observed with oxidative aging at wavenumbers greater than 2000 cm^{-1}, the spectra were plotted from 600 cm^{-1} to 2000 cm^{-1} to make the graphs clearer to the reader. In all subfigures, the carbonyl I and sulfoxides (S) absorbance peaks, located at the wavenumber 1700 cm^{-1} and 1030 cm^{-1}, respectively, are shown. The increase in these absorbance peaks is usually associated with the formation of oxidation products.

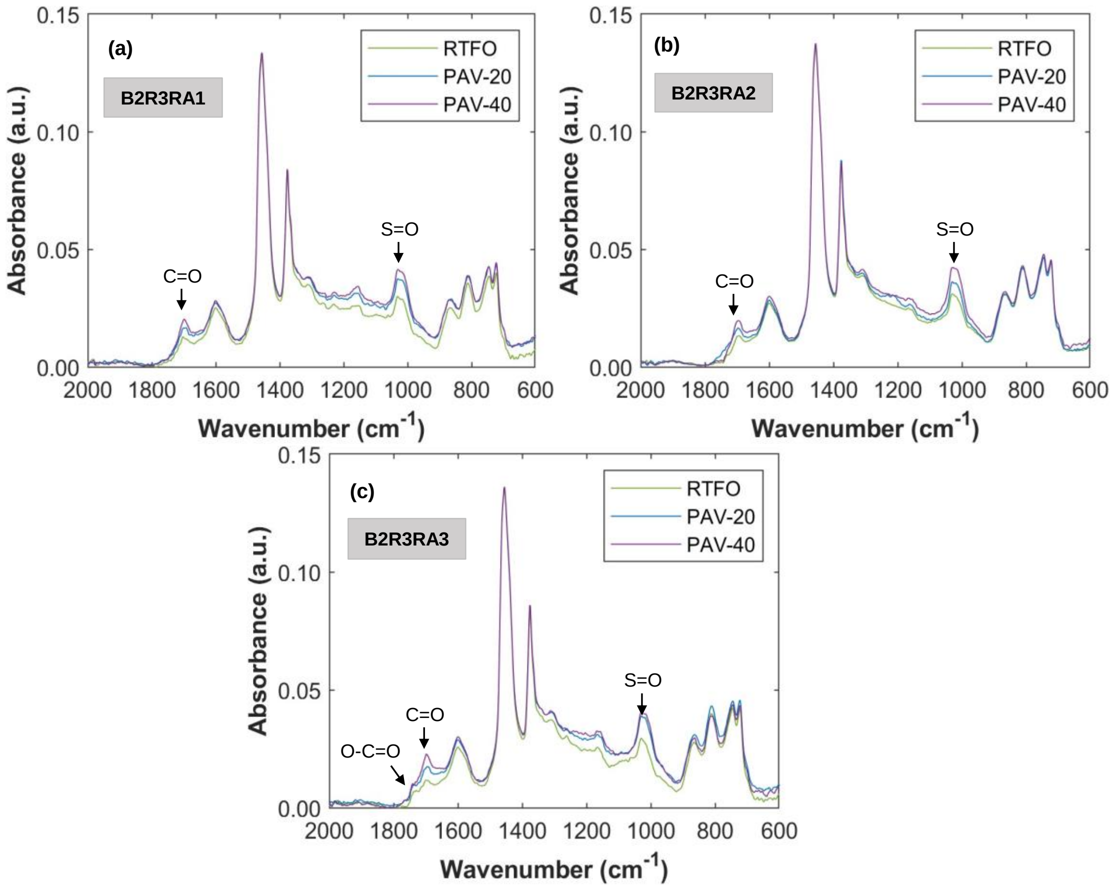

Figure 27. FTIR Spectra for B2R3 Blends: (a) B2R3RA1; (b) B2R3RA2; (c) B2R3RA3. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

In general, virgin binders and blends showed an increase in the carbonyl and Sulfoxide (C+S) peaks with an increase in long-term aging time. However, the rate of change of C+S peaks with respect to aging time is specific for each blend, as shown in Figure 29 for a subset of the blends. The growth of C+S peaks with respect to long-term aging time for the rest of the binders is provided in Appendix I. Further, a peak at 1743 cm^{-1} was observed for blends prepared with RA3, RA4, RA5, and RA6. This peak has been observed in other studies with bio-based additives, and it is attributed to the presence of compounds with carbonyl groups from esters, ketones, or acids (Fini et al., 2020b; Garcia-Culacon et al., 2017).

A complementary analysis was conducted to correlate the growth of chemical aging indices with the rheological properties that are believed to be associated with the material's durability. Based on the findings of the durability analysis in this study, the $GR_{15^\circ C}$ and R_{MC} were used for this purpose. Although only the PAV-20 and PAV-40 aging conditions were discussed previously, RTFO data are presented herein to have three points and show the linear relationship between the rheological properties and the oxidation indices.

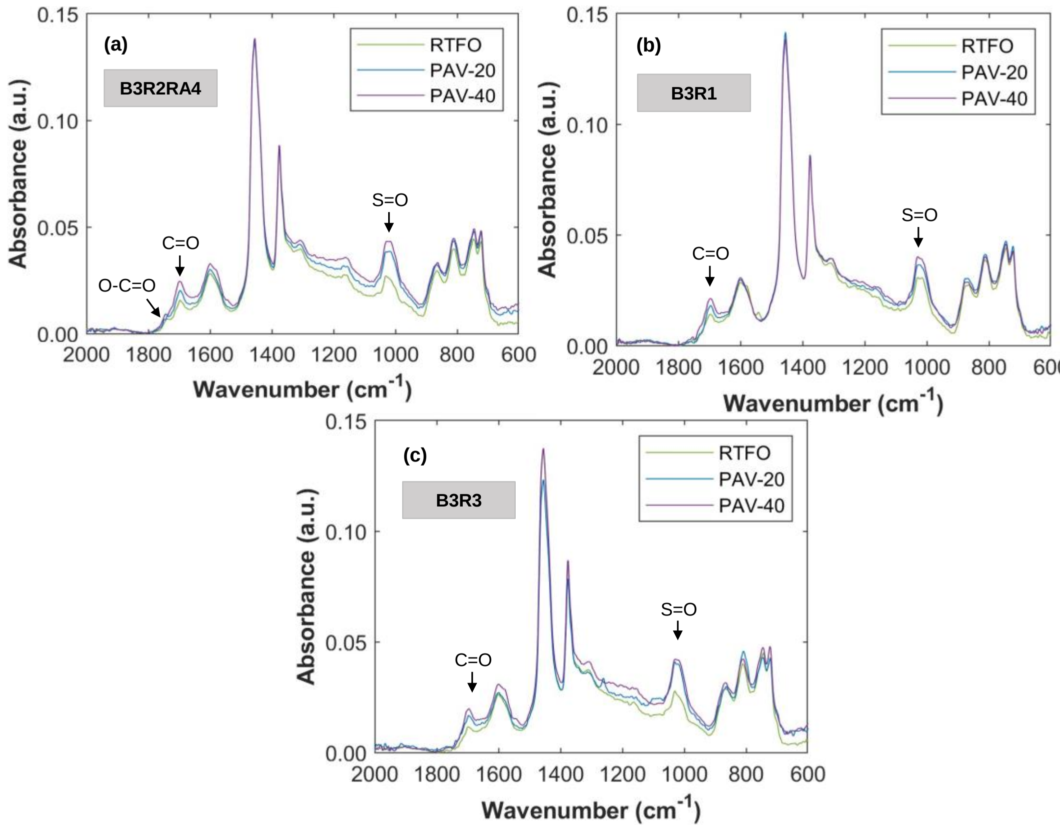

Figure 28. FTIR Spectra for B3 Blends: (a) B3R2RA4; (b) B3R1; (c) B3R3. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

Figures 29b and 29c show the relationship between log $GR_{15°C}$ and R_{MC} with C+S peaks, with slopes that represent a type of hardening susceptibility. The rate of change of log $GR_{15°C}$ and R_{MC} with respect to C+S growth was calculated for the remaining blends. Corresponding tables are provided in Appendix I. As observed collectively from all data presented and discussed in this section and Appendix I, the B3 binder exhibited the least sensitivity to oxidation among the virgin binders, as measured by the rate of change of C+S with respect to long-term aging time; however, this binder experienced a greater increase in log $GR_{15°C}$ and R_{MC} than B1 and B3 with respect to C+S growth.

Analyzing the oxidation parameters and their relationship to durability-related parameters becomes more complicated for the blends since each constituent of the binders (virgin and recycled) might present different oxidation kinetics, in addition to the complexity associated with the specific chemical structure of the RA and the dosage used for each case. Therefore, the inferences of the effect of RAs on the oxidation and hardening susceptibility of the blends should be made based on the same virgin plus recycled binder combination. For example, RA4 exhibited the highest hardening susceptibility when defined using log $GR_{15°C}$ for the B1R1 blends, followed by RA3. For the same set of blends, RA1 showed the highest hardening susceptibility in terms of R_{MC}, followed by RA4. RA6 exhibited the lowest aging susceptibility for both parameters.

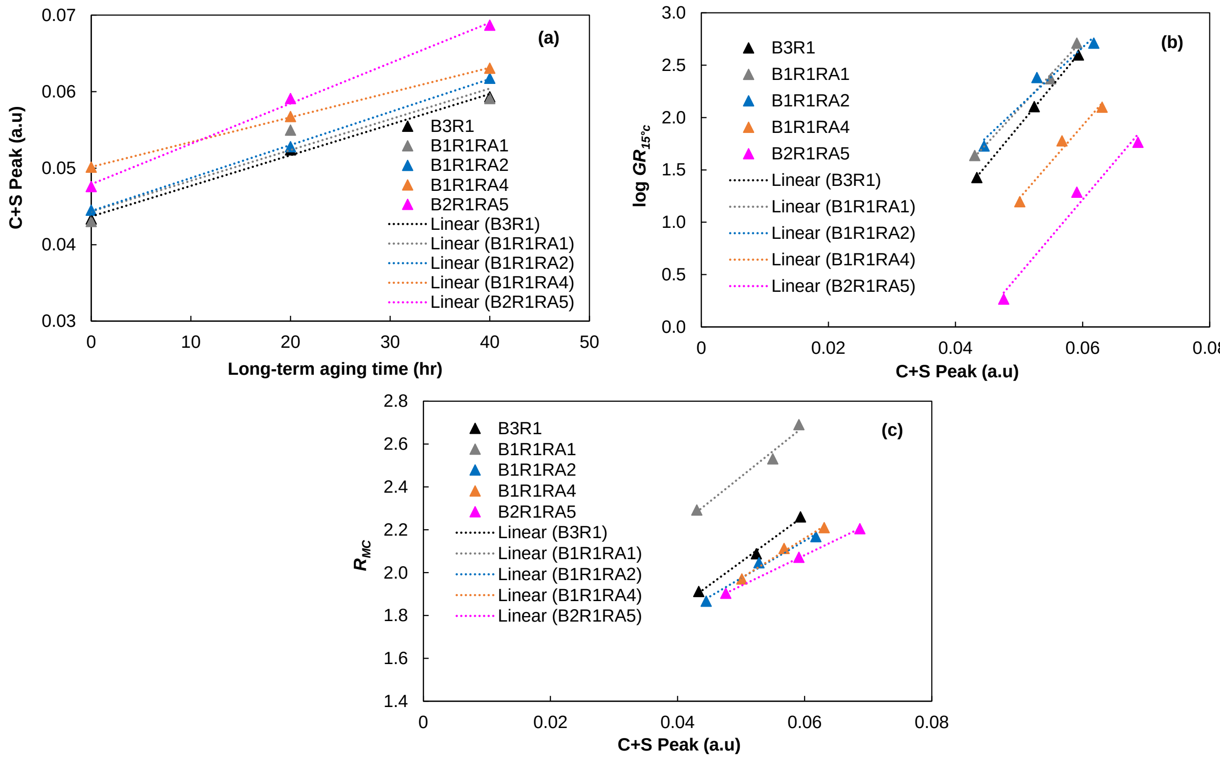

Figure 29. FTIR for a Subset of Source 1 Blends: (a) changes of C+S with respect to aging time; (b) change of log $GR_{25°C}$ with respect to C+S; (c) change of R_{MC} with respect to C+S. FTIR = Fourier transform infrared spectroscopy; C = carbonyl; S = sulfoxide; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; GR = Glover-Rowe parameter; R = rheological index.

For the B1R2 blends, RA6 also exhibited the lowest aging susceptibility compared to RA2, RA3, RA4, and RA5; however, for this set of blends, RA3 showed higher susceptibility than RA4, indicating that the relative ranking of hardening flipped. The change in ranking can be attributed to the interaction between R1 and R2 with the chemical structure of the different RAs and the dosage recommended by the manufacturer for each blend to restore the PGL to -22°C. Although some general inferences can be made, for example, B1R2 blends showed generally lower slopes than B1R1 and B2R1 blends, care should be taken when comparing the chemo-rheological relationships of different RAs since the presence of competing carbonyl peaks from fatty acids and esters in the different RAs might be influencing and biasing the results.

As discussed by Epps-Martin et al. (2020) in NCHRP Project 09-58, FTIR alone does not provide sufficient information to evaluate RAs since the growth of oxidation products does not translate consistently into the deterioration of performance. Further, chemo-mechanical and hardening susceptibility analyses focus mainly on rates of changes in rheological properties with respect to the growth of oxidation products. However, this parameter itself does not provide information on where the blends are located in the black space diagram; this means that although there might be a blend with low hardening susceptibility, it might present $GR_{15°C}$ and R_{MC} values outside the proposed limits for durability-related cracking.

Saturate, Aromatic, Resin, and Asphaltene (SARA) Test Results

The research team attempted to conduct SARA analysis in accordance with the method proposed by Sakib and Bhasin (2019). However, after numerous attempts and procedural refinements, repeatable and reproducible results for the maltenes fractions (saturates, aromatics, resins) could not be achieved. Given these challenges, a small set of samples were sent to an outside testing services laboratory for Iatroscan analysis. The results indicated that VTAE-based RAs primarily affect the saturates content and RAs derived from triglycerides mainly affect the resins contents, matching reports in the literature (Haghshenas et al., 2020). However, changes in SARA composition invoked by the RAs could not be directly tied to rheology or aging susceptibility, at least partially because most RA blends contained PG 64S-22 virgin binders whereas the reference blends contained PG 58-28 virgin binder and the effects of the virgin binder on the SARA composition was more pronounced than the RAs. Therefore, additional testing was not conducted.

Laboratory Evaluation of Asphalt Mixtures

In Phase II of the study, a few recycled binder blends that were evaluated in Phase I were selected for further laboratory evaluation. This evaluation involved replicating previously designed existing asphalt mixtures. A total of 10 mixtures were produced and assessed in the laboratory, divided into two groups: Group I: Mixtures B3R2, B3R2RA4, B3R3, B1R3RA6, B3R1, B2R1RA5, and B1R1RA2; and Group II: Mixtures b1R3RA5, B1R1RA1, and B1R1RA4. The main distinction between the two groups is that Group I underwent more extensive testing in the laboratory compared to Group II, as indicated in Table 14.

Table 14. Experimental Program for Phase II of the Study

<table>
<tr><th rowspan="3">Group</th><th rowspan="3">Mix ID</th><th colspan="2" rowspan="2">Verification</th><th colspan="10">Aging Condition / Performance Test</th></tr>
<tr><th colspan="6">STOA</th><th colspan="3">LTOA 3D 95</th><th>LTOA 1D 95</th></tr>
<tr><th>Aggregate Gradation</th><th>Mix Design</th><th>CML</th><th>APA</th><th>IDT-CT</th><th>|E*|</th><th>CF</th><th>SSR</th><th>IDT-CT</th><th>|E*|</th><th>CF</th><th>IDT-CT</th></tr>
<tr><td>I</td><td>B3R2</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td></td><td>B3R2RA4</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td></td><td>B3R3</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td></td><td>B1R3RA6</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td></td><td>B3R1</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td></td><td>B2R1RA5</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td></td><td>B1R1RA2</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>II</td><td>B1R3RA5</td><td>✓</td><td>✓</td><td>✓</td><td>--</td><td>✓</td><td>✓</td><td>✓</td><td>--</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td></td><td>B1R1RA1</td><td>✓</td><td>✓</td><td>✓</td><td>--</td><td>✓</td><td>✓</td><td>✓</td><td>--</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td></td><td>B1R1RA4</td><td>✓</td><td>✓</td><td>✓</td><td>--</td><td>✓</td><td>✓</td><td>✓</td><td>--</td><td>--</td><td>--</td><td>--</td><td>--</td></tr>
</table>

STOA = short-term oven aged; LTOA = long-term oven aged; 3D 95 = 3 days at 95°; 1D 95 = 1 day at 95°C; CML = Cantabro mass loss; APA = Asphalt Pavement Analyzer; IDT-CT = indirect tensile cracking test; |E*| = dynamic modulus; CF = cyclic fatigue; SSR = stress sweep rutting.

Aggregate Gradations and Volumetric Properties of Evaluated Mixtures

As discussed previously, this study considered three mixtures produced using aggregate and RAP materials from three different sources in Virginia. The variations in the evaluated mixtures, as part of Phase II, were limited to the virgin binder and RAs used. The combined mixture gradation for each source was verified, as shown in Figure 30. It is important to note that although all the aggregate and RAP stockpiles were individually verified for Source 3, the contractor did not provide the combined mix design gradation for comparison. Therefore, the combined mixture was accepted as is for further mixture verification.

Table 15 summarizes the volumetric properties for the 10 evaluated mixtures. The major change noted among the mixtures was a decrease in the OBC for Source 3 mixtures (i.e., 5.7%) compared to the OBC for Source 1 and 2 mixtures (i.e., 6.4%). All evaluated mixtures had an air-void content at OBC ranging from 2.6% to 4.5%; a VMA ranging from 15.5% to 18.0%; and a VFA ranging from 72.4% to 83.1%.

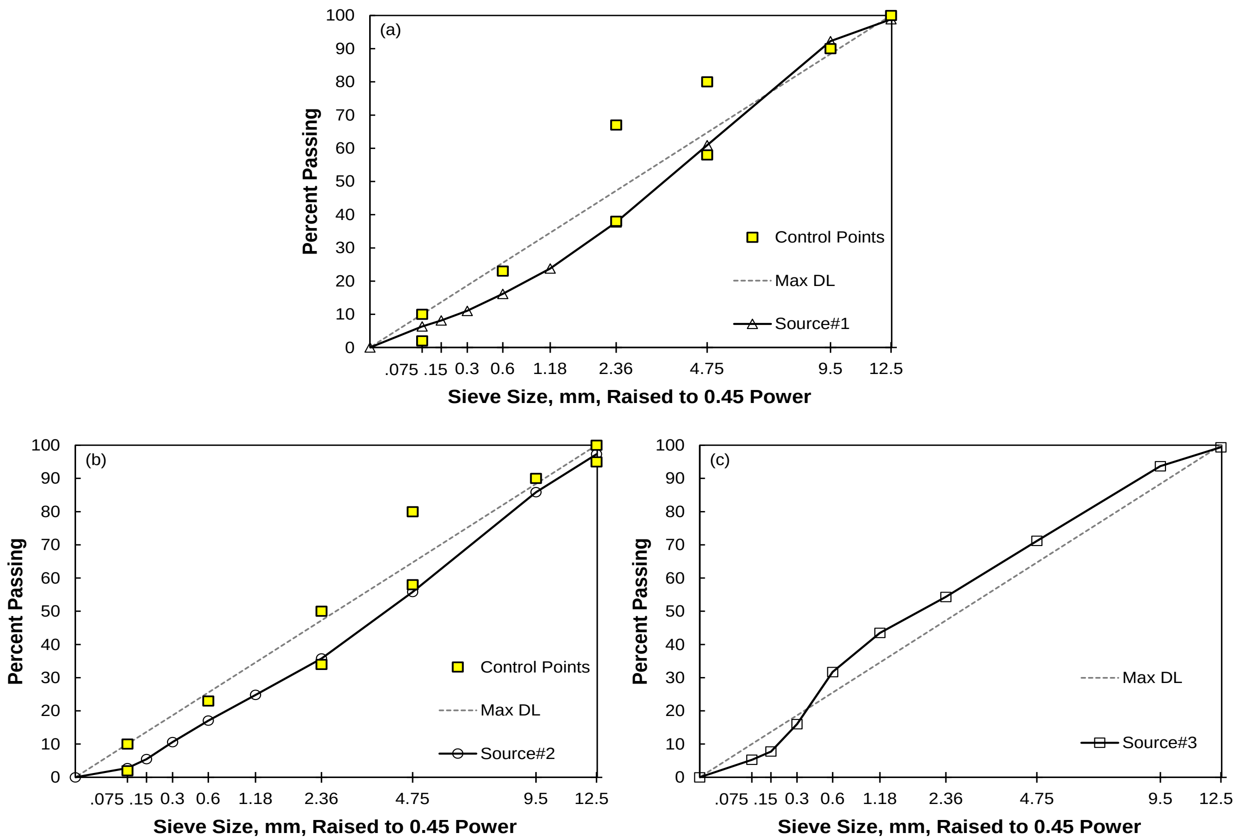

Figure 30. Combined Gradations for All Three Sources: (a) Source 1 from Salem; (b) Source 2 from Burkeville; (c) Source 3 from Chesapeake. DL = density line.

Table 15. Composition and Volumetric Properties for All Evaluated Mixtures

Parameter	Mix ID									
	B3R2	B3R2RA4	B3R3	B1R3RA6	B3R1	B2R1RA5	B1R1RA2	B1R3RA5	B1R1RA1	B1R1RA4
Composition										
RAP Content, %	35	35	45	45	40	40	40	45	40	40
RAP Source	R2	R2	R3	R3	R1	R1	R1	R3	R1	R1
Virgin Binder Source	B3	B3	B3	B1	B3	B2	B1	B1	B1	B1
Asphalt Binder PG	58-28	58-28	58-28	64S-22	58-28	64S-22	64S-22	64S-22	64S-22	64S-22
RA Source	No RA	RA4	No RA	RA6	No RA	RA5	RA2	RA5	RA1	RA4
RA Dosage[a], %	0.0	1.2	0.0	3.9	0.0	9.2	4.3	8.6	15.4	6.2
Volumetric Properties										
N_{design}, gyrations	50	50	50	50	50	50	50	50	50	50
NMAS, mm	12.5	12.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Binder Content, %	5.7	5.7	5.7	5.7	6.4	6.4	6.4	5.7	6.4	6.4
Rice SG (G_{mm})	2.485	2.482	2.454	2.456	2.545	2.535	2.530	2.449	2.528	2.521
Aggregate Effective SG (G_{se})	2.717	2.713	2.678	2.680	2.830	2.816	2.810	2.671	2.807	2.798
Aggregate Bulk SG (G_{sB})	2.698	2.698	2.637	2.637	2.765	2.765	2.765	2.637	2.765	2.765
VTM, %	3.0	2.6	4.5	4.4	3.7	4.5	4.3	4.3	4.2	3.6
VMA, %	15.8	15.5	16.2	16.1	17.5	18.0	18.0	16.2	18.0	17.8
VFA, %	80.8	83.1	72.4	72.5	75.7	75.2	76.2	73.5	76.7	79.6
FA Ratio	0.51	0.51	1.03	1.04	1.12	1.09	1.08	1.01	1.07	1.05

RAP = reclaimed asphalt pavement; B = virgin binder; R = RAP binder; RA = recycling agent; PG = performance grade; S = standard traffic; N_{design} = number of Superpave design gyrations; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA ratio= fines to asphalt ratio.

[a] Dosage is provided by weight of virgin binder.

Durability Assessment of Mixtures (Cantabro Test Results)

Figure 31 shows the ML for Source 1, 2, and 3 mixtures. The mean ML for Source 1 mixtures ranged from 4.2% to 6.3%, with an average coefficient of variation (COV) of 8%. For Source 2 mixtures, the mean ML ranged from 7.7% to 8.2%, with an average COV of 11%. Last, the ML of Source 3 mixtures ranged from 6.3% to 7.2%, with an average COV of 14%. In most cases, the mixtures with RAs exhibited ML values similar to those of their reference conditions, indicating a similar durability and resistance to abrasion under loading. A superior performance was observed with B2R1RA5, which seemed to exhibit a lower ML (Appendix J provides the details of the statistical analysis). Further, the results indicated that Source 1 and 3 mixtures met the VDOT BMD Cantabro criterion of 7.5% whereas Source 2 mixtures did not, regardless of the binder type/source used in the mixture. Hence, it is necessary to modify other factors in the mix design, such as gradation, binder content, etc., to achieve a mixture with satisfactory durability and resistance to abrasion.

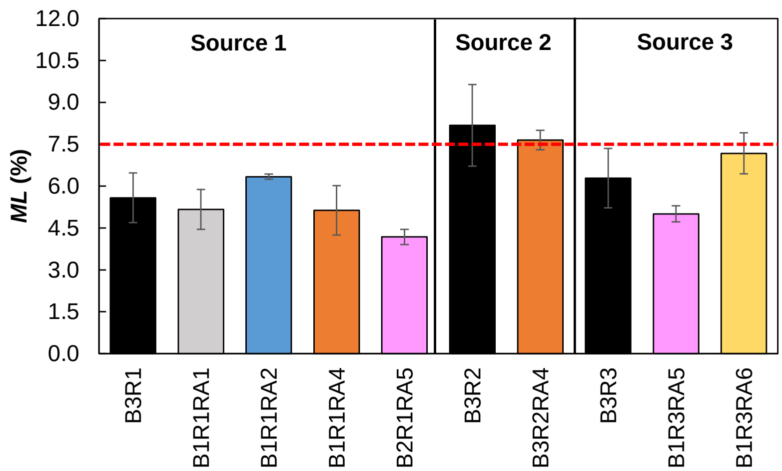

Figure 31. Performance Test Data for Cantabro Mass Loss of Source 1, 2, and 3 Mixtures. I-bars indicate mass loss variability ± 1 standard deviation. ML = mass loss; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent. Red dashed line = balanced mix design special provision limit for surface asphalt mixtures with A and D designations.

Mechanical Properties of Mixtures (LVE Test Results)

Figure 32 presents the |E*| master curves in logarithmic and semi-logarithmic scales and the δ master curves for Source 1 mixtures at the STOA condition using a reference temperature of 21.1°C. Figures 32a and 32b show the 2S2P1D model fitting of the dynamic modulus obtained using FlexMAT Cracking, Version 2.1.3b. Figure 32b shows that blending the PG 64S-22 binder (B1) with RAs at the dosage recommended by each manufacturer to restore the PGL of the blended binder system to -22°C yielded asphalt mixtures with a modulus generally lower than for B3R1 at the high reduced frequency range (corresponding to low temperatures). This was the case for most mixtures except B1R1RA2, which did not present a significantly different modulus master curve than B3R1 at a 95% confidence level. The details of the statistical analysis performed on |E*| and δ data are provided in Appendix K.

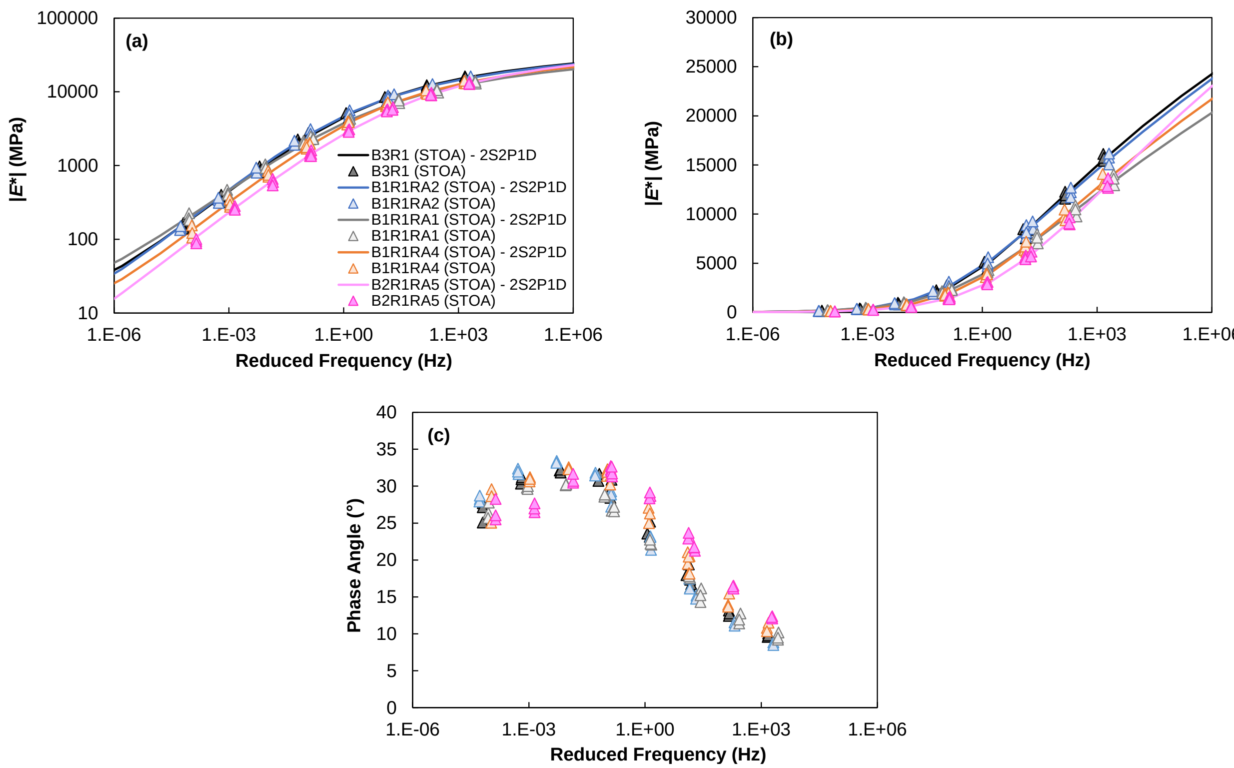

Figure 32. Linear Viscoelastic Characterization of Source 1 Mixtures: (a) dynamic modulus in logarithmic space; (b) dynamic modulus in semi-logarithmic space; (c) phase angle. |E*| = dynamic modulus; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

It is well documented that the effect of oxidative aging on the modulus of asphalt mixtures is more pronounced at the low reduced frequencies (corresponding to high temperatures) since at this condition, the modulus is associated with the binder rheological response (Saleh et al., 2020). Of interest, the statistical analysis revealed that the modulus of B1R1RA1 and B1R1RA4 was significantly different than that of B3R1 at the high reduced frequency range (corresponding to low temperatures) but not at the low reduced frequency range, where usually the effect of aging is present. This and previous observations suggest that although most RAs have a softening effect, the relative decrease in modulus is not constant throughout the complete frequency and temperature domains and depends on the specific RA/dosage used.

Figure 32c presents the phase angle master curves of Source 1 mixtures. The results indicate that B2R1RA5 had a more viscous material response than B3R1 at most frequencies and temperatures. Different trends are observed with the rest of the mixtures in Figure 32c. For instance, B1R1RA4 has phase angle values significantly different than for B3R1 at the high but not at the low reduced frequency range. The opposite behavior was exhibited by B1R1RA1. The results indicate that although there is a softening effect of RA1 at low temperatures, this is not necessarily accompanied by a change in the viscous versus elastic tendencies of the material. In general, the relative increase in phase angle depends on the RA type and probably RA dosage.

Figures 33a and 33b present the dynamic modulus master curves in logarithmic and semi-logarithmic scales for Source 2 mixtures at the STOA condition using a reference temperature of 21.1°C. The results indicated no significant effect of the RA4 on the dynamic modulus of the B3R2 system. Similar results are seen in the phase angle master curve presented in Figure 33c. These observations can challenge the effectiveness of the RA4 product; however, it should be recalled that the dosage level used for this mixture was 0.9% by the total weight of binder, which may be insufficient to produce significant changes in the LVE response of the material.

Figures 34a and 34b present the dynamic modulus master curves in logarithmic and semi-logarithmic scales for Source 3 mixtures at the STOA condition using a reference temperature of 21.1°C. B1R3RA6 exhibited the same dynamic modulus master curve as the reference mixture, B3R1. This result (the RA mixture having the same master curve as the reference mixture) was already seen with B1R1RA2 and B3R1. At first glance, it might seem that the dosage selected for B1R3RA6 and B1R1RA2 was either too low or the RA was ineffective. However, it should be recalled that these mixtures are benchmarked in this study against their reference mixture, which does not necessarily represent a control condition. Since B1R1 and B1R3 (control mixtures) are probably stiffer than B3R1 and B3R3 (reference mixtures), respectively, it is believed that RA6 and RA2 at the specified dosages are effective in reducing the modulus of the control mixture. Such effectiveness cannot be quantified given that the dynamic modulus of B1R1 and B1R3 was not characterized in this study; however, it is still important from a practical perspective that a similar performing mixture can be achieved using a PG 64S-22 binder with RAs.

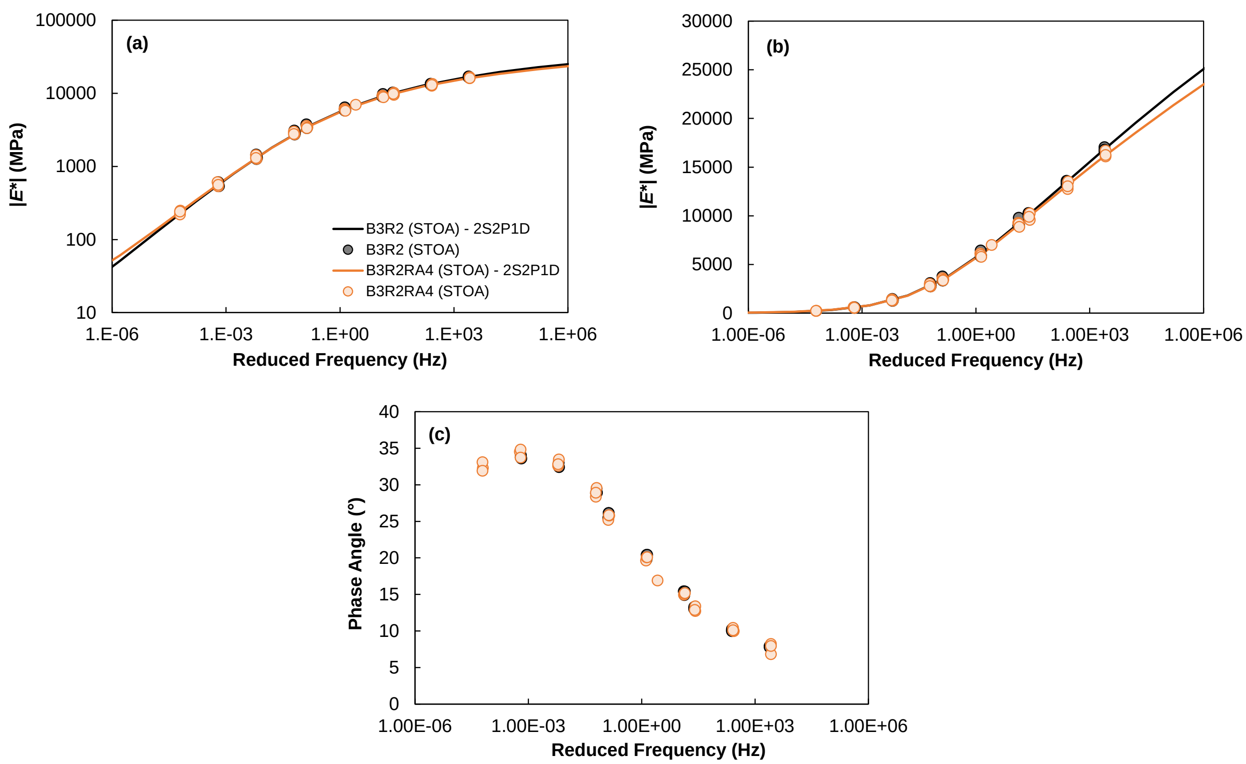

Figure 33. Linear Viscoelastic Characterization of Source 2 Mixtures: (a) dynamic modulus in logarithmic space; (b) dynamic modulus in semi-logarithmic space; (c) phase angle. |E*| = dynamic modulus; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

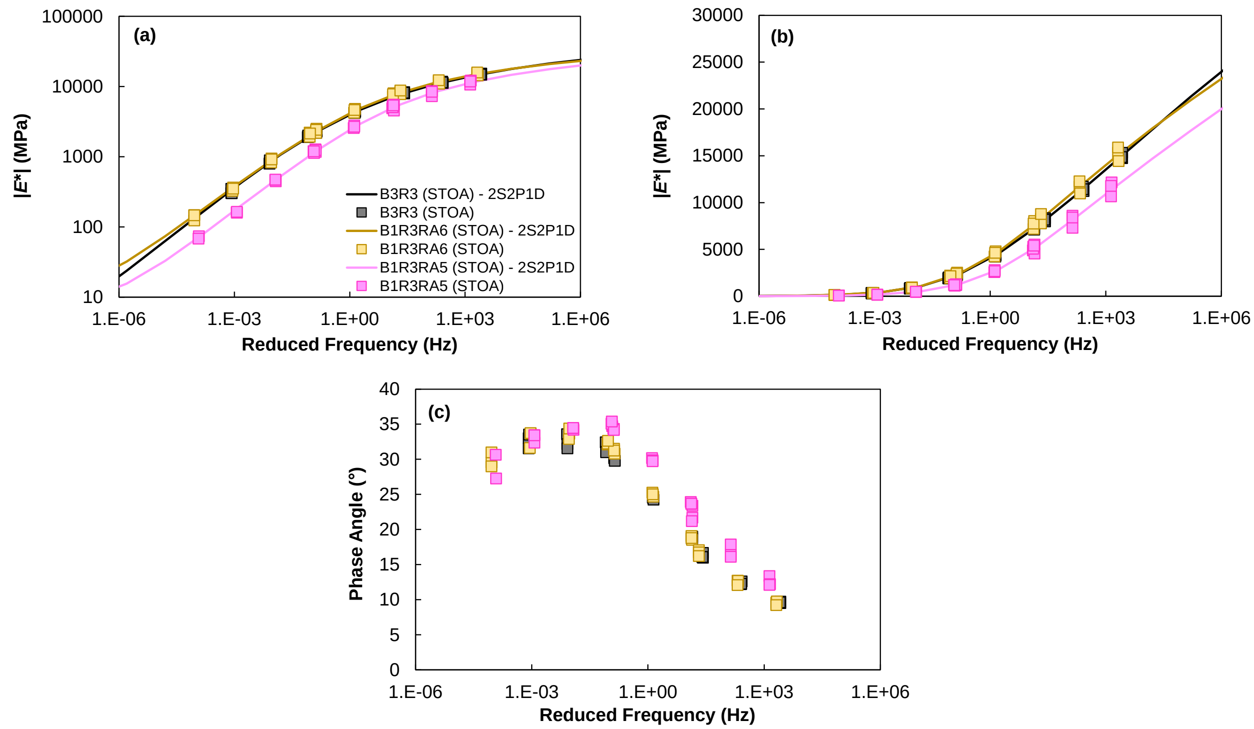

Figure 34. Linear Viscoelastic Characterization of Source 3 Mixtures: (a) dynamic modulus in logarithmic space; (b) dynamic modulus in semi-logarithmic space; (c) phase angle. |E*| = dynamic modulus; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Figures 34a and 34b show that B1R3RA5 has modulus values lower than the reference mixture, which was also observed with B2R1RA5 and B3R1. Both results are attributed to the relatively high dosage of RA5 specified by the manufacturer and align with what was observed from the binder analysis presented previously.

