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

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Final Report VTRC 26-R09

VIRGINIA TRANSPORTATION RESEARCH COUNCIL
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Standard Title Page - Report on Federally Funded Project

1. Report No.: FHWA/VTRC 26-R09	2. Government Accession No.:	3. Recipient's Catalog No.:

4. Title and Subtitle:	5. Report Date:
Verification of Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures	August 2025
	6. Performing Organization Code:

7. Author(s):
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8. Performing Organization Report No.:
VTRC 26-R09

9. Performing Organization and Address:
Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903

10. Work Unit No. (TRAIS):

11. Contract or Grant No.:
124560

12. Sponsoring Agencies' Name and Address:

Virginia Department of Transportation	Federal Highway Administration
1401 E. Broad Street	400 North 8th Street, Room 750
Richmond, VA 23219	Richmond, VA 23219-4825

13. Type of Report and Period Covered:
Final

14. Sponsoring Agency Code:

15. Supplementary Notes:
This is an SPR-B report

16. Abstract:

The use of reclaimed asphalt pavement (RAP) in asphalt mixtures has been steadily increasing for years, nationally and internationally, given the economic and associated environmental benefits of using such material. However, using RAP in asphalt mixtures poses some challenges regarding durability and performance that are often associated with the highly aged binder in RAP. The balanced mix design (BMD) that the Virginia Department of Transportation (VDOT) adopted for 9.5- and 12.5-mm nominal maximum aggregate size dense-graded surface mixtures with A and D designations addresses some of these challenges. Nonetheless, the gradual statewide implementation of the BMD framework and the lack of BMD specifications for certain types of asphalt mixtures that may contain RAP encourage the evaluation of other solutions to potentially mitigate some of the aforementioned challenges in the meantime. Softer binders or additives such as recycling agents (RAs) have been gaining considerable attention in the asphalt industry as a potential solution, but no specifications exist for the performance evaluation of RAs and their acceptance in Virginia. The Virginia Transportation Research Council in collaboration with North Carolina State University conducted VDOT Research Project No. 117566, Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures for Virginia, resulting in two performance-based frameworks: one for the assessment of RA products for inclusion into VDOT's Approved Product List and the second for designing asphalt mixtures with high RAP content and RA in accordance with VDOT's BMD specifications.

The objective of this study was to verify the engineered frameworks proposed in VDOT Project No. 117566. Six virgin asphalt binders, 5 RAP sources, and 8 RA products were evaluated and combined to produce 12 asphalt binder blends and 11 asphalt mixtures in combination with the binder blends and mixtures evaluated in Project No. 117566. The binder blends were subjected to short- and long-term aging, and the corresponding rheological properties and performance grades were obtained. The asphalt mixtures were subjected to short- and long-term oven aging and further tested for durability (Cantabro), cracking resistance (indirect tensile cracking test), and rutting resistance (Asphalt Pavement Analyzer).

The asphalt binder results showed that the proposed framework in VDOT Project No. 117566 yielded an optimized RA dosage consistently less than the supplier-recommended dosage to restore the low-temperature performance grade of the recycled binder blend. The rejuvenation path index was confirmed to be independent of the RA dosage and could be used for acceptance of other RAs into VDOT's Approved Product List. Lower asphalt content showed lower cracking tolerance index and higher Cantabro mass loss values, with some mixtures failing the BMD thresholds. The Asphalt Pavement Analyzer rutting test could not discriminate between the mixtures' rutting susceptibility. The new binder blends and mixtures confirmed the negative relationship between cracking tolerance index and Glover-Rowe parameter, highlighting the importance of binder properties on the mixtures' cracking performance. A preliminary cracking tolerance index aging sensitivity of 45% was verified and proposed. Based on the findings, this study proposes two recommendations: (1) adopting the performance-based framework verified in this project, accompanied by a Virginia Test Method and an automated Excel-based program for the RA assessment, and (2) validating the framework with field trials and under production conditions in future research projects.

17. Key Words:	18. Distribution Statement:
Recycling agent, long-term oven aging, aging sensitivity, pavements, asphalt surface mixtures, balanced mix design.	No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report):	20. Security Classif. (of this page):	21. No. of Pages:	22. Price:
Unclassified	Unclassified	58	

FINAL REPORT

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

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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

August 2025
VTRC 26-R09

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ABSTRACT

The use of reclaimed asphalt pavement (RAP) in asphalt mixtures has been steadily increasing for years, nationally and internationally, given the economic and associated environmental benefits of using such material. However, using RAP in asphalt mixtures poses some challenges regarding durability and performance that are often associated with the highly aged binder in RAP. The balanced mix design (BMD) that the Virginia Department of Transportation (VDOT) adopted for 9.5- and 12.5-mm nominal maximum aggregate size dense-graded surface mixtures with A and D designations addresses some of these challenges. Nonetheless, the gradual statewide implementation of the BMD framework and the lack of BMD specifications for certain types of asphalt mixtures that may contain RAP encourage the evaluation of other solutions to potentially mitigate some of the aforementioned challenges in the meantime. Softer binders or additives such as recycling agents (RAs) have been gaining considerable attention in the asphalt industry as a potential solution, but no specifications exist for the performance evaluation of RAs and their acceptance in Virginia. The Virginia Transportation Research Council in collaboration with North Carolina State University conducted VDOT Research Project No. 117566, *Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures for Virginia*, resulting in two performance-based frameworks: one for the assessment of RA products for inclusion into VDOT's Approved Product List and the second for designing asphalt mixtures with high RAP content and RA in accordance with VDOT's BMD specifications.

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The asphalt binder results showed that the proposed framework in VDOT Project No. 117566 yielded an optimized RA dosage consistently less than the supplier-recommended dosage to restore the low-temperature performance grade of the recycled binder blend. The rejuvenation path index was confirmed to be independent of the RA dosage and could be used for acceptance of other RAs into VDOT's Approved Product List. Lower asphalt content showed lower cracking tolerance index and higher Cantabro mass loss values, with some mixtures failing the BMD thresholds. The Asphalt Pavement Analyzer rutting test could not discriminate between the mixtures' rutting susceptibility. The new binder blends and mixtures confirmed the negative relationship between cracking tolerance index and Glover-Rowe parameter, highlighting the importance of binder properties on the mixtures' cracking performance. A preliminary cracking tolerance index aging sensitivity of 45% was verified and proposed. Based on the findings, this study proposes two recommendations: (1) adopting the performance-based framework verified in this project, accompanied by a Virginia Test Method and an automated Excel-based program for the RA assessment, and (2) validating the framework with field trials and under production conditions in future research projects.

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INTRODUCTION

Overview

Most asphalt mixtures produced in Virginia contain reclaimed asphalt pavement (RAP) because of the associated economic and environmental benefits. There is growing interest within the industry to further increase the amounts of RAP used, which poses challenges regarding mixture durability and performance if the mixtures are not designed in an engineered manner. The balanced mix design (BMD) procedure, adopted by the Virginia Department of Transportation (VDOT) for 9.5- and 12.5-mm nominal maximum aggregate size (NMAS) dense-graded surface mixtures with A and D designations, can help mitigate performance-related challenges of mixtures incorporating RAP (Diefenderfer et al., 2021a, 2021b; VDOT, 2020).

One potential solution to address the challenges associated with these mixtures, especially the mixtures with higher RAP contents, is using additives such as recycling agents (RAs) and softer binders, provided that engineered or performance-based frameworks—whether at the component and/or mixture level—are employed. For the purpose of this report, high RAP mixtures refer to asphalt mixtures with RAP content greater than 30% by total weight of the mixture. However, VDOT currently lacks specific guidelines or specifications to evaluate the acceptability of RAs and their use in mixtures. To address this issue, the Virginia Transportation Research Council (VTRC) in collaboration with North Carolina State University conducted a research project to evaluate the short- and long-term effectiveness of RAs in improving the performance of asphalt mixtures, particularly those mixtures with relatively high RAP contents (Habbouche et al., 2023). This effort is referred to hereafter as VDOT Project No. 117566. Another objective of VDOT Project No. 117566 was to establish a performance-based framework for determining the 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 using locally available materials, which were then compared in terms of laboratory performance with commonly used virgin asphalt binders and asphalt mixtures with various RAP contents in Virginia.