Figure 34c presents the phase angle master curves of Source 3 mixtures. The results indicate that B1R3RA5 has a more viscous material response than B3R3 at most frequencies and temperatures. On the other hand, B1R3RA6 exhibited similar viscous versus elastic behavior as B3R3.

Assessment of Cracking Performance for Evaluated Mixtures

IDT-CT Results and Analyses

Figure 35 presents the CT_{index} obtained from the results of the IDT-CT for Source 1, 2, and 3 mixtures. The CT_{index} presented in Figure 35 represents the average of three replicates using the trim method (Habbouche et al., 2022). As mentioned, a higher CT_{index} indicates a better cracking performance. The results presented in Figure 35 indicate that all Source 1 mixtures with RAs exhibited a similar or higher CT_{index} than that for B3R1, which suggests that a similar or better cracking performance can be achieved with the combination of a PG 64S-22 binder and RAs. The statistical analysis using a 95% confidence level revealed that all mixtures exhibited a significantly higher CT_{index} than that for B3R1 except B1R1R2.

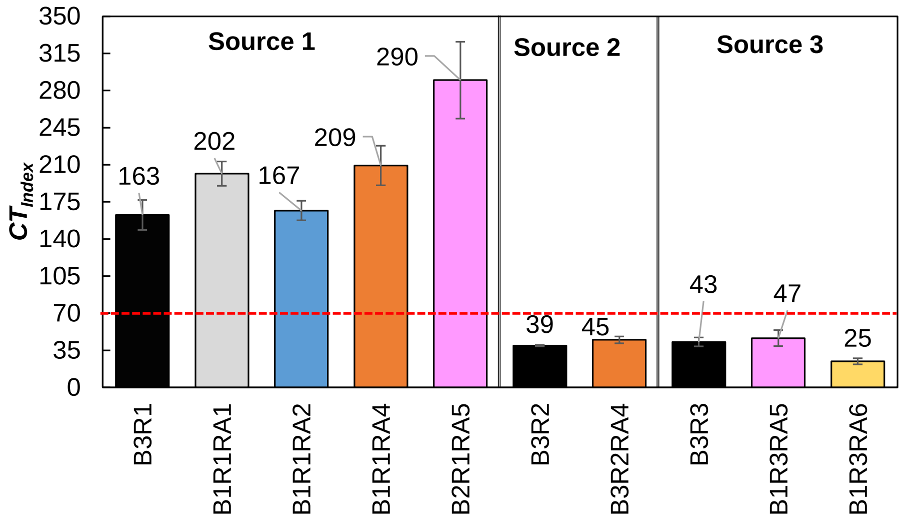

Figure 35. Performance Test Data for the IDT-CT for Source 1, 2, and 3 Mixtures. I-bars indicate CT index variability ± 1 standard deviation. IDT-CT = indirect tensile cracking test; CT = cracking tolerance; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent. Red dashed line = balanced mix design special provision limit for surface asphalt mixtures with A and D designations.

Regarding Source 2 materials, a slight increase of the average CT_{index} from 39 to 45 was evidenced when RA4 was added to B3R2. Nevertheless, this slight increase was not statistically insignificant, probably due to the relatively low dosage added in this case. The results also indicated that B1 in combination with RA5 can yield a mixture with a CT_{index} similar to that of B3R3. However, this was not the case for B1R3RA6, which exhibited a CT_{index} of 25. The details of the statistical analysis are provided in Appendix J.

The results presented in Figure 35 highlight the effect of binder content on the CT_{index}. It can be seen that for Source 1 mixtures (binder content of 6.4%), the average CT_{index} ranges from 163 to 290 whereas for Source 2 and 3 mixtures (binder content of 5.7%), it ranges from 25 to 47. These results suggest that the CT_{index} is probably more sensitive to the binder content of the mixture than to the rheological characteristics of the binder used (or that can be achieved with incorporating RAs in the mixture). Therefore, a BMD framework for the design of asphalt mixtures with RAs should explicitly consider binder content, RA type and dosage, and the interaction of these factors. This aspect becomes fundamentally important in modifying a mix design, for example B3R2 and B3R3, that does not meet the VDOT BMD criterion of 70 established for mixtures with A and D designations.

Figure 36 shows the CT_{index} interaction diagram for Source 1, 2, and 3 mixtures. This diagram was constructed to provide a better understanding of the effect of RAs on the CT_{index} with respect to the reference mixture. As shown, most of the mixtures with RAs had work of fracture values lower and l_{75}/m_{75} values higher than each mixture's reference. The lack of control mixtures in this analysis makes it impossible to determine whether RAs affect primarily the toughness or ductility of the recycled asphalt mixture and to what extent. Nevertheless, the overall results may suggest that binder content affects mainly the l_{75}/m_{75} parameter, as two clear clusters of data are visible over the x-axis in Figure 36.

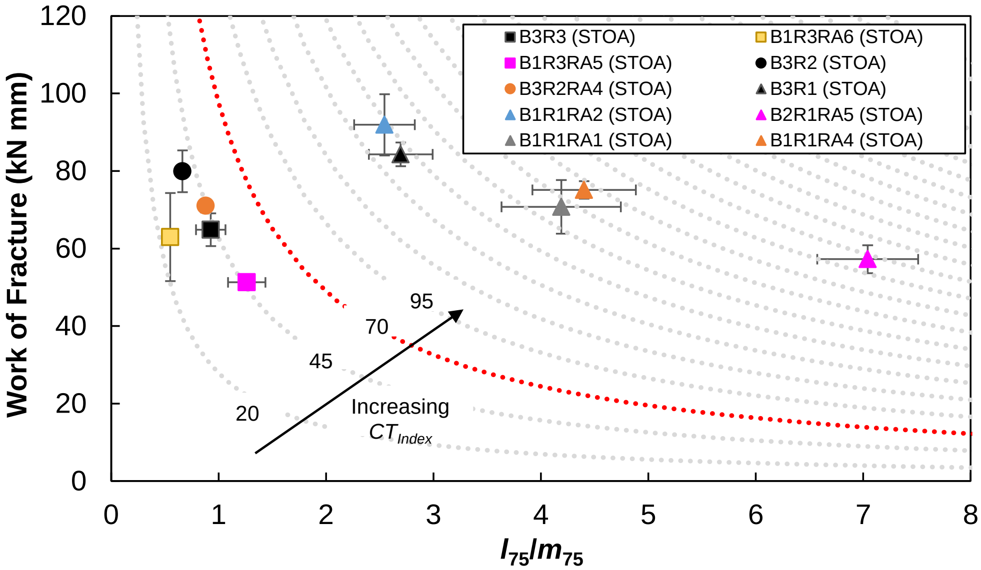

Figure 36. IDT-CT Interaction Diagram of Source 1, 2, and 3 Mixtures. I-bars indicate parameter variability ± 1 standard deviation. IDT-CT = indirect tensile cracking test; CT = cracking tolerance; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent. Red dashed line = balanced mix design special provision limit for surface asphalt mixtures with A and D designations.

Direct Tension CF Test Results and Analyses

The damage characteristic curves of Source 1 mixtures are presented in Figure 37a. This figure shows that B1R1RA1 and B1R1RA2 exhibit similar damage characteristics to B3R1, as their C versus S curves almost overlap. It should be noted that B1R1R1 does seem to follow the power law–based function used to fit C as a function of S when S is greater than approximately 250,000. This observation suggests that RA1 modifies not only the LVE response of the mixture in untypical patterns (as seen before) but also the damage characteristics of the material. The consequences of the lack of fitting at the end of the C versus S curve are unclear; however, the results suggest that other functional forms, e.g., exponential function, should be used to characterize the reduction of pseudo-stiffness as a function of damage. Further, distinct behavior was observed with B1R1RA4 and especially B2R1RA5, which present damage characteristics curves in a lower position than B3R1. However, the damage characteristics curves alone should not be used to judge the fatigue resistance (or the effect of RAs on fatigue resistance) of asphalt mixtures. As explained by Wang et al. (2022), mixtures with lower modulus usually appear lower on the C versus S plot than mixtures with high modulus values. Further, the behavior related to the C versus S curve positioning is not necessarily associated with better or worse fatigue performance since comparisons of equivalent damage levels across the different mixtures do not consider equivalent microstructural phenomena such as crack length or area and the curves does not provide information on the material's resistance to deformation (Underwood et al., 2010; Zeiada et al., 2014).

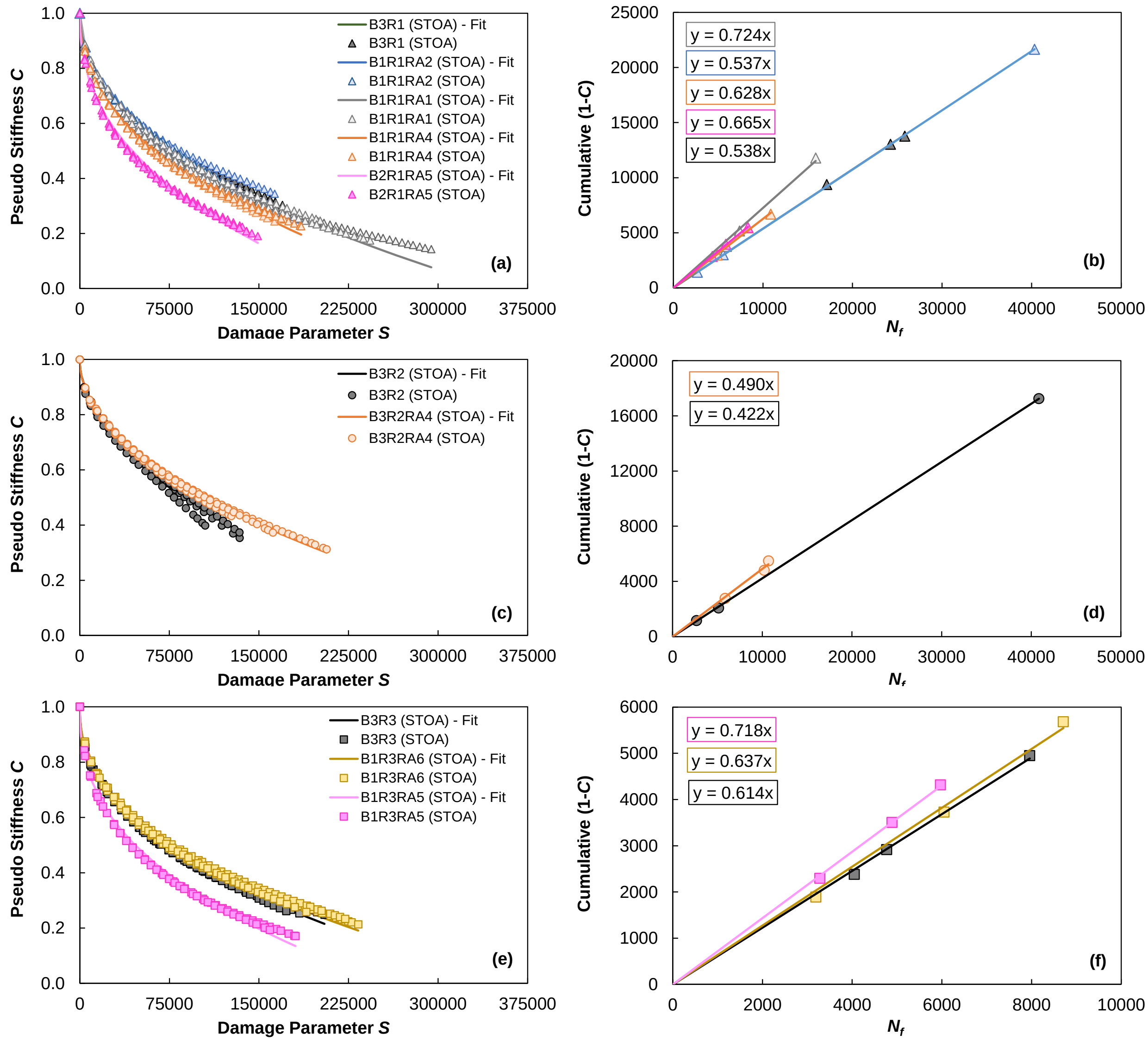

Figure 37. Cyclic Fatigue Test Data for Source 1, 2, and 3 Mixtures: (a) damage characteristic curve for Source 1; (b) failure criteria for Source 1; (c) damage characteristic curve for Source 2; (d) failure criteria for Source 2; I damage characteristic curve for Source 3; (f) failure criteria for Source 3. C = pseudo-stiffness; S = damage parameter; N_f = number of cycles to failure; STOA = short-term oven aging; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Figure 37b shows the relationship between the cumulative reduction in pseudo-stiffness (1-C) and the number of cycles, and the slope of such relationship, D^R, for Source 1 mixtures. As mentioned previously, a higher D^R generally indicates a superior ability to absorb energy before failure. Figure 37b shows that all mixtures containing RAs had a greater average reduction in pseudo-stiffness up to failure than B3R1 except B1R1RA2, which exhibits fundamentally the same D^R value. In this case, the highest D^R was obtained by blending B1 with RA1, followed by RA5, RA4, and RA2.

The damage characteristic curves of Source 2 mixtures are presented in Figure 37c. As shown, the two mixtures overlap until S is approximately 50,000; after this, the C versus S curves start to deviate more evidently as the damage characteristic curve of B3R2RA4 becomes flatter. Further, the experimental data follow the power law–based function used to fit C as a function of S. Figure 37d suggests that modifying the B3R2 mixture with RA4, with as low as 0.90% of RA by weight of the total binder, increases the D^R value of the mixture from 0.422 to 0.490.

The damage characteristic curves of Source 3 mixtures are presented in Figure 37e. The results suggest that B1R3RA6 has essentially the same damage characteristic curve as B3R3 and a slightly higher D^R, as shown in Figure 37f. Further, the results indicate that the RA5-modified mixture had a C versus S curve significantly lower than for B3R3 and B1R3RA6 and a D^R value substantially higher.

The S_{app} values for the mixtures in Figure 19 are presented in Figure 38 using the climatic data of Charlottesville, Virginia, and the climate from which each mixture was produced. As mentioned previously, S_{app} accounts for the two main factors that govern the fatigue cracking potential of asphalt mixtures, i.e., the stiffness and damage resistance of the mixtures. It can be seen in Figure 38 that the Source 1 mixtures with RAs have S_{app} values higher than for B3R1, suggesting a greater fatigue resistance. For Source 2 materials, B3R2RA4 exhibits a higher S_{app} value than B3R2 due to the increase in D^R and no change in the dynamic modulus of the mixture. Last, Figure 38 shows that a higher S_{app} can be obtained with RA5 instead of RA6 at the dosage specified by each manufacturer. The details of the statistical analysis are provided in Appendix J.

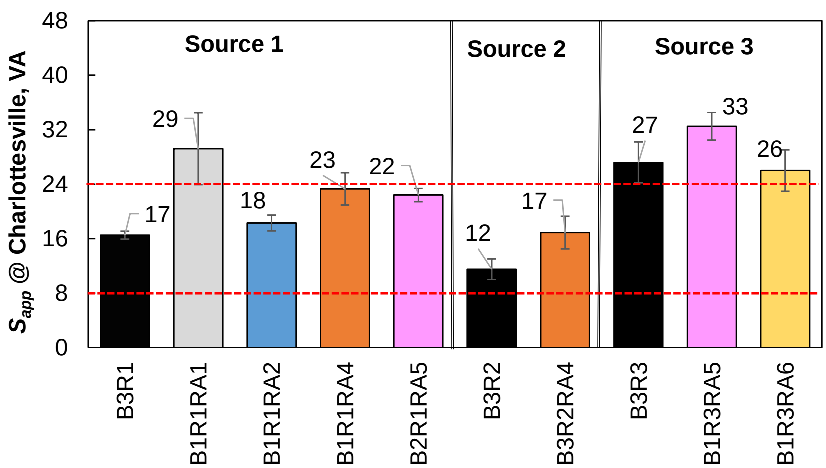

Figure 38. Cyclic Fatigue Test Data in Terms of S_{app} Values for Source 1, 2, and 3 Mixtures Determined Using Charlottesville Climatic Data. S_{app} = apparent damage capacity; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent. Red dashed lines represent the corresponding range for standard traffic.

Assessment of Rutting Performance for Evaluated Mixtures

APA Rut Test Results and Analyses

Figure 39 shows the APA rut depths measured after the application of 8,000 loading cycles at 64°C for Source 1, 2, and 3 mixtures. It should be noted that only the first tier of mixtures was evaluated for rutting characterization.

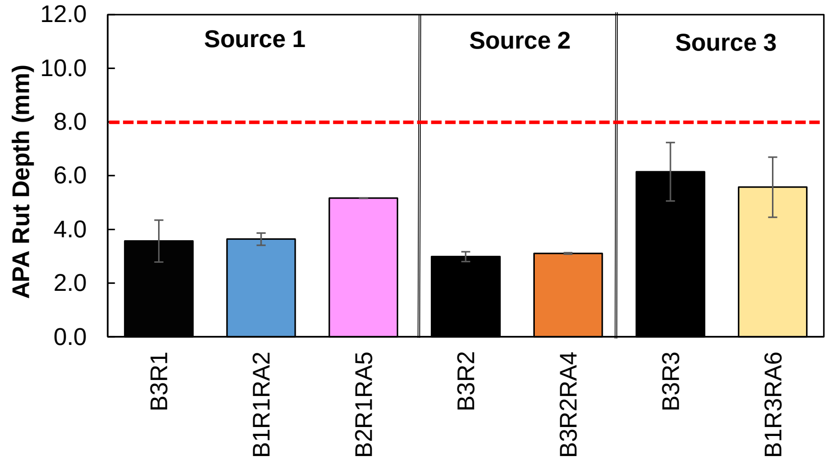

Figure 39. Performance Test Data for APA Rut Depth of Source 1, 2, and 3 Mixtures. I-bars indicate rut depth variability ± 1 standard deviation. APA = Asphalt Pavement Analyzer; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent. Red dashed line = balanced mix design special provision limit for surface asphalt mixtures with A and D designations.

The rut depths of Source 1 mixtures ranged from 3.56 mm to 5.17 mm, with an average COV of 9.4%. For Source 2 mixtures, the rut depth ranged from 2.98 mm to 3.10 mm, with an average COV of 3.5%. Last, the rut depths of Source 3 mixtures ranged from 5.57 mm to 6.14 mm, with an average COV of 18%. In most cases, the mixtures with RA exhibited statistically the same rut depths as their reference mixture except B2R1RA5, with an average rut depth 44% higher than for the reference mixture. The details of the statistical analysis are provided in Appendix L. Further, all mixtures evaluated in this study met the VDOT BMD rut depth criterion of 8.0 mm at 64°C (represented by the red dashed line in Figure 39).

The results of the APA rut test indicated that the cracking performance and durability of the recycled asphalt mixtures can be improved with the use of RAs, as shown in the previous section using CT_{index}, without adversely affecting the rutting potential of the mixtures. Even when a relatively high dosage of RA is used and high CT_{index} values are obtained, such as for B2R1RA5, the APA rut depth remained far below the 8.0 mm rut depth limit.

SSR Test Results and Analyses

The RSI results are shown in Figure 40 for all the mixtures using the climatic data of Charlottesville, Virginia. The RSI analysis using the specific climatic data for the location where each mix design was produced, as well as the viscoplastic strain obtained in the high- and low-temperature SSR test, is presented in Appendix L. The RSI values of Source 1 mixtures ranged from 5.9% to 8.0%. For Source 2 mixtures, the RSI ranged from 7.7% to 7.9%. Last, the RSI values for Source 3 mixtures ranged from 12.6% to 13.2%. In general, the RSI results confirmed the findings obtained with the APA rut test, which suggest that the rutting performance of the recycled asphalt mixtures does not seem be significantly affected by the incorporation of RAs when the RA dosage is selected to achieve a blended PGL of -22°C.

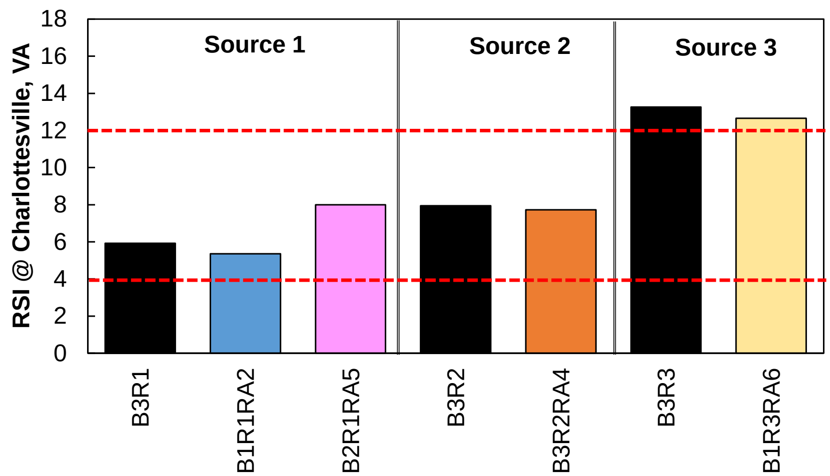

Figure 40. Performance Test Data for SSR Test of Source 1, 2, and 3 Mixtures Determined Using Charlottesville Climatic Data. SSR = stress sweep rutting; RSI = rutting strain index; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent. Red dashed lines represent the corresponding range for standard traffic.

Most of the asphalt mixtures exhibited RSI values ranging from 4.0% to 12.0%, the recommended threshold for the standard traffic category (less than 10 million equivalent single axle loads). Nevertheless, VDOT does not specify an RSI pass/fail criterion; hence, the threshold limit provided here is for reference purposes only. Source 3 mixtures (both reference and RA mixtures) exhibited RSI values higher than 12.0%, despite the fact of having relatively similar binder characteristics when compared to Source 1 and Source 2 mixtures. This observation suggests that other factors inherent in the Source 3 mix design, such as gradation, aggregate angularity, etc., are probably contributing to the increased rutting potential observed. The details of the statistical analysis are provided in Appendix L.

Aging Assessment

Aging Sensitivity by Means of |E| LVE Properties*

Several mixtures from all three sources were evaluated for short- and long-term aging LVE properties. These constituted three reference mixtures, B3R1, B3R2, and B3R3, and a respective mixture containing an RA such as B2R1RA5, B3R2RA4, and B1R3RA6. An additional mixture, B1R1RA2, was further included to encompass the variety of RAs included in this study.

Figure 41 shows the measured dynamic modulus data along with the model fit for Source 1 for short- and long-term aging conditions. As expected, dynamic modulus increased with aging across all mixtures. This increment in dynamic modulus was more pronounced at lower frequencies than at higher frequencies, where the aging conditions appear to converge. Further, it can be seen from the vertical shift in dynamic modulus master curves that the sensitivity to aging is less in the reference mixture than in the mixtures containing RAs.

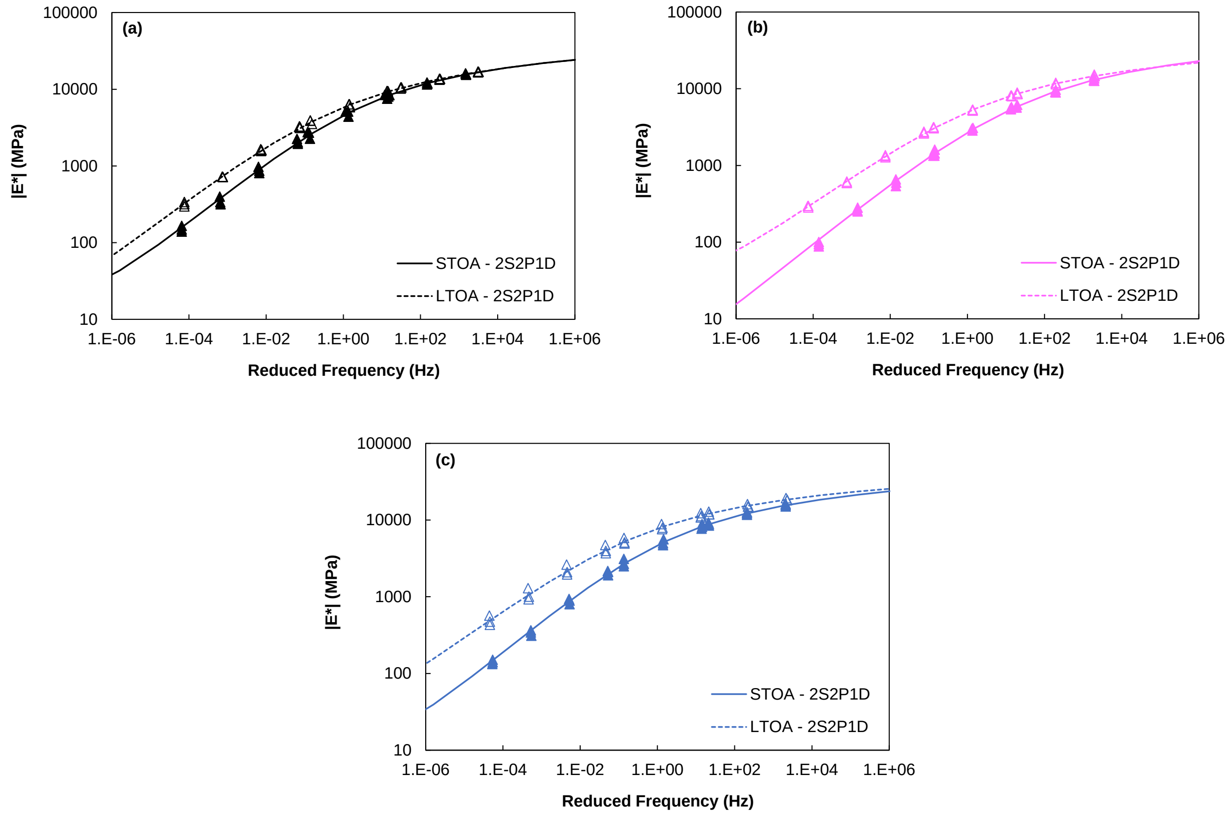

Figure 41. Dynamic Modulus |E*| Master Curves for Three Source 1 Mixtures at STOA and LTOA Conditions: (a) B3R1; (b) B2R1RA5; (c) B1R1R2. STOA = short-term oven aging; LTOA = long-term oven aging; |E*| = dynamic modulus; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Figure 42 shows the measured dynamic modulus data along with the model fit for Source 2 mixtures for short- and long-term aging conditions. As expected, the dynamic modulus increased with aging for the reference mixture and the mixture containing RA. For the short-term aging condition, both mixtures had similar dynamic modulus values; however, for the long-term aging condition, the mixture containing RA (B3R2RA4) had a lower dynamic modulus than the reference mixture. In this particular case, the reference mixture was also the control mixture and the only variable changing between the two mixtures was the addition of RA for B3R2RA4. The lower dynamic modulus of B3R2RA4 after long-term aging compared to the reference mixture indicates the efficacy of using the RA in recycled mixtures.

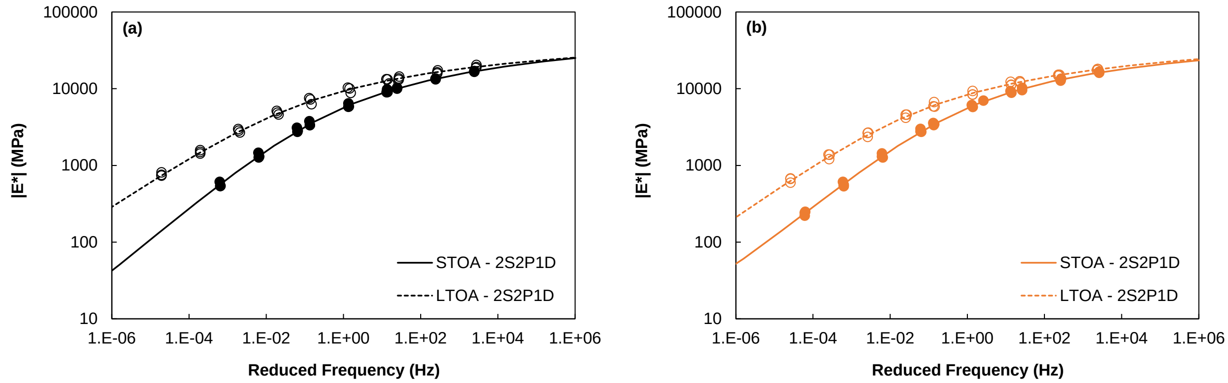

Figure 42. Dynamic Modulus |E*| Master Curves for Two Source 2 Mixtures at STOA and LTOA Conditions: (a) B3R2; (b) B3R2RA4. STOA = short-term oven aging; LTOA = long-term oven aging; |E*| = dynamic modulus; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Figure 43 shows the measured dynamic modulus data along with the model fit for Source 3 mixtures for short- and long-term aging conditions. As expected, the dynamic modulus increased with aging for the reference mixture and the mixture containing RA. In this case, the mixture containing RA had a higher PG binder (B1), so the dynamic modulus of B1R3RA6 was a little higher than for B3R3 for both short- and long-term aging conditions. In terms of aging sensitivity, B3R3 and B1R3RA6 were observed to have similar sensitivity to aging, as indicated by the vertical shift after long-term aging. As seen previously with mixtures from other sources, the differences in dynamic modulus are exacerbated at the lower frequencies and tend to converge at very high frequencies.

Recent studies have shown that the sensitivity to aging in terms of dynamic modulus and phase angle can be tracked by an LVE aging index, log|E*|/sin(δ), given the well-documented instances of |E*| and δ being aging indicators or trackers (Mensching et al., 2022; Elwardany et al., 2023). It must be noted that the LVE aging index should be seen as an aging index and may not necessarily indicate the changes in the cracking performance of the aged mixtures. Figure 44 shows the LVE aging index for the studied mixtures and that it increases with long-term aging, as is intuitive from the understanding of the LVE concept that stiffness should increase and the phase angle should decrease with aging.

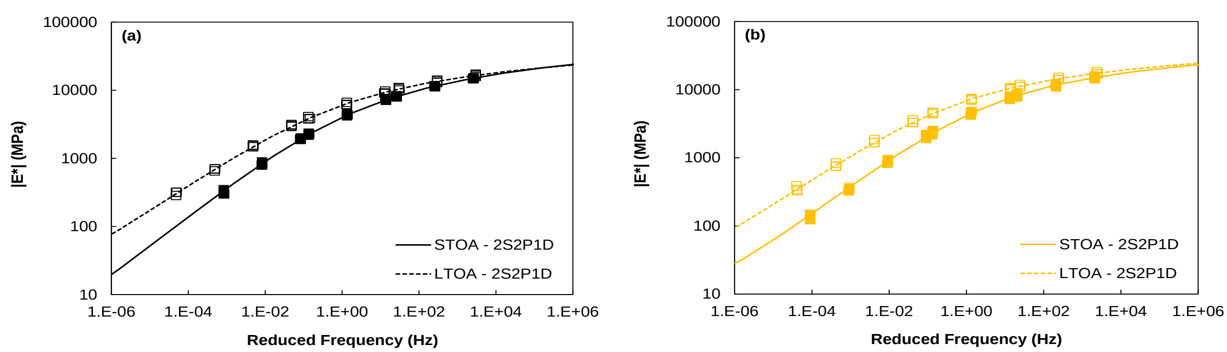

Figure 43. Dynamic Modulus |E*| Master Curves for Two Source 3 Mixtures at STOA and LTOA Conditions: (a) B3R3; (b) B1R3RA6. STOA = short-term oven aging; LTOA = long-term oven aging; |E*| = dynamic modulus; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

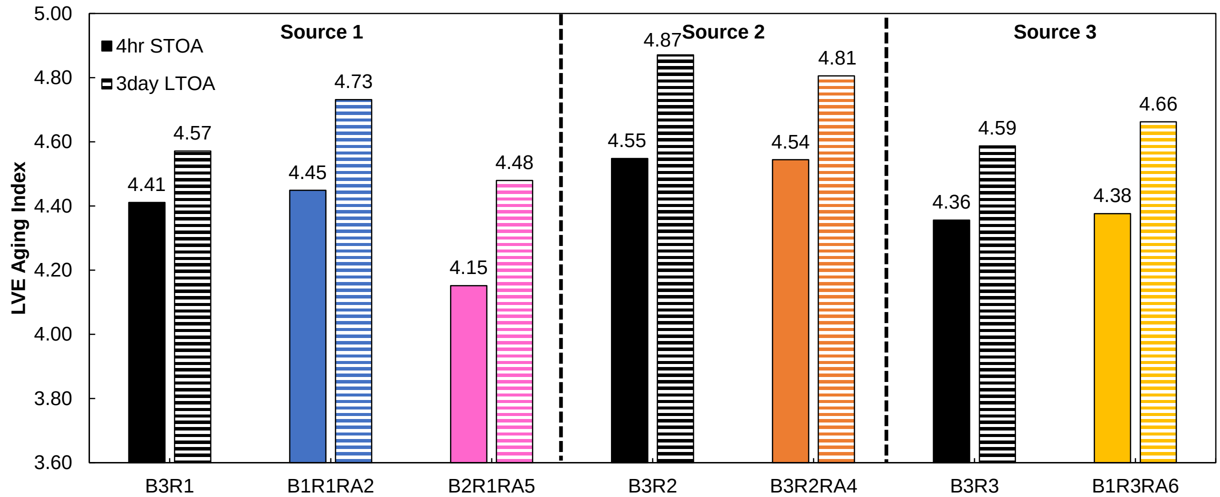

Figure 44. LVE Aging Index for Source 1, 2, and 3 Mixtures at STOA and LTOA Conditions. STOA = short-term oven aging; LTOA = long-term oven aging; LVE = linear viscoelastic; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Aging Sensitivity by Means of Cracking Properties

Figure 45 shows the CT_{index} values for mixtures produced using materials sampled from all three sources under different aging conditions. In addition to the 3-day LTOA protocol, a 1-day LTOA at 95°C protocol was used for certain mixtures from Source 1. This was done to track the rapidity of decline in cracking performance of mixtures containing RAs.

It can be seen that the CT_{index} decreased as the mixture transitioned from the STOA condition to the 3-day LTOA condition, with a significant decrease across all mixtures. It is noteworthy that for B1R1RA1 and B1R1RA2, which were subjected to 1-day LTOA, the decrease in CT_{index} was significant, whereas the subsequent decrease with 3-day LTOA was comparatively less pronounced. This indicates that the initial degradation in cracking performance is more prominent in mixtures containing RAs and the rate of degradation decreases as the LTOA duration increases. However, in the case of B2R1RA5, the degradation in CT_{index} after 1-day LTOA is not as substantial as in the previous two mixtures, but it becomes significant after 3-day LTOA. One possible explanation for this disparity is the higher dosage of RA5 in the mixture compared to others, which initially slows down the degradation but then rapidly descends after 1-day LTOA.

Another noteworthy point is that the mixtures exhibit more variation in cracking performance after LTOA rather than after STOA, which can be advantageous in distinguishing mixtures containing RAs. However, the optimal duration of LTOA required to achieve this differentiation remains to be determined.

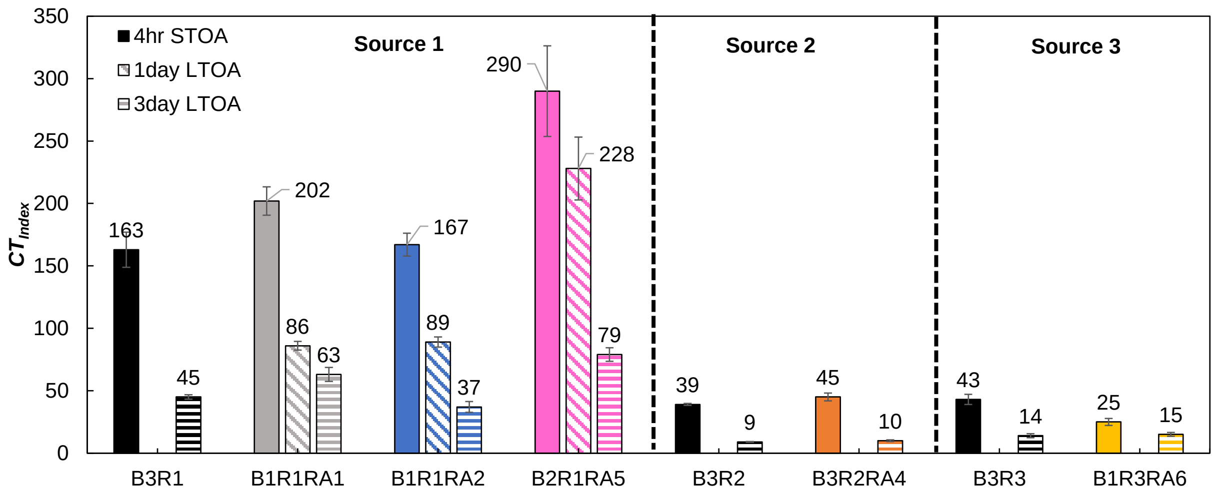

Figure 45. Performance Test Data for IDT-CT of Source 1, 2, and 3 Mixtures Under Different Aging Conditions. I-bars indicate CT index variability ± 1 standard deviation. IDT-CT = indirect tensile cracking test; CT = cracking tolerance; STOA = short-term oven aging; LTOA = long-term oven aging; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Figure 46 shows the S_{app} value for mixtures from all three sources, and it is evident that S_{app} generally decreases with aging. In some cases, such as B2R1RA5 and B3R3, there was a slight increase in the S_{app} value. However, in light of the allowable variation limits, these can be considered similar to that of the short-term aging condition. Further, it can be observed that the decrease in S_{app} value was not as drastic as the decrease in CT_{index} with aging. Both the CT_{index} and S_{app} indicated that mixtures from Source 2 exhibited poorer cracking performance. This can be attributed to a stiffer PG grade of RAP2, which was higher than that of RAP1 and RAP3. In addition, although RAP1 and RAP3 had similar high-temperature PGs, Source 1 mixtures had a higher %AC, leading to a higher CT_{index} value. On the other hand, Source 3 mixtures had a finer gradation, resulting in a higher S_{app} value.