Background

As part of VDOT Project No. 117566, component materials, including asphalt binders, RAP materials, and RAs, were collected to fulfill the study's objectives. Virgin asphalt binders with a performance grade (PG) of 64S-22, commonly used in Virginia, were sampled from two different sources (referred to hereafter as B1 and B2). In addition, a softer virgin asphalt binder with PG 58-28 was sampled from one source (hereafter, B3). RAP materials were collected from three representative sources in Virginia (hereafter, R1, R2, and R3). Six commonly used RAs, including rejuvenators and softeners, were procured (hereafter, RA1, RA2, RA3, RA4, RA5, and RA6). RA1 is a paraffinic oil (vacuum tower asphalt extender); 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 (NCAT, 2014). In this study, each RA supplier was asked to estimate an RA dosage that would restore the low-temperature PG of the recycled binder blend to -22°C, using blend ratios consistent with the blend ratios from the respective parent job mix formula of the mixture in which each RA was used.

Twenty-six binder blends containing various types and combinations of virgin binders, recovered RAP binders, and RAs were evaluated in the study. Table 1 summarizes the combinations in the evaluation. For instance, the nomenclature B1R1RA1 is a blend produced using virgin binder B1, RAP binder from Source 1 (R1), and RA1.

Table 1. Summary of Combinations Evaluated as Part of VDOT Project No. 117566

Binder Source	RAP Source	RA1	RA2	RA3	RA4	RA5	RA6	No RA
B1	R1	B1R1RA1	B1R1RA2	B1R1RA3	B1R1RA4	–	B1R1RA6	–
	R2	–	B1R2RA2	B1R2RA3	B1R2RA4	B1R2RA5	B1R2RA6	–
	R3	–	B1R3RA2	B1R3RA3	B1R3RA4	B1R3RA5	B1R3RA6	–
B2	R1	–	–	B2R1RA3	–	B2R1RA5	B2R1RA6	–
	R2	–	–	–	B2R2RA4	B2R2RA5	–	–
	R3	B2R3RA1	B2R3RA2	B2R3RA3	–	–	–	–

Binder Source	RAP Source	RA1	RA2	RA3	RA4	RA5	RA6	No RA
B3	R1	–	–	–	–	–	–	B3R1
	R2	–	–	–	B3R2RA4	–	–	B3R2[a]
	R3	–	–	–	–	–	–	B3R3

– = blends not evaluated in this study; B = binder; R = RAP binder; RA = recycling agent; RAP = reclaimed asphalt pavement.
[a]No binder data, only mixtures were tested. The highlighted cells refer to binder combinations that were further evaluated through mixture testing. The combinations in red text were used to establish the maximum 45% criterion for the cracking tolerance index aging sensitivity parameter.

The existing VDOT-approved job mix formulas were used to fabricate the mixtures using the collected materials, which included various binder-RAP-aggregate and binder-RAP-RA-aggregate combinations. Ten mix designs were evaluated to verify compliance with the requirements specified in the Virginia BMD special provisions, which included evaluations under short- and long-term oven aging (STOA and LTOA) conditions in terms of volumetric properties, durability, resistance to cracking, and resistance to rutting. The corresponding combinations of these mixtures are highlighted in blue in Table 1. It is worth noting that the LTOA protocol was the only exception adopted in this study that differed from the protocol outlined in the Virginia BMD special provisions. The following discussion presents more details of the LTOA protocol.

One unique recommendation of VDOT Project No. 117566 was a new LTOA protocol. This protocol specifies that the loose asphalt mixture be conditioned in the oven at 95°C for 1 day (24 hours) after completing STOA conditioning (4 hours at compaction temperature). After LTOA conditioning, the mixture is allowed to cool to room temperature and then reheated to the compaction temperature. The indirect tensile cracking test (IDT-CT) is then performed in accordance with Virginia Test Method-143 on a minimum of five LTOA-conditioned specimens, and the average cracking tolerance index (CT index) value is reported. The CT index aging sensitivity (CTAS), measuring the percentage change (typically a reduction) between the CT index at STOA [$(\text{CT index})_{\text{STOA}}$] and the CT index at 1-day LTOA [$(\text{CT index})_{\text{1day LTOA}}$], is calculated per Equation 1. For mixtures containing RA, a maximum CTAS of 45% was recommended. This threshold was established based on testing of three mixtures (i.e., B1R1A1, B1R1RA2, and B2R1RA5, which are identified with red text in Table 1).

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

Established Engineered Frameworks

Based on the findings of the study (Habbouche et al., 2023), two frameworks were recommended as part of Project No. 117566. The first framework addresses the inclusion of RA products in VDOT's APL (Figure 1). The second framework focuses on designing surface mixtures with RA products (Figure 2). The study recommended adopting these two frameworks to assess the acceptability of RA products, pending further verification with different component materials (Habbouche et al., 2023). The verification analysis corresponds to the scope of the present project.

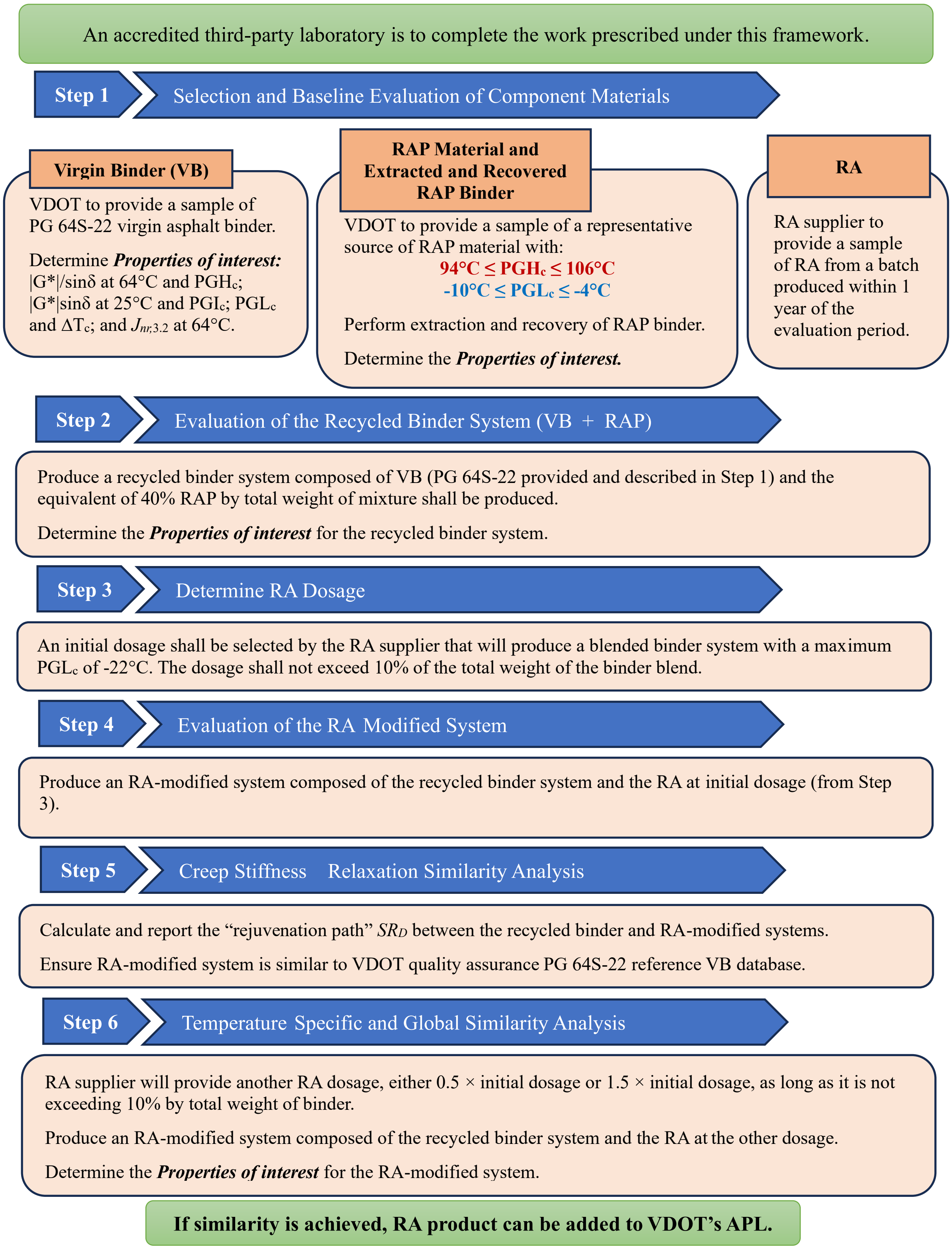

Figure 1. Engineered Framework for Inclusion of RA Products in VDOT's APL Proposed as Part of VDOT Project No. 117566. δ = phase angle; ΔT_c = difference in critical low-temperature; APL = Approved Product List; $|G^*|$ = dynamic shear modulus; $J_{nr,3.2}$ = nonrecoverable creep compliance; PG = performance grade; PGH_c = critical high temperature PG; PGI_c = critical intermediate temperature PG; PGL_c = critical low temperature PG; RA = recycling agent; RAP = reclaimed asphalt pavement; S = standard traffic; VB = virgin binder.

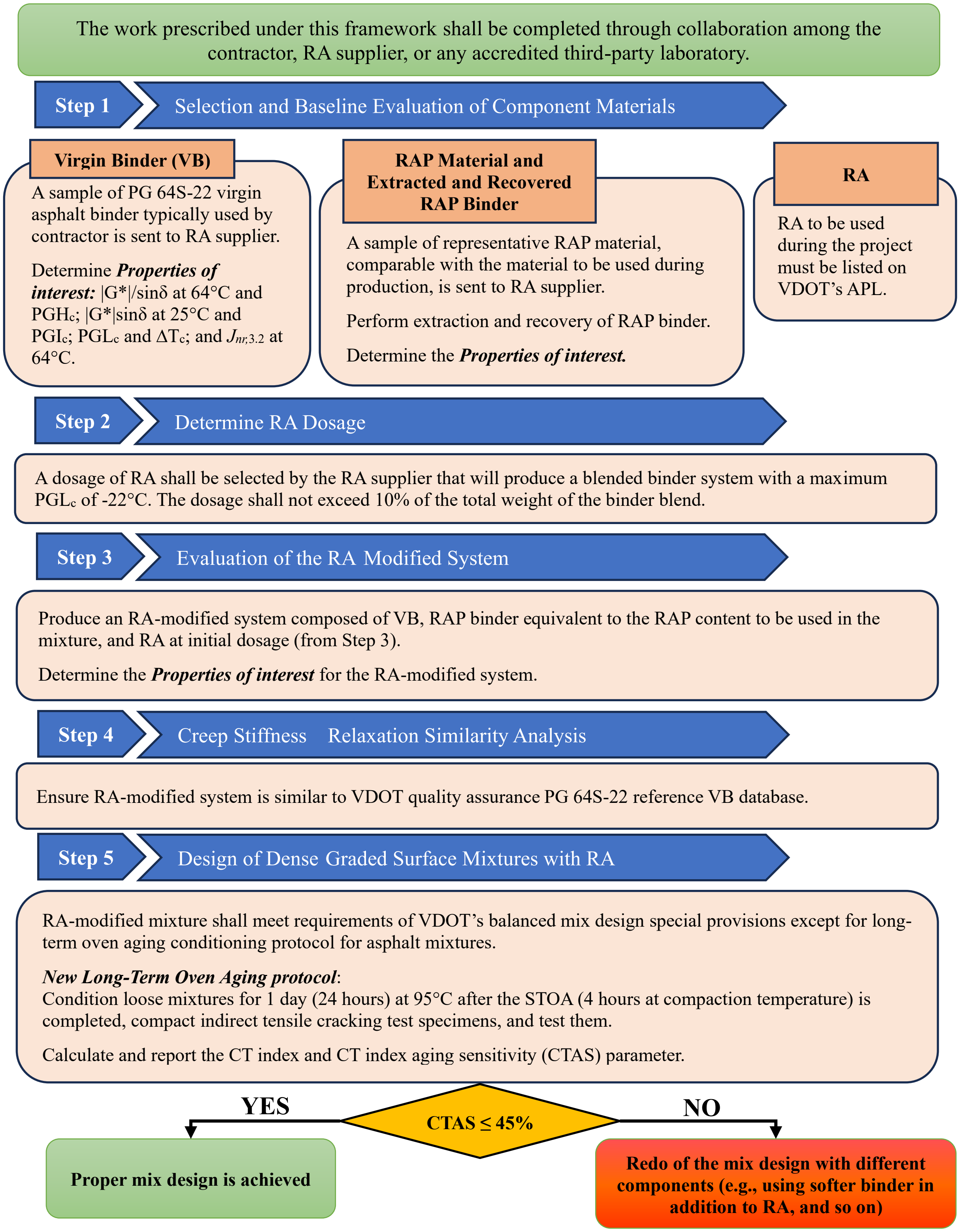

Figure 2. Engineered Framework for Designing Surface Mixtures with RA Products Proposed as Part of VDOT Project No. 117566. **δ = phase angle; ΔT_c = difference in critical low-temperature; APL = Approved Product List; CT = cracking tolerance; |G*| = dynamic shear modulus; $J_{nr,3.2}$ = nonrecoverable creep compliance; PG = performance grade; PGH_c = critical high temperature PG; PGI_c = critical intermediate temperature PG; PGL_c = critical low temperature PG; RA = recycling agent; RAP = reclaimed asphalt pavement; S = standard traffic; STOA = short-term oven aging; VB = virgin binder.**

PURPOSE AND SCOPE

The objective of this study was to build on the completed efforts in Virginia regarding the inclusion of RAs in surface mixtures and to verify the two recently developed performance-based engineered frameworks recommended as part of VDOT Project No. 117566 in a laboratory setting.

The scope of work consisted of:

- Evaluating aging sensitivity of additional mixtures after LTOA of 1 day at 95°C through IDT-CT.
- Selecting and testing additional RA-modified combinations. Additional combinations of virgin binder, RAP, and RAs, whose binder data are available from VDOT Project No. 117566, were considered for further asphalt mixture testing.
- Selecting and testing new component materials, including virgin binders, RAP, aggregates, and RAs, from high RAP and RA field trials for binder and mixture testing in the laboratory.
- Developing a Virginia Test Method outlining the proposed frameworks for RA acceptance and design of asphalt mixtures with high RAP and RA.

METHODS

Field Trials

The first high RAP mixture with RA, constructed in 2022, was a 9.5-mm NMAS mixture containing 40% RAP and incorporating RA6, a green bio-based asphalt rejuvenator similar to the asphalt rejuvenator used in VDOT Project No. 117566. RA6 was intended to soften and restore the rheological properties of the aged binder, improve the workability and compactability of the asphalt mixture, and deliver the required roadway performance and durability. The mixture was produced during 2 days and placed on Route 2401 (Riverside Parkway/Woodridge Parkway) in Ashburn, Virginia. The coordinates for the section's start and end points are (39.072611, -77.473389) and (39.076611, -77.476472), respectively. The virgin asphalt binder and RAP material collected from this trial were labeled B4 and R4, respectively. The RA-modified binder system and its corresponding mixture were referred to as B4R4RA6.