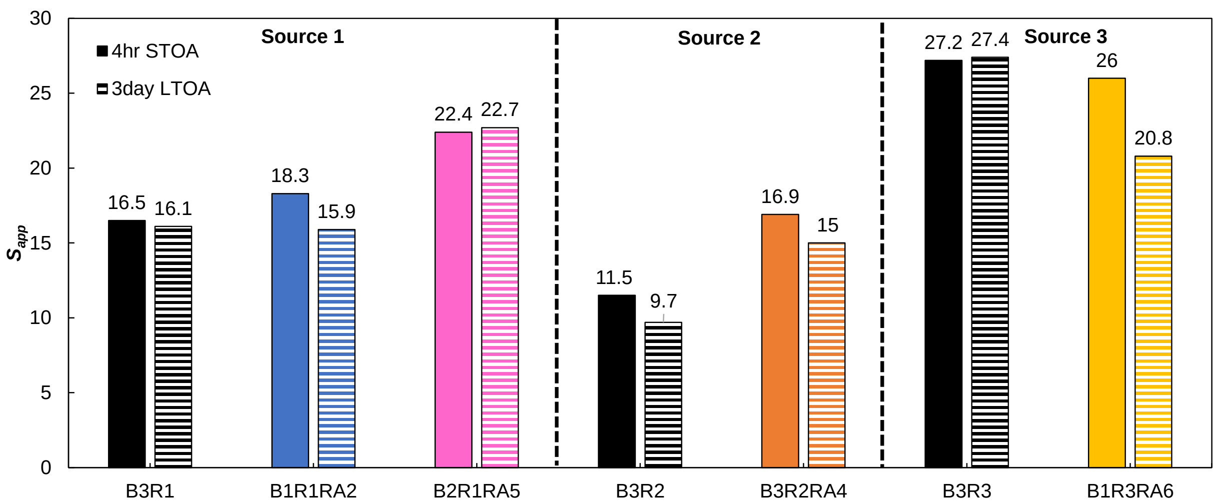

Figure 46. Cyclic Fatigue Test Data in Terms of S_{app} Values for Source 1, 2, and 3 Mixtures Under Different Aging Conditions. S_{app} = apparent damage capacity; STOA = short-term oven aging; LTOA = long-term oven aging; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

An effort was made to correlate the LVE aging index with the results of the cracking tests, revealing a clear correspondence between the LVE aging index and the CT_{index}. Specifically, a smaller LVE index corresponds to a higher CT_{index} in the STOA condition, and a larger LVE aging index corresponds to a lower CT_{index} in the LTOA condition. Figure 47 shows the results of the STOA and LTOA conditions for the evaluated mixtures, with an arrow indicating the direction of aging along the anticipated progression of indices. Similar trends were identified by Elwardany et al. (2023) and Mensching et al. (2022).

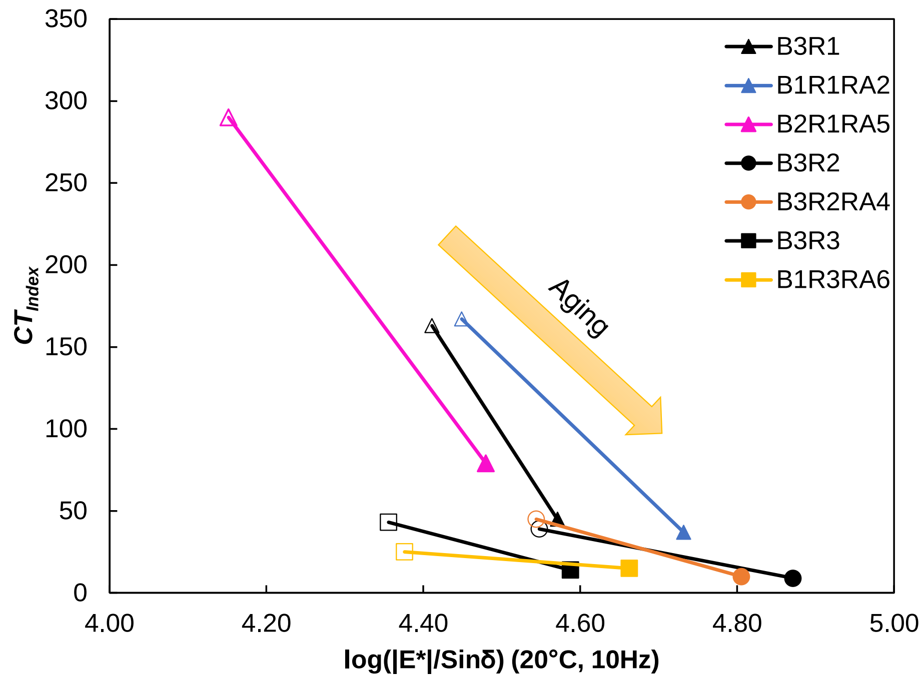

Figure 47. Relationship Between CT_{index} and LVE Aging Index for Source 1, 2, and 3 Mixtures Under Different Aging Conditions. Open shapes indicate 4-hour short-term oven aging; filled shapes indicate 3-day long-term oven aging at 95°C in addition to short-term oven aging. CT = cracking tolerance; |E*| = dynamic modulus; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Cross-Scale Binder and Mixture Evaluation and Analysis

In terms of binder durability analysis, different parameters were evaluated, and some key insights were obtained:

- RA1 blends generally have the most inferior rheological properties compared to the PG 64S-22 virgin binders. These blends are generally identified through ΔT_c at PAV-20 and GR parameter values.

- RA2 and reference blends often also have intermediate-temperature properties (|G*|×sinδ and GR parameter values) compared to PG 64S-22 binders. In several cases, RA2 blends failed to meet m-value requirements for binders with a PGL of -22°C.

- RA3 blend results were more mixed because some cases with inferior ΔT_c values were identified and some were not. In general, these blends compared more favorably to the PG 64S-22 virgin binders at the PAV-40 than at the PAV-20 aging condition.

- RA4 and RA6 blends are deemed equal or better to PG 64S-22 virgin blends based on the majority of the parameters evaluated with exceptions in specific blends. This does not include the inferences from R_{MC}, T_{45}, and GR_{15^oC}.

- RA5 blends exhibited better rheological properties when compared to those of PG 64S-22 virgin binders. This is the only RA that consistently yielded better GR_{15^oC} values than those of a PG 64S-22 binder.

In terms of the mixture durability analysis, which had fewer corresponding mixtures than the binder blends tested, CT_{index} and S_{app} at the STOA and 3-day LTOA conditions conveyed the following key insights, as illustrated in Figures 45 and 46:

- RA1 and RA2 mixtures such as B1R1RA1 and B1R1RA2 showed a higher CT_{index} than all other mixtures except B2R1RA5, which continued to show the better cracking performance. However, the CT_{index} dropped significantly after 3-day LTOA where RA1 still ranked higher than reference mixture B3R1, whereas RA2 ranked lower than the reference mixture. This observation for RA2 seemed consistent for S_{app} for the STOA and 3-day LTOA conditions. It was interesting to note that these RAs performed better even though their rheological performance as assessed by GR_{15^oC} and ΔT_c suggested otherwise. Further investigations were carried out to study these two RAs in addition to RA5, which consistently showed better performance across binder and mixture scales, as discussed in the next subsection.

- RA4 and RA6 mixtures such as B3R2RA4 and B1R3RA6 showed comparable performance with the reference mixtures B3R2 and B3R3, respectively, and worse performance in terms of the CT_{index} than in terms of $S_{app.}$ These RAs can be deemed better than or equal to the reference mixtures in terms of the CT_{index} at the 3-day LTOA condition and S_{app} at the STOA condition.

- For RA5-based mixtures, B2R1RA5 showed the highest CT_{index} at the STOA condition, which aligns with the binder observations. It continued to show a higher CT_{index} for the 3-day LTOA condition.

- The ability to differentiate between different mixtures in terms of the CT_{index} decreases from the STOA to the 3-day LTOA. This can be seen in Figure 48 where the CT_{index} seems to converge once a certain LVE aging index parameter threshold is reached. From the evaluated mixtures in this study, a preliminary LVE threshold of ~4.45 MPa was determined.

As discussed, an apparent opposite rheological and mixture performance for RA1 and RA2 blends and corresponding mixtures was observed based on binder and mixture indices. In order to investigate further, the two mixtures B1R1RA1 and B1R1RA2 along with an RA5 mixture, B2R1RA5, which ranked consistently across binder and mixture scales, were aged and tested after 1-day LTOA using the IDT-CT. In addition to the $GR_{15°C}$ parameter, the newly proposed fatigue cracking index S_L, based on the LAS test, was used to compare and contrast the binder performance with the mixture cracking performance from the IDT-CT. Parameters $GR_{25°C}$, $|G^*|\sin(\delta)$, and ΔT_c (°C), although tracking with aging, did not result in the same trend or ranking of mixtures and corresponding binder blends. Although B2R1RA5 ranked highest across STOA, 1-day LTOA, and 3-day LTOA conditions, B1R1RA1 and B1R1RA2 switched rankings for 1-day LTOA and 3-day LTOA in terms of the CT_{index}. It is interesting to note that the cracking performance predicted by the binder parameters resulted in a trend similar to that of the mixture cracking performance at 1-day LTOA. Figures 48 and 49 show the S_L and $GR_{15°C}$ at PAV-20 and PAV-40 compared to the CT_{index} at 1-day LTOA, and in both cases, there is agreement in the binder and mixture performance.

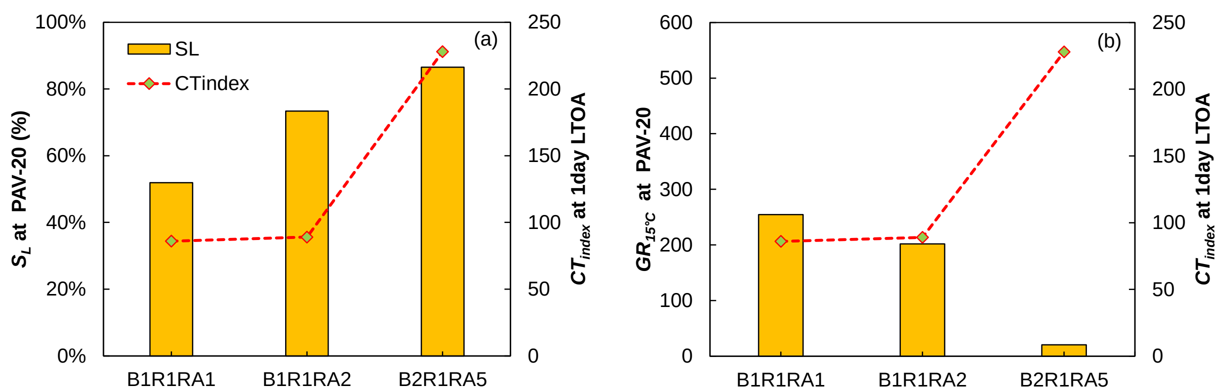

Figure 48. Comparison of CT_{index} at 1-day LTOA of Selected Asphalt Mixtures With Parameters of Corresponding Binder Blends Under PAV-20 Aging Conditions: (a) S_L; (b) $GR_{15°C}$. B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent; PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; CT = cracking tolerance, LTOA = long-term oven aging.

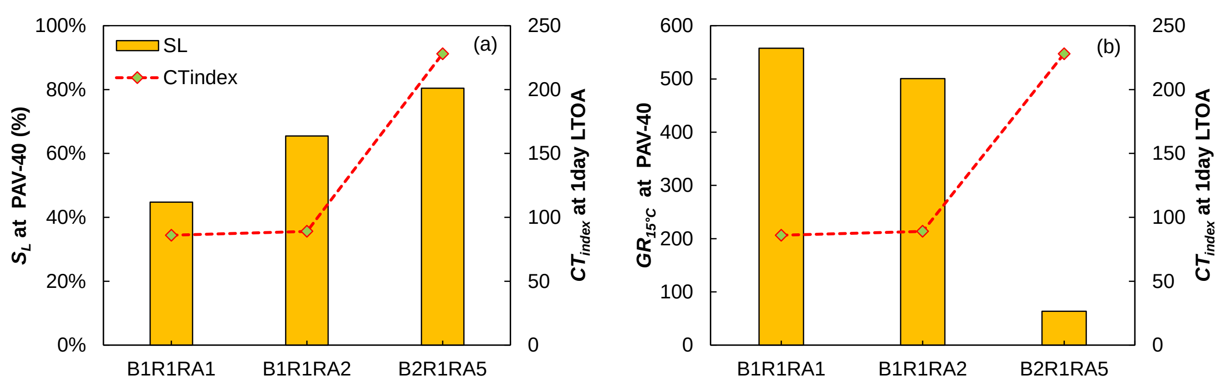

Figure 49. Comparison of CT_{index} at 1-day LTOA of Selected Asphalt Mixtures With Parameters of Corresponding Binder Blends Under PAV-40 Aging Conditions: (a) S_L; (b) $GR_{15°C}$. B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent; PAV = pressure aging vessel; PAV-40 = PAV for a duration of 40 hours; CT = cracking tolerance, LTOA = long-term oven aging.

RA1 and RA2 mixtures showed a significant degradation of cracking performance with aging, unlike the RA5 mixture for 1-day LTOA, as can be seen in Figure 45. Moreover, the two binder parameters (S_L and $GR_{15°C}$) were evaluated to track these changes with aging. However, for 3-day LTOA, the LVE aging index parameter was observed to cross the threshold and converge. As a result, the ability and accuracy of the binder parameters to predict mixture performance diminished. The aging sensitivity of the binder and mixture parameters can be calculated using Equations 19 through 21.

$$(CT_{index})^{1day\ LTOA}_{aging\ sensitivity} = \left[\frac{(CT_{index})_{STOA} - (CT_{index})_{1day\ LTOA}}{(CT_{index})_{STOA}}\right] * 100 \quad \text{[Eq. 19]}$$

$$(GR_{15°C})_{aging\ sensitivity} = \left[\frac{(GR_{15°C})_{PAV-40} - (GR_{15°C})_{PAV-20}}{(GR_{15°C})_{PAV-40}}\right] * 100 \quad \text{[Eq. 20]}$$

$$(S_L)_{aging\ sensitivity} = \left[\frac{(S_L)_{PAV-20} - (S_L)_{PAV-40}}{(S_L)_{PAV-20}}\right] * 100 \quad \text{[Eq. 21]}$$

It can be seen in Figure 50 that although both binder cracking parameters correlate well with the mixture cracking performance sensitivity with aging for the 1-day LTOA condition compared to the STOA condition, only S_L was able to capture the trend correctly. For $GR_{15°C}$, a higher value (i.e., a higher aging sensitivity) was associated with a lower aging sensitivity in terms of the CT_{index}, which is counterintuitive. A higher binder aging sensitivity is reflected in higher mixture aging sensitivity in terms of only S_L and CT_{index}, respectively. Further, it can be seen from Figure 51 that at 3-day LTOA, none of the evaluated binder parameter aging sensitivities correlated well with the mixture aging sensitivity.

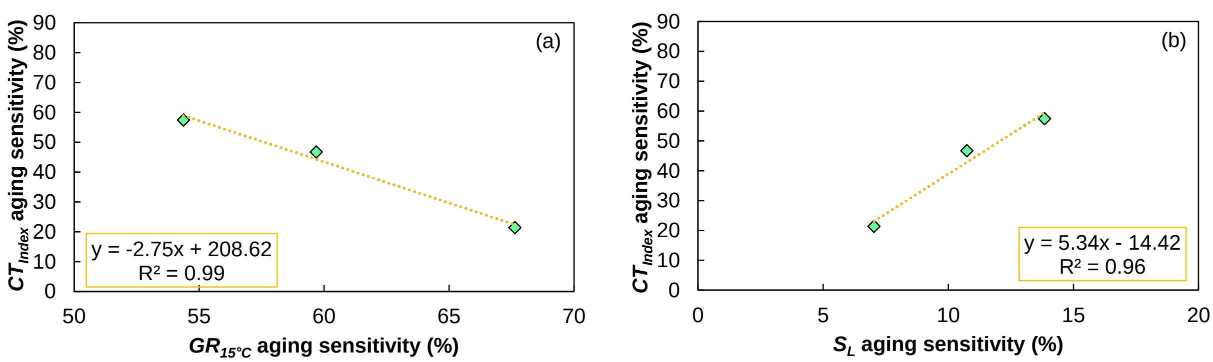

Figure 50. Cross-Scale Correlation Between 1-day CT_{index} Aging Sensitivity and Binder Aging Sensitives: (a) $GR_{15°C}$; (b) S_L. CT = cracking tolerance, GR = Glover-Rowe; S_L = stress level at peak stored pseudo-strain energy.

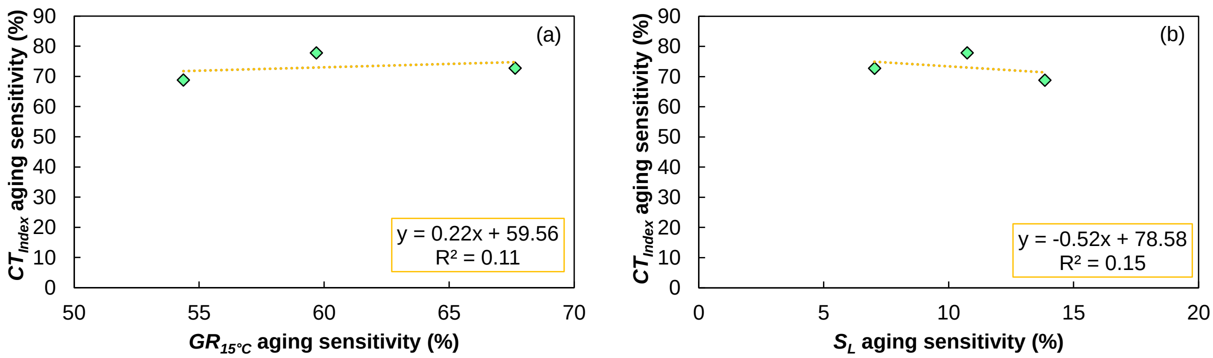

Figure 51. Cross-Scale Correlation Between 3-day CT_{index} Aging Sensitivity and Binder Aging Sensitives: (a) $GR_{15°C}$; (b) S_L. CT = cracking tolerance, GR = Glover-Rowe; S_L = stress level at peak stored pseudo-strain energy.

It must be noted that both S_L and CT_{index} were able to rank consistently with the CT_{index}; however, only S_L was able to capture and track the sensitivity with aging from binder to mixture scale at 1-day LTOA. Based on this observation, there is evidence to suggest the use of 1-day LTOA to develop CT_{index} thresholds in terms of aging sensitivity as it enables consistent cross-scale evaluations across binder and mixture scales.

Figures 52a and 52b show the cross-scale correlation between the 1-day LTOA CT_{index} aging sensitivity and binder $GR_{15°C}$ and between the 1-day LTOA CT_{index} aging sensitivity and mixture LVE aging index parameter at STOA, respectively. It can be noticed that for a $GR_{15°C}$ of 180 kPa (lower threshold for onset of cracking) and an LVE of 4.45 (previously determined in this study), a preliminary threshold of 45% is observed for the 1-day LTOA CT_{index} aging sensitivity. It should be noted that this threshold is preliminary and was determined using only three data points. Further validation is needed.

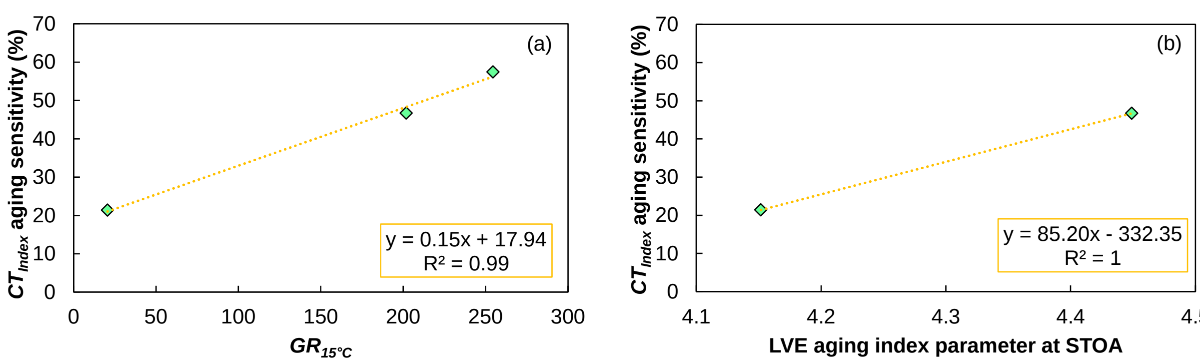

Figure 52. Cross-Scale Correlation Between 1-day CT_{index} Aging Sensitivity and (a) Binder Parameter $GR_{15°C}$ and (b) Mixture Parameter LVE. CT = cracking tolerance, GR = Glover-Rowe; LVE = linear viscoelastic.

Preliminary Verification of Results

Numerous field trials were planned and constructed during the 2019 paving season through a collaborative effort with industry, VDOT's Materials Division, the VDOT districts, and the Virginia Transportation Research Council (VTRC). These trials constituted the first applications of the BMD specifications to design, produce, and place asphalt mixtures with RAP contents of up to 40% in Virginia. The field trials focused on the application of the BMD concept, production variability, comparisons of mixtures, and differences in specimen test response with and without reheating of the loose mixture for fabrication. More details about these trials can be found elsewhere (Diefenderfer et al., 2021b).

Nine mixtures were evaluated from the two field trials; the mixtures incorporated combinations of different RAP contents, two binder grades (i.e., PG 64S-22 and PG 58-28), two RA products (RA3 and RA5), and two warm mix asphalt additives. In addition to the volumetric and gradation analysis, the Cantabro test, IDT-CT, and APA rut test were performed on laboratory-produced design specimens and non-reheated and reheated plant-produced, laboratory-compacted specimens. Seven of the nine mixtures are of interest in this study. The corresponding binder contents and performance data are summarized in Table 16.

Table 16. Summary of Binder Contents and Performance Data for Selected 2019 Field Trials

District	Mixture ID	Mixture Details	Type of Specimens	BC, %	CML, %	APA Rut Depth, mm	CT_{index} STOA	CT_{index} LTOA	CT_{index} Aging Sensitivity
Northern Virginia	19-A-I reference	SM-9.5A, 30% RAP + PG 64S-22	Design	5.60	6.3	4.8	78	--	--
			Non-Reheated	5.54	4.8	5.3	127	--	--
			Reheated	5.49	7.9	5.4	74	--	--
	19-A-II	SM-9.5A, 40% RAP + PG 58-28	Design	5.60	8.8	--	--	--	--
			Non-Reheated	5.52	5.2	6.5	249	--	--
			Reheated	5.57	3.8	4.0	115	--	--
	19-A-V	SM-9.5A, 40% RAP + PG 64S-22 + RA3	Design	5.50	6.6	5.1	89	--	--
			Non-Reheated	5.49	3.9	5.4	119	--	--
			Reheated	5.63	5.3	5.3	80	--	--
Salem	19-B-I reference	SM-9.5D, 26% RAP + PG 64S-22	Design	5.70	--	--	--	--	--
			Non-Reheated	5.85	5.4	--	52	--	--
			Reheated	5.92	7.8	4.7	108	--	--
	19-B-II	SM-9.5D, 26% RAP + PG 64S-22 + RA3	Design	5.70	--	--	--	--	--
			Non-Reheated	5.64	5.1	5.2	232	--	--
			Reheated	5.90	5.8	4.4	124	--	--
	19-B-III reference	SM-9.5D, 26% RAP + PG 64S-22	Design	5.70	--	--	--	--	--
			Non-Reheated	5.99	2.5	5.4	110	--	--
			Reheated	5.85	5.9	5.0	151	--	--
	19-B-IV	SM-9.5D, 26% RAP + PG 64S-22 + RA5	Design	5.70	--	--	--	--	--
			Non-Reheated	5.48	4.3	4.5	91	--	--
			Reheated	5.27	5.2	3.7	86	--	--

BC = binder content; CML = Cantabro mass loss; APA = Asphalt Pavement Analyzer; CT = cracking tolerance; STOA = short-term oven aging; LTOA = long-term oven aging; SM = surface mixtures; RAP = reclaimed asphalt pavement; A and D = mixture designations; PG = performance grade; S = standard traffic; RA = recycling agent; -- = mixture not tested or data not available.

In 2020, five field trials encompassing 12 mixtures were constructed in accordance with VDOT's BMD special provision for SMs with high RAP contents. Typical dense-graded Superpave SMs were used as controls. The mixtures included combinations of different RAP contents, two binder grades (i.e., PG 64S-22 and PG 58-28), four RAs (among these, three were evaluated in this study, RA3, RA4, and RA5), and fiber. Eight of the 12 mixtures were of interest in this study.

Moreover, a collaborative BMD experiment by VTRC, VDOT, and Virginia Tech was planned and executed at the Virginia Accelerated Pavement Testing Facility located at the Virginia Tech Transportation Institute. The purpose of this experiment was to evaluate the application of the BMD concept to designing durable and longer-lasting mixtures in Virginia with a focus on mixtures with RAP contents up to 60%. Six test lanes were constructed. These lanes featured the use of typical mixtures and those with high RAP contents, softer binders, warm mix asphalt additives, and an RA (in this case, RA3). Four of the six mixtures were of interest in this study. The corresponding binder contents and performance data for the 2020 mixtures of interest are summarized in Table 17.

During the 2022 paving season, a high RAP mixture with RA that featured the use of 40% RAP content and a green bio-based asphalt rejuvenator (RA6) was constructed. The mixture was produced over 2 days with no controls. The corresponding binder contents and performance data for the 2022 mixture are summarized in Table 18.

For all mixtures containing RAs, the dosage rate differed from those evaluated in the primary experiment. However, similar to the primary experiment, the dosage rate was recommended by the manufacturer. Based on the test results, mixtures containing relatively high RAP contents, RAs, and/or softer binder (i.e., PG 58-28) may be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements. Further, the summarized results in Tables 16 through 18 indicated that the evaluated asphalt mixtures containing high RAP contents, RAs, and/or softer binder can yield performance that is equal to or better than the performance of their counterpart control/reference mixtures (with 30% RAP).

The current version of the VDOT BMD special provision require that mixtures undergo evaluation under LTOA conditions during design. The current VDOT BMD LTOA procedure involves aging loose laboratory-produced mixture for 8 hours at 135ºC following STOA conditioning (4 hours at the compaction temperature). The LTOA CT_{index} values in Tables 16 through 18 represent these outcomes under these conditions. It is important to note that this additional requirement was implemented in 2020, which means there are no available LTOA CT_{index} data for mixtures from 2019. Further, only a few of the 2020 mixtures have the corresponding data.

Table 17. Summary of Binder Contents and Performance Data for Selected 2020 Field Trials

District	Mixture ID	Mixture Details	Type of Specimens	BC, %	CML, %	APA Rut Depth, mm	CT_{index} STOA	CT_{index} LTOA	CT_{index} Aging Sensitivity
Northern Virginia	20-A-1 reference	SM-9.5D, 30% RAP + PG 64S-22	Design	5.50	7.4	6.2	92	42	54.3
			Non-Reheats	5.67	3.6	5.4	138	--	--
			Reheats	5.44	6.8	3.8	89	--	--
	20-A-2	SM-9.5D, 40% RAP + PG 64S-22 + RA3	Design	5.60	6.2	6.3	75	68	9.3
			Non-Reheats	5.57	3.5	5.3	169	--	--
			Reheats	5.49	5.5	5.0	100	--	--
	20-A-3	SM-9.5D, 40% RAP + PG 58-28	Design	5.60	6.7	7.4	73	47	35.6
			Non-Reheats	5.56	3.4	3.6	109	--	--
			Reheats	5.42	5.6	4.7	79	--	--
Fredericks-burg	20-B-1 reference	SM-9.5A, 30% RAP + PG 64S-22	Design	5.30	9.6	4.9	61	42	31.1
			Non-Reheats	5.39	4.4	5.6	172	--	--
			Reheats	5.37	6.3	5.8	99	--	--
	20-B-2	SM-9.5A, 40% RAP + PG 64S-22 + RA5	Design	5.60	6.5	5.0	146	58	60.3
			Non-Reheats	5.49	3.2	5.2	210	--	--
			Reheats	5.39	4.9	6.1	127	--	--
	20-B-3	SM-9.5A, 40% RAP + PG 58-28	Design	5.60	6.1	3.6	130	49	62.3
			Non-Reheats	5.23	4.2	4.7	125	--	--
			Reheats	5.19	6.3	4.7	76	--	--
Richmond	20-D-1 reference	SM-12.5A, 30% RAP + PG 64S-22	Design	5.80	--	--	--	--	--
			Non-Reheats	5.86	5.4	3.4	91	--	--
			Reheats	5.72	7.4	4.1	67	--	--
	20-D-2	SM-12.5A, 35% RAP + PG 58-28 + RA4	Design	6.20	2.1	3.9	94	32	66.0
			Non-Reheats	6.15	3.3	4.6	101	--	--
			Reheats	5.96	5.1	6.2	129	--	--
Salem	20-HVS-I reference	SM-9.5A, 30% RAP + PG 64S-22	Design	5.60	2.9	5.4	58	--	
			Non-Reheats	5.56	7.2	3.8	126	--	--
			Reheats	5.44	9.5	4.0	54	--	--
	20-HVS-IV	SM-9.5A, 45% RAP + PG 64S-22 + RA3	Design	6.20	2.8	7.2	96	--	--
			Non-Reheats	6.23	4.3	6.0	291	--	--
			Reheats	6.15	6.8	5.7	90	--	--
	20-HVS-V	SM-9.5A, 45% RAP + PG 58-28	Design	6.00	2.7	4.9	141	--	--
			Non-Reheats	6.07	5.3	4.7	177	--	--
			Reheats	6.00	6.6	4.2	82	--	--
	20-HVS-VI	SM-9.5A, 60% RAP + PG 58-28 + RA3	Design	6.00	4.0	3.7	128	--	--
			Non-Reheats	5.89	4.1	5.3	268	--	--
			Reheats	6.14	5.5	5.9	84	--	--

ID = identity; BC = binder content; CML = Cantabro mass loss; APA = Asphalt Pavement Analyzer; CT = cracking tolerance; STOA = short-term oven aging; LTOA = long-term oven aging; SM = surface mixtures; RAP = reclaimed asphalt pavement; A and D = mixture designations; PG = performance grade; S = standard traffic; RA = recycling agent; HVS = heavy vehicle simulator; -- = mixture was not tested or data are not available.

Table 18. Summary of Binder Content and Performance Data for High RAP With RA: 2022 Field Trial

District	Mixture ID	Mixture Details	Type of Specimens	BC, %	CML, %	APA Rut Depth, mm	CT_{index} STOA	CT_{index} LTOA	CT_{index} Aging Sensitivity
Northern Virginia	22-A	SM-9.5D, 40% RAP + PG 64S-22	Design	5.50	3.5	4.6	96	42	56.3
			Non-Reheats	5.65	5.1	3.9	104	--	--
			Reheats	5.60	7.9	2.9	68	--	--

ID = identity; BC = binder content; CML = Cantabro mass loss; APA = Asphalt Pavement Analyzer; CT = cracking tolerance; STOA = short-term oven aging; LTOA = long-term oven aging; SM = surface mixtures; RAP = reclaimed asphalt pavement; D = mixture designation; PG = performance grade; S = standard traffic; RA = recycling agent; -- = mixture not tested or data not available.

The CT_{index} aging sensitivity was calculated using Equation 19. The resultant CT_{index} aging sensitivity values ranged from 9.3% to 66.0%, with an average value of 46.9%. The two long-term aging protocols (i.e., 8 hours at 135°C and 1-day LTOA at 95°C) correspond to different aging durations in the field; therefore, the recommended threshold for CT_{index} aging sensitivity set at 45% for 1-day LTOA at 95°C may not applicable to the mixtures tested after 8 hours at 135°C. The CT_{index} aging sensitivity values were provided for documentation purposes only and for further analysis as part of the ongoing study focusing on determining long-term aging protocols for BMD mixtures. It is important to note that the decision to switch from 135°C to 95°C in this study was motivated by the concerns regarding the potential adverse impact of high aging temperatures on the chemical make-up of RAs and, as a consequence, on the performance of RA.

Figure 53 shows the pavement surface conditions of three sections featuring the use of various RAs in Northern Virginia (Sections 19-A-V, 20-A-2, and 22-A) as examples. These sections are currently in very good condition after 4 years, 3 years, and 1 year for Sections 19-A-V, 20-A-2, and 22-A, respectively, as shown in Figure 53. Since the evaluated sections were placed during the 2019, 2020, and 2022 construction seasons, the corresponding performance data and observations are still considered preliminary, and the performance of these sections will continue to be monitored.

(a) (b)

(c)

Figure 53. Photographs of Mixtures: (a) Section 19-A-V, 4 years post-paving; (b) Section 20-A-2, 3 years post-paving; (c) Section 22-A, 1-year post-paving.

Developed Frameworks

Based on the findings of this study, two frameworks are recommended. The first addresses the inclusion of RA products on VDOT's APL. The second focuses on integrating RA products into the mix designs of SMs.

Framework 1: For Inclusion of RAs in VDOT's APL

The work prescribed under this framework is to be completed by an accredited third-party laboratory.

Step 1: Selection and Baseline Evaluation of Component Materials

- *Asphalt Binder.* A sample of PG 64S-22 virgin asphalt binder, typically used in Virginia, will be sent to the RA supplier. The following properties of the virgin binder shall be provided: |G*|/sinδ at 64°C and PGHc (AASHTO T 315 and AASHTO M 320); |G*|sinδ at 25°C and PGIc (AASHTO T 315 and AASHTO M 320); PGLc and ΔTc (AASHTO T 313 and AASHTO M 320); and $J_{nr,3.2}$ at 64°C (AASHTO T 350 and AASHTO M 332).

- *RAP Material and Extracted and Recovered RAP Binder*

  — A representative source of RAP material will be sent to the RA supplier. The RAP material will be selected in a way that the extracted and recovered asphalt binder has a high-temperature PG ranging from 94°C to 106°C and a low-temperature PG ranging from -10°C to -4°C.

  — The asphalt binder shall be extracted from the RAP material in accordance with AASHTO T 164 and then recovered in accordance with AASHTO T 319. The binder content of the RAP shall be reported. The following properties of the RAP binder shall be provided: |G*|/sinδ at 64°C and PGHc (AASHTO T 315 and AASHTO M 320); |G*|sinδ at 25°C and PGIc (AASHTO T 315 and AASHTO M 320); and PGLc and ΔTc (AASHTO T 313 and AASHTO M 320).

- *Recycling Agent.* A sample of the RA to be evaluated shall be collected from a batch produced within 1 year of the period of evaluation.

Step 2: Evaluation of the Recycled Binder System

- A recycled binder system composed of virgin binder (PG 64S-22 provided and described in Step 1) and the equivalent of 40% RAP by total weight of mixture shall be produced.

- The following properties of the recycled binder system shall be measured: |G*|/sinδ at 64°C and PGHc (AASHTO T 315 and AASHTO M 320); |G*|sinδ at 25°C and PGIc (AASHTO T 315 and AASHTO M 320); PGLc and ΔTc (AASHTO T 313 and AASHTO M 320); and $J_{nr,3.2}$ at 64°C (AASHTO T 350 and AASHTO M 332).

Step 3: Dosage of the Recycling Agent

- The RA supplier shall select an initial dosage (ID) of the RA that will produce a blended binder system with a maximum PGLc of -22°C. The RA dosage shall not exceed 10% of the total weight of the binder blend.

Step 4: Evaluation of the RA-Modified System

- An RA-modified system composed of the recycled binder system and the RA at the initial dosage recommended in Step 3 shall be produced.

- The following properties of the RA-modified system shall be measured: |G*|/sinδ at 64°C and PGHc (AASHTO T 315 and AASHTO M 320); |G*|sinδ at 25°C and PGIc

(AASHTO T 315 and AASHTO M 320); PGLc and ΔTc (AASHTO T 313 and AASHTO M 320); and $J_{nr,3.2}$ at 64°C (AASHTO T 350 and AASHTO M 332).

Step 5: Creep Stiffness—Relaxation Similarity Analysis

- The rejuvenation path SR_D between the recycled binder system and the RA-modified system shall be calculated and reported (see Figure 17).

- The rejuvenation path SR_D shall be sufficient to ensure that the RA-modified system is similar to the VDOT QA reference binder database for PG 64S-22 binder.

Step 6: Temperature-Specific and Global Similarity Analysis

- The RA supplier shall select another RA dosage, either 0.5xID (half of the initial dosage of the RA determined and provided in Step 3) or 1.5xID (one and one-half times the initial dosage of the RA determined and provided in Step 3). In all cases, 0.5xID or 1.5xID, the other selected dosage shall not exceed 10% of the total weight of the binder blend.

- An RA-modified system composed of the recycled binder system and the RA at the other dosage recommended in Step 6 shall be produced.

- The following properties of the RA-modified system shall be measured: |G*|/sinδ at 64°C and PGHc (AASHTO T 315 and AASHTO M 320); |G*|sinδ at 25°C and PGIc (AASHTO T 315 and AASHTO M 320); PGLc and ΔTc (AASHTO T 313 and AASHTO M 320); and $J_{nr,3.2}$ at 64°C (AASHTO T 350 and AASHTO M 332).

- A test of the statistical similarity of the recycled binder system and the RA-modified systems at the optimum and other dosages shall be conducted with respect to the VDOT QA reference binder database for PG 64S-22 binder (see Figure 13).

If similarity is achieved, the RA product, along with all corresponding details, can be added to VDOT's APL. This validity will remain in effect for up to 3 years from the approval date provided that the formulation of the RA product has not been altered.

Framework 2: For Design BMD Asphalt SMs With RAs

The work prescribed under this framework shall be completed through collaboration among the contractor, RA supplier, and/or any accredited third-party laboratory. RAs that are not listed on VDOT's APL should undergo the testing indicated in Framework 1, which addresses the inclusion of RA products on VDOT's APL, and be approved before being incorporated into mix designs.

Step 1: Selection and Baseline Evaluation of Component Materials

- *Asphalt Binder*

  — A sample of PG 64S-22 virgin asphalt binder that is typically used by the contractor at a selected plant will be sent to the RA supplier.

  — The following properties of the virgin binder shall be measured: |G*|/sinδ at 64°C and PGHc (AASHTO T 315 and AASHTO M 320); |G*|sinδ at 25°C and PGIc (AASHTO T 315 and AASHTO M 320); PGLc and ΔTc (AASHTO T 313 and AASHTO M 320); and $J_{nr,3.2}$ at 64°C (AASHTO T 350 and AASHTO M 332).

- *RAP Material and Extracted and Recovered RAP Binder*

  — A representative sample of RAP material, comparable to the one to be used during production, will be sent to the RA supplier.

  — The asphalt binder shall be extracted from the RAP material in accordance with AASHTO T 164 and then recovered in accordance with AASHTO T 319. The binder content of the RAP stockpile shall be reported.

  — The following properties of the RAP binder shall be measured: |G*|/sinδ at 64°C and PGHc (AASHTO T 315 and AASHTO M 320); |G*|sinδ at 25°C and PGIc (AASHTO T 315 and AASHTO M 320); and PGLc and ΔTc (AASHTO T 313 and AASHTO M 320).

- *Recycling Agent.* The RA to be used during the project must be listed on VDOT's APL.

Step 2: Dosage of the Recycling Agent

- The RA supplier shall select a dosage of RA that will restore the recycled binder system to a maximum low-temperature continuous PG grade of -22°C. The dosage shall not exceed 10% of the total weight of the binder blend.

Step 3: Evaluation of the RA-Modified System

- An RA-modified system composed of the virgin binder, RAP binder equivalent to the RAP content to be used in the mixture, and RA at the dosage recommended in Step 2 shall be produced.

- The following properties of the RA-modified system shall be measured: |G*|/sinδ at 64°C and PGH_c (AASHTO T 315 and AASHTO M 320); |G*|sinδ at 25°C and PGI_c (AASHTO T 315 and AASHTO M 320); PGL_c and ΔT_c (AASHTO T 313 and AASHTO M 320); and $J_{nr,3.2}$ at 64°C (AASHTO T 350 and AASHTO M 332).

Step 4: Creep Stiffness—Relaxation Similarity Analysis

- The RA-modified system shall be similar in terms of low-temperature properties to the VDOT QA reference binder database for PG 64S-22 (see Figure 17).

Step 5: Design of Dense-Graded Surface Mixtures With RA

- The contractor shall meet the requirements of VDOT's BMD special provisions with the exception of the LTOA conditioning protocol for asphalt mixtures.

- New LTOA Protocol: Loose asphalt mixture shall be conditioned in the oven at a temperature of 95°C for 1 day (24 hours) after the STOA (4 hours at compaction temperature) is completed. As part of the LTOA protocol, the loose mixture shall be placed into a pan such that the layer thickness shall approximately be equal to the nominal maximum aggregate size of the mixture. After LTOA conditioning, the mixture shall be allowed to cool to room temperature and then reheated to the compaction temperature. Finally, the mixture shall be compacted to 7 ± 0.5% air-void content with a height of 62 ± 1 mm and a diameter of 150 ± 2 mm using the SGC.

- A minimum of five 1-day LTOA specimens shall be tested in accordance with VTM-143. The mean CT_{index} value shall be reported and labeled as (CT_{index})1dayLTOA. The single operator testing tolerance in terms of COV shall be applied for the mix design IDT-CT test for 1-day LTOA specimens.

- CT_{index} aging sensitivity, measuring the % change (typically a reduction) between (CT_{index})STOA and (CT_{index})1-day LTOA and labeled as $(CT_{index})_{aging\ sensitivity,}^{1day\ LTOA}$ shall be calculated using the following equation. A mixture with RA shall meet a requirement of a maximum $(CT_{index})_{aging\ sensitivity}^{1day\ LTOA}$ of 45%.

$$(CT_{index})_{aging\ sensitivity}^{1day\ LTOA} = \left[\frac{(CT_{index})_{STOA} - (CT_{index})_{1day\ LTOA}}{(CT_{index})_{STOA}}\right] * 100$$

If a proper mix design is not achieved with a PG 64S-22 binder and an RA dosage lower than 10% by total weight of binder, the producer can restart from Step 1 while considering a softer grade of the binder (in this case PG 58-28) in addition to the RA.

CONCLUSIONS

- *There is a clear need for the establishment of an engineered framework to classify, assess the acceptability of, and provide a unified dosage selection method for RAs when used in asphalt mixtures*. This framework should provide standardized criteria and guidelines for evaluating the suitability and performance of RAs, enabling their effective and responsible use in asphalt construction projects.

- *There is a clear need to develop methodologies that effectively integrate cost considerations into the selection and evaluation of RAs for their use in recycled pavements.*

- *There is clear need to conduct thorough investigations into the environmental impacts of chemically active RAs in both the short term and long term and to gain a better understanding of the emissions associated with the use of RAs in recycled asphalt mixtures, considering their widespread application in production, mixing, and compaction processes.*

- *RAs can provide performance-based improvements to and increase the use of recycled materials in asphalt mixtures provided that a correct and suitable dosage of RA product is determined through a performance-based testing framework.* This was evidenced through the findings of the literature review; the positive feedback of state DOTs, contractors, and RA suppliers; the laboratory test results on the binder blends and asphalt mixtures used in this study; and the promising initial field performance of asphalt mixtures with RAs placed in Virginia.

- *The effectiveness of RAs in improving the properties of asphalt binder blends is specific to the product being used, and the extent of the improvements achieved is also specific to the temperature(s) or conditions targeted.* The binder test results in this study indicated that the working mechanism of RA products is different, even for products belonging to the same classification category.

- *The effectiveness of RAs in improving the properties of asphalt mixtures is specific to the product being used, and the extent of the improvements achieved is also specific to the performance metrics evaluated (i.e., durability, cracking, and rutting).*

- *Mixtures containing high RAP contents with RAs can be designed and produced to meet the current performance thresholds for BMD and satisfy the requirements for volumetric properties, gradation, and asphalt content. In addition, the laboratory performance test results obtained from similar mixtures evaluated in this study indicate that these asphalt mixtures can be designed and produced in a way that their performance is equal to or better than the performance of their counterpart high RAP mixtures with softer binders (i.e., PG 58-28).*

- *The overall trends in performance improvements observed in the binder and mixture testing were similar, but the extent and rate of the improvement were different and RA specific.* This could be attributed to the rate of blending occurring in binder and mixture media and the amount of binder available and activated in RAP within the mixture.

- *The mixture tests used in VDOT's current BMD framework (i.e., Cantabro test, IDT-CT, and APA rut test) can capture the changes resulting from the use of different types of RAs.*

- *The use of multiple LTOA protocols in this study demonstrated that aging condition has a significant influence on the measured performance of the asphalt binder blends and mixtures. In addition, the rate of aging exhibited by certain RAs varies depending on the specific product and serves as a crucial indicator of the stability of the RA.*

- *Successful asphalt mixture performance with the use of RAs can be achieved when an established framework for selection of a RA product and associated dosage is coupled with local practices for asphalt mixture design and acceptance such as RAP stockpile management program and BMD methodology.*

- *The early performance of field trials featuring asphalt mixtures with RAs in Virginia is promising.*

RECOMMENDATIONS

1. *VDOT's Materials Division should consider adopting the performance-based framework outlined in this study to streamline the evaluation process and determine the acceptability of RA products for inclusion on VDOT's APL.* The undertaking of the framework to assess the viability of a given RA should be executed with locally available materials. This can be accomplished by evaluating a target binder blend composed of virgin asphalt binder (PG 64S-22), extracted and recovered asphalt binder from RAP stockpile with a high-temperature PG ranging from 94°C to 106°C and a low-temperature PG ranging from -10°C to -4°C, and the RA product being evaluated. The properties of the resultant binder blend should be compared against the existing QA database of PG 64S-22 and PG 64H-22 virgin binders used in Virginia for SMs with A and D designations, respectively.

2. *VTRC should validate the performance-based frameworks recommended in this study to evaluate the short- and long-term effectiveness of RAs in enhancing the performance of asphalt mixtures, particularly those with high RAP contents.* This validation process would constitute the first application of the recommended frameworks and would involve conducting evaluations on component materials and asphalt mixtures sampled from recently completed, ongoing, and upcoming field trials using high RAP with RA mixtures.

3. *VDOT's Materials Division and VTRC should consider using the Cantabro test, APA rut test, and IDT-CT to assess the performance characteristics of mixtures produced with RAs that are designed using the BMD methodology. These mixtures should meet the existing BMD performance criteria at the STOA condition. In addition, these mixtures should meet the newly determined CT_{index} aging sensitivity criterion (maximum 45%) after being subjected to the newly identified LTOA protocol of 1 day (24 hours) at 95°C.* Overall, the data presented and discussed in this report showed that these tests at the prescribed aging conditions were able to capture the impact of RAs on the performance of asphalt mixtures. The data also showed that the recommended rheological parameter SR_D is specific of the RA used but is independent of RA dosage, RAP content, RAP binder, and virgin binder, indicating that RAs can be used as a tool to improve the performance of any mixture.

4. *VTRC should continue to monitor the performance of the field trials featuring the use of high RAP contents, RAs, and softer binders using the BMD methodology.* This monitoring would contribute to more accurate predictions of the service life for the corresponding mixtures by comparing the control mixtures with those containing RAs and/or softer binders, as the existing sections continue to age over time.

5. *VTRC should conduct a study to characterize the binder availability in typical RAP stockpiles in Virginia.* Currently, a default correction factor of 0.4% is applied to the available binder content of RAP determined by the ignition method in accordance with VTM 102. This would provide quantifiable information to determine how RAP availability should be accounted for in mix design methods for Virginia.

6. *VTRC should conduct a study to evaluate the effectiveness of RAs at activating the available RAP binder for improved blending with virgin asphalt binder, which results in improved performance of asphalt mixtures.*

7. *VTRC should conduct a study to establish a protocol for assessing the quality (stiffness) and consistency of RAP stockpiles.* In this study, the RAP used was tightly controlled. The potential variation of RAP properties (e.g., gradation, RAP binder content, and stiffness) for a given stockpile may significantly influence the performance of corresponding asphalt mixtures.

8. *VTRC should conduct a study to quantify the environmental and economic impacts of using asphalt SMs with high RAP contents and/or RAs.* This could be achieved by conducting a life-cycle assessment and a life-cycle cost analysis on selected case studies of field trials that feature the use of high RAP contents and/or RAs.

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

With regard to Recommendation 1, VTRC will work with VDOT's Materials Division to develop a draft Virginia Test Method accompanied with a process using Microsoft Excel or any other program as seen suitable, which will outline instructions for input elements related to the base recycled and RA-modified systems, while also providing outputs for assessing the compatibility of the evaluated RA. This work is expected to be completed in 2025.

With regard to Recommendation 2, VTRC will work with VDOT's Northern Virginia District on two high RAP with RA field trials, one constructed during the 2022 paving season and to be constructed during the 2023 paving season. Moreover, VTRC will work with VDOT's Hampton Roads District on one upcoming high RAP with RA field trial during the 2023 paving season. A successful conclusion of this implementation item will serve toward supporting the use of SMs with RAs, specifically those with high RAP contents. This effort will be documented as part of a technical report. This work is expected to be completed by fall 2024.

With regard to Recommendation 3, VTRC will continue to collaborate with VDOT's Materials Division to assess the viability of designing and producing mixtures with RAs and/or softer binders. This will include using the Cantabro test, APA rut test, and IDT-CT to assess the durability, resistance to rutting, and both short- and long-term cracking performance of these mixtures, respectively. Moreover, VTRC will collaborate with VDOT's Materials Division to develop a roadmap that provides guidance on the specific needs and activities to be addressed prior to the implementation of mixtures with RAs and/or softer binders.

With regard to Recommendation 4, VTRC will draft and submit a research needs statement to the appropriate VTRC Pavement Research Advisory Committee Subcommittee by no later than Fiscal Year 2025. As part of this potential effort, VTRC will monitor the performance of sections featuring the use of high RAP, RA products, and/or softer binders in Virginia for the next 5 to 7 years in order to capture a more representative documentation of field performance for these types of paving materials.

With regard to Recommendations 5 and 6, VTRC drafted and submitted a research needs statement to the VTRC Pavement Research Advisory Committee for ranking with the intent of initiating the effort in Fiscal Year 2024.

With regard to Recommendation 7, NCHRP IDEA Project N-245 (VTRC Project No. 123773), Simple and Rapid Tests for Assessing Quality and Consistency of Reclaimed Asphalt Pavement (RAP) for Recycled Asphalt Mixture Applications, is ongoing. The overarching objective of this effort is to provide a framework to determine and assess RAP binder stiffness and its consistency within RAP stockpiles through simple and practical tests. The outcome of this effort is anticipated to become available in Spring 2025.

With regard to Recommendation 8, VTRC and VDOT have recently submitted a proposal and been awarded a grant to quantify the environmental benefits of greener pavements in Virginia, in response to the FHWA's climate challenge initiative. This effort primarily focuses on quantifying emissions associated with sustainable pavements. As part of the experimental program, both conventional and special asphalt mixtures featuring the use of high RAP contents with RAs agents are included in as case studies. Moreover, VTRC will draft a research needs statement to assess the economic impacts of using asphalt SMs with high RAP contents and/or RAs and will submit it to the appropriate VTRC Pavement Research Advisory Subcommittee by no later than Fiscal Year 2025.

Benefits

This study provided VDOT with an engineered framework for the evaluation of RAs in relation to their inclusion on the APL. In addition, the study provided VDOT with a performance-based framework to assess the viability of RAs when incorporated into conventional and high RAP mixtures. The established frameworks empower material designers to systematically assess and select RAs for improved asphalt mixture performance, while owner/agency quality assurance/acceptance programs can confidently assess the compliance and performance of these asphalt mixtures. The established frameworks coupled with the BMD methodology enable the use of truly innovative asphalt mixtures such as those incorporating high RAP contents and/or RAs with promising performance prospects. This promotes sustainable and efficient road construction practices, leading to improved pavement performance and reduced environmental impact.

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APPENDIX A

STATE DEPARTMENT OF TRANSPORTATION SURVEY

This survey is designed to collect key information from agencies (State Departments of Transportation) to assess the current state of practice on the use of recycling agents (RAs) in asphalt mixtures with reclaimed asphalt pavement (RAP) and/or recycled asphalt shingles (RAS). This questionnaire includes six modules of questions related to permissivity and usage of RAP, RAS, and RAs, production-related attributes and quality assurance, and associated experience, challenges, advantages, and disadvantages. The survey responses will be analyzed and presented in the deliverable of the VDOT/NCSU project UPC117566 entitled "*Evaluating recycling Agents' Acceptance for Virginia: test Protocols and Performance-Based Threshold Criteria*" http://vtrc.virginiadot.org/ProjDetails.aspx?id=710 https://trid.trb.org/view/1713387.

Please complete this questionnaire ***to the best of your knowledge*** by ***November 20, 2020***. The survey will take approximately 20-30 minutes to complete. If you prefer, you may respond to these questions by phone. To do so, please contact ***Jhony Habbouche*** either by email at Jhony.habbouche@vdot.virginia.gov or by phone at (434) 293-1423 to arrange a date and time. If you have any questions, please use the contact information (above) to reach out to ***Jhony Habbouche***.

Thank you in advance for your participation. Your response will help researchers, developers, and material designers establish an engineered framework and a practical testing protocol to evaluate the ***acceptance and performance*** of recycling agents (RAs) when used in asphalt mixtures.

Q1- Contact Information

Name	
Position / Title	
Agency	
Address (City, State & Zip Code)	
Phone	
Email	

May we contact you for more information?

☐Yes.

☐Please contact this person instead (please provide name, phone number, and / or email address).

☐No.

<u>Q2- Permissivity and Usage of RAP</u>

The purpose of this module is to seek information regarding permissivity and usage of RAP by State Department of Transportations. In this module, two categories of surface mixes are defined:

- ***"Typical surface mixes"*** referring to everyday surface asphalt mixes typically used by the State; these mixes may or may not contain RAP material.
- ***"High RAP surface mixes"*** referring to surface asphalt mixes produced with relatively high RAP content. This definition is considered State-specific and can vary among States.

a- Does your agency currently *<u>specify or allow</u>* the use of RAP in surface mixes of asphalt pavements?

☐Yes

☐No

☐Not Sure

[If "No" or "Not Sure" are selected, <u>please skip to "o"</u>]

b- How does your agency currently *<u>quantify</u>* RAP in surface mixes?

☐Using percentage by weight of asphalt mixes (%RAP)

☐Using recycled binder ratio (RBR) (by definition, *RBR* is the ratio of the RAP binder content to the mix total binder content)

☐Not Sure

c- Does your agency currently *<u>specify or allow</u>* the use of *<u>high RAP surface mixes</u>* in asphalt pavements?

☐Yes

What mix would your State consider as a high RAP mix (in terms of minimum %RAP or RBR)?

☐No

☐Not Sure

d- According to your specifications, how much RAP is *<u>permitted</u>* in your surface asphalt mixes? (Check all that apply)

☐Not allowed by current specifications

Please provide reason(s) for such restriction (if selected)

☐Required

Please briefly describe and specify typical percentages of RAP (including maximum limit if any) by weight of mixes or in terms of RBR (if selected)

☐Allowed as an option

Please briefly describe and specify typical percentages of RAP (including maximum limit if any) by weight of mixes or in terms of RBR (if selected)

☐Allowed as a separate bid item

Please briefly describe and specify typical percentages of RAP (including maximum limit if any) by weight of mixes or in terms of RBR (if selected)

☐Used previously

Please provide reason (s) for discontinuation of use

☐No available information

e- What is your current state of practice with regard to characterizing RAP when used at typical application rates (e.g. physical and/or rheological characterization, gradation, binder content …)?

☐Following standard test method(s) / procedure(s)

Please list # or IDs of standard(s)/ procedure(s) or paste e-links (if selected)

☐Following best / typical / special practices of the State

Please describe briefly (if selected)

☐No current standard test method(s) / procedure(s)

☐Others

Please describe briefly (if selected)

f- If your State currently permits high RAP mixes, does your current state of practice with regard to <u>characterizing</u> RAP change between typical surface mixes and high RAP surface mixes?

☐Yes

Please describe briefly (if selected)

☐No

☐Not Sure

g- What is your current state of practice with regard to <u>designing</u> surface asphalt mixes with RAP?

☐Following standard test method(s) / procedure(s)

Please list # or IDs of standard(s)/ procedure(s) or paste e-links (if selected)

☐Following best / typical / special practices of the State

Please describe briefly (if selected)

☐No current standard test method(s) / procedure(s)

☐Others

Please describe briefly (if selected)

[If "No current standard test method(s) / procedure(s)" are selected, please skip to part "i"]

h- What performance tests and corresponding threshold criteria / measures are implemented by your State when designing surface asphalt mixes with typical RAP contents? *If possible and available, please share special provisions*.

i- If your State currently permits high RAP mixes, does your current state of practice with regard to *designing* surface asphalt mixes with RAP change between typical surface mixes and high RAP surface mixes?

☐Yes

Please describe briefly (if selected)

☐No

☐Not Sure

[If "No" or "Not Sure" are selected, please skip to part "k"]

j- What performance tests and corresponding threshold criteria / measures are implemented by your State when designing high RAP surface mixes? *If possible and available, please share specifications or special provisions*.

k- Does your State require specific practices on managing/processing RAP for high RAP surface mixes? (e.g., limiting NMAS of RAP, Fractionation, Route specific RAP stockpiling (not combining RAP together from different routes), etc…)

l- **Does your State require the use of a softer virgin binder grade when using high RAP mixes compared to virgin mixtures? If so, please describe the conditions under which a softer virgin binder grade is required.**

m- **Does your State follow a specified procedure for material preheating and mixing when preparing laboratory fabricated mixtures containing RAP? If so, please indicate the standard procedure followed and/or describe (e.g., RAP is preheated for no more than 2 hours at 110°C. Virgin aggregate is heated 15°C above the mixing temperature and the virgin binder is heated to the mixing temperature. The virgin aggregate and RAP are first mixed and then the virgin binder is added, etc.).**

n- **What, if any, premature distresses or failures of pavements have you commonly observed with your high RAP surface mixes?**

☐Do not allow / use high RAP surface mixes
☐No premature distresses or failures have been observed to date
☐Bleeding
☐Rutting and shoving
☐Fatigue cracking
☐Reflective cracking
☐Thermal cracking
☐ Roughness
☐Other distresses

Please identify (if selected)

☐Not Sure

o- **What are the main *roadblocks to a greater usage of RAP* in your State? (Check all that apply)**

☐No significant roadblocks
☐Specifications-related limits

Please describe briefly (if selected)

☐Lack of mix design methods and engineering-based design procedures
☐Lack of RAP availability
☐Lack of processing in terms of RAP variability
☐Lack of project selection criteria
☐Lack of agency experience
☐Previous unsuccessful experiences

☐Opposition from competing industries
☐Reluctance to changes by industries
☐Poor pavement performance associated with premature distresses and/or failures
Please describe briefly (if selected)

☐Others
Please specify below (if selected)

Q3- Permissivity and Usage of RAS

The purpose of this module is to seek information regarding the permissivity and usage of RAS in surface asphalt mixtures by State Department of Transportations.

a- Does your agency currently *specify or allow* the use of RAS in surface mixes of asphalt pavements?
☐Yes
☐No
☐Not Sure
[If "No" or "Not Sure" are selected, please skip to "j"]

b- How does your agency currently *quantify* RAS in surface mixes?
☐Using percentage by weight of asphalt mixes (%RAS)
☐Using recycled binder ratio (RBR) (by definition, *RBR* is the ratio of the RAS binder content to the mix total binder content)
☐Not Sure

c- According to your specifications, how much RAS is *permitted* in your surface asphalt mixes? (Check all that apply)
☐Not allowed by current specifications
Please provide reason(s) for such restriction (if selected)

☐Required
Please briefly describe and specify typical percentages of RAS (including maximum limit if any) by weight of mixes or in terms of RBR (if selected)

☐Allowed as an option
Please briefly describe and specify typical percentages of RAS (including maximum limit if any) by weight of mixes or in terms of RBR (if selected)

☐Allowed as a separate bid item

Please briefly describe and specify typical percentages of RAS (including maximum limit if any) by weight of mixes or in terms of RBR (if selected)

☐Used previously

Please provide reason (s) for discontinuation of use

☐No available information

d- What is your current state of practice with regard to characterizing RAS?

☐Following standard test method(s) / procedure(s)

Please list # or IDs of standard(s)/ procedure(s) or paste e-links (if selected)

☐Following best / typical / special practices of the State

Please describe briefly (if selected)

☐No current standard test method(s) / procedure(s)

☐Others

Please describe briefly (if selected)

e- What is your current state of practice with regard to *designing* surface asphalt mixes with RAS?

☐Following standard test method(s) / procedure(s)

Please list # or IDs of standard(s)/ procedure(s) or paste e-links (if selected)

☐Following best / typical / special practices of the State

Please describe briefly (if selected)

☐No current standard test method(s) / procedure(s)

☐Others

Please describe briefly (if selected)

[If "No current standard test method(s) / procedure(s)" are selected, please skip to part "g"]

f- What performance tests and corresponding threshold criteria / measures are implemented by your State when designing surface asphalt mixes with RAS? *If possible and available, please share special provisions*.

g- Does your State require the use of a softer virgin binder grade when using RAS in mixes compared to virgin mixtures? If so, please describe the conditions under which a softer virgin binder grade is required.

h- Does your State follow a specified procedure for material preheating and mixing when preparing laboratory fabricated mixtures containing RAS? If so, please indicate the standard procedure followed and/or describe (e.g., RAS is preheated at the mixing temperature for 30 min. Virgin aggregate is heated 15°C above the mixing temperature and the virgin binder is heated to the mixing temperature. The virgin aggregate and RAS are first mixed and then the virgin binder is added).

i- What, if any, premature distresses or failures of pavements, if any, have you observed with your RAS surface mixes?

☐Do not allow / use RAS surface mixes
☐No premature distresses or failures have been observed to date
☐Bleeding
☐Rutting and shoving
☐Fatigue cracking
☐Reflective cracking
☐Thermal cracking
☐ Roughness
☐Other distresses

Please identify (if selected)

☐Not Sure

j- What are the main *roadblocks to a greater usage of RAS* in your State? (Check all that apply)

☐No significant roadblocks
☐Specifications-related limits

Please describe briefly (if selected)

☐Lack of mix design methods and engineering-based design procedures
☐Lack of RAS availability
☐Lack of processing in terms of RAS variability

☐Lack of project selection criteria
☐Lack of agency experience
☐Previous unsuccessful experiences
☐Opposition from competing industries
☐Reluctance to changes by industries
☐Poor pavement performance associated with premature distresses and/or failures

Please describe briefly (if selected)

☐Others

Please specify below (if selected)

Q4-Permissivity and Usage of Recycling Agents (RAs)

The purpose of this module is to seek information regarding the permissivity and usage of recycling agents (RAs) by State Department of Transportations. RAs are defined as additives / products with chemical and physical characteristics designed to rejuvenate or soften the aged asphalt binder of the RAP and/or RAS materials.

a- Does your agency currently *specify or allow* the use of RAs in surface asphalt mixes?

☐Yes
☐Yes but only for surface mixes with high RAP/RAS content
☐No
☐Not Sure
☐Others

Please describe briefly (if selected)

[If "No" or "Not Sure" are selected, please skip to "i"]

b- What is your current practice with regard to *using RAs* in surface asphalt mixes? (Check all that apply)

☐Not allowed by current specifications

Please provide reason(s) for such restriction (if selected)

☐Required

Please briefly describe and specify typical dosages by weight of asphalt binder (if selected)

☐Allowed as an option

Please briefly describe and specify maximum dosages by weight of asphalt binder (if selected)

☐Used previously

Please provide reason (s) for discontinuation of use

☐No available information

c- Does your agency include RAs on its approved product list (APL)?

☐Yes

☐No

☐Not sure

[If "No' or "Not sure" are selected, please skip to part "e"]

d- Please briefly describe what is and how the framework was established to add RA products to the State official approval list products (e.g., based on previous successful experience and promising field performance in or outside the State, based on the outcomes of a research effort, etc…).

e- How does your agency select RAs in terms of types/brands to be used in surface asphalt mixtures when needed?

☐RAs on approved products lists are to be solely used

☐Agency relies on the efforts of contractors and/or RAs supplier

☐Not sure

☐Others

Please describe briefly (if selected)

f- How does your agency characterize RAs in terms of dosage in surface asphalt mixes? (Check all that apply)

☐RAs on approved products lists are to be solely used with prescribed known rates

☐Agency relies on the efforts of contractors and/or RAs suppliers

☐Not sure

☐Agency has its own method of determining appropriate dosage

Please describe briefly (if selected)

☐Others

Please describe briefly (if selected)

g- What performance tests and corresponding threshold criteria / measures on binders and/or mixtures are implemented by your State when designing surface asphalt mixes with RAs? *If possible and available, please share special provisions*.

h- What, if any, premature distresses or failures of pavements have you commonly observed with surface mixes with RAs?

☐No premature distresses or failures have been observed to date
☐Bleeding
☐Rutting and shoving
☐Fatigue cracking
☐Reflective cracking
☐Thermal cracking
☐Roughness
☐Other distresses

Please identify (if selected)

☐Not Sure

i- What are the main *roadblocks to utilizing recycling agents (RAs)* in your State? (Check all that apply)

☐No significant roadblocks
☐Specifications-related limits

Please describe briefly (if selected)

☐Lack of tests and criteria to determine dosage rate and/or performance
☐Lack of mix design methods and engineering-based design procedures
☐Lack of RAs availability
☐Cost of RAs
☐Lack of project selection criteria
☐Lack of agency experience
☐Lack of contractors' expertise in using RAs
☐Previous unsuccessful experiences
☐Distrust of actual effectiveness
☐Opposition from competing industries
☐Reluctance to changes by industries
☐Poor pavement performance associated with premature distresses and/or failures

Please describe briefly (if selected)

☐Others

Please describe briefly (if selected)

<u>Q5- Production and Quality Assurance</u>

Quality Assurance: briefly indicate *<u>any changes</u>* from current quality assurance programs and / or practices when executed specifically for asphalt surface mixes containing RAP/RAS <u>with RAs</u> (changes from typical surface mixes). What types of acceptance testing do you specify?

<u>Q6- Experience: Best Practices and Lessons Learned</u>

a- Please provide any *"lessons learned"*, good or bad that you may have, regarding the use of RAs in surface asphalt mixtures with RAP/RAS in your State?

b- Do you have any additional information, current or historical, that you would like to share? If yes, please outline the information in the space provided below or provide links or contact information for more details.

☐Yes; please provide links below or email copies to Jhony.habbouche@vdot.virginia.gov. Is there anyone we could contact for more information? (Please provide name and contact information.)

☐No.

<u>Acknowledgment-</u>

The research team thanks you for your time, effort, and information.
This completes the survey.

APPENDIX B

SURVEY FOR SUPPLIERS OF RECYCLING AGENTS

This survey is designed to collect key information from suppliers of recycling agents (RAs) to assess the current state of practice on the use of these products in asphalt mixtures with reclaimed asphalt pavement (RAP) and/or recycled asphalt shingles (RAS). The survey responses will be analyzed and presented ***anonymously*** in the deliverable of the VDOT/NCSU project UPC117566 entitled "*Evaluating recycling Agents' Acceptance for Virginia: test Protocols and Performance-Based Threshold Criteria*" http://vtrc.virginiadot.org/ProjDetails.aspx?id=710 https://trid.trb.org/view/1713387.

Please complete this questionnaire by ***November 13, 2020***. This survey will take approximately 15-20 minutes to complete. If you prefer, you may respond to these questions by phone. To do so, please contact ***Jhony Habbouche*** either by email at Jhony.habbouche@vdot.virginia.gov or by phone at (434) 293-1423 to arrange a date and time. If you have questions, please use the contact information (above) to reach out to ***Jhony Habbouche***.

Thank you in advance for your participation. Your response will help researchers, developers, and material designers establish an engineered framework and a practical testing protocol to evaluate the ***acceptance and performance*** of recycling agents (RAs) when used in asphalt mixtures.

Q1- Contact Information

Name	
Position / Title	
Agency	
Address (City, State & Zip Code)	
Phone	
Email	

May we contact you for more information?

☐Yes.

☐Please contact this person instead (please provide name, phone number, and / or email address).

☐No.

Q2- What *types of RA(s)* does your company produce?

☐Paraffinic Oil

Please provide brand name(s) and typical dosage rate(s) (if selected)

☐Aromatic Extracts

Please provide brand name(s) and typical dosage rate(s) (if selected)

☐Napthenic Oils

Please provide brand name(s) and typical dosage rate(s) (if selected)

☐Triglycerides and Fatty Acids

Please provide brand name(s) and typical dosage rate(s) (if selected)

☐Tall Oils

Please provide brand name(s) and typical dosage rate(s) (if selected)

☐Not Sure

Please provide brand name(s) and typical dosage rate(s) (if selected)

☐Others

Please provide brand name(s) and typical dosage rate(s) (if selected)

Q3- What is your current state of practice with regard to *characterizing RA(s)* (e.g. physical, chemical, and/or rheological characterization …)?

☐Following standard test method(s) / procedure(s)

Please list # or IDs of standard(s)/ procedure(s) or paste e-links (if selected)

☐Following best / typical / special practices of the company

Please describe briefly (if selected)

☐No current standard test method(s) / procedure(s)

☐Others

Please describe briefly (if selected)

Q4- How do you establish a *suitable dosage rate* of your RA(s) for a given asphalt mixture?

Q5- **What *blending protocol* do you recommend for laboratory mix design of surface mixes containing your RA(s)? (Blending with virgin asphalt binder, blending with recycled material, blending with virgin aggregate, others…), please elaborate if possible.**

Q6- **What *blending protocol* do you follow during plant production and field operations of surface mixes containing your RA(s)? (Blending with virgin asphalt binder, blending with recycled material, blending with virgin aggregate, others…), please elaborate if possible.**

Q7- **Do you support including RA(s) on the approved product lists (APLs) of State DOTs?**

☐Yes

Please elaborate briefly (if selected)

☐No

Please elaborate briefly (if selected)

☐Not sure

[If "No' or "Not sure" are selected, please skip to part "Q9"]

Q8- **Based on your experience, please briefly describe what would be or how the framework to add RA products to States' official approval list products should be established (e.g., based on previous successful experience and promising field performance of mixes including your RA(s) in or outside the State, based on the outcomes of a research effort, based on virgin binder-RA blend-related parameters and threshold criteria, based on aged binder-RA blend-related parameters and threshold criteria, etc…).**

Q9- **In your opinion, what are the main roadblocks to utilizing recycling agents (RAs) in the USA? (Check all that apply)**

☐No significant roadblocks

☐Specifications-related limits

Please describe briefly (if selected)

☐Lack of tests and criteria to determine dosage rate and/or performance

☐Lack of mix design methods and engineering-based design procedures

☐Lack of RAs availability

☐Lack of project selection criteria

☐Lack of agency experience

☐Lack of contractors' expertise in using RAs

☐Lack of DOT support

☐Previous unsuccessful experiences
☐Opposition from competing industries
☐Reluctance to changes by industries
☐Poor pavement performance associated with premature distresses and/or failures
Please describe briefly (if selected)

☐Others
Please describe briefly (if selected)

Q10- Quality Control: briefly indicate specific current quality control programs and / or practices your company executes on asphalt mixes produced with your RA(s).

Q11- Does your product have a *shelf life*? If so, what is it?

Q12- For how long your product(s) is expect to remain stable in the *"recycling agent – binder" blend?*

Q13- Would you like to participate in our study? Your participation *(in an anonymous way)* can include sending a sample of your RA(s) to be included in our experimental program or by simply sharing information on mix design, construction, materials, and/or performance monitoring for surface mixes that include your RA(s).

☐Yes;
Please provide name and contact for more information.

☐No.

Q14- Do you have any additional information, current or historical, that you would like to share? If yes, please outline the information in the space provided below or provide links or contact information for more details.

☐Yes; please provide links below or email copies to Jhony.habbouche@vdot.virginia.gov. Is there anyone we could contact for more information? (Please provide name and contact information.)

☐No.

Acknowledgment-
The research team thanks you for your time, effort, and information.
This completes the survey.

APPENDIX C

SURVEY FOR ASPHALT CONTRACTORS IN VIRGINIA

This survey is designed to collect key information from selected contractors in Virginia with previous experience to assess the current state of practice on the use of recycling agents (RAs) in asphalt mixtures with reclaimed asphalt pavement (RAP). The survey responses will be analyzed and presented ***anonymously*** in the deliverable of the VDOT/NCSU project UPC117566 entitled "*Evaluating recycling Agents' Acceptance for Virginia: test Protocols and Performance-Based Threshold Criteria*" http://vtrc.virginiadot.org/ProjDetails.aspx?id=710 https://trid.trb.org/view/1713387.

In this questionnaire, two categories of surface mixes are defined:

- ***"Typical surface mixes"*** referring to everyday surface asphalt mixes typically used by the State; these mixes may or may not contain RAP material.
- ***"High RAP surface mixes"*** referring to surface asphalt mixes produced with relatively high RAP content (>30% by total weight of mixtures according to VA BMD special provisions 2020).

Please complete this questionnaire by ***November 13, 2020***. This survey will take approximately 15-30 minutes to complete. If you prefer, you may respond to these questions by phone. To do so, please contact ***Jhony Habbouche*** either by email at Jhony.habbouche@vdot.virginia.gov or by phone at (434) 293-1423 to arrange a date and time. If you have questions, please use the contact information (above) to reach out to ***Jhony Habbouche***.

Thank you in advance for your participation. Your response will help researchers, developers, and material designers establish an engineered framework and a practical testing protocol to evaluate the ***acceptance and performance*** of recycling agents (RAs) when used in asphalt mixtures.

Q1- Contact Information

Name	
Position / Title	
Agency	
Address (City, State & Zip Code)	
Phone	
Email	

May we contact you for more information?

☐Yes.

☐Please contact this person instead (please provide name, phone number, and / or email address).

☐No.

<u>Q2-</u> What is your current state of practice with regard to *<u>characterizing</u>* RAP (e.g. physical and/or rheological characterization, gradation, binder content …)?

<u>Q3-</u> Does your current state of practice with regard to *<u>characterizing</u>* RAP change between typical surface mixes and high RAP surface mixes?

☐Yes

Please describe briefly (if selected)

☐No

☐Not Sure

<u>Q4-</u> Please provide any specific practices on *<u>managing/processing RAP</u>* for high RAP surface mixes? (e.g., limiting NMAS of RAP, Fractionation, Route specific RAP stockpiling (not combining RAP together from different routes), etc…)

<u>Q5-</u> Please provide any specific practices on *<u>stockpiling RAP</u>* at your plant?

<u>Q6-</u> How do your select *<u>Recycling Agents (RAs)</u>* in terms of ***<u>types/brands</u>* to be used in surface asphalt mixtures when needed?**

<u>Q7-</u> Please provide any specific changes / modifications required to be made to your plant when producing surface mixes (typical or high RAP surface mixes) *<u>with RAs.</u>* How are RAs added to the mixes?

<u>Q8-</u> In case RAs were added to the virgin binder, what are your common practices in terms of storage conditions of the RA-binder blend (e.g., duration, temperature, agitation …)?

<u>Q9-</u> Please indicate *<u>any changes</u>* of current practice in terms of <u>producing</u> surface mixes (typical or high RAP surface mixes) *<u>with RAs</u>* at your plant (e.g., mixing time, mixing temperature, special additives [Warm mix additive and / or specific liquid anti-strip being used], and so on).

<u>Q10-</u> Please indicate *<u>any changes</u>* of current practice in terms of *<u>placement of surface mixes (typical or high RAP surface mixes) with RAs.</u>* (e.g., any adjustment for thickness, compaction effort, and so on). Can the same paving equipment still be used for these special mixes?

<u>Q11-</u> Please indicate *<u>any changes</u>* of current *<u>quality control programs and / or practices</u>* executed specifically for *<u>surface mixes (typical or high RAP surface mixes) with RAs</u>* (changes from typical surface mixes field projects).

<u>Q12-</u> What, if any, premature distresses or failures of pavements have you commonly observed with surface mixes with RAs?

☐No premature distresses or failures have been observed to date
☐Bleeding
☐Rutting and shoving
☐Fatigue cracking
☐Reflective cracking
☐Thermal cracking
☐Roughness
☐Other distresses
Please identify (if selected)

☐Not Sure

<u>Q13-</u> In your opinion, what are the *<u>main roadblocks to a greater usage of RAP</u>* in the projects that you work on? (Check all that apply)

☐No significant roadblocks
☐Specifications-related limits
Please describe briefly (if selected)

☐Lack of mix design methods and engineering-based design procedures
☐ Inability to meet State required mixture design volumetric targets consistently during production
☐Lack of RAP availability
☐Lack of processing in terms of RAP variability
☐Lack of project selection criteria
☐Lack of agency experience
☐Lack of DOT support
☐Previous unsuccessful experiences
☐Opposition from competing industries
☐Reluctance to changes by industries

☐Poor pavement performance associated with premature distresses and/or failures

Please describe briefly (if selected)

☐Others

Please specify below (if selected)

Q14- In your opinion, what are the *main roadblocks to utilizing recycling agents (RAs)* in the projects that you work on? (Check all that apply)

☐No significant roadblocks

☐Specifications-related limits

Please describe briefly (if selected)

☐Lack of tests and criteria to determine dosage rate and/or performance

☐Lack of mix design methods and engineering-based design procedures

☐Lack of RAs availability

☐Lack of project selection criteria

☐Lack of agency experience

☐Lack of contractors' expertise in using RAs

☐Lack of DOT support

☐Previous unsuccessful experiences

☐Distrust of actual effectiveness

☐Opposition from competing industries

☐Reluctance to changes by industries

☐Poor pavement performance associated with premature distresses and/or failures

Please describe briefly (if selected)

☐Others

Please describe briefly (if selected)

Q15- Quality Control: briefly indicate *any changes* from current quality control programs and / or practices when executed specifically for asphalt surface mixes (typical or high RAP surface mixes) *with RAs* (changes from typical surface mixes).