The second high RAP with RA mixture, constructed during the 2023 paving season, was also a 9.5-mm NMAS mixture with 40% RAP content that incorporated a polyester oil-based asphalt rejuvenator, referred to hereafter as RA7. This RA was intended to improve mixture cracking without adversely affecting rutting performance, reduce mix cost by incorporating higher RAP contents without performance issues, reduce viscosity and improve mix workability, and reduce stiffness of the aged binder. The mixture was produced during the course of 2 nights and placed on Route 659 (Gum Spring Road) in Bull Run, Virginia. The coordinates for the section's start and end points are (38.886639, -77.541500) and (38.845111, -77.545167), respectively. The virgin asphalt binder and RAP material collected from this trial were labeled

B5 and R5, respectively. The RA-modified binder system and its corresponding mixture were referred to as B5R5RA7.

The third high RAP with RA mixture, constructed during the 2023 paving season, was a 12.5-mm NMAS mixture with 40% RAP content that incorporated a high-purity petrochemical-based asphalt rejuvenator, referred to hereafter as RA8. Like other RAs, RA8 was used to reduce the risk of cracking, enhance the durability of asphalt pavements, and increase the amount of RAP in asphalt mixtures without affecting the final performance. The mixture was produced during 2 days and placed on Route 620 in Isle of Wight, Hampton Roads, Virginia. The coordinates for the section's start and end points are (36.96415, -76.68993) and (36.96132, -76.66515), respectively. The virgin asphalt binder and RAP material collected from this trial were labeled B6 and R6, respectively. The RA-modified binder system and its corresponding mixture were referred to as B6R6RA8.

Appendix A summarizes field trial information, including route numbers, start and end coordinates, districts, counties, and lanes of interest.

Testing and Characterization of Asphalt Binders and Asphalt Binder Blends

Extraction and Recovery of Asphalt Binders

Extraction of the asphalt binder from the different RAP sources 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 *n*-propyl bromide 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).

Recycling Agent Dosing and Blending

In this study, the RA suppliers determined the RA dosage necessary to restore the low-temperature PG of the recycled binder system to -22°C. This request was based on the fact that typical virgin binders used for surface mixtures with A and D designations in Virginia are PG 64S-22 binders. The suppliers were given information regarding the PG of virgin binders, PG of RAP binders, RAP content in the asphalt mixture (i.e., 35%, 40%, or 45%), binder content of RAP, and total binder content of the corresponding asphalt mixture. However, the specific method the RA suppliers used to determine the required 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 because they are stiffer than the virgin binder and require higher temperatures to achieve sufficient fluidity for blending. The component materials were blended using a power drill equipped with a paddle attachment for 1 minute. RA was then incorporated using a pre-weighed 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 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 using a pressurized aging vessel for 20 hours is referred to as PAV-20 hereafter.

Performance Grading and Multiple Stress Creep Recovery Testing

Asphalt binder performance grading was performed in accordance with AASHTO M 320, *Standard Specification for Performance-Graded Asphalt Binder* (AASHTO, 2017), and AASHTO M 332, *Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test* (AASHTO, 2019).

Difference in Critical Low-Temperature Performance Grade 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 2 (FHWA, 2021) and specified in AASHTO R 118, *Standard Practice for Characterizing the Relaxation Behavior of Asphalt Binders Using the Delta T_c (ΔT_c) Parameter* (AASHTO, 2023). Both temperatures were determined using the bending beam rheometer data 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 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 equal to the specification value of 300 MPa.

$$\Delta T_c = T_{c,S} - T_{c,m} \qquad \text{Equation 2}$$

Temperature-Frequency Sweep Test

Temperature-frequency sweep tests were conducted on the asphalt binder blends with test temperatures ranging from 45ºC to 5ºC (at 10ºC intervals) and test frequencies ranging from 0.1 to 15 Hz per temperature. No standard currently exists for the construction of a binder master curve. This study adopted a similar analysis method used in the previous VDOT Project No. 117566. The analysis consisted of a free-shifting approach to a reference temperature of 25ºC without a predefined function form to determine the time-temperature shift factors. The shift factors were then fitted to a second-order polynomial function. Subsequently, the Christensen-Anderson model was used to fit the |G*| and δ master curves. Additional details on the construction of the master curves can be found elsewhere (Fried and Castorena, 2023).

R-value

The *R*-value is a rheological index that can be related to binder fatigue properties and performance. The R-value was calculated by subtracting the logarithmic value of the dynamic shear modulus (|G*|) from the logarithmic value of the glassy modulus at the crossover frequency. The |G*| at crossover frequency was obtained using the Christensen-Anderson model fit to the |G*| master curve.

Glover-Rowe Parameter

The Glover-Rowe parameter (GRP) was originally defined by Glover et al. (2005) and was reformulated for greater practical use by Rowe et al. (2011) (Anderson et al., 2011). GRP is determined at 15°C and a frequency of 0.005 rad/s and is expressed using Equation 3. GRP captures both rheological parameters needed to characterize binder viscoelastic behavior: stiffness (represented by |G*|) and relaxation (represented by the phase angle, δ). GRP refers to nonload cracking at intermediate temperature, and its limits relate to specific environmental conditions. The universal limits of GRP, 180 kPa and 600 kPa, are generally used as a reference to track the effect of aging and relative performance evaluation of binders. The |G*| and δ values for GRP calculation were determined at 15°C and 0.005 rad/s from the temperature-frequency sweep test data and were obtained using the time-temperature shift factors.

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

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 164, *Standard Method of Test for Quantitative Extraction of Asphalt Binder From Hot Mix Asphalt (HMA), Method A* (AASHTO, 2018). 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, 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 OBC specified in the job mix formula at an N_{design} of 50 gyrations (VDOT, 2020). Three specimens were compacted at each OBC - 0.5%, OBC, and OBC + 0.5% to obtain a relationship between air-void and binder content. A mix design was verified if the air-void content at OBC fell within the 3.0-to-4.5% range (Habbouche et al., 2023). For cases in which OBC did not yield the air-void content within the acceptable range, OBC was adjusted to achieve an air-void content within the 3.0-to-4.5% range.

Asphalt Mixture Aging Protocols

The asphalt mixtures were aged under STOA and LTOA protocols. The STOA protocol consisted of placing the loose asphalt mixtures in the oven at the compaction temperature. A 2-hour duration was used for the mix design and to fabricate specimens for rutting performance characterization, while a 4-hour duration was used for cracking characterization. The LTOA protocol specified aging the loose mixtures for 1 day at 95°C after STOA was performed, representing approximately 4 years of field aging in Virginia at a pavement depth of 20 mm (Kim et al., 2021).

Cantabro Mass Loss

The Cantabro mass loss was determined at room temperature (i.e., approximately 25°C) to evaluate the durability of asphalt mixtures in accordance with AASHTO T 401, *Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens* (AASHTO, 2022). Volumetric pills, 150 mm in diameter by 115 ± 5 mm in height, compacted to N_{design} gyrations, were used in this test. A lower mass loss indicates increased durability.

Indirect Tensile Cracking Test

IDT-CT was conducted at 25°C in accordance with American Society for Testing Materials (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 International, 2019). All test specimens were 150 mm in diameter by 62 mm in height and were tested at 7.0 ± 0.5% air voids. The CT index was calculated from the test load-displacement curve collected during testing. A higher CT index value indicates greater resistance to cracking.