Q16- Please provide any *"lessons learned"*, good or bad that you may have, regarding the use of RAs in surface asphalt mixtures that you have produced and placed?

Acknowledgment-

The research team thanks you for your time, effort, and information.

This completes the survey.

APPENDIX D

SURVEY FOR ASPHALT BINDER SUPPLIERS IN VIRGINIA

This survey is designed to collect key information from asphalt binder suppliers in Virginia to help expand on the current state of practice on the use of recycling agents in asphalt mixtures. The survey responses will be analyzed and presented ***anonymously*** in the deliverable of the VDOT/NCSU project UPC117566 entitled "*Evaluating recycling Agents' Acceptance for Virginia: test Protocols and Performance-Based Threshold Criteria*" http://vtrc.virginiadot.org/ProjDetails.aspx?id=710 https://trid.trb.org/view/1713387.

Please complete this questionnaire by ***February 12, 2021***. This survey will take approximately 15-30 minutes to complete. If you prefer, you may respond to these questions by phone. To do so, please contact ***Jhony Habbouche*** either by email at Jhony.habbouche@vdot.virginia.gov or by phone at (434) 293-1423 to arrange a date and time. If you have questions, please use the contact information (above) to reach out to ***Jhony Habbouche***.

Thank you in advance for your participation. Your response will help researchers, developers, and material designers establish an engineered framework and a practical testing protocol to evaluate the ***acceptance and performance*** of recycling agents when used in asphalt mixtures.

Q1- Contact Information

Name	
Position / Title	
Agency	
Address (City, State & Zip Code)	
Phone	
Email	

May we contact you for more information?

☐Yes.

☐Please contact this person instead (please provide name, phone number, and / or email address).

☐No.

Q2- Please provide an approximate tonnage of PG 64-22, PG 58-28, and PG 58-22 asphalt binders supplied by your organization to projects constructed in the Commonwealth of Virginia for the last three years. To answer this question, please consider filling the table below.

Year	Asphalt Binder	Quantity Supplied (tons)	Comments (if available)
2020	PG 64-22		
	PG 58-28		
	PG 58-22		
2019	PG 64-22		
	PG 58-28		
	PG 58-22		
2018	PG 64-22		
	PG 58-28		
	PG 58-22		

Q3- Please provide any specific practices you follow (if available) to *chemically characterizing* your asphalt binders (asphalt binder composition by means of SARA analysis, absorbance spectra using Fourier Transform Infrared [FTIR] spectroscopy, molecular weights using Gel Permeation Chromatography [GPC], others…..).

Q4- Please provide what crude oil sources do you use to produce and supply asphalt binders for the Commonwealth of Virginia. Based on your experience and your observations, please elaborate on the potential impact of crude oil source selection on the properties of the delivered asphalt binders to the Commonwealth of Virginia.

Q5- What *blending protocol* would you recommend for *laboratory mix design* of asphalt mixes containing your asphalt binders and any recycling agents? (Blending with virgin asphalt binder, blending with recycled material, blending with virgin aggregate, following guidelines provided by recycling agent suppliers, others…), please elaborate if possible.
Note: In case "following guidelines provided by recycling agent suppliers" was selected, please provide what recycling agent product(s) you have experienced so far. In case of multiple, please elaborate on if the procedure(s) among different recycling agent suppliers were different.

Q6- What *blending protocol* would you recommend to follow *during plant production and field operations* of asphalt mixes containing your asphalt binders and any recycling agents? (Blending with virgin asphalt binder, blending with recycled material, blending with virgin aggregate, following guidelines provided by recycling agent suppliers, others…), please elaborate if possible.

Q7- Do you support including recycling agents on the approved product lists (APLs) of State DOTs?

☐Yes, ***Please elaborate briefly (if selected)***

☐No, ***Please elaborate briefly (if selected)***

☐Not sure

Q8- For how long do you expect your asphalt binders will remain stable in the *"binder-recycling agent" blend* (before mixing with aggregates)? What are (if available) or what would be the metrics/parameters employed by your organization to check the shelf life of the *"binder-recycling agent" blend*?

Q9- Please provide any *concerns* you may have if recycling agents were more frequently used in the production of asphalt mixtures in Virginia.

Q10- Please provide any *challenges* you may have if recycling agents were more frequently used in the production of asphalt mixtures in Virginia.

Acknowledgment-

The research team thanks you for your time, effort, and information.
This completes the survey.

APPENDIX E

GRADATIONS OF AGGREGATE AND RAP STOCKPILES

The individual aggregate stockpile and RAP gradations for each source were verified with the JMF. Table E1 lists the aggregate and RAP stockpiles from each source along with their proportions in the respective JMF. The gradations for Source 1, Source 2, and Source 3 are shown in Figures E1, E2, and E3, respectively.

Table E1. Characteristics of Aggregate and RAP Stockpiles Used in This Study

Source 1: Salem, VA			Source 2: Burkeville, VA			Source 3: Chesapeake, VA		
Stockpile	**Type**	**JMF**	**Stockpile**	**Type**	**JMF**	**Stockpile**	**Type**	**JMF**
RAP#1	RAP	45%	RAP#2	RAP	35%	RAP#3	RAP	40%
#9	Aggregate	14%	17’s	Aggregate	20%	Sand	Aggregate	20%
MS	Aggregate	10%	78’s	Aggregate	25%	17’s	Aggregate	21%
#8	Aggregate	31%	8’s	Aggregate	10%	8’s	Aggregate	19%
			17’s	Aggregate	10%			

VA = Virginia; JMF = job-mix formula; RAP = reclaimed asphalt pavement; MS = manufactured sand.

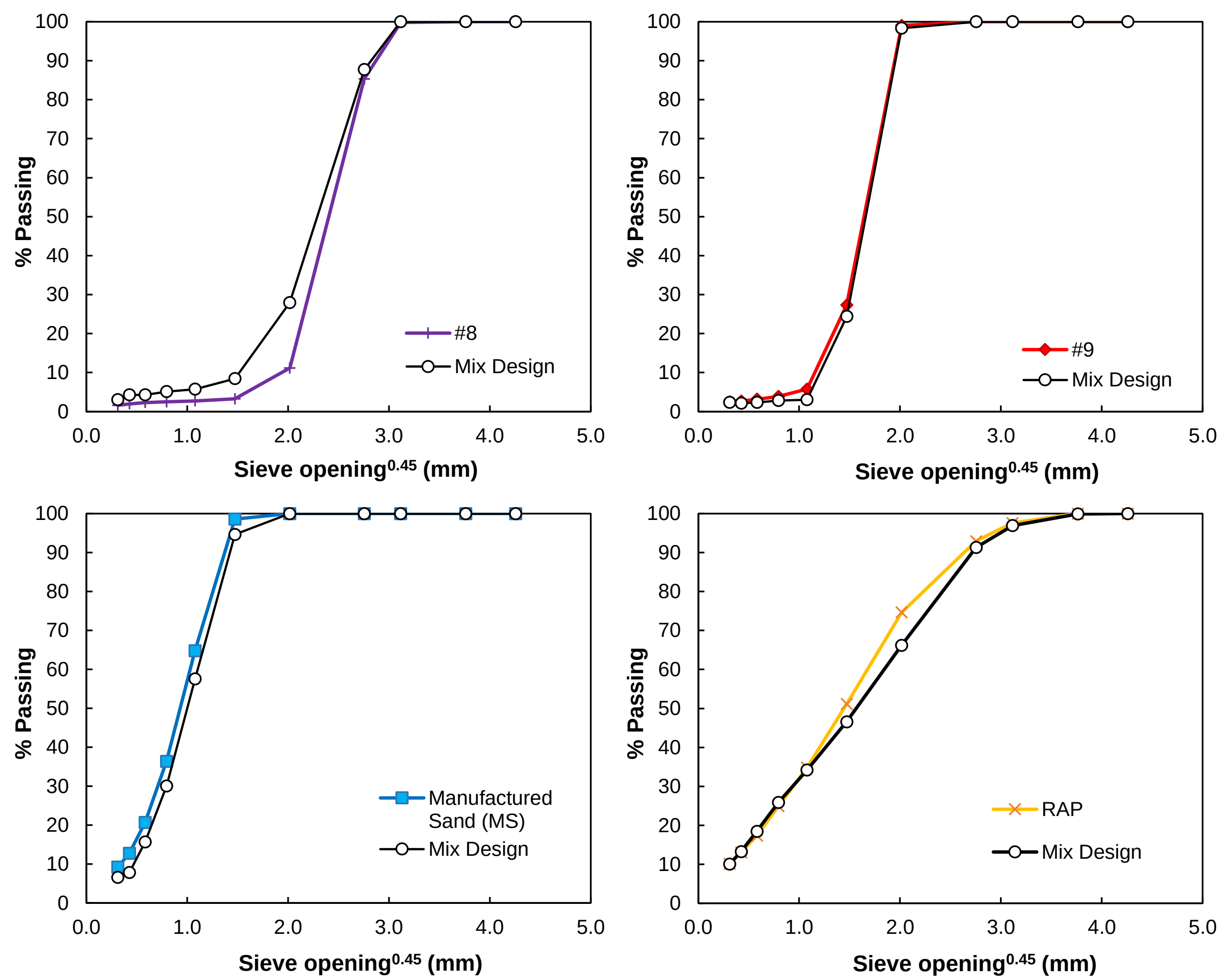

Figure E1. Source 1 Aggregate and RAP Stockpile Gradations. RAP = reclaimed asphalt pavement.

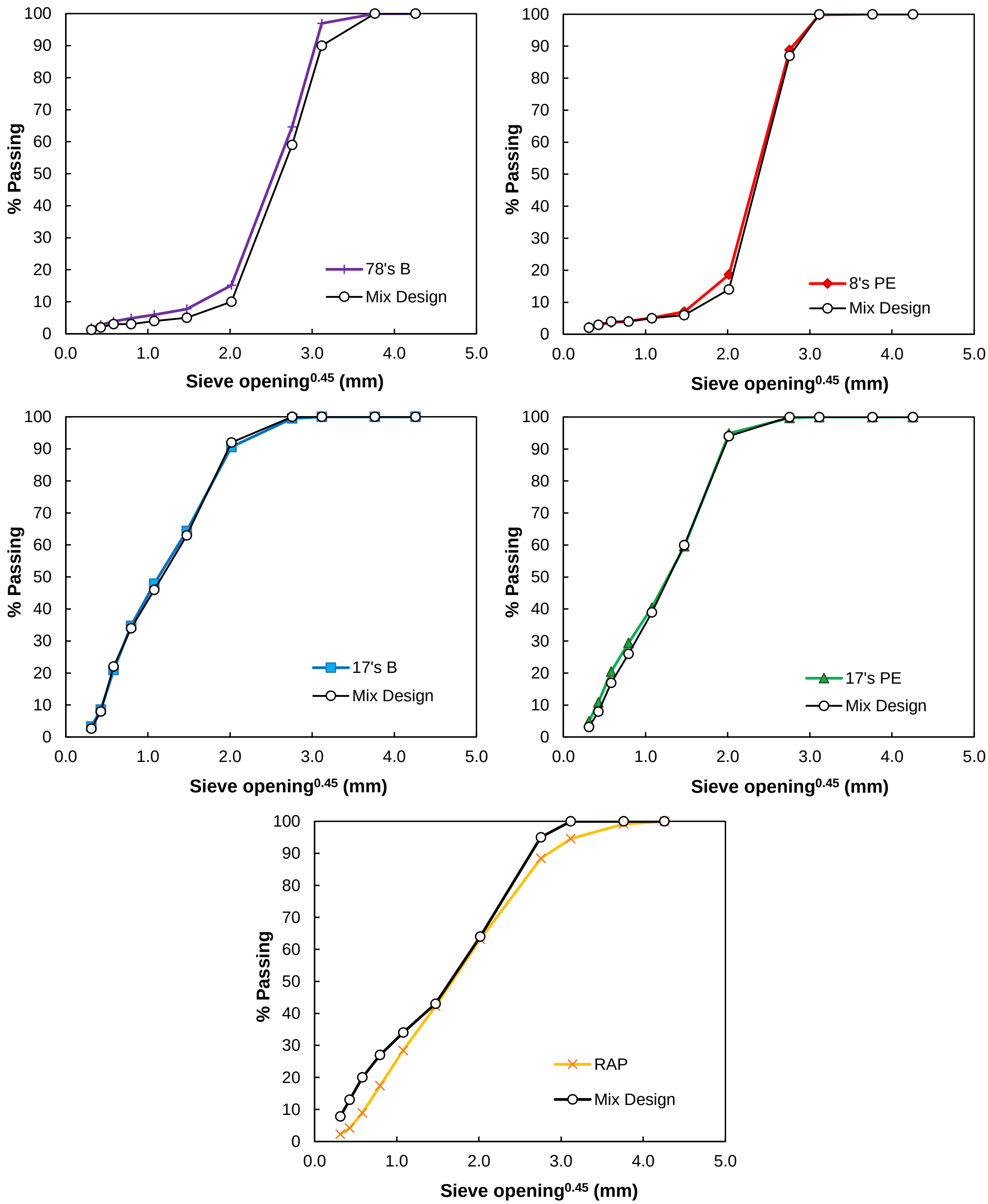

Figure E2. Source 2 Aggregate and RAP Stockpile Gradations. RAP = reclaimed asphalt pavement.

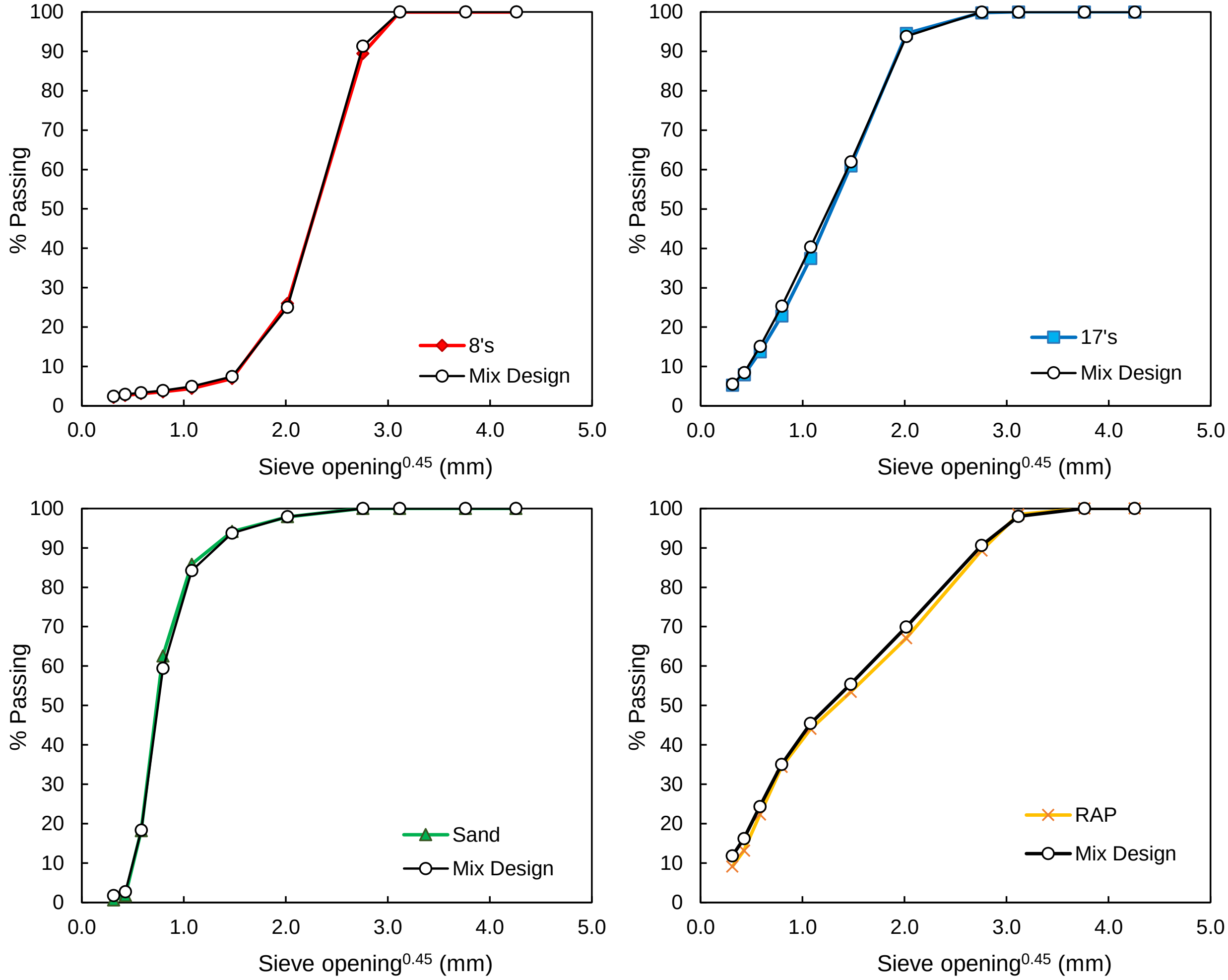

Figure E3. Source 3 Aggregate and RAP Stockpile Gradations. RAP = reclaimed asphalt pavement.

APPENDIX F

HIGH-, INTERMEDIATE-, AND LOW-TEMPERATURE SIMILARITY ANALYSIS

This appendix presents the results of the similarity analysis conducted on the 26 RA-modified blends, 3 virgin binders, and 1 recycled blend evaluated in this project. It is important to note that in certain cases, the MD^2 value was reported as "data not available" (NA) because not all properties necessary for the similarity analysis were measured.

Table F1. Similarity Analysis Results for the Materials Evaluated

Binder	MD^2			
	Global	HT	LT	IT
B1	21	4	2	1
B1R1RA1	183	75	42	8
B1R1RA2	126	110	14	9
B1R1RA3	79	13	28	2
B1R1RA4	NA	NA	19	5
B1R1RA6	NA	NA	17	125
B1R2	323	290	66	89
B1R2RA2	132	121	17	19
B1R2RA3	47	43	1	0
B1R2RA4	108	63	3	8
B1R2RA6	75	74	1	4
B1R3RA2	NA	NA	3	77
B1R3RA2	95	80	3	3
B1R3RA3	46	18	8	2
B1R3RA4	NA	NA	15	125
B1R3RA5	145	9	84	53
B1R3RA6	49	25	13	1
B2	16	5	0	1
B2R1RA3	79	50	3	0
B2R1RA5	170	8	111	43
B2R1RA6	NA	NA	18	125
B2R2RA4	NA	NA	0	77
B2R2RA5	NA	NA	63	47
B2R3RA1	NA	NA	43	25
B2R3RA2	NA	NA	4	77
B2R3RA3	NA	NA	7	77
B3	NA	NA	NA	85
B3R1	NA	NA	1	77
B3R2RA4	NA	NA	0	77
B3R3	NA	NA	5	125

MD = Mahalanobis distance; HT = high temperature; IT = intermediate temperature; LT = low temperature; B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent; NA = data not available.

APPENDIX G

ASSESSMENT OF DURABILITY USING BINDER TEST RESULTS

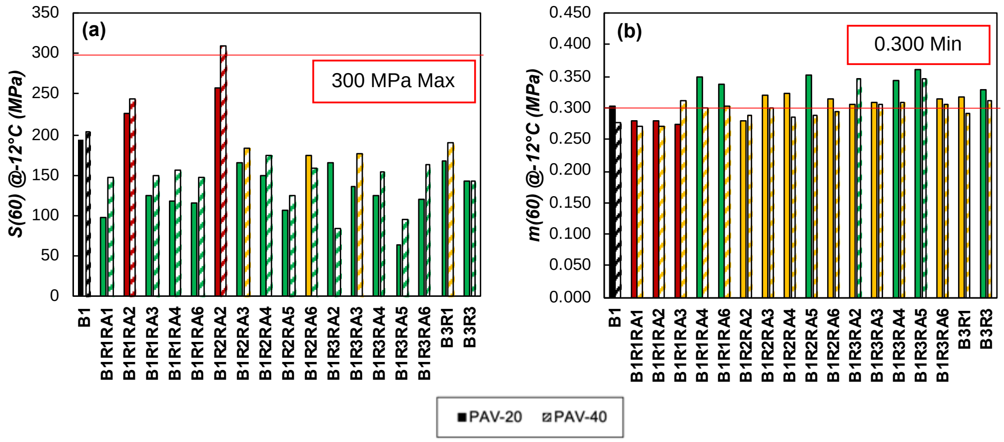

Figure G1. Low-Temperature Point Parameters: (a) stiffness S(60); (b) coefficient of relaxation m(60). Colors convey Dunnett's test results: green, yellow, and red indicate better, equal, and worse results relative to B1, respectively. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

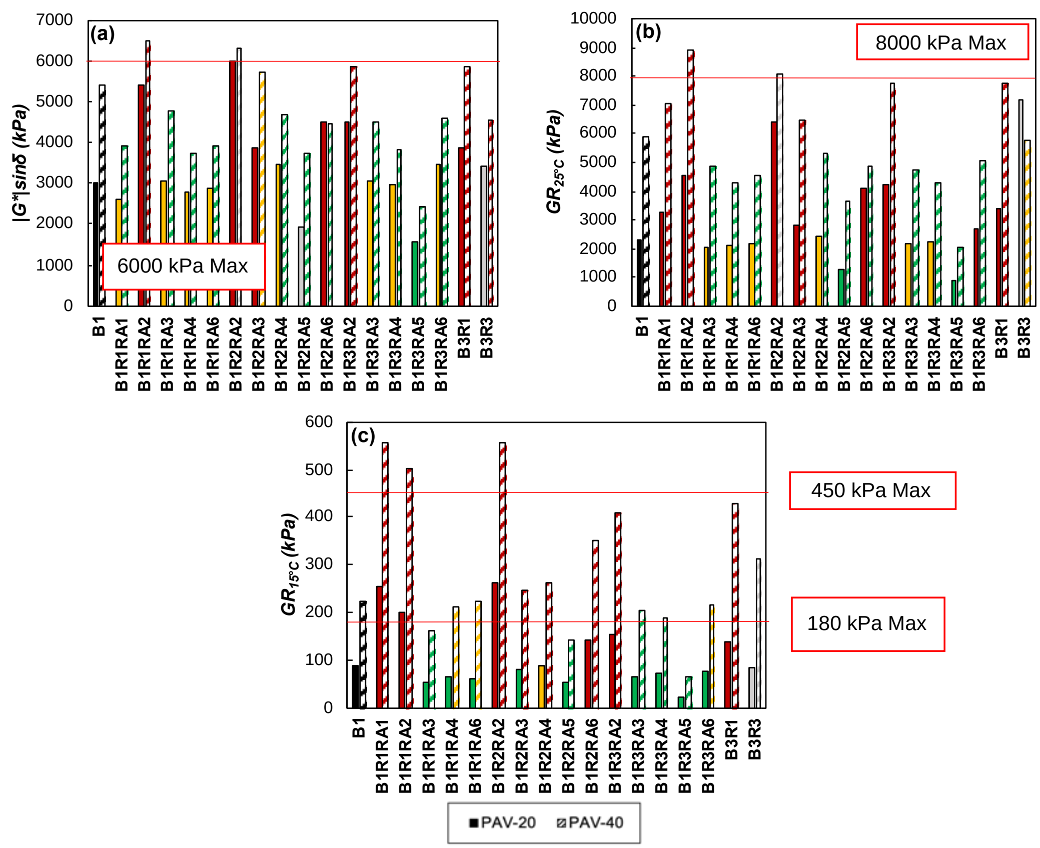

Figure G2. Intermediate-Temperature Point Parameters: (a) |G*|sin(δ); (b) $GR_{25°C}$; (c) $GR_{15°C}$. Colors convey Dunnett's test results: green, yellow, and red indicate better, equal, and worse results relative to B1, respectively. Gray indicates Dunnett's test could not be conducted due to unequal variance. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

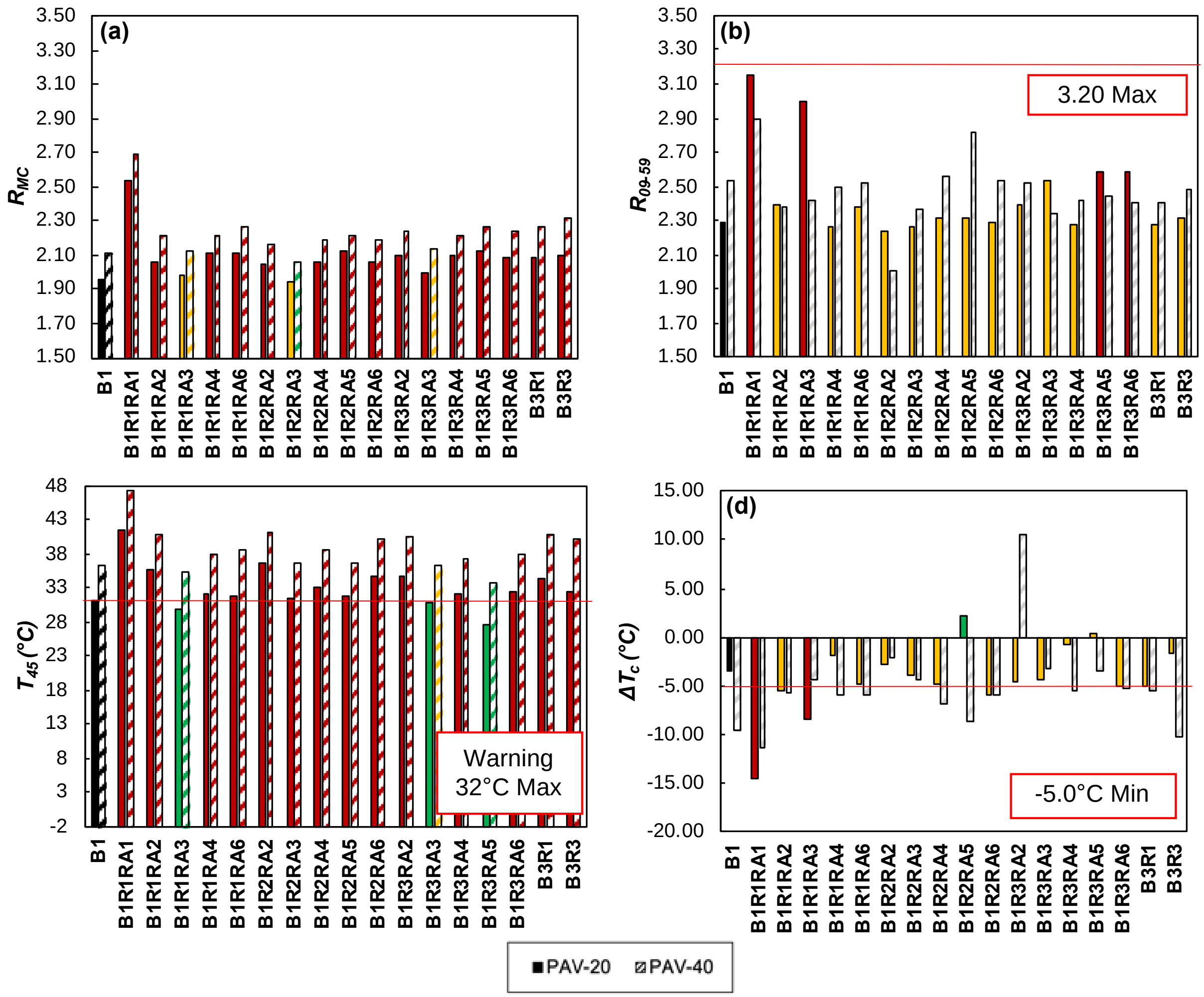

Figure G3. Rheological Balance Parameters: (a) R_{MC}; (b) $R_{09\text{-}59}$; (c) T_{45}; (d) ΔT_c. Colors correspond to performance; black is target, green is better performance, yellow is equal performance, red is worse performance, gray is removed. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Table G1. Bartlett's p-Value of Selected Paramaters of Materials Subjected to PAV-20 Aging

Bartlett's p-Value	All Blends PAV-20	Blend(s) Removed PAV-20	Blend(s) Removed|PAV-20	
S(60)	0.5127	0.5127		
m(60)	0.6519	0.6519		
$GR_{15°C}$	0.1794	0.1794		
T_{45}	0.5011	0.5011		
R_{MC}	0.9356	0.9356		
$R_{09\text{-}59}$	0.0912	0.0912		
ΔT_c	0.0063	0.4727	B1R3RA5	B2R1RA5
$GR_{25°C}$	0.0001	0.6469	B3R3	
$\|G^*\|\sin(\delta)$	0.0202	0.2876	B3R3	

PAV = pressure aging vessel; PAV-20 = PAV for 20 hours; S(60) = creep stiffness; m(60) = coefficient of relaxation; GR = Glover-Rowe parameter; T = temperature; T = temperature; R = rheological index; ΔT_c = difference in critical low temperature; G* = shear dynamic modulus; δ = phase angle; B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent. Cells highlighted in green indicate parameters with Bartlett's p-value lower than 0.05. Cells highlighted in red indicate parameters with Bartlett's p-value greater than 0.05.

Table G2. Bartlett's p-Value of Selected Paramaters of Materials Subjected to PAV-40 Aging

Bartlett's p-Value	All Blends PAV-40	Blend(s) Removed PAV-40	Blend(s) Removed|PAV-40		
S(60)	0.1193	0.1193			
m(60)	0.0938	0.0938			
$GR_{15°C}$	0.0415	0.0678	B3R3		
T_{45}	0.1029	0.1029			
R_{MC}	0.7055	0.7055			
$R_{09\text{-}59}$	0.0024	0.0423	B1	B2R1RA6	B3R3
ΔT_c	0.0106	0.4798	B1	B2R2RA5	
$GR_{25°C}$	0.0001	0.1944	B1R2RA2		
$\|G^*\|\sin(\delta)$	0.0001	0.1125	B1R2RA2		

PAV = pressure aging vessel; PAV-40 = PAV for 40 hours; S(60) = creep stiffness; m(60) = coefficient of relaxation; GR = Glover-Rowe parameter; T = temperature; T = temperature; R = rheological index; ΔT_c = difference in critical low temperature; G* = shear dynamic modulus; δ = phase angle; B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent. Cells highlighted in green indicate parameters with Bartlett's p-value lower than 0.05. Cells highlighted in red indicate parameters with Bartlett's p-value greater than 0.05.

Table G3. Comparison of Various Paraemters for Blends to Those of Target B1|PAV-20

Blend	Comparison to Target (B1|PAV-20)		
	Worse	Equal	Better
B3R1	R_{MC}, T_{45}, |G*|×sinδ, $GR_{25°C}$, $GR_{15°C}$	$R_{09\text{-}59}$, m(60), ΔT_c	S(60)
B1R1RA1	R_{MC}, T_{45}, $R_{09\text{-}59}$, m(60), ΔT_c, $GR_{25°C}$, $GR_{15°C}$	|G*|×sinδ	S(60)
B1R1RA2	R_{MC}, T_{45}, S(60), m(60), |G*|×sinδ, $GR_{25°C}$, $GR_{15°C}$	$R_{09\text{-}59}$, ΔT_c	
B1R1RA3	$R_{09\text{-}59}$, m(60), ΔT_c	R_{MC}, |G*|×sinδ, $GR_{25°C}$	T_{45}, S(60), $GR_{15°C}$
B1R1RA4	R_{MC}, T_{45}	$R_{09\text{-}59}$, ΔT_c, |G*|×sinδ, $GR_{25°C}$	S(60), m(60), $GR_{15°C}$
B1R1RA6	R_{MC}, T_{45}	$R_{09\text{-}59}$, ΔT_c, |G*|×sinδ, $GR_{25°C}$	S(60), m(60), $GR_{15°C}$
B1R2RA2	R_{MC}, T_{45}, S(60), |G*|×sinδ, $GR_{25°C}$, $GR_{15°C}$	$R_{09\text{-}59}$, m(60), ΔT_c	
B1R2RA3	T_{45}, |G*|×sinδ, $GR_{25°C}$	R_{MC}, $R_{09\text{-}59}$, m(60), ΔT_c	S(60), $GR_{15°C}$
B1R2RA4	R_{MC}, T_{45}	$R_{09\text{-}59}$, m(60), ΔT_c, G*sin*δ*, $GR_{25°C}$, $GR_{15°C}$	S(60)
B1R2RA5	R_{MC}, T_{45}	$R_{09\text{-}59}$	S(60), m(60), ΔT_c, $GR_{25°C}$, $GR_{15°C}$
B1R2RA6	R_{MC}, T_{45}, |G*|×sinδ, $GR_{25°C}$, $GR_{15°C}$	$R_{09\text{-}59}$, S(60), m(60), ΔT_c	
B3R3	R_{MC}, T_{45}	$R_{09\text{-}59}$, ΔT_c	S(60), m(60)
B1R3RA2	R_{MC}, T_{45}, |G*|×sinδ, $GR_{25°C}$, $GR_{15°C}$	$R_{09\text{-}59}$, m(60), ΔT_c	S(60)
B1R3RA3	R_{MC}	$R_{09\text{-}59}$, m(60), ΔT_c, |G*|×sinδ, $GR_{25°C}$	T_{45}, S(60), $GR_{15°C}$
B1R3RA4	R_{MC}, T_{45}	$R_{09\text{-}59}$, ΔT_c, |G*|×sinδ, $GR_{25°C}$	S(60), m(60), $GR_{15°C}$
B1R3RA5	R_{MC}, $R_{09\text{-}59}$	ΔT_c	T_{45}, S(60), m(60), |G*|×sinδ, $GR_{25°C}$, $GR_{15°C}$
B1R3RA6	R_{MC}, T_{45}, $R_{09\text{-}59}$, $GR_{25°C}$	m(60), ΔT_c, |G*|×sinδ,	S(60), $GR_{15°C}$
B2		$R_{09\text{-}59}$, S(60), m(60), ΔT_c, |G*|×sinδ, $GR_{25°C}$	R_{MC}, T_{45}, $GR_{15°C}$

PAV = pressure aging vessel; PAV-20 = PAV for 20 hours; S(60) = creep stiffness; m(60) = coefficient of relaxation; GR = Glover-Rowe parameter; T = temperature; T = temperature; R = rheological index; ΔT_c = difference in critical low temperature; G* = shear dynamic modulus; δ = phase angle; B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent.

Table G4. Comparison of Various Paraemters for Blends to Those of Target B1|PAV-40

Blend	Comparison to Target (B1|PAV-40)		
	Worse	Equal	Better
B3R1	R_{MC}, T_{45}, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$	*S(60)*, m(60)	
B1R1RA1	R_{MC}, T_{45}, $GR_{25^\circ C}$, $GR_{15^\circ C}$	m(60)	S(60), $\|G^*\|\times\sin\delta$
B1R1RA2	R_{MC}, T_{45}, S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$	m(60)	
B1R1RA3		R_{MC}, m(60)	T_{45}, S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$
B1R1RA4	R_{MC}, T_{45}	*m(60)*, *$GR_{15^\circ C}$*	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B1R1RA6	R_{MC}, T_{45}	*m(60)*, *$GR_{15^\circ C}$*	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B1R2RA2	R_{MC}, T_{45}, S(60), $GR_{15^\circ C}$	m(60)	
B1R2RA3	T_{45}, $GR_{25^\circ C}$, *$GR_{15^\circ C}$*	S(60), m(60), $\|G^*\|\times\sin\delta$	R_{MC}
B1R2RA4	R_{MC}, T_{45}, *$GR_{15^\circ C}$*	m(60)	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B1R2RA5	R_{MC}, T_{45}	*m(60)*	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$
B1R2RA6	R_{MC}, T_{45}, $GR_{15^\circ C}$	m(60)	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B3R3	R_{MC}, T_{45}	*m(60)*, $GR_{25^\circ C}$	S(60), $\|G^*\|\times\sin\delta$
B1R3RA2	R_{MC}, T_{45}, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$		S(60), m(60)
B1R3RA3		R_{MC}, *T_{45}*, *S(60)*, m(60)	$\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$
B1R3RA4	R_{MC}, T_{45}	*m(60)*	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$
B1R3RA5	R_{MC}		T_{45}, S(60), m(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$
B1R3RA6	R_{MC}, T_{45}	m(60), *$GR_{15^\circ C}$*	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B2	*$\|G^*\|\times\sin\delta$*, *$GR_{25^\circ C}$*	S(60), m(60)	R_{MC}, T_{45}, $GR_{15^\circ C}$

PAV = pressure aging vessel; PAV-40 = PAV for 40 hours; S(60) = creep stiffness; m(60) = coefficient of relaxation; GR = Glover-Rowe parameter; T = temperature; T = temperature; R = rheological index; ΔT_c = difference in critical low temperature; G* = shear dynamic modulus; δ = phase angle; B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent.

Table G5. Comparison Various Paraemters for Blends to Those of Target B2|PAV-20

Blend	Comparison to Target (B2|PAV-20)		
	Worse	Equal	Better
B3R1	R_{MC}, T_{45}, ΔT_c, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$	$R_{09\text{-}59}$, m(60)	S(60)
B2R1RA3	R_{MC}, T_{45}, ΔT_c	$R_{09\text{-}59}$, m(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$	S(60)
B2R1RA5	R_{MC}, T_{45}	$R_{09\text{-}59}$	T_{45}, S(60), m(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$
B2R1RA6	R_{MC}, T_{45}	$R_{09\text{-}59}$, ΔT_c, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$	S(60), m(60)
B2R2RA4	R_{MC}, T_{45}, $GR_{25^\circ C}$, $GR_{15^\circ C}$	$R_{09\text{-}59}$, S(60), m(60), ΔT_c, $\|G^*\|\times\sin\delta$	
B2R2RA5	R_{MC}	T_{45}, $R_{09\text{-}59}$	S(60), m(60), ΔT_c, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$
B3R3	R_{MC}, T_{45}, $GR_{15^\circ C}$	$R_{09\text{-}59}$, m(60), ΔT_c	S(60)
B2R3RA1	R_{MC}, T_{45}, $R_{09\text{-}59}$, ΔT_c, $GR_{15^\circ C}$	m(60), $GR_{25^\circ C}$	S(60), $\|G^*\|\times\sin\delta$
B2R3RA2	R_{MC}, T_{45}, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$	$R_{09\text{-}59}$, m(60), ΔT_c	S(60)
B2R3RA3	R_{MC}, T_{45}, $GR_{15^\circ C}$	$R_{09\text{-}59}$, m(60), ΔT_c, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$	S(60)
B1	R_{MC}, T_{45}, $GR_{15^\circ C}$	$R_{09\text{-}59}$, S(60), m(60), ΔT_c, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$	

PAV = pressure aging vessel; PAV-20 = PAV for 20 hours; S(60) = creep stiffness; m(60) = coefficient of relaxation; GR = Glover-Rowe parameter; T = temperature; T = temperature; R = rheological index; ΔT_c = difference in critical low temperature; G* = shear dynamic modulus; δ = phase angle; B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent.

Table G6. Comparison Various Paraemters for Blends to Those of Target B2|PAV-40

Blend	Comparison to Target (B2|PAV-40)		
	Worse	Equal	Better
B3R1	R_{MC}, T_{45}, $GR_{25^\circ C}$, $GR_{15^\circ C}$	$R_{09\text{-}59}$, *S(60)*, m(60), ΔT_c	$\|G^*\|\times\sin\delta$
B2R1RA3		R_{MC}, T_{45}, *S(60)*, m(60), ΔT_c, $GR_{15^\circ C}$	$R_{09\text{-}59}$, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B2R1RA5	R_{MC}	$R_{09\text{-}59}$	T_{45}, S(60), m(60), ΔT_c, $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$, $GR_{15^\circ C}$
B2R1RA6	R_{MC}, T_{45}, *$GR_{15^\circ C}$*	*S(60)*, *m(60)*, ΔT_c	$\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B2R2RA4	R_{MC}, T_{45}, $GR_{15^\circ C}$	$R_{09\text{-}59}$, S(60), m(60), ΔT_c, $GR_{25^\circ C}$	$\|G^*\|\times\sin\delta$
B2R2RA5	R_{MC}, *T_{45}*	$R_{09\text{-}59}$	S(60), m(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B3R3	R_{MC}, T_{45}, *ΔT_c*, $GR_{15^\circ C}$	m(60)	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B2R3RA1	R_{MC}, T_{45}, $GR_{15^\circ C}$	$R_{09\text{-}59}$, m(60), ΔT_c	S(60), $\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B2R3RA2	R_{MC}, T_{45}, *S(60)*, $GR_{25^\circ C}$, $GR_{15^\circ C}$	m(60), $\|G^*\|\times\sin\delta$	$R_{09\text{-}59}$, ΔT_c
B2R3RA3	R_{MC}, T_{45}, $GR_{15^\circ C}$	$R_{09\text{-}59}$, *S(60)*, m(60), ΔT_c	$\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$
B1	R_{MC}, T_{45}, $GR_{15^\circ C}$	S(60), m(60)	$\|G^*\|\times\sin\delta$, $GR_{25^\circ C}$

PAV = pressure aging vessel; PAV-40 = PAV for 40 hours; S(60) = creep stiffness; m(60) = coefficient of relaxation; GR = Glover-Rowe parameter; T = temperature; T = temperature; R = rheological index; ΔT_c = difference in critical low temperature; G* = shear dynamic modulus; δ = phase angle; B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent.

APPENDIX H

LINEAR AMPLITUDE SWEEP (LAS) TEST RESULTS AND INDICES ANALYSIS

Introduction

The LAS test was proposed as a time-efficient test relying on the S-VECD model to characterize the fatigue properties of asphalt binders. Although the test has emerged as a commonly used method for evaluating the fatigue properties of asphalt binders, recent studies have revealed limitations associated with the current performance indices derived from this test. These limitations include assessment of the impact of asphalt modifiers on binder fatigue behavior and the effect of aging on the long-term performance of asphalt binders. In addition, the fatigue properties of asphalt binders have been found to improve with increased binder aging, contrary to initial expectations. Although many indices based on the LAS test have been proposed, there is still a lack of an index that works universally in terms of estimating fatigue life with aging and particularly capturing the effect of modifiers, in the current case, RAs, on fatigue properties of asphalt binders.

Fatigue Life Estimation Using the LAS Test

The fatigue life (i.e., N_f) at different strain levels for each binder blend was estimated in accordance with AASHTO T 391 (AASHTO, 2020). Although the recycled binder blends showed either a similar or better fatigue life compared to the corresponding virgin binders, the N_f at a given strain level (such as 5% or 15%) was found to be higher at the PAV-40 aging condition than at the PAV-20 aging condition for most cases. This observation implies better fatigue resistance at the higher age condition, which is counterintuitive and averse to the collective understanding of the pavement community. However, if a higher strain level such as 35% was chosen, the expected trend was observed. Chen and Bahia (2021) observed the same in their study and recommended using higher strains to evaluate changes in fatigue properties with aging. Table H1 shows the fatigue life estimations at different strain levels for both aging conditions.

Table H1. Fatigue Life Estimation for All Evaluated Binders at Different Strain Levels

Binder	N_f at 5%		N_f at 15%		N_f at 35%	
	PAV-20	PAV-40	PAV-20	PAV-40	PAV-20	PAV-40
B1	14,189	35,165	13.29	18.97	0.06	0.06
B1R1RA1	1,634,934	4,065,023	606.04	794.86	1.37	1.10
B1R1RA2	49,371	81,034	31.15	26.93	0.11	0.06
B1R1RA3	38,625	55,356	47.15	34.71	0.27	0.12
B1R1RA4	39,627	120,165	41.45	66.67	0.21	0.21
B1R2RA2	14,025	7,203	7.96	2.42	0.02	0.01
B1R2RA3	24,737	16,623	27.40	7.38	0.14	0.02
B1R2RA4	32,009	7,695	31.77	5.32	0.15	0.02
B1R2RA5	19,560	62,333	23.23	46.06	0.13	0.18
B1R2RA6	27,733	30,813	21.96	13.61	0.09	0.04
B1R3RA2	40,539	86,831	28.62	33.12	0.11	0.08
B1R3RA3	31,484	51,305	35.50	31.46	0.19	0.10
B1R3RA4	39,545	104,901	42.01	63.67	0.21	0.21
B1R3RA5	83,360	108,444	144.02	109.51	1.07	0.54
B1R3RA6	54,924	74,523	56.91	42.40	0.28	0.13
B2	14,893	19,120	21.28	13.78	0.14	0.05
B2R1RA3	14,077	41,492	19.49	29.32	0.12	0.11
B2R1RA5	30,088	110,274	44.32	119.10	0.29	0.61
B2R1RA6	34,967	81,916	42.42	48.20	0.24	0.16
B2R2RA4	22,948	16,602	24.11	9.09	0.12	0.03
B2R2RA5	16,722	87,045	26.49	82.98	0.18	0.39
B2R3RA1	248,431	1,408,892	184.94	498.05	0.72	1.08
B2R3RA2	27,698	28,191	29.24	15.00	0.15	0.04
B2R3RA3	11,528	18,944	12.06	11.42	0.06	0.04
B3	53,825	152,375	105.90	154.32	0.87	0.76
B3R1	53,981	191,977	42.64	73.66	0.17	0.17
B3R2RA4	32,678	31,194	27.24	14.67	0.11	0.04
B3R3	62,950	170,776	64.43	81.34	0.32	0.22

PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; N_f = fatigue parameter.

Aging Index Analysis

Linear Viscoelasticity

The LAS test is composed of two parts. First, an LVE fingerprint test is run at very low strains, and second, a linear amplitude sweep is run. The complex shear modulus and phase angle data from the LVE fingerprint test can be used to calculate the LVE aging index parameter log(|G*|/Sin(δ)), which was proposed by Elwardany et al. (2023) and Mensching et al. (2022). This LVE aging index parameter is calculated at the test temperature of 16°C and at a frequency of 10 Hz for both aging conditions and tracks perfectly with aging. The complex shear modulus is expected to increase and the phase angle is expected to decrease with aging, and the LVE aging index parameter perfectly captures both behaviors as it increases with aging. Figure H1 shows the LVE aging index for all blends for both aging conditions.

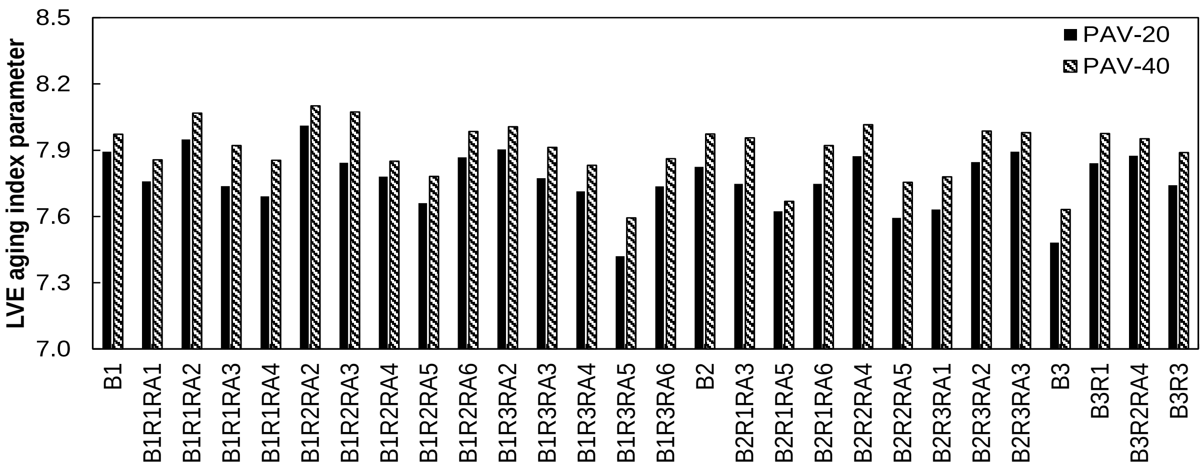

Figure H1. LVE Aging Index Parameter for All Evaluated Binders Under PAV-20 and PAV-40 Aging Conditions. LVE = linear viscoelastic; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours.

The LVE aging index property is a reasonable parameter to capture the changes in LVE properties and yields consistent results. However, it must be noted that it lacks any direct correlation with fatigue performance and thus a binder that shows higher sensitivity to aging through the LVE aging index property may not necessarily have poorer cracking performance compared to the binder that shows less sensitivity. However, it can be an effective index in tracking the changes in LVE properties of the binder with aging and rejuvenation. From an aging perspective, the higher value in the LVE aging index property indicates a higher degree of aging as captured by complex shear modulus and phase angle. From a rejuvenation perspective, a blend with certain RA can show a lower value compared to the reference binder, for example, B1R2RA4 as compared to B1. This result indicates less sensitivity of this binder blend to aging, which may be attributed to the presence of RA4 in addition to other properties such as RAP binder properties, dosage level, percentage of RAP binder used, etc. One way to look at the aging sensitivity is to compare the LVE aging index parameter at PAV-20 and PAV-40, as shown in Equation H1.

$$LVE_{aging\ sensitivity} = \frac{[\log(\frac{|G^*|}{sin\delta})]_{PAV-40} - [\log(\frac{|G^*|}{sin\delta})]_{PAV-20}]}{[\log(\frac{|G^*|}{sin\delta})]_{PAV-20}} \quad \text{[Eq. H1]}$$

Figure H2 shows the LVE aging sensitivity of the binder blends, and it can be seen that most of the RA blends have a higher aging sensitivity in terms of their LVE properties. In the case of B1 and B2, which have the same PG but different sources, the aging sensitivity differs greatly. The RA blends generally have a higher aging sensitivity than the virgin binders except B1R1RA4, B2R1RA5, and B2R3RA3. RA3 blends show higher aging sensitivity as part of B1R2RA3 and B2R1RA3 whereas in other cases they show much lower aging sensitivity, for example, B2R3RA3. This result indicates that several other factors such as source of virgin binder and nature of RAP binder in addition to RA type and dosage play a part in determining the overall aging sensitivity of the binder blends.

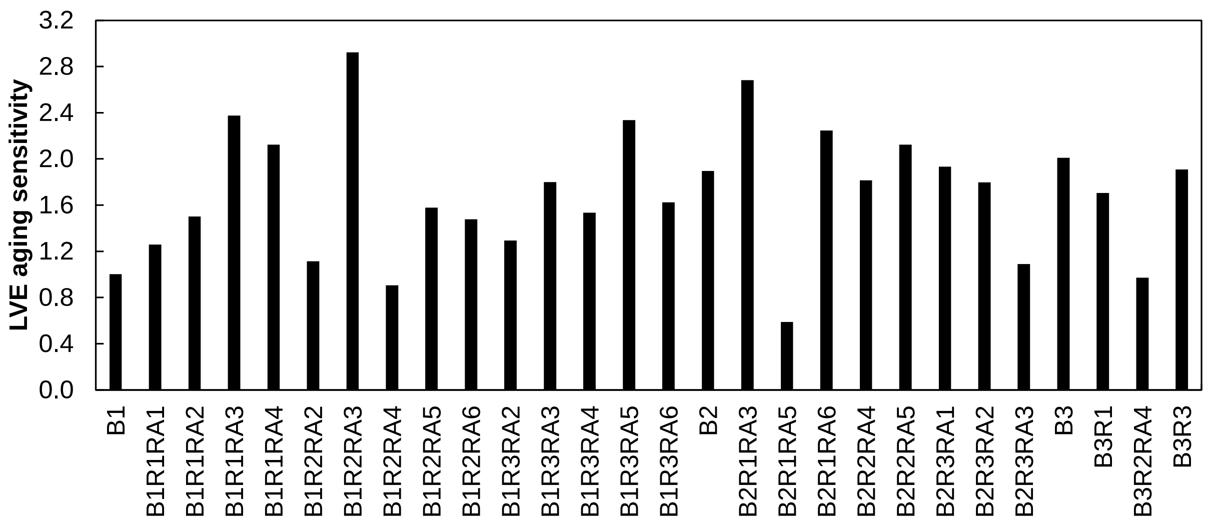

Figure H2. LVE Aging Sensitivity for All Evaluated Binder Blends. LVE = linear viscoelastic; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Existing Fatigue Performance Indices

The second part of the LAS test is a strain sweep from 0% to 30% at a frequency of 10 Hz. Several aging indices have been proposed in the literature to capture the fatigue properties of asphalt binders using this linear amplitude strain sweep. The study binder blends were evaluated using the following indices, and an attempt was made to evaluate their trend with respect to aging.

Average Reduction in Integrity Up to Failure (I^R). Zhang et al. (2022) proposed a parameter, I^R, to evaluate the fatigue properties of different asphalt binders using the insights from the mixture failure criterion, D^R, proposed by Wang and Kim (2019). I^R is defined as the average reduction in integrity up to failure and is a measure of the degradation of fatigue resistance over time. It is defined by Equation H2.

$$I^R = \frac{\int_0^{N_f}(1-C)dN}{N_f} \quad \text{[Eq. H2]}$$

where

N_f = number of load cycles until failure
C = pseudo-stiffness.

Zhang et al. (2022) argued that a higher I^R is preferred as it indicates that the material has a greater ability to resist fatigue cracking. As a result, it can be inferred that a stiffer or severely aged binder will have a lower I^R compared to a less-aged binder. It must be noted that the failure definition used by the authors is defined as number of load cycles at peak stress. Figure H3 shows the schematic for the calculation of I^R.

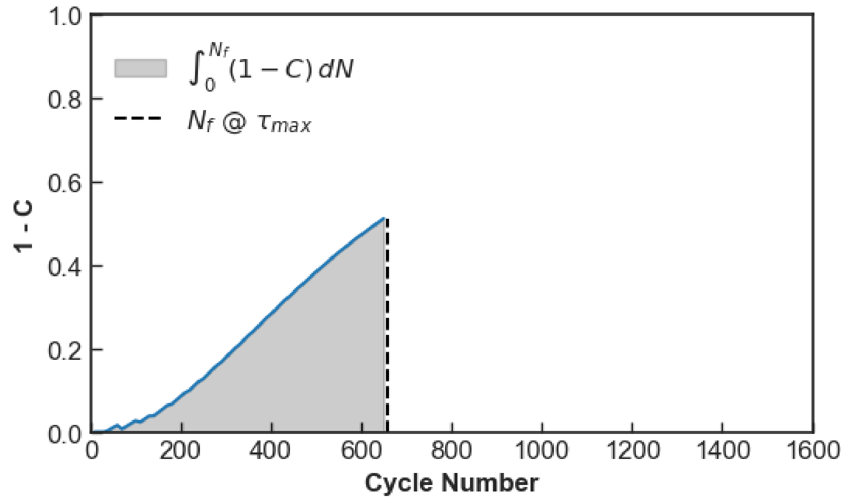

Figure H3. Schematic for the Calculation of I^R

The binders in this study were evaluated for I^R, and it can be seen from Figure H4 that the binder blends mostly have a higher I^R compared to the virgin binders at either the PAV-20 or PAV-40 aging condition. This observation suggests a higher fatigue resistance of these blends; however, this resistance decreases with aging as expected and is captured by I^R except for B2R1RA5, where it seems to increase. This behavior can be attributed to the way the I^R parameter is calculated to capture the fatigue resistance with aging, which does not consider the post-peak behavior. It is interesting to note that B2R1RA5 has the highest dosage of all RAs, as shown in Table 4 of this report, which may affect its fatigue performance with aging. Further, RA2 blends tend to have among the lowest I^R values whereas B3 binder, which is a softer grade, has a higher I^R value.

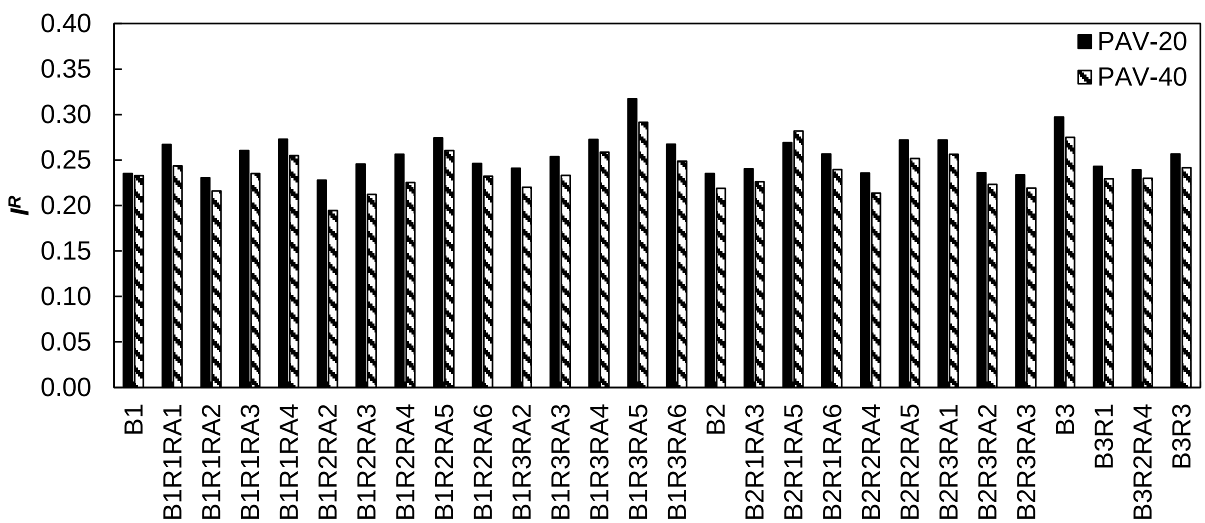

Figure H4. Average Reduction in Integrity Up to Failure (I^R) for All Evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours.

Strain Tolerance Up to Failure (ε_T). Zhang et al. (2022) after having proposed I^R, argued that this parameter did not consider the post-peak behavior of the stress-strain curve, as only data up to failure point (defined as peak stress) were used in the calculation of I^R. They observed that the binder sample retained some load carrying capacity after peak stress and noted flatter and longer post-peak stress-strain curves for polymer modified binders over unmodified binders, which could be attributed to the cross-linkages of the polymer networks even after the peak stress point. In order to capture this post-peak behavior, the authors proposed ε_T as a parameter and defined it as the strain level after the peak when the stress reduced to 25% of its peak value. The authors argued that the post-peak strain level at 25% of peak stress has low variability and an ability to capture the effect of different modifiers. Figure H5 shows the schematic for the calculation of ε_T. A higher strain tolerance is indicative of higher fatigue cracking resistance, and this parameter is expected to decrease with aging. The strain tolerance was calculated for the studied binders, and it was found that this parameter was not able to capture the impact of aging for all of them except B1R2RA2. This result is shown in Figure H6 where this parameter is calculated and plotted at PAV-40 and PAV-20 aging conditions. It can be seen that only one blend, which in this case was B1R2RA2, showed a decrease in strain tolerance (post-peak) with aging.

It has been seen that the binder response for the post-peak behavior can show substantially varying ranges in terms of the stress-strain curve and that calculation of the inflection or end points as a percentage of peak load or peak stress can occur at significantly different percentiles. For example, in the case of B1R1RA1, strain tolerance (post-peak) could not be even calculated because the test stopped before the stress response could reach 25% of peak stress. A similar observation about the post-peak behavior in an LAS test was made by Chen et al. (2021).

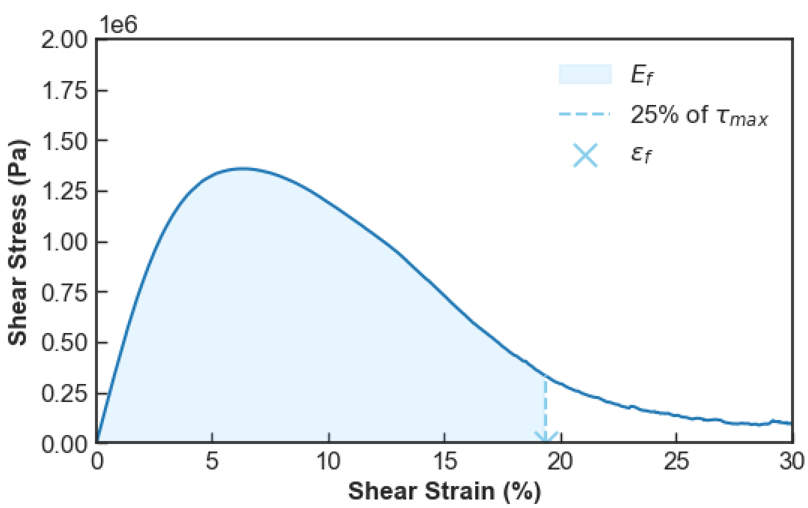

Figure H5. Schematic for the Calculation of ε_T and E_f

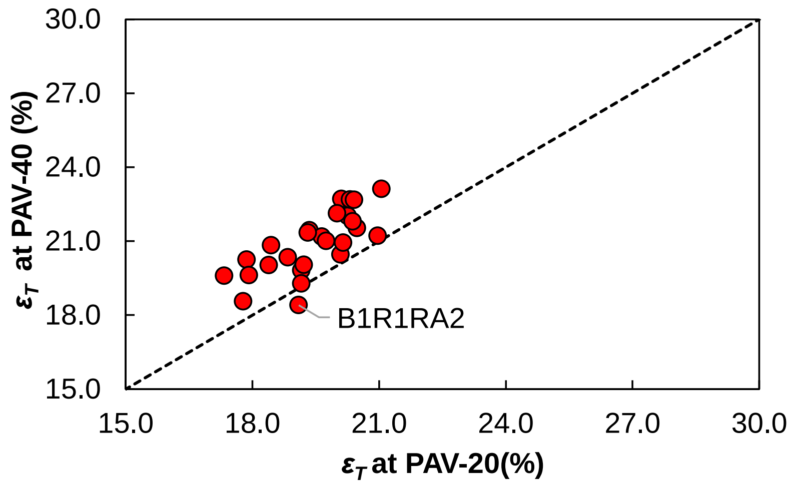

Figure H6. Strain Tolerance Up to Failure (Post Peak) for All Evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Strain Energy Tolerance (E_f). Zhang et al. (2022) also attempted to integrate the load and displacement history of the binder samples tested with an LAS test by looking at the concept of energy. In fact, the Superpave binder grading parameter for intermediate temperature, $|G^*|\sin(\delta)$, was intended to limit the amount of energy dissipated during a loading cycle to minimize the development and extent of fatigue cracking. Several authors have used energy-based parameters to evaluate, characterize, and/or limit the initiation of fatigue cracking (Mohammad et al., 2012; Ozer et al., 2016). In a similar development, an energy-based index was proposed by Zhang et al. (2022) building on the previously discussed strain tolerance up to failure parameter. They defined strain energy tolerance (E_f) as the area under the stress-strain curve up to the end point for the fatigue tolerance limit, that is, 25% of the peak stress. Both the fatigue tolerance up to failure and the strain energy tolerance are schematically shown in Figure H5. A higher value of E_f is expected to yield better fatigue resistance, and it is expected to decrease with increasing aging sensitivity.

The binders in this study were evaluated for E_f, and it was found that this parameter (similar to fatigue tolerance) may not have a consistent trend with aging. Most of the binder blends did not follow the expected trend except for B1R2RA2, B1R2RA4, and B2R1RA5, which can be seen in Figure H7. In the case of B1R1RA1 and B2R3RA1, this parameter could not be calculated as the test stopped before the stress could reach 25% of its peak value for either one or both of the tested aging conditions.

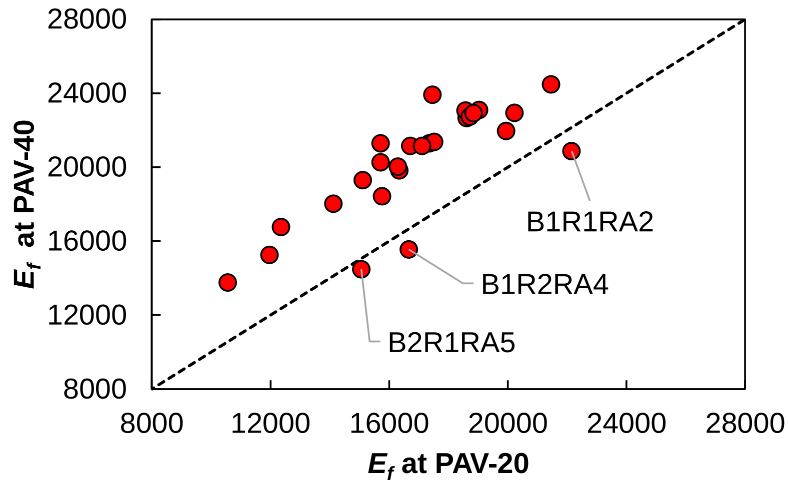

Figure H7. Strain Energy Tolerance for All Evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Fatigue Resistance Energy Index (FREI). FREI is an index parameter proposed by Zhou et al. (2017) using the pre-peak stress-strain curve of the LAS test. The components of the parameter rely solely on the second part of the LAS test, so the LVE fingerprint test of the LAS test is not needed to obtain this index. It is based on fracture mechanics principles as opposed to continuum damage mechanics, and the authors use phenomenological insights from a time sweep test at a constant shear strain to develop FREI for the LAS test. FREI is calculated using Equation H3.

$$FREI = \frac{J_{f-\tau_{max}}}{G_{0.5*\tau_{max}}}(\Upsilon_{0.5*\tau_{max}})^2 \quad \text{[Eq. H3]}$$

where

$J_{f-\tau_{max}}$ = shear fracture energy calculated until the peak shear stress
$G_{0.5*\tau_{max}}$ = apparent shear modulus calculated at 50% of peak shear stress in the pre-peak response
$\Upsilon_{0.5*\tau_{max}}$ = shear strain at 50% of peak shear stress.

The phenomenological understanding of FREI can be understood by observing three aspects of binder response under the strain sweep part of the LAS test. First, a material with higher fracture energy is normally expected to have better fatigue resistance. Second, larger shear strain at 50% of peak shear stress indicates better flexibility and relaxation capacity when the binder reaches one-half of its maximum shear loading capacity. Third, a larger shear modulus, in this case, the apparent shear modulus at 50% peak shear stress, often leads to a higher susceptibility to cracking. The components of FREI are shown schematically in Figure H8. In general, a higher FREI is considered to indicate better cracking resistance, and it is expected to decrease with aging.

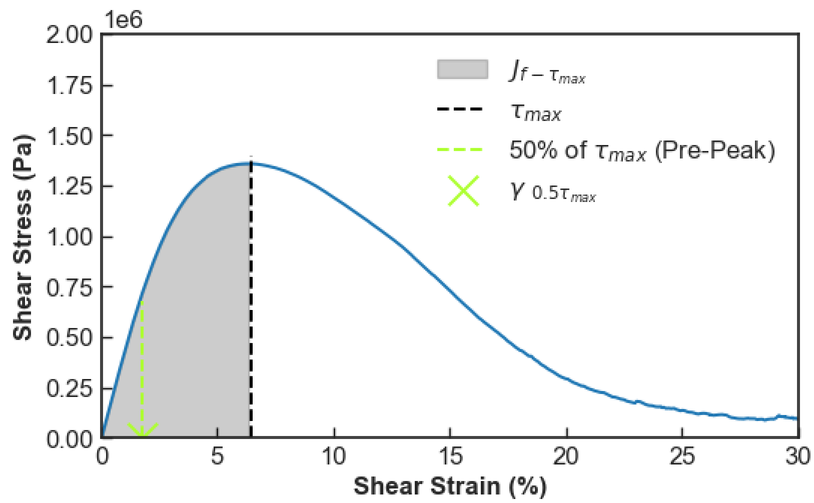

Figure H8. Schematic for the Calculation of FREI. FREI = fatigue resistance energy index.

FREI was calculated for the studied binder for both the PAV-20 and PAV-40 aging conditions as per Equation H3, and the results are shown in Figure H9. It can be seen that B1- and B2-based binder blends with RAs have a higher FREI compared to the two control binders B1 and B2 as opposed to B3-based binder blends. Further, FREI decreases with aging as expected for all binders except B2R1RA5, where it slightly increases. This single case outlier can again be viewed from a dosage perspective as B2R1RA5 has the highest dosage of an RA across all binder blends. Therefore, in addition to the factors such as type of RAP binder, type of RA, source of virgin binder, etc., FREI seems to be affected by RA dosage, especially higher dosages close to 10%, which is usually the DOT-permissible RA dosage prevalent in several states including North Carolina (Fried et al., 2022; Habbouche et al., 2022).

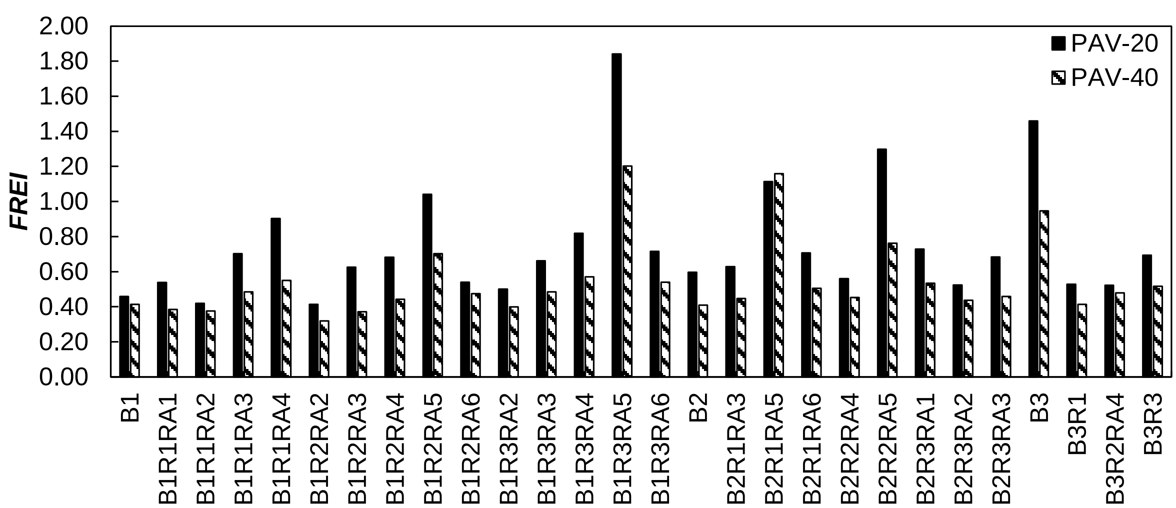

Figure H9. Fatigue Energy Resistance Index (FREI) for All evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Fatigue Factor of Binder (FF_B). In 2014, a large database of asphalt binder data was collected by Petrobras Research Center in Brazil and after the fatigue behavior of asphalt mixtures and binders was analyzed, a notable correlation was observed by means of the so-called fatigue factor of the mixture (FFM) and fatigue factor of the binder (FF_B) (Martins, 2014). Later in 2021, Possebon (2021) classified the asphalt binders based on FF_B; however, the range of FF_B used was observed to be very narrow and may not encompass all of the binders. Overall, FF_B is an empirical index and is calculated as shown in Equation H4. A higher value of FF_B is related to better fatigue performance, and it is expected to decrease with aging (Hennig Osmari et al., 2019; Tavares Marinho Filho et al., 2022).

$$FF_B = \left[\frac{\log(N_{f,1.25\%})+\log(N_{f,2.50\%})}{2}\right] * (\log(0.025) - \log(0.0125)) \quad \text{[Eq. H4]}$$

where

$N_{f,\,1.25\%}$ = fatigue life estimated at 1.25% strain
$N_{f,\,2.50\%}$ = fatigue life estimated at 2.50% strain.

In this study, FF_B was calculated and analyzed for the studied binders for the two aging conditions. All the binders showed excellent fatigue performance as per Possebon's classification; however, FF_B did not track with aging for almost all blends. It can be observed in Figure H10 that FF_B for PAV-40 is higher than for PAV-20 for all blends except B1R2RA2 and B1R2RA4, similar to E_f aging sensitivity. The primary reason for a counterintuitive trend of FF_B with aging can be attributed to the use of fatigue life (N_f) estimations at comparable strain levels such 1.25% and 2.5%, which are known not to track well with aging, as discussed previously.

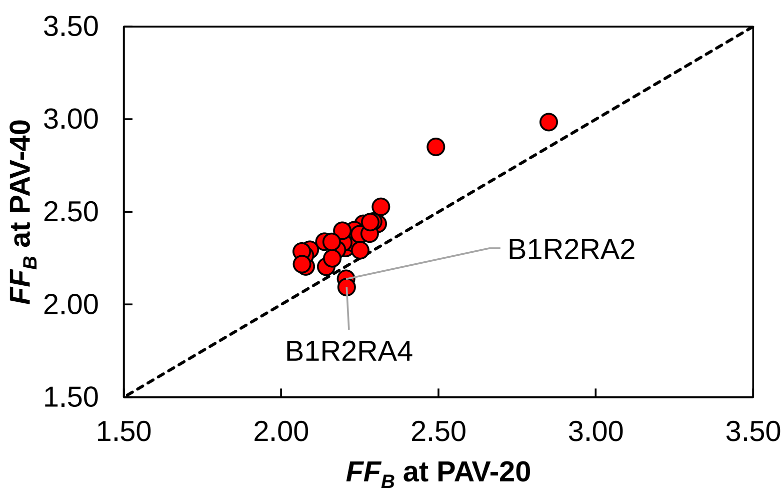

Figure H10. Comparison of FF_B for All Evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Reduction in Shear Modulus Until Peak Shear Stress ($\Delta|G^*|_{peak\ \tau}$). Mainieri et al. (2021) proposed an alternative method to analyze the LAS test results to derive a practical parameter that relates more directly to the loss of material integrity. They used an apparent complex shear modulus for the second part of the LAS test and tracked it for the entire strain sweep. The authors argued that the reduction in material integrity from the start of the test until the peak stress condition is indicative of the binder's ability to tolerate damage without losing capacity. In order to calculate $\Delta|G^*|_{peak\ \tau}$, only the pre-peak stress-strain response is used, and it is calculated using Equation H5. A higher value of $\Delta|G^*|_{peak\ \tau}$ is indicative of a better ability of the binder to tolerate greater loss in material integrity before its capacity to resist deformation decreases post-peak shear stress. With aging, $\Delta|G^*|_{peak\ \tau}$ is expected to decrease (Singhvi et al., 2021).

$$\Delta|G^*|_{peak\ \tau} = \left[\frac{|G^*|_{start} + |G^*|_{peak\ \tau}}{|G^*|_{start}}\right] * 100 \qquad \text{[Eq. H5]}$$

The studied binders were evaluated using $\Delta|G^*|_{peak\ \tau}$ for both the PAV-20 and PAV-40 aging conditions as per Equation H5. It can be seen from Figure H11 that most of binder blends have a higher or similar $\Delta|G^*|_{peak\ \tau}$ for both aging conditions except for B3-based binder blends, which show a lower $\Delta|G^*|_{peak\ \tau}$ compared to B3. Further, all binders show a decrease in $\Delta|G^*|_{peak\ \tau}$ with aging except B2R1RA5, which is similar to the observations made from previously presented indices such as FREI and I^R. The highest aging sensitivity in terms of $\Delta|G^*|_{peak\ \tau}$ was shown by B1R2RA2, and the lowest was shown by B1 binder.

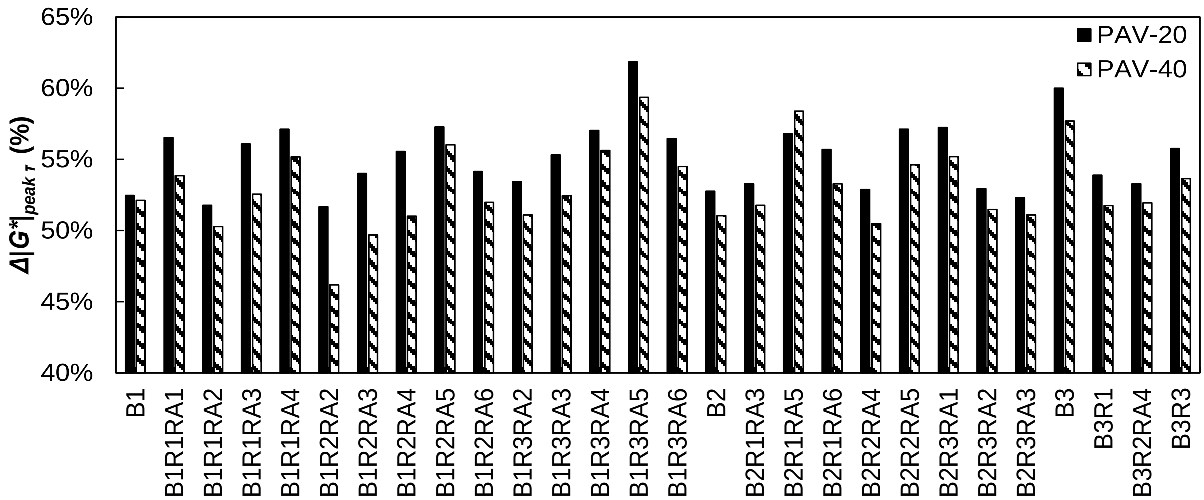

Figure H11. $\Delta|G^*|_{peak\ \tau}$ for All Evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

These indices and others are summarized in Table H2, and their significance with respect to fatigue performance, aging, and rejuvenation is provided in Table H3.