Asphalt Pavement Analyzer Rut Test

The Asphalt Pavement Analyzer (APA) rut test was performed in accordance with AASHTO T 340, *Standard Method of Test for Determining the Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)* (AASHTO, 2019). All test specimens were 150 mm in diameter by 75 mm in height and were tested at 7.0 ± 0.5% air voids.

After 8,000 cycles were applied at 64°C, the deformation of the specimen, rut depth, was measured. A lower APA rut depth indicates greater resistance to rutting.

RESULTS AND DISCUSSION

Laboratory Evaluation of Component Materials

Virgin Asphalt Binders and Reclaimed Asphalt Pavement Binders

Table 2 summarizes the PG results for both the virgin and RAP binders. All the virgin binders met their intended grades. The RAP binder demonstrates a wide span in grades from PG 82-10 (R4) to PG 106+02 (R3). The ΔT_c values of the virgin binders exceed the ΔT_c values of the RAP binders, indicating better relaxation characteristics.

Table 2. Summary of Performance Grading for Virgin and RAP Binders

Binder	PGH_c (°C)	PGI_c (°C)	PGL_c (°C)	ΔT_c (°C)	AASHTO M 320 PG
B1	68.1	21.6	– 22.4	– 3.0	PG 64-22
B2	67	22.1	– 24.6	– 1.2	PG 64-22
B3	60.6	15.1	– 30.3	1.0	PG 58-28
B4	66.7	20.4	– 24.9	– 2.7	PG 64-22
B5	65.8	19.9	– 25.1	– 4.8	PG 64-22
B6	66.3	21.1	– 23.7	– 4.8	PG 64-22
R1	95.5	36.2	– 7.9	– 8.6	PG 94-04
R2	107.1	46.0	– 3.8	– 4.7	PG 106+02
R4	86.6	32.0	– 11.4	– 11.2	PG 82-10
R5	99.5	34.3	– 3.3	– 17.3	PG 94+02
R6	94.2	35.3	– 9.7	– 10.3	PG 94-04

ΔT_c = critical temperature difference; B = virgin binder; PG = performance grade; PGH_c = continuous high-temperature PG; PGI_c = continuous intermediate-temperature PG; PGL_c = continuous low-temperature PG; R = reclaimed asphalt pavement (RAP) binder.

Laboratory Evaluation of Asphalt Binder Blends

Binder Blends within Engineered Framework

The engineered frameworks proposed in a previous study (Habbouche et al. 2023) were used to evaluate the potential acceptance of RAs used in this study with respect to VDOT's quality assurance (QA) reference database for PG 64S-22 binders. The RA dosage that the supplier recommended was compared with the optimized dosage obtained from the similarity analysis method (Habbouche et al., 2023; Preciado et al., 2023). The optimized dosage is the one that yields the minimum distance (i.e., minimum Mahalanobis distance) or greatest similarity between a given RA-modified system (virgin binder, RAP binder, and RA) and the centroid of VDOT's QA reference database for PG 64S-22 binders. The similarity analysis can be conducted using respective asphalt binder parameters related to high, intermediate, and low temperature properties, or collectively by evaluating all three temperature properties simultaneously. Figure 3 compares the recommended and the optimized RA dosages for RA6, RA7, and RA8. Recall that the supplier-recommended dosages were determined to restore the low-temperature rheological properties of the recycled binder system (virgin binder and RAP binder).

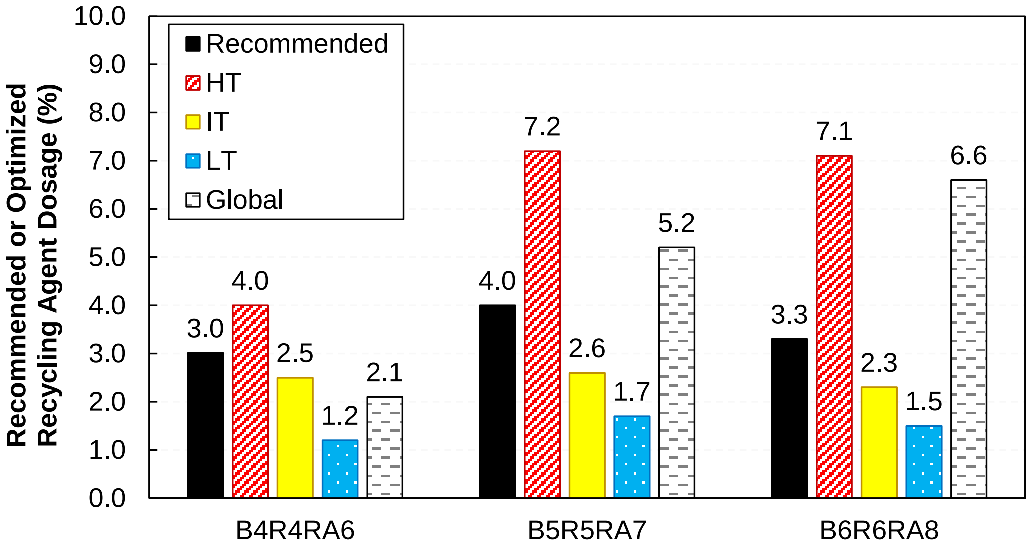

Figure 3. Comparison between the Recommended Recycling Agent (RA) Dosage from the Supplier versus the Optimized Dosage Obtained from the Engineered Framework RA Acceptance Using High Temperature (HT), Intermediate Temperature (IT), Low Temperature (LT), and Global Similarity Analysis. B = virgin binder; R = reclaimed asphalt pavement (RAP) binder.

Figure 3 shows that the optimized RA content differs depending on the desired binder rheological property to be restored using RA (i.e., high temperature, intermediate temperature, low temperature, or global). Given that the RA supplier recommended an RA dosage that would restore the low-temperature rheological properties, a direct comparison can be made between the recommended dosage from the supplier (solid-black bar) and the low-temperature-optimized dosage (dotted blue bar). Figure 3 shows that the supplier-recommended dosage is consistently higher than the optimized one, suggesting that a lower RA dosage would have been sufficient to restore the low-temperature rheological properties of the recycled binder blend (virgin and RAP binder).

Figures 4 and 5 present the respective low- and high-temperature rheological properties of the RA-modified system for Sources 4, 5, and 6 compared with VDOT's QA reference database for PG 64S-22 binders. Figure 4 shows that the recycled binder system for Sources 4, 5, and 6 (i.e., VB + RAP) met the Superpave requirement for creep stiffness (i.e., *S* less than or equal to 300 MPa) but did not meet the requirement for the *m*-value (i.e., *m*-value greater than or equal to 0.300), both at 12°C and 60 seconds of creep loading. When the RA was added, the RA-modified system (VB + RAP + RA) met the *S* and *m*-value Superpave specification limits, suggesting that adding RA effectively restored the low-temperature rheological properties of the binder blend. Moreover, the three RAs could have been approved for inclusion in VDOT's APL given that their corresponding RA-modified systems intercept VDOT's QA reference dataset for virgin binders PG 64S-22.

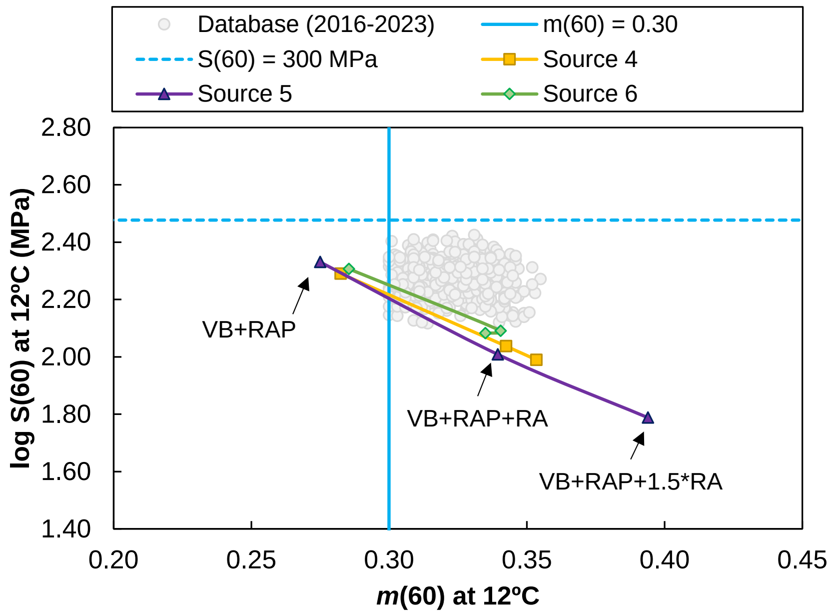

Figure 4. Comparison of Low-Temperature Rheological Properties of RA-Modified System between Sources 4, 5, and 6 and VDOT's Quality Assurance Reference Database for PG 64S-22 Binders. PG = performance grade; RA = recycling agent; RAP = reclaimed asphalt pavement; S = standard traffic; VB = virgin binder.

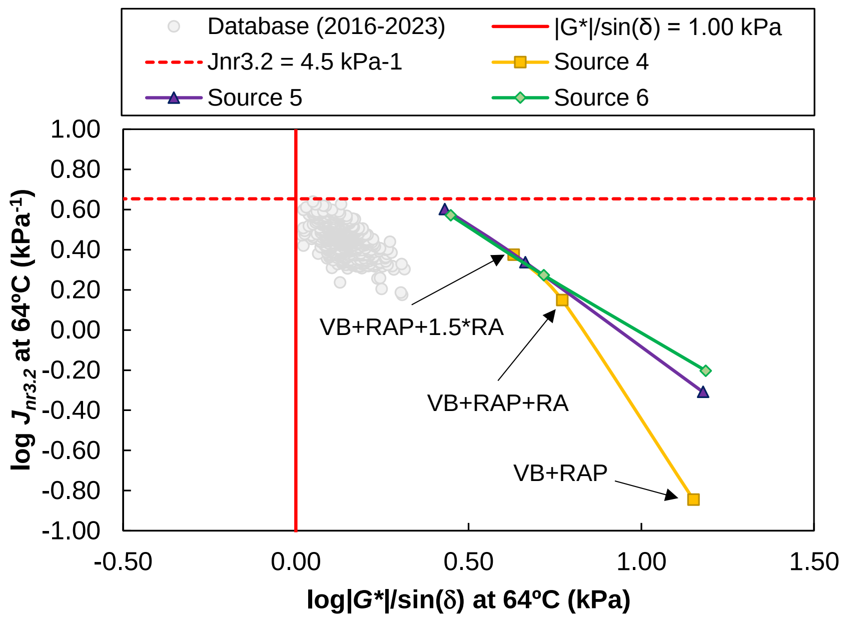

Figure 5. Comparison of High-Temperature Rheological Properties of RA-Modified System between Sources 4, 5, and 6 and VDOT's Quality Assurance Reference Database for PG 64S-22 Binders. PG = performance grade; RA = recycling agent; RAP = reclaimed asphalt pavement; S = standard traffic; VB = virgin binder.

Figure 4 also shows that when RA is used, the resulting RA-modified system moves closer to the center of VDOT's QA dataset. If the lower and optimized RA dosage was used (as shown in Figure 3) in lieu of the recommended dosage by the supplier, the resulting blend would have been even closer to the VDOT's QA dataset centroid, demonstrating the effectiveness of using the Mahalanobis distance approach to optimize the RA dosage for a given binder blend.

Additional testing was conducted using 1.5 times the dosage recommended by the supplier to produce new RA-modified systems (VB + RAP + 1.5RA) for the B4R4RA6 (Source 4), B5R5RA7 (Source 5), and B6R6RA8 (Source 6) binder blends. The purpose of these tests was to verify whether the rejuvenation path index (SR_D), proposed in a previous study (Habbouche et al., 2023), is independent of the RA dosage. Although previous studies have evaluated the effect of RA dosage on SR_D (Preciado et al., 2024), this study includes additional component materials (virgin binder, RAP, and RA) used for further verification. Figures 4 and 5 show the results for the new blends at 1.5 times the recommended RA dosage for the low- and high-temperature rheological spaces, respectively. Table 3 presents the SR_D values for the evaluated blends. One can see that SR_D is, in fact, independent of the RA dosage for both low- and high-temperature rheological properties, given that (1) a visual inspection of Figures 4 and 5 suggests that the slope between the recycled binder system (VB + RAP) and the two RA-modified systems (VB + RAP + RA or VB + RAP + 1.5RA) is constant, and (2) Table 3 shows that similar values of SR_D were obtained at the recommended dosage and the 1.5 times recommended dosage for any given RA product. At the higher dosage, researchers observed a different trend for Source 6 (or B6R6RA8), as shown in Figure 3. The 1.5 times RA dosage reduced the *m*-value, suggesting that RA8 is less effective in restoring the low-temperature rheological properties (*S* and *m*-value) at such a higher dosage and, thus, is more susceptible to being affected by variations among sample replicates during asphalt binder testing. In terms of high-temperature properties (Figure 5), the RA8 at the 1.5 times dosage was more effective because a more pronounced variation in both log ($|G^*|/\sin(\delta)$) and log ($J_{nr,3.2}$) was observed. This observation agrees with the expected performance of such RA showing a greater effect on the high-temperature properties than the low-temperature ones (Wang et al., 2024). In this sense, the findings suggest that the SR_D index is RA dosage independent, validating its use as an index for assessing and potentially accepting the RA into VDOT's APL. Moreover, given that Step 6 in the RA acceptance framework (Figure 1) was developed to verify the linearity between the logarithm of *S* and *m*-value, this step could now be removed.

Table 3. Summary of Rejuvenation Path Index (SR_D) for Different Blends and at Different RA Dosages

Virgin Binder	RAP Binder	Recycling Agent	Recycling Agent Dosage	Rejuvenation Path Index (SR_D)
B4	R4	RA4	ID	4.2
B4	R4	RA4	1.5 × ID	4.2
B5	R5	RA5	ID	5.0
B5	R5	RA5	1.5 × ID	4.6
B6	R6	RA6	ID	3.9
B6	R6	RA6	1.5 × ID	4.5

B = virgin binder; ID = initial dosage; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Asphalt Binder Analysis

Table 4 shows the PG results of the binder blends. All reference and RA blends had a PGH of either 64°C or 70°C, except for the blends produced with a higher RA dosage that had PGH of 58°C, indicating these blends failed to meet the minimum PGH of 64°C required for Virginia's climate. Three of the four reference blends did not meet the maximum PGL of -22°C required for Virginia's climate. All RA blends had a PGL of either -22°C or -28°C, except B1R1RA1 and B1R1RA2. The ΔT_c values of the reference blends and the B1R1RA1 and B1R1RA2 blends fall below -5°C, which is a common limit imposed (Asphalt

Institute, 2019), signifying potentially poor relaxation characteristics and associated thermal cracking resistance.