Table H2. Summary of Indices Based on the Linear Amplitude Sweep (LAS) Test

Index	Definition/Equation	Reference
Average reduction in integrity up to failure (I^R)	$I^R = \frac{\int_0^{N_f} (1-C)\,dN}{N_f}$	Zhang et al., 2020; 2021
Strain tolerance up to failure (ε_T)	Strain level corresponding with the 25% maximum stress point	Zhang et al., 2020; 2021
Strain energy tolerance (E_f)	Area under the stress–strain curve up to the 25% maximum stress point	Zhang et al., 2020; 2021
Fatigue resistance energy index (FREI)	$FREI = \frac{J_{f-\tau_{\max}}}{G_{0.5\tau_{\max}}} \left(\gamma_{0.5\tau_{\max}}\right)^2$	Zhou et al., 2017
Fatigue factor of binder (FF_B)	$FF_B = \left[\frac{\log\left(N_{f,1.25\%}\right) + \log\left(N_{f,2.50\%}\right)}{2}\right] \times \left(\log(0.025) - \log(0.0125)\right)$	Martins, 2014; Possebon, 2021
$\Delta\|G^*\|_{\text{peak }\tau}$	Percent reduction in $\|G^*\|$ measured from the start of the test until the peak shear-stress condition	Mainieri et al., 2021; Singhvi et al., 2021
R ratio and N_f based on R ratio	$R = \frac{A_{PS}^F - A_{TS}^F}{A_{PS}^F} = 1 - \frac{\int \tau^T dy}{\int \tau^P dy}$ $N_f = \frac{2fD^{1+(1-C)\alpha}}{\left[1+(1-C)\alpha\right](QC)^{\alpha}} \gamma^{-2\alpha}$	Saboo, 2020
F ratio	$F = \frac{\tau_D}{\gamma_F}; \tau_D = \frac{\tau_p - \tau_A}{\tau_p} \times 100$	Chaudhary et al., 2021

Table H3. Significance of Indices Based on the Linear Amplitude Sweep (LAS) Test

Index	Significance With Respect to		
	Fatigue	Aging	Rejuvenation
Average reduction in integrity up to failure (I^R)	The higher the better	Should decrease with aging	Should increase upon rejuvenation
Strain tolerance up to failure (ε_T)	The higher the better	Should decrease with aging	Should increase upon rejuvenation
Strain energy tolerance (E_f)	The higher the better	Should decrease with aging	Should increase upon rejuvenation
Fatigue resistance energy index (FREI)	The higher the better	Should decrease with aging	Should increase upon rejuvenation
Fatigue factor of binder (FF_B)	The higher the better	Should decrease with aging	Should increase upon rejuvenation
$\Delta\lvert G^*\rvert_{peak\ \tau}$	The higher the better	Should decrease with aging	Should increase upon rejuvenation
R ratio and N_f based on R ratio	The higher the N_f, the better	Should decrease with aging	Should increase upon rejuvenation
F ratio	The lower the better	Should increase with aging	Should decrease upon rejuvenation

Novel Fatigue Performance Index Based on PSE Principles

Most indices evaluated in the previous section consider different aspects of the stress-strain behavior response under a strain-controlled linear amplitude sweep. These can be broadly grouped into five categories: (1) those that consider some representation of material integrity and its degradation as a metric such as I^R and $\Delta\lvert G^*\rvert_{peak\ \tau}$, where both of these consider peak stress as occurrence of failure; (2) those indices that are based on energy principles such as E_f; (3) those indices that are based on strain tolerance such as ε_T; (4) phenomenological indices such as FREI that combine energy principles, stiffness, and ductility aspects into a single parameter; and (5) empirical indices such FF_B that are based on observations and correlations from large datasets employing fatigue life estimations across binders and mixtures. One thing that stays consistent across all these indices is that failure is considered at the occurrence of peak stress. However, in proposing a unified failure criterion for asphalt binders, Wang et al. (2015) showed that PSE-based analysis yields more consistent fatigue failure across binders and mixtures and can serve as a fundamental relationship for full fatigue characterization of an asphalt binder. The evidence for this was further established by Wang and Kim (2019), who proposed a PSE-based fatigue failure criterion for asphalt mixtures that required less testing for full characterization. PSE-based analysis was explored to evaluate novel indices that can capture fatigue performance across different binders for different aging conditions.

Pseudo-Strain Energy (PSE)-Based Analysis. Figure H12 shows the PSE definitions employed in an LAS test. The undamaged line presents the LVE response of the binder to serve as a reference as if no damage took place with increasing loading. The blue dotted line represents the measured response, which shows deviation from the undamaged line as loading progresses, indicating the occurrence of damage.

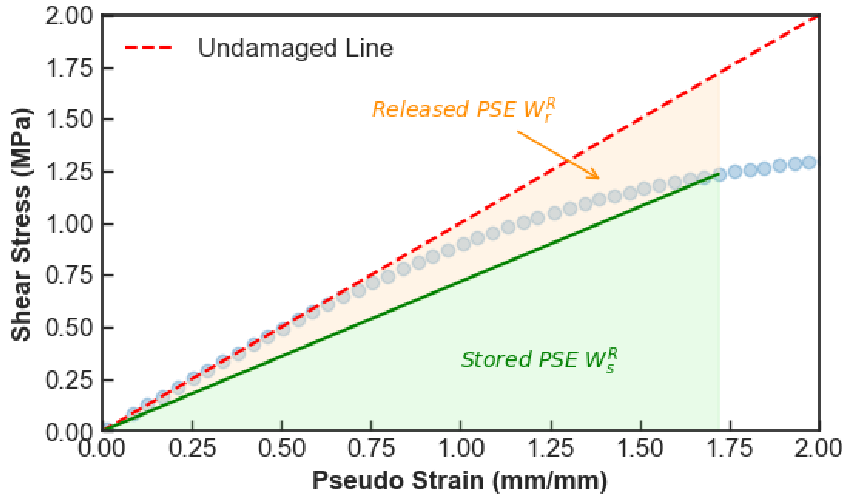

Figure H12. Liner Amplitude Sweep–Based Pseudo-Strain Energy Definitions. The undamaged line presents the linear viscoelastic response of the binder to serve as a reference as if no damage took place with increasing loading. The blue dotted line represents the measured response, which shows deviation from the undamaged line as loading progresses, indicating the occurrence of damage.

The damage evolution within the S-VECD model framework is based on Schapery's work potential theory (Schapery, 1984) where the damage evolution rate is expressed as shown in Equation H6.

$$\frac{dS}{dt} = \left(\frac{dW^R}{dS}\right)^{\alpha} \quad \text{[Eq. H6]}$$

where

S = internal state variable (ISV) representing damage
α = material-dependent constant in its undamaged state
W^R = work performed as expressed in Equation H7
t = time.

$$W^R = \frac{1}{2} C(S)(\Upsilon^R)^2 \quad \text{[Eq. H7]}$$

where

C(S) = pseudo-stiffness expressed as shown in Equation H8.

$$C(S) = \frac{\tau_p}{\Upsilon_p^R * DMR} \quad \text{[Eq. H8]}$$

where

τ_p = peak shear stress
Υ_p^R = peak pseudo-strain for a given cycle expressed as shown in Equation H9
DMR = dynamic modulus ratio expressed in Equation H10.

$$\Upsilon_p^R = \frac{1}{G_R}\Upsilon_p * |G^*|_{LVE} \quad \text{[Eq. H9]}$$

$$DMR = \frac{|G^*|_{fingerprint}}{|G^*|_{LVE}} \quad \text{[Eq. H10]}$$

where

G_R = arbitrary reference modulus taken as 1
Υ_p = peak shear strain for a given cycle
|G*| = complex shear modulus from the fingerprint frequency sweep test of the LAS test and LVE modulus at that frequency and temperature.

It can be seen from Equation H9 that γ_p^R is essentially equivalent to the LVE stress response for a given loading history.

For a particular data point from the LAS test, the stored and released PSE as shown in Figure H12. Stored PSE or W_s^R is calculated using Equation H11.

$$W^R = \frac{\left(\frac{1}{2}\right) * \tau_p * \Upsilon_p^R}{DMR} = \frac{1}{2} * C * (\Upsilon_p^R)^2 \quad \text{[Eq. H11]}$$

An increasing W_s^R indicates that the material retains the ability to store additional energy as the loading amplitude (as a consequence, the energy input) increases. On the other hand, a decrease in W_s^R indicates that the material is losing its ability to store PSE as the loading input increases, indicating failure has occurred. Based on this energy-based understanding, Wang et al. (2015) proposed peak of stored PSE as the occurrence of failure in an LAS test instead of peak stress. They verified the fatigue life based on this failure definition and a drop in phase angle data and found a good agreement, indicating peak in stored PSE is a reliable indicator to define fatigue failure in an LAS test. The current study builds on this energy-based failure definition to propose a novel index that captures the ability of binders to withstand fatigue cracking in terms of stress level and strain tolerance at peak PSE.

Stress Level at Peak Stored PSE (S_L). The experimental results demonstrate that the stored PSE shows a peak within the current LAS test framework in accordance with AASHTO TP 391-20. This peak generally occurs after the peak stress has occurred, as shown in Figure H13, indicating that the binder continues to retain its ability to store additional energy after the peak stress condition.

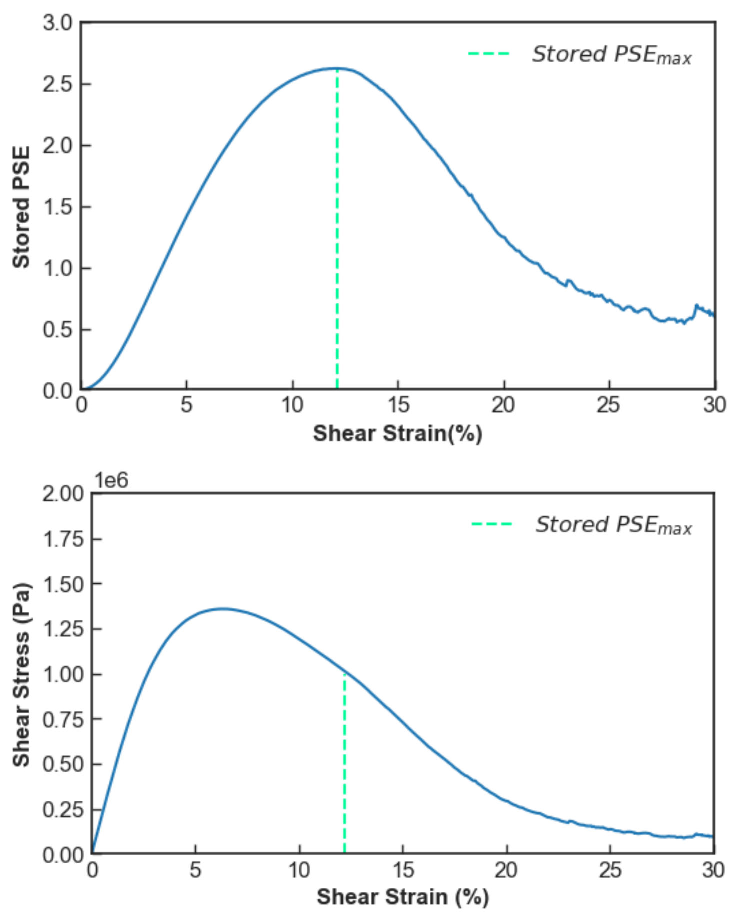

Figure H13. Schematic for Peak Stored PSE and the Corresponding Shear Stress. PSE = pseud-strain energy.

As can be seen from Equations H8, H9, and H11, the stored PSE is dependent on shear stress along with time, which is specific for a particular loading scheme. Therefore, the shear stress at the peak stored PSE can be considered a metric to compare the shear capacity until failure. In other words, it refers to the ability to the binder to continue resisting fatigue failure even after the peak stress is reached. In order to obtain a normalized parameter, the ratio of stress at peak stored PSE to the peak stress referred to as the stress level at peak stored PSE (S_L) is considered as an index parameter to characterize the fatigue resistance of asphalt binders and is calculated using Equation H12. A higher value of S_L indicates a higher fatigue resistance capacity. It is expected to decrease with aging.

$$S_L = \left(\frac{\tau_{peak\ stored\ PSE}}{\tau_{peak\ stress}}\right) * 100 \qquad \text{[Eq. H12]}$$

The studied binders were evaluated using S_L for both the PAV-20 and PAV-40 aging conditions, and it was found that S_L for unmodified binders B1, B2, and B3 was higher for most of the corresponding binder blends containing RAs. The RA5 blends, which generally have a higher RA dosage, showed a higher S_L as compared to other binder blends. RA1, which was observed to have a negative impact on cracking performance, showed a low S_L across aging conditions. S_L was observed to capture the impact of aging consistently across all studied binders and decreases with aging, as shown in Figure H14. Among the RA blends, RA1 blends showed the highest sensitivity to aging, with S_L decreasing by about 14% and 28% for the B1R1RA1 and B2R3RA1 blends, respectively.

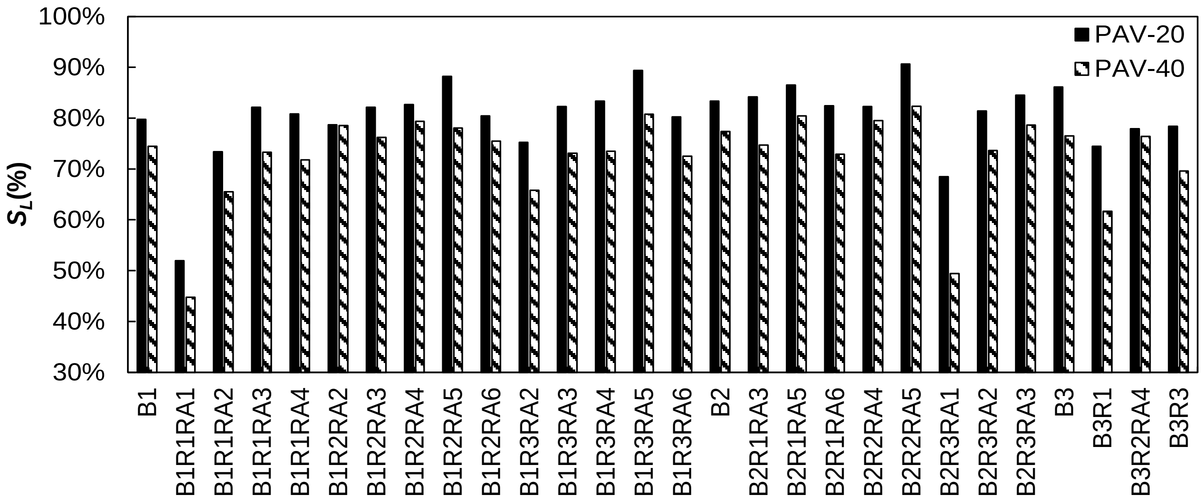

Figure H14. S_L for All Evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

In terms of ranking the binders at respective aging conditions, RA1 blends showed the worst fatigue performance for both the PAV-20 and PAV-40 aging conditions whereas most RA5 blends showed the best fatigue performance for both aging conditions in terms of S_L. Binder B3, which is a PG58-28 binder and is expected to show better fatigue performance owing to a softer grade, ranks high in terms of S_L. The relative ranking of the studied binders in terms of S_L is tabulated in Table H4 for the PAV-20 and PAV-40 aging conditions. It can be seen that the relative ranking changes from the PAV-20 to the PAV-40 aging condition; however, as discussed, most of the best and the worst binder blends in terms of fatigue performance retained the same or similar relative ranking. The change in rankings can be attributed to varying sensitivity to aging of the base binders, RAP binders, RA types, source of respective binders, the interaction of these three constituents in the binder blends, RA dosage, etc., among several other factors.

Table H4. Relative Ranking of Binder Blends Based on S_L for PAV-20 and PAV-40 Aging Conditions

Binder	Relative Ranking	
	PAV-20	PAV-40
B1	20	15
B1R1RA1	28	28
B1R1RA2	26	25
B1R1RA3	14	18
B1R1RA4	17	22
B1R2RA2	21	7
B1R2RA3	15	12
B1R2RA4	10	5
B1R2RA5	3	8
B1R2RA6	18	13
B1R3RA2	24	24
B1R3RA3	12	19
B1R3RA4	8	17
B1R3RA5	2	2
B1R3RA6	19	21
B2	9	9
B2R1RA3	7	14
B2R1RA5	4	3
B2R1RA6	11	20
B2R2RA4	13	4
B2R2RA5	1	1
B2R3RA1	27	27
B2R3RA2	16	16
B2R3RA3	6	6
B3	5	10
B3R1	25	26
B3R2RA4	23	11
B3R3	22	23

PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Comparison With LVE Index Parameter and Validation With Mixture Aging

As shown previously, the LVE aging index parameter tracks perfectly with aging and has proven useful in assessing the aging sensitivity of binder blends in terms of their LVE properties. S_L, which is a fatigue performance index based on PSE principles, is also able to track the change in fatigue performance with aging. Figure H.15 shows a two-dimensional plot that considers S_L along with the LVE aging index parameter for the two aging conditions of PAV-20 and PAV-40. It can be seen that S_L tracks perfectly with the LVE aging index parameter. This provides further support for S_L to be used as a fatigue performance index based on the LAS test.

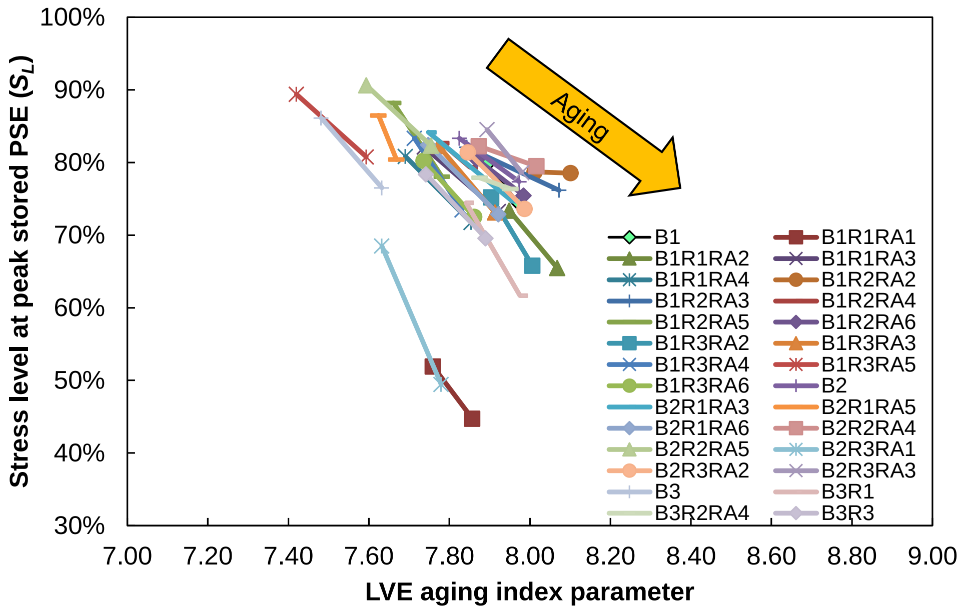

Figure H15. Comparison of S_L With LVE Aging Index Parameter for All Evaluated Binder Blends Under PAV-20 and PAV-40 Aging Conditions. LVE = linear viscoelastic; PAV = pressure aging vessel; PAV-20 = PAV for a duration of 20 hours; PAV-40 = PAV for a duration of 40 hours; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

A subset of the binder blends was shortlisted, and corresponding mixtures were fabricated and tested for the IDT-CT. The details of the testing were provided previously. In this section, the focus is on three mixtures, namely, B1R1RA1, B1R1RA2, and B2R1RA5, that were tested for three mixture aging conditions such as STOA, 1-day long-term oven aging (LTOA), and 3-day LTOA, as discussed previously. The CT_{index} of these three mixtures was compared across the three aging conditions, and an aging sensitivity in terms of the CT_{index} was calculated using Equations H13 and H14.

$$(CT_{index})^{1day\ STOA}_{aging\ sensitivity} = \left[\frac{(CT_{index})_{STOA} - (CT_{index})_{1day\ LTOA}}{(CT_{index})_{STOA}}\right] * 100 \quad \text{[Eq. H13]}$$

$$(CT_{index})^{3day\ STOA}_{aging\ sensitivity} = \left[\frac{(CT_{index})_{STOA} - (CT_{index})_{3day\ LTOA}}{(CT_{index})_{STOA}}\right] * 100 \quad \text{[Eq. H14]}$$

In terms of the binder fatigue performance index, S_L was compared across the two aging conditions of PAV-20 and PAV-40, and a similar aging sensitivity was calculated using Equation H15.

$$(S_L)_{aging\ sensitivity} = \left[\frac{(S_L)_{PAV-20} - (S_L)_{PAV-40}}{(S_L)_{PAV-20}}\right] * 100 \quad \text{[Eq. H15]}$$

As noted from the aging assessment of mixtures, the CT_{index} shows a significant discrimination of mixtures after 1-day LTOA over 3-day LTOA, and the aging sensitivity for the 1-day LTOA captures that change in the CT_{index}, as shown in Equation H13. The aging sensitivity in terms of S_L for the corresponding binder blends was calculated and compared with mixture aging sensitivity after 1-day LTOA. The basic idea was to determine whether S_L is able to capture the degradation in cracking performance with aging as reflected in the mixture testing. Figure H16 shows the comparison across binder and mixture scales, and it can be seen that there is good agreement between the binder and mixture aging sensitivities as captured by S_L and the CT_{index}, respectively.

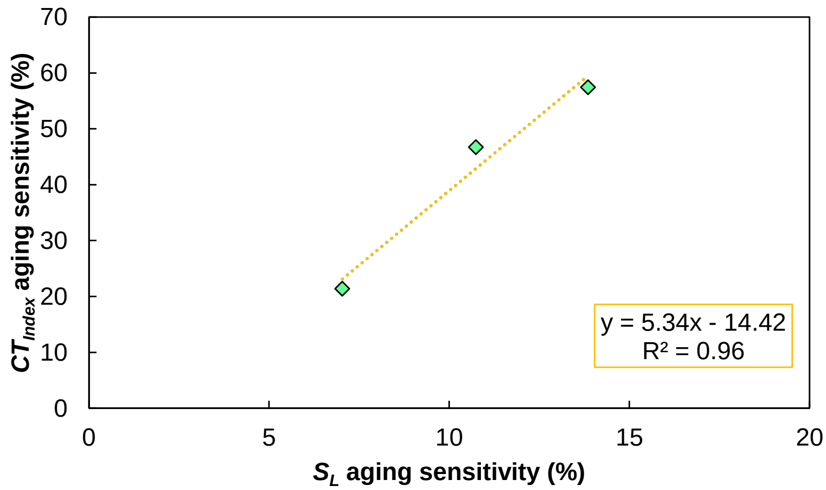

Figure H16. Aging Sensitivity Across Binder and Mixture Scales for B1R1RA1, B1R1RA2, and B2R1RA5. B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Further, if these three binder blends were to be ranked in terms of S_L for the PAV-20 and PAV-40 aging conditions as shown previously in Table H4, the order would be B2R1RA5 > B1R1RA2 > B1R1RA1. It must be noted that B1R1RA1 was shown to be the worst across all tested binders and B1R1RA2 also ranked very low whereas B2R1RA5 ranked at or close to the top among the best-performing binder blends. On the other hand, at mixture scale in terms of the CT_{index}, the relative ranking at STOA and 3-day LTOA is B2R1RA5 > B1R1RA1 > B1R1RA2 whereas the order at 1-day LTOA is the same as observed from binder S_L assessment across the PAV-20 and PAV-40 aging conditions. This observation also suggests a closer look at S_L as a possible index for assessing the fatigue performance of binder blends that may translate consistently to the mixture scale in terms of the IDT-CT.

It should be noted that a very limited number of mixtures were used to compare the fatigue performance across the two scales, so the efficacy of using S_L as an index still needs to be validated with a larger set of mixtures. This study is still preliminary in nature and warrants further research in order to propose any screening of RAs based on S_L.

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APPENDIX I

FOURIER TRANSFORM INFRARED SPECTROSCOPY (FTIR) TEST RESULTS

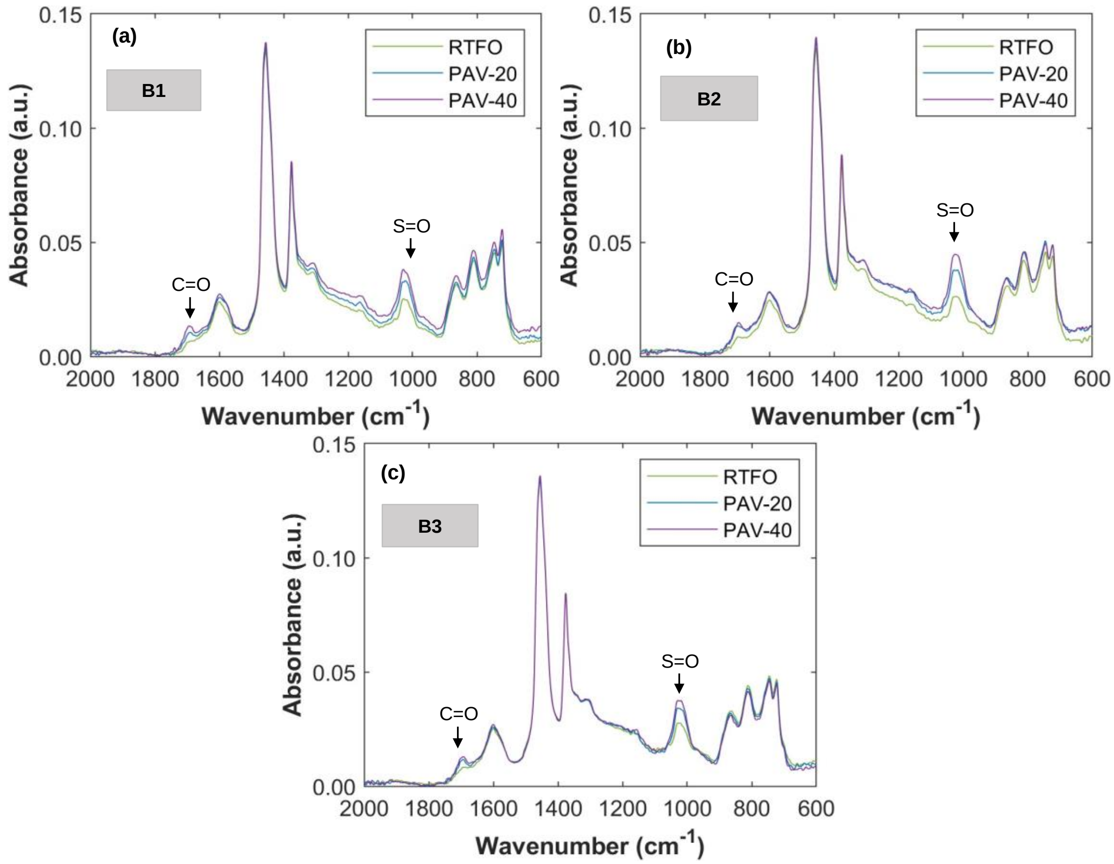

Figure I1. FTIR Spectra for Virgin Binders: (a) B1; (b) B2; (c) B3. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

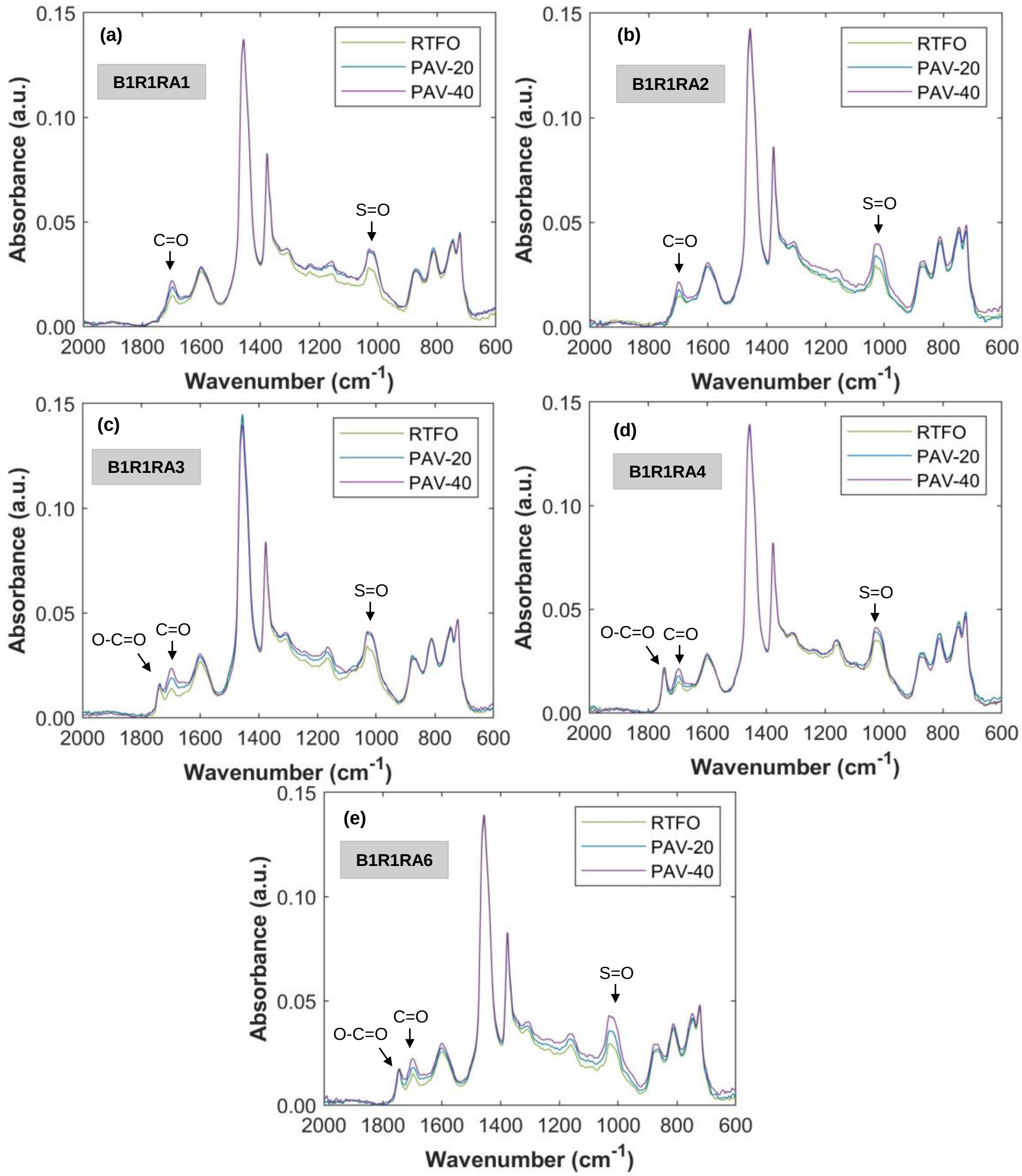

Figure I2. FTIR Spectra for B1R1 Blends: (a) B1R1RA1; (b) B1R1RA2; (c) B1R1RA3; (d) B1R1RA4; (e) B1R1RA6. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

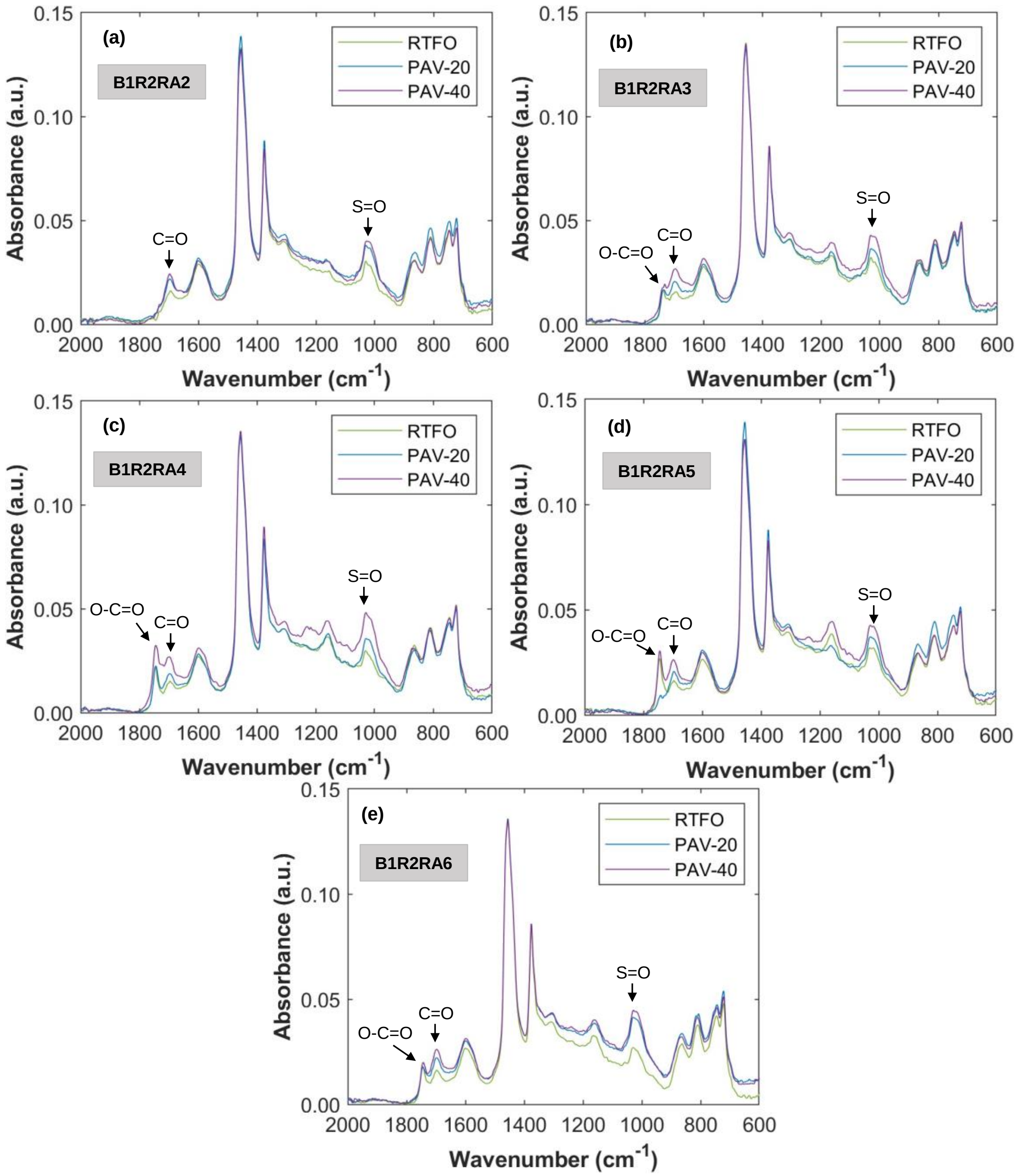

Figure I3. FTIR Spectra for B1R2 Blends: (a) B1R2RA2; (b) B1R2RA3; (c) B1R2RA4; (d) B1R2RA5; (e) B1R2RA6. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

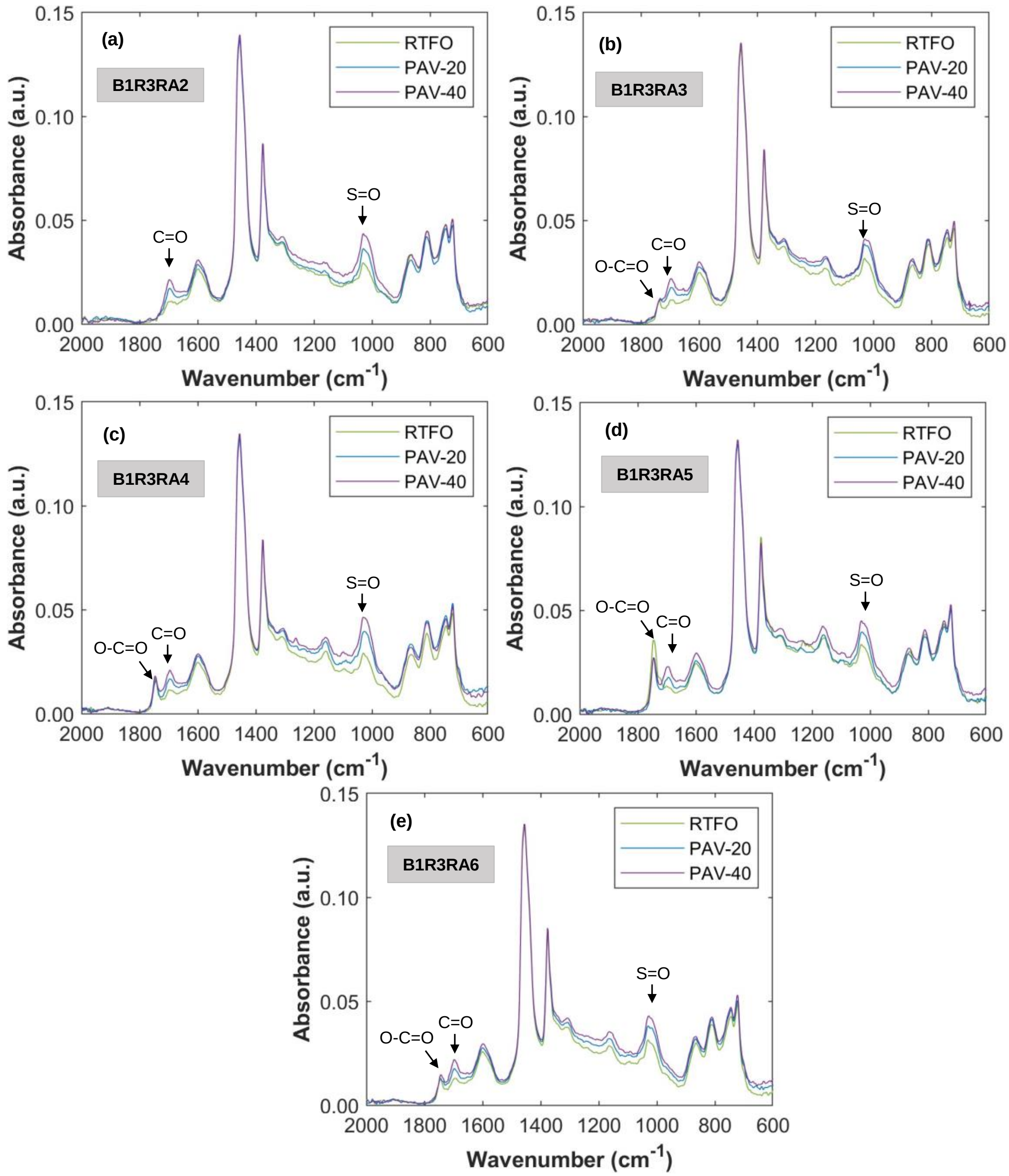

Figure I4. FTIR Spectra for B1R3 Blends: (a) B1R3RA2; (b) B1R3RA3; (c) B1R3RA4; (d) B1R3RA5; (e) B1R3RA6. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