Table 4. Summary of Performance Grading for the Binder Blends

Blend	PGH_c (°C)	PGI_c (°C)	PGL_c (°C)	ΔT_c (°C)	AASHTO M 320 PG
B3R1	72.9	23.2	– 23.1	– 5.1	PG 70-22
B4R4	73.8	26.4	– 20.0	– 6.0	PG 70-16
B5R5	76.4	26.6	– 19.5	– 5.7	PG 76-16
B6R6	76.6	25.8	– 19.9	– 5.5	PG 76-16
B1R1RA1	73.6	19.2	– 19.5	– 14.5	PG 70-16
B1R1RA2	75.3	25.3	– 18.6	– 5.6	PG 70-16
B1R1RA4	71.5	20.4	– 27.5	– 1.8	PG 70-22
B2R1RA5	66.7	16.9	– 30.3	– 2.1	PG 64-28
B1R2RA3	71.8	23.4	– 23.7	– 3.9	PG 70-22
B2R2RA4	74.5	22.9	– 23.6	– 2.8	PG 70-22
B3R2RA4	72.8	23.1	– 24.1	– 3.0	PG 70-22
B2R2RA5	67.7	16.3	– 30.1	1.4	PG 64-28
B4R4RA6	69.3	19.7	– 26.6	– 4.3	PG 64-22
B5R5RA7	66.5	18.1	– 26.3	– 3.7	PG 64-22
B6R6RA8	66.8	18.9	– 26.3	– 2.1	PG 64-22
B4R4RA6-High	63.6	16.8	– 29.0	– 4.5	PG 58-28
B5R5RA7-High	60.7	12.1	– 32.4	– 1.4	PG 58-28
B6R6RA8-High	61.5	16.1	– 26.2	– 3.7	PG 58-22

ΔT_c = critical temperature difference; B = virgin binder; PG = performance grade; PGH_c = continuous high-temperature PG; PGI_c = continuous intermediate-temperature PG; PGL_c = continuous low-temperature PG; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent. The cells highlighted in red indicate that the low-temperature performance grade of -22°C was not restored. The cells highlighted in blue indicate that the low-temperature performance grade of -22°C was restored while also meeting a minimum high-temperature grade of 64°C. The cells highlighted in green indicate that the low-temperature performance grade was improved while also meeting a minimum high-temperature grade of 64°C. The cells highlighted in yellow indicate that the minimum high temperature grade of 64°C was not met.

Figure 6 shows the GRP results for the binder blends. Except for B1R1RA1 and B1R1RA2, the RA blends exhibit lower GRP values than their respective reference blend at a given age level. Notably, these RA blends, along with B4R4, B5R5, and B6R6, exceed the damage onset threshold proposed by Anderson et al. (2011) at the PAV-20 age level, indicating potential susceptibility to block cracking. RA5, RA6, RA7, and RA8 achieved more significant GRP reductions relative to the respective reference than other RAs, with higher dosages for RA6, RA7, and RA8 showing only marginal additional benefits. Notably, the reference blends for R4, R5, and R6 included a PG 64S-22 virgin binder. In contrast, the R1 and R2 reference blends included a PG 58-28 virgin binder, potentially contributing to the greater differences in the RA blends.

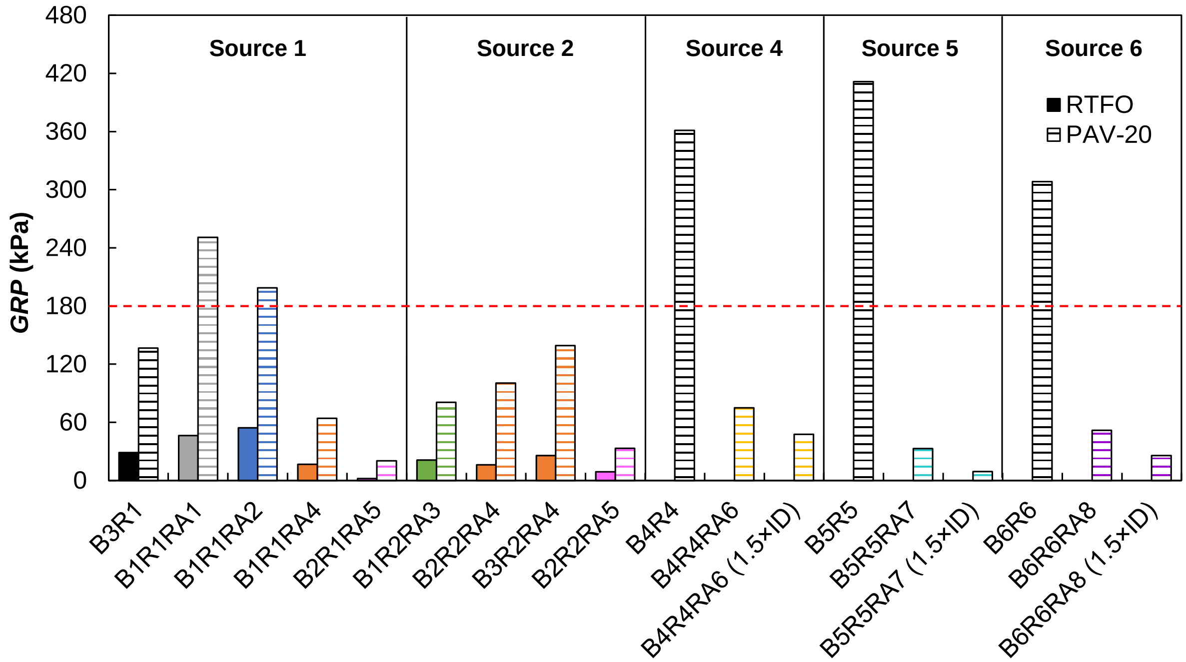

Figure 6. Glover-Rowe Parameter Results for the Binder Blends. Red dashed line represents the threshold above which the asphalt binder is more prone to nonload-related cracking. B = virgin binder; GRP = Glover-Rowe parameter; ID = initial dosage of RA; PAV-20 = pressurized aging vessel for 20 hours; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin-film oven.

Figure 7 shows the R-value results for the binder blends. Generally, higher R-values are associated with higher cracking susceptibility because of an imbalance in modulus and relaxation characteristics. As expected, R-value increases from the rolling thin-film oven to PAV-20 condition for a given blend, reflecting aging's negative effect on cracking resistance. Although the RA blends generally displayed lower PGs and GRP values than their reference blends, R-value trends are less consistent. B1R1RA1 shows the most distinct R-value, greatly exceeding that of B1R1. The other RA blends show similar or lower R-values to the respective reference blend. Notably, higher dosages of RA6, RA7, and RA8 led to a marginal increase in R-values, suggesting that the increased dosages may have slightly disrupted the balance between modulus and relaxation properties, potentially causing a negative effect on cracking resistance.

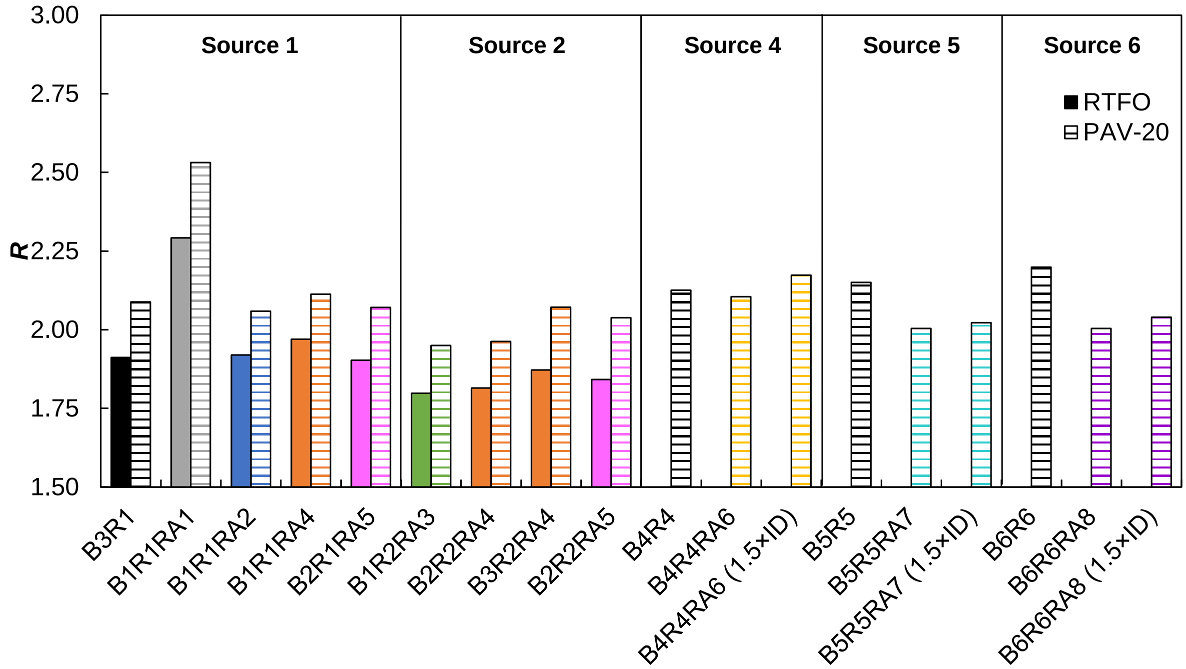

Figure 7. Rheological Index Results for the Binder Blends. B = virgin binder; ID = initial dosage of RA; PAV-20 = pressurized aging vessel for 20 hours; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; RTFO = rolling thin-film oven.

Laboratory Evaluation of Asphalt Mixtures

Mix Design Verification

Table 5 presents the mixture verification results. Mixtures were considered verified if their air-void content at the design compaction level (50 gyrations) fell between 3.0 and 4.5% as prescribed in the BMD special provision for surface mixtures with A and D designations. Table 6 shows the mixture verification results for the Source 1 and Source 2 mixtures.

Table 5. Mixture Verification Results of the Source 4, 5, and 6 Mixtures

Mixture Identification	B4R4RA6	B5R5RA7	B6R6RA8
Asphalt Binder Content, %	5.9	5.9	5.3
Rice SG (G_{mm})	2.692	2.651	2.486
Aggregate Effective SG (G_{se})	2.995	2.941	2.700
Aggregate Bulk SG (G_{sb})	2.973	2.912	2.697
VTM, %	3.8	3.9	3.7
VMA, %	18.1	17.7	15.9
VFA, %	79.0	78.0	76.7
FA Ratio	1.01	1.08	0.82

B = virgin asphalt binder; FA ratio = fines to asphalt ratio; R = RAP binder; RA = recycling agent; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregates; VFA = voids filled with asphalt.

Table 6. Mixture Verification Results of Source 1 and Source 2 Mixtures

Mixture Identification	B3R1	B1R1RA1	B1R1RA2	B1R1RA4	B2R1RA5	B3R2	B1R2RA3	B2R2RA4	B3R2RA4	B2R2RA5	B2R2RA5-LD
Asphalt Binder Content, %	6.4	6.4	6.4	6.4	6.4	5.7	5.7	5.7	5.7	5.7	5.7
Rice SG (G_{mm})	2.545	2.528	2.530	2.521	2.535	2.485	2.465	2.475	2.482	2.486	2.478
Aggregate Effective SG (G_{se})	2.830	2.807	2.81	2.798	2.816	2.717	2.696	2.709	2.713	2.722	2.712
Aggregate Bulk SG (G_{sb})	2.765	2.765	2.765	2.765	2.765	2.698	2.698	2.698	2.698	2.698	2.698
VTM, %	3.7	4.2	4.3	3.6	4.5	3.0	3.6	3.5	2.6	4.3	3.4
VMA, %	17.5	18.0	18.0	17.8	18.0	15.8	17.0	16.5	15.5	16.8	16.3
VFA, %	75.7	76.7	76.2	79.6	75.2	80.8	78.8	78.8	83.1	74.5	79.2
FA Ratio	1.12	1.07	1.08	1.05	1.09	0.51	0.49	0.50	0.51	0.52	0.51

B = virgin asphalt binder; FA ratio = fines to asphalt ratio; LD = lower dosage; R = RAP binder; RA = recycling agent; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregates; VFA = voids filled with asphalt.

Durability Assessment of Asphalt Mixtures (Cantabro Test Results)

Figure 8 shows the mass loss for Source 2, 4, 5, and 6 mixtures using different combinations of virgin binders (B1, B2, B4, B5, and B6) and RAs (RA3, RA4, RA5, RA6, RA7, and RA8). A one-way analysis of variance (ANOVA) was conducted at a 95% confidence level to assess the differences in mass loss between different mixtures. The ANOVA demonstrated statistical differences among mixtures, with a p-value of less than 0.0001. To identify the mixtures with significantly different mass loss, Tukey's Honest Significant Difference (HSD) test was performed at a 95% confidence level. The letters above the bars in Figure 8 convey the statistical groupings of mixtures within a given source with statistically equivalent means. Mixtures that share the same letter indicate that the difference between their mean values is not significantly different at a 95% confidence level. In contrast, mixtures with the same letters are considered significantly similar at a 95% confidence level. The mixture with the highest mean value has the "A" designation, and the mixture with the lowest mean value has the highest letter (in alphabetical order) among the tested conditions. The data in Figure 8 met the assumptions of normal distribution and equal variance.

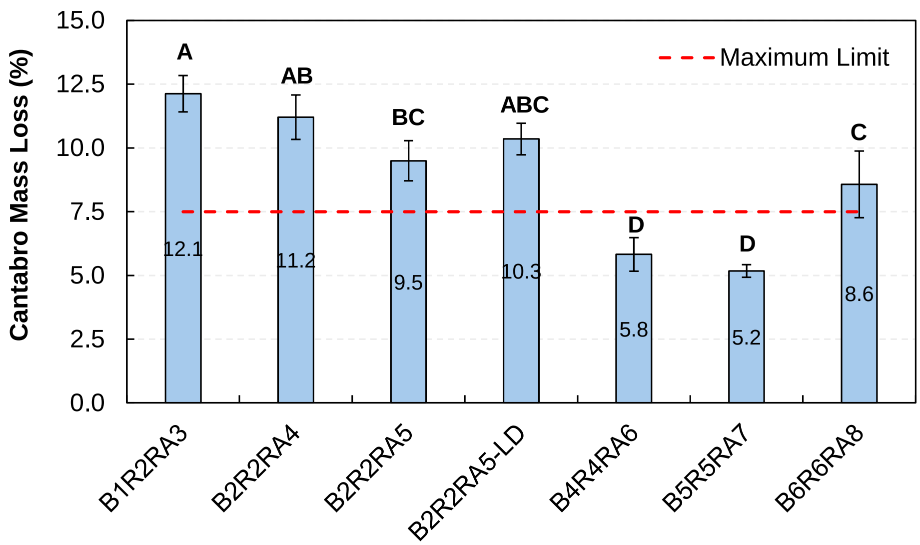

Figure 8. Mass Loss Data from Cantabro Test for Source 2, 4, 5, and 6 Mixtures. I-bars indicate mass loss variability and correspond to ±1 standard deviation. Uppercase letters represent Tukey's Honest Significant Difference statistical groupings. B = virgin binder; LD = lower dosage of recycling agent; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent. Red dashed line = balanced mix design special provision limit for asphalt surface mixtures with A and D designations.

For Sources 2 and 6, the mass loss exceeded the performance criterion of 7.5%, as prescribed in VDOT's BMD special provision, suggesting poor durability performance for the mixtures. This observation agrees with the previous VTRC study (Habbouche et al., 2023), in which mixtures with the same RAP (R2) but with different virgin binder and RA combinations (i.e., B3R2 and B3R2RA4) also exhibited mass loss values greater than the performance criterion. Sources 4 and 5 were the only sources