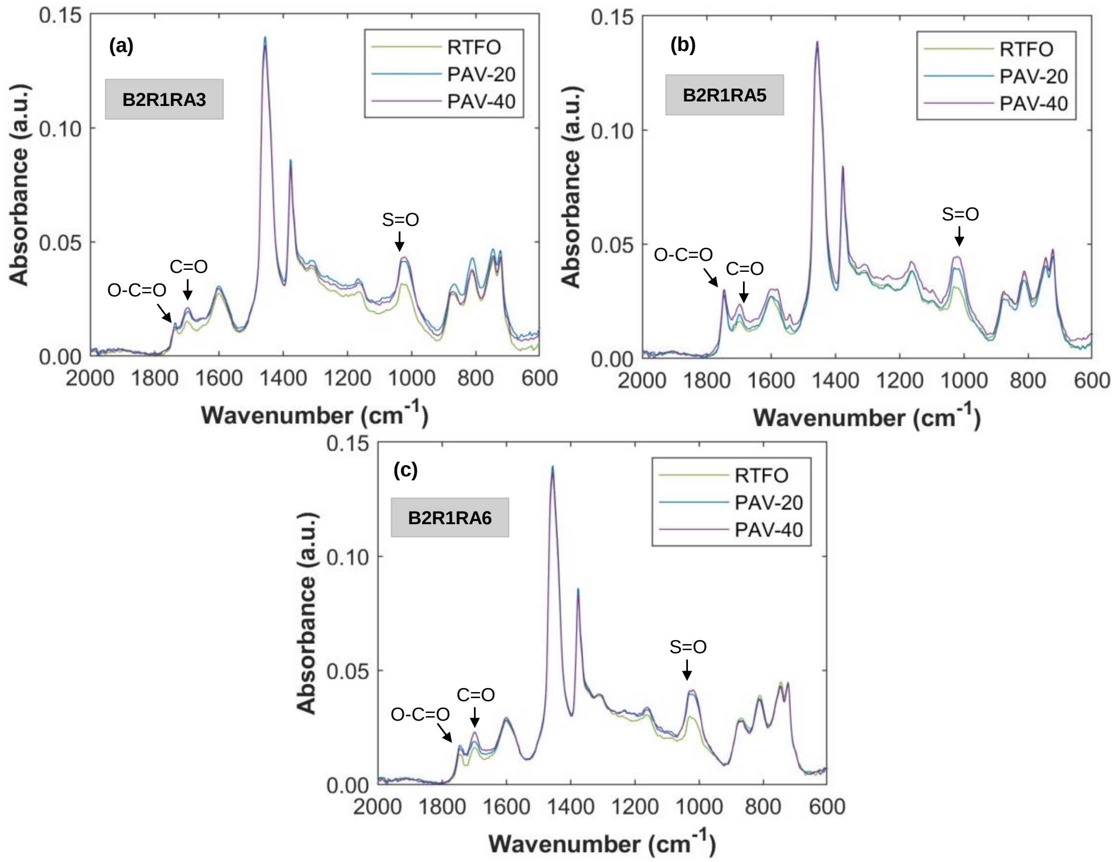

Figure I5. FTIR Spectra for B2R1 Blends: (a) B2R1RA3; (b) B2R1RA5; (c) B2R1RA6. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

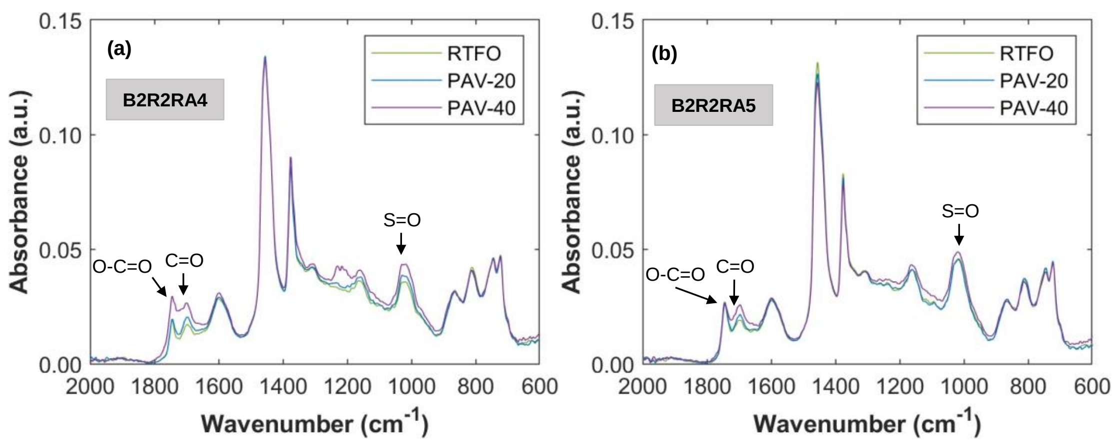

Figure I6. FTIR Spectra for B2R2 Blends: (a) B2R2RA4; (b) B2R2RA5. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

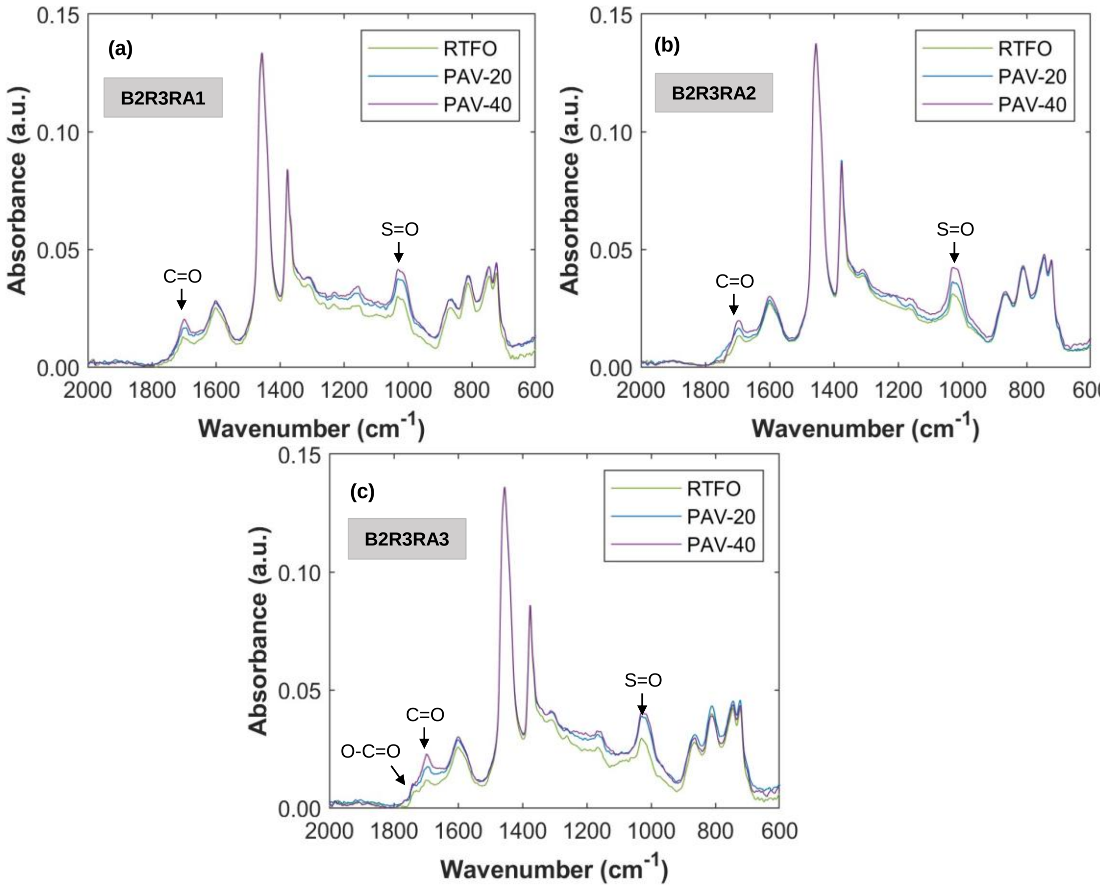

Figure I7. FTIR Spectra for B2R3 Blends: (a) B2R3RA1; (b) B2R3RA2; (c) B2R3RA3. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

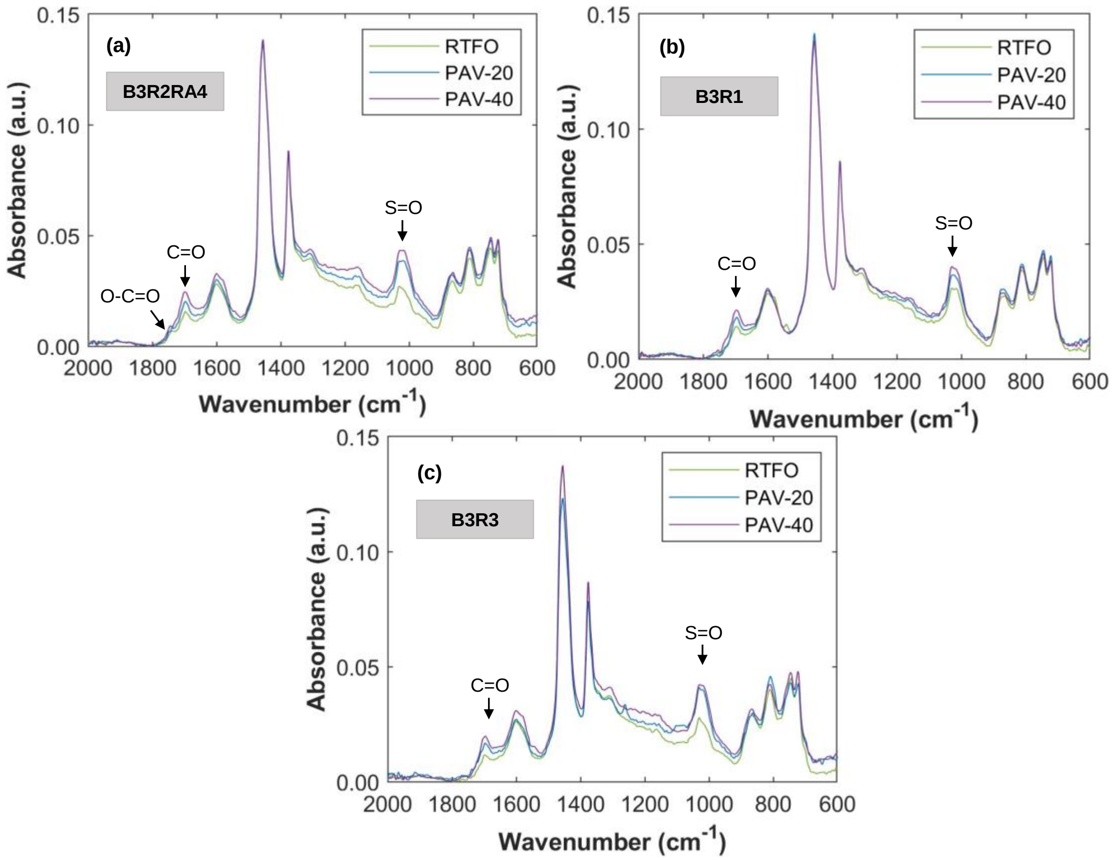

Figure I8. FTIR Spectra for B3 Blends: (a) B3R2RA4; (b) B3R1; (c) B3R3. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin film oven (short-term aging); PAV = pressure aging vessel; PAV-20 = aging in PAV for 20 hours; PAV-40 = aging in PAV for 40 hours.

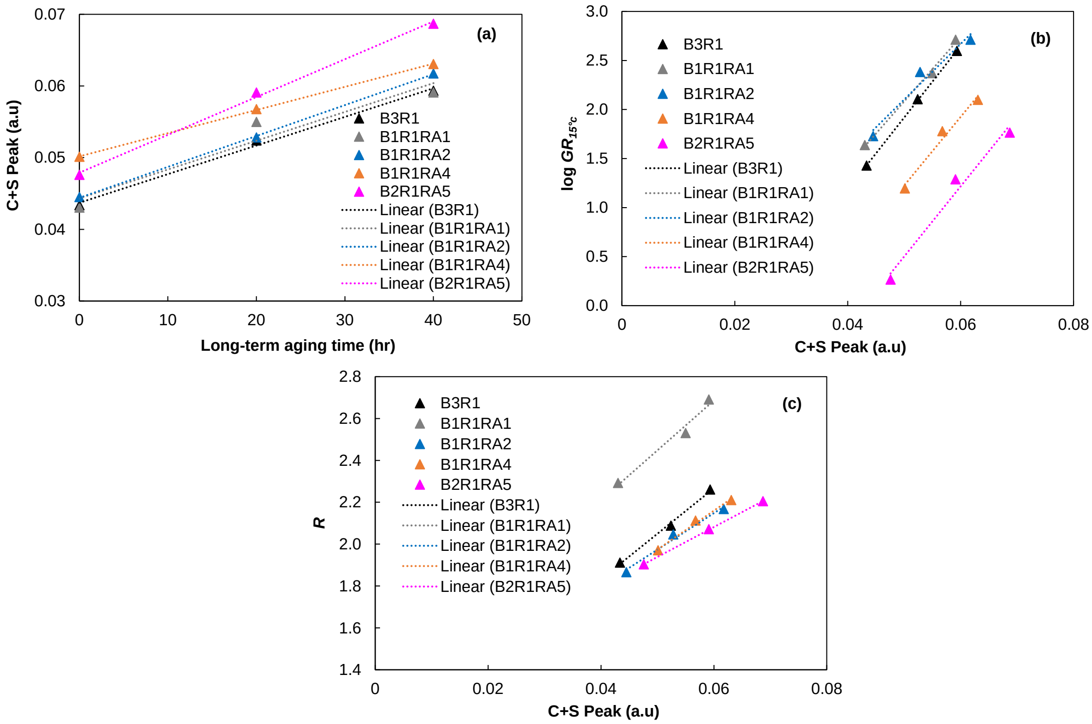

Figure I9. FTIR Data for a Subset of Source 1 Blends: (a) changes of C+S with respect to aging time; (b) change of log $GR_{25°C}$ with respect to C+S; (c) change of R with respect to C+S. FTIR = Fourier transform infrared spectroscopy; B = virgin asphalt binder; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; C = carbonyl; S = sulfoxide; GR = Glover-Rowe parameter; R = rheological index.

Table I1. Growth of C+S Peaks With Respect to Long-Term Aging Time

RAP	Virgin Binder	Recycling Agent						
		RA1	**RA2**	**RA3**	**RA4**	**RA5**	**RA6**	**No RA**
R1	B1	4.02E-04	4.31E-04	4.23E-04	3.24E-04	-	5.35E-04	-
	B2	-	-	4.54E-04	-	5.28E-04	4.63E-04	-
	B3	-	-	-	-	-	-	4.00E-04
R2	B1	-	1.87E-04	5.89E-04	7.60E-04	5.38E-04	6.99E-04	-
	B2	-	-	-	4.18E-04	2.27E-04	-	-
	B3	-	-	-	-	-	-	-
R3	B1	-	6.10E-04	4.84E-04	6.66E-04	5.25E-04	5.21E-04	-
	B2	4.35E-04	4.45E-04	5.89E-04	-	-	-	-
	B3	-	-	-	-	-	-	5.67E-04

R = RAP = reclaimed asphalt pavement; B = virgin asphalt binder; RA = recycling agent; C = carbonyl; S = sulfoxide; - = combination was not evaluated.

Table I2. Growth of log $GR_{15°C}$ With Respect to C+S Growth

RAP	Virgin Binder	Recycling Agent						
		RA1	RA2	RA3	RA4	RA5	RA6	No RA
R1	B1	65.6	56.7	67.9	69.9	-	56.1	-
	B2	-	-	61.9	-	71.6	66.7	-
	B3	-	-	-	-	-	-	73.3
R2	B1	-	44.7	44.3	33.3	55.1	35.8	-
	B2	-	-	-	73.1	44.4	-	-
	B3	-	-	-	-	-	-	-
R3	B1	-	45.4	41.1	38.9	63.8	53.0	-
	B2	80.4	66.2	41.6	-	-	-	-
	B3	-	-	-	-	-	-	51.9

R = RAP = reclaimed asphalt pavement; B = virgin asphalt binder; RA = recycling agent; C = carbonyl; S = sulfoxide, - = combination was not evaluated.

Table I3. Growth of R_{MC} With Respect to C+S Growth

RAP	Virgin Binder	Recycling Agent						
		RA1	RA2	RA3	RA4	RA5	RA6	No RA
R1	B1	23.7	17.4	15.7	18.5	-	14.6	-
	B2	-	-	13.2	-	14.3	15.1	-
	B3	-	-	-	-	-	-	21.7
R2	B1	-	12.3	11.1	9.5	13.3	9.4	-
	B2	-	-	-	18.0	9.8	-	-
	B3	-	-	-	-	-	-	-
R3	B1	-	14.9	9.8	10.1	14.4	15.7	-
	B2	30.3	20.8	11.3	-	-	-	-
	B3	-	-	-	-	-	-	16.6

R = RAP = reclaimed asphalt pavement; B = virgin asphalt binder; RA = recycling agent; C = carbonyl; S = sulfoxide; - = combination was not evaluated.

APPENDIX J

ADDITIONAL DURABILITY AND CRACKING PERFORMANCE TEST RESULTS AND ANALYSIS

Statistical Analysis of Durability and Cracking-Related Parameters

A statistical analysis of the durability and cracking-related parameters evaluated in this study was conducted with the aim of identifying any significant difference in durability and cracking performance with respect to the reference mixture of each source. Further, comparing the statistical tests from different parameters allows for assessing the capacity of each test result to discriminate performance. The results of the analysis are presented in Table J1, Table J2, and Table J3 for Source 1, 2, and 3 mixtures, respectively.

Table J1. p-Values Obtained in Dunnett's Test for Durability- and Cracking-Related Parameters of Source 1 Mixtures

Mixture	CT_{index}	G_f	l_{75}	m_{75}	S_{app} at 15°C	ML
B3R1	1.000	1.000	1.000	1.000	1.000	1.000
B1R1RA1	0.121	0.010	0.994	0.001	0.001	--
B1R1RA2	0.997	0.284	0.622	1.000	0.792	0.225
B1R1RA4	0.058	0.243	0.837	0.006	0.032	--
B2R1RA5	<0.001	<0.001	0.014	<0.001	0.068	0.033

CT = cracking tolerance; G_f = work fracture energy; l = displacement; m = slope; S_{app} = apparent damage; ML = mass loss; B = virgin binder; R = reclaimed asphalt pavement; RA = recycling agent; -- = data not available because mixture was not characterized. B3R1 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different and is marked in red.

Table J2. p-Values Obtained in Dunnett's Test for Durability- and Cracking-Related Parameters of Source 2 Mixtures

Mixture	CT_{index}	G_f	l_{75}	m_{75}	S_{app} at 15°C	ML
B3R2	1.000	1.000	1.000	1.000	1.000	1.000
B3R2RA4	0.043	0.022	0.630	0.001	0.031	0.764

CT = cracking tolerance; G_f = work fracture energy; l = displacement; m = slope; S_{app} = apparent damage; ML = mass loss; B = virgin binder; R = reclaimed asphalt pavement; RA = recycling agent. B3R2 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different and is marked in red.

Table J3. p-Values Obtained in Dunnett's Test for Durability- and Cracking-Related Parameters of Source 3 Mixtures

Mixture	CT_{index}	G_f	l_{75}	m_{75}	S_{app} at 15°C	ML
B3R3	1.000	1.000	1.000	1.000	1.000	1.000
B1R3RA6	0.009	0.924	0.036	0.014	0.835	0.301
B1R3RA5	0.629	0.097	0.560	0.151	0.098	--

CT = cracking tolerance; G_f = work fracture energy; l = displacement; m = slope; S_{app} = apparent damage; ML = mass loss; B = virgin binder; R = reclaimed asphalt pavement; RA = recycling agent; -- = data is not available because mixture was not characterized. B3R3 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different and is marked in red.

Location-Specific S_{app} Values

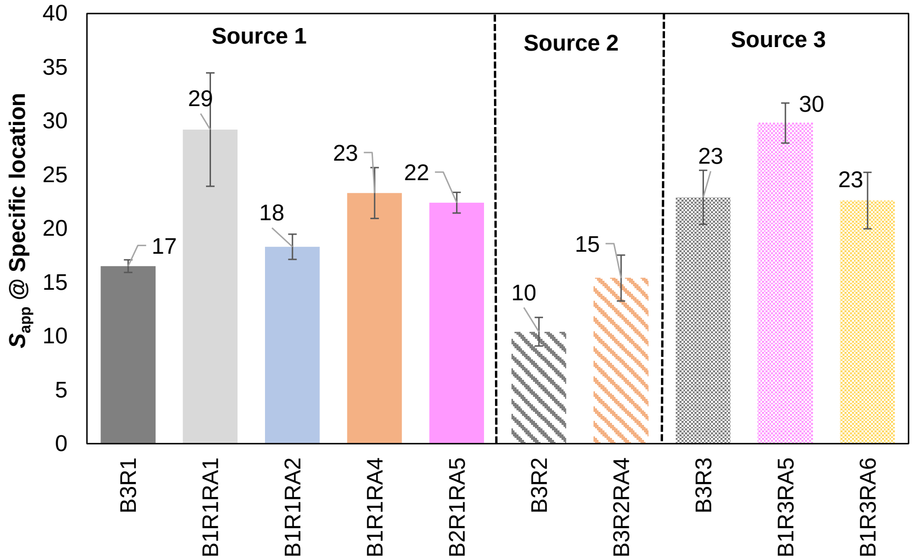

Figure J1. Cyclic Fatigue Performance Test Data in Terms of S_{app} Values for Source 1, 2, and 3 Mixtures Determined Using Local Specific Climatic Data: Blacksburg, Virginia, for Source 1 mixtures (15°C); Mecklenburg, Virginia, for Source 2 mixtures (18°C); and Chesapeake, Virginia, for Source 3 mixtures (21°C). S_{app} = apparent damage capacity. B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

APPENDIX K

DYNAMIC MODULUS AND PHASE ANGLE TEST RESULTS

Statistical Analysis

A statistical analysis of the dynamic modulus and phase angle results for each temperature and frequency combination was conducted. The analysis was conducted for Source 1, 2, and 3 materials, and the RA mixture results were compared against the results of the corresponding reference mixture (B3R1, B3R2, and B3R3). In doing so, Dunnett's test was conducted using a significance level of $\alpha = 0.05$. This test was selected over the Tukey test since the interest is in benchmarking the mixtures with RAs against the reference mixture and not among themselves. Further, Bartlett's test was used to test homoscedasticity prior to conducting Dunnett's test. The results of the statistical analysis are shown in Table K1 and Table K2 for Source 1, Table K3 and Table K4 for Source 2, and Table K5 and Table K6 for Source 3 mixtures.

Table K1. p-Values Obtained in Dunnett's Test for the Dynamic Modulus of Source 1 Mixtures

Mixture	0.1 Hz 40°C	1 Hz 40°C	10 Hz 40°C	0.1 Hz 20°C	1 Hz 20°C	10 Hz 20°C	0.1 Hz 4°C	1 Hz 4°C	10 Hz 4°C
B3R1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B1R1RA1	0.055	0.367	0.998	0.542	0.037	0.003	0.082	0.009	0.001
B1R1RA2	0.967	1.000	0.999	0.650	0.814	0.994	0.431	0.878	0.998
B1R1RA4	0.312	0.169	0.072	0.008	0.005	0.002	0.001	0.001	0.001
B2R1RA5	0.028	0.002	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent. B3R1 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Table K2. p-Values Obtained in Dunnett's Test for the Phase Angle of Source 1 Mixtures

Mixture	0.1 Hz 40°C	1 Hz 40°C	10 Hz 40°C	0.1 Hz 20°C	1 Hz 20°C	10 Hz 20°C	0.1 Hz 4°C	1 Hz 4°C	10 Hz 4°C
B3R1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B1R1RA1	0.035	<0.001	<0.001	0.019	0.119	0.669	0.111	0.355	0.934
B1R1RA2	0.017	0.002	0.841	0.526	0.196	0.084	0.068	0.046	0.019
B1R1RA4	0.987	0.559	0.397	0.087	0.036	0.019	0.022	0.024	0.016
B2R1RA5	<0.001	0.004	0.383	0.011	<0.001	<0.001	<0.001	<0.001	<0.001

B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent. B3R1 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Table K3. p-Values Obtained in Dunnett's Test for the Dynamic Modulus of Source 2 Mixtures

Mixture	0.1 Hz 40°C	1 Hz 40°C	10 Hz 40°C	0.1 Hz 20°C	1 Hz 20°C	10 Hz 20°C	0.1 Hz 4°C	1 Hz 4°C	10 Hz 4°C
B3R2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B3R2RA4	0.854	0.744	0.582	0.864	0.919	0.764	0.316	0.266	0.110

B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent. B3R2 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Table K4. p-Values Obtained in Dunnett's Test for the Phase Angle of Source 2 Mixtures

Mixture	0.1 Hz 40°C	1 Hz 40°C	10 Hz 40°C	0.1 Hz 20°C	1 Hz 20°C	10 Hz 20°C	0.1 Hz 4°C	1 Hz 4°C	10 Hz 4°C
B3R2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B3R2RA4	0.375	0.342	0.450	0.194	0.465	0.790	0.673	0.673	0.653

B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent. B3R2 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Table K5. p-Values Obtained in Dunnett's Test for the Dynamic Modulus of Source 3 Mixtures

Mixture	0.1 Hz 40°C	1 Hz 40°C	10 Hz 40°C	0.1 Hz 20°C	1 Hz 20°C	10 Hz 20°C	0.1 Hz 4°C	1 Hz 4°C	10 Hz 4°C
B3R3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B1R3RA6	0.347	0.397	0.558	0.160	0.237	0.185	0.858	0.883	0.928
B1R3RA5	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent. B3R3 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Table K6. p-Values Obtained in Dunnett's Test for the Phase Angle of Source 3 Mixtures

Mixture	0.1 Hz 40°C	1 Hz 40°C	10 Hz 40°C	0.1 Hz 20°C	1 Hz 20°C	10 Hz 20°C	0.1 Hz 4°C	1 Hz 4°C	10 Hz 4°C
B3R3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
B1R3RA6	0.990	0.059	0.005	0.161	0.156	0.895	0.934	0.926	0.713
B1R3RA5	<0.001	<0.001	<0.001	<0.001	0.033	0.847	<0.001	<0.001	<0.001

B = virgin asphalt binder; R = reclaimed asphalt pavement binder; RA = recycling agent. B3R3 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Supplementary Dynamic Modulus Master Curve Analysis

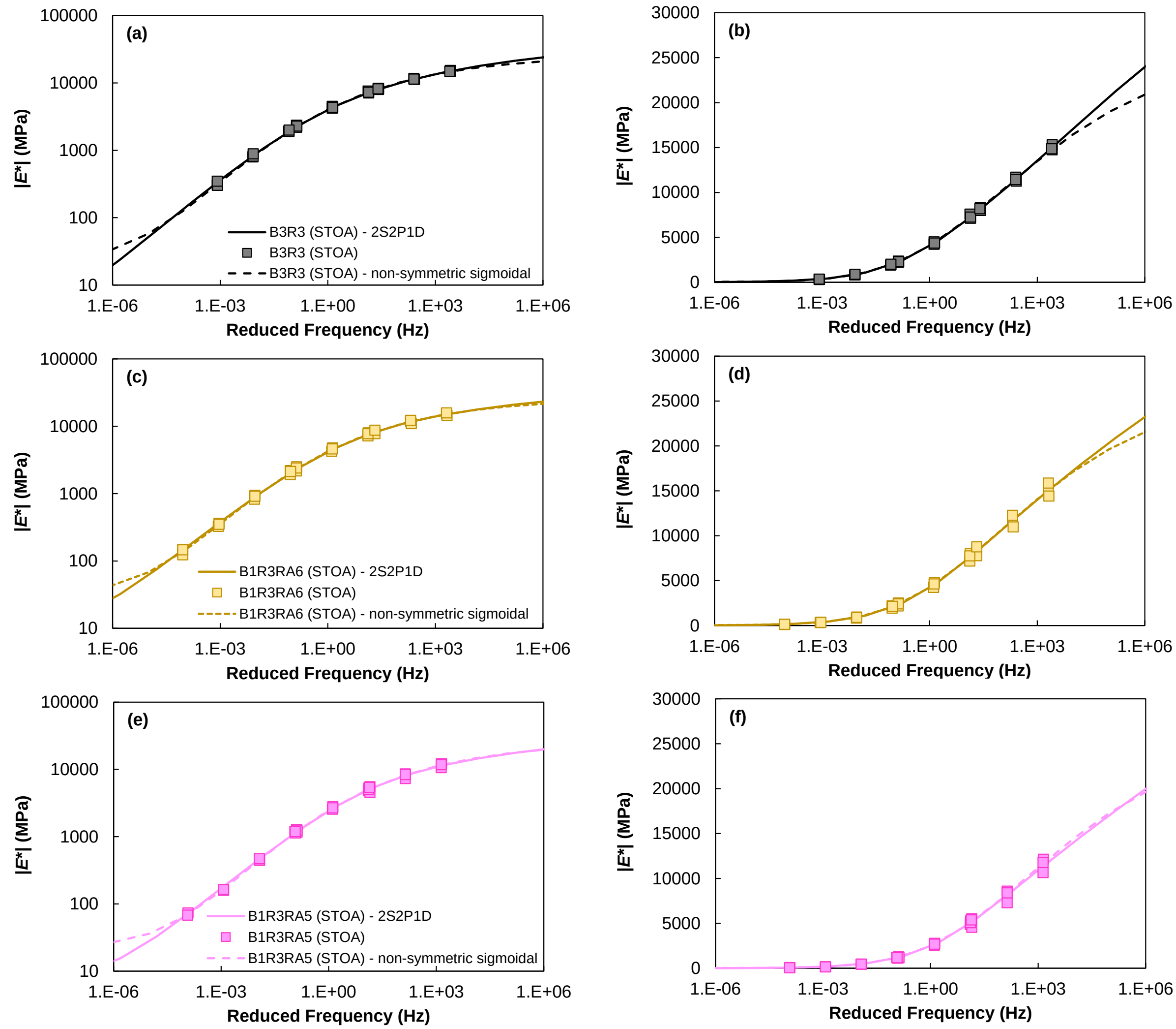

Figure K1. Dynamic Modulus Master Curves Fitted Using 2S2P1D and Non-Symmetric Sigmoidal Model: (a) B3R3 in logarithmic space; (b) B3R3 in semi-logarithmic space; (c) B1R3RA6 in logarithmic space; (d) B1R3RA6 in semi-logarithmic space; (e) B1R3RA5 in logarithmic space; (f) B1R3RA5 in semi-logarithmic space. |E*| = dynamic modulus; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent; S = spring; P = parabola; D = dashpot; STOA = short-term oven aged.

APPENDIX L

ADDITIONAL RUTTING PERFORMANCE TEST RESULTS AND ANALYSIS

Statistical Analysis for APA Rut Depth

A statistical analysis was conducted to identify any significant differences in the rutting performance of the RA mixtures with respect to the reference mixture of each source. The results are presented in Table L1, Table L2, and Table L3 for Source 1, 2, and 3 mixtures, respectively.

Table L1. p-Values Obtained in Dunnett's Test for APA Rut Depth of Source 1 Mixtures

Mixture	APA Rut Depth at 64°C and 8,000 cycles (mm)
B3R1	1.000
B1R1RA2	0.984
B2R1RA5	0.068

APA = Asphalt Pavement Analyzer; B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent. B3R1 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Table L2. p-Values Obtained in Dunnett's Test for APA Rut Depth of Source 2 Mixtures

Mixture	APA Rut Depth at 64°C and 8,000 cycles (mm)
B3R2	1.000
B3R2RA4	0.469

APA = Asphalt Pavement Analyzer; B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent. B3R2 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Table L3. p-Values Obtained in Dunnett's Test for APA Rut Depth of Source 3 Mixtures

Mixture	APA Rut Depth at 64°C and 8,000 cycles (mm)
B3R3	1.000
B1R3RA6	0.655

APA = Asphalt Pavement Analyzer; B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent. B3R3 is used as the control mixture. A p-value less than 0.05 indicates that the pairs are significantly different.

Additional SSR Test Results

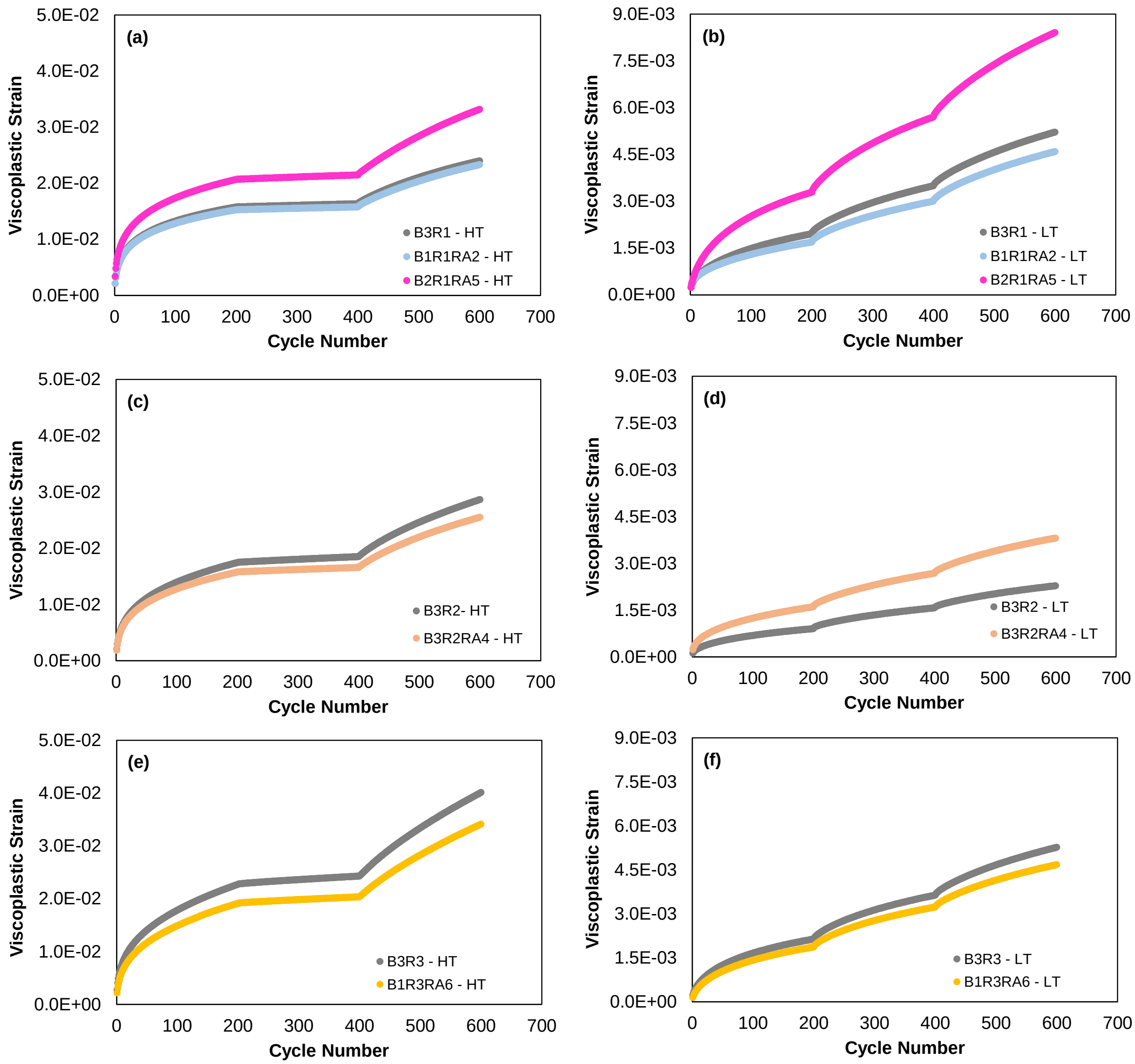

Figure L1. SSR Test Results: (a) ε_{vp} for Source 1 mixtures at high temperature (HT); (b) ε_{vp} for Source 1 mixtures at low temperature (LT); (c) ε_{vp} for Source 2 mixtures at HT; (d) ε_{vp} for Source 2 mixtures at LT; (e) ε_{vp} for Source 3 mixtures at HT; (f) ε_{vp} for Source 3 mixtures at LT. ε_{vp} = viscoplastic strain; SSR = stress sweep rutting; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.

Location-Specific RSI

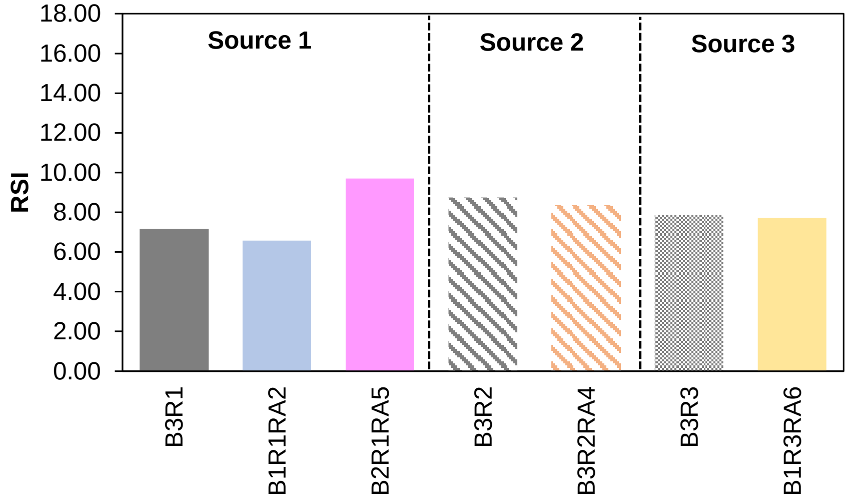

Figure L2. RSI Results for Source 1, 2, and 3 Mixtures Calculated Using the Specific Climatic Data (Source 1 = Blacksburg, Virginia; Source 2 = Mecklenburg, Virginia; and Source 3= Chesapeake, Virginia). RSI = rutting strain index; B = virgin binder; R = reclaimed asphalt pavement (RAP); RA = recycling agent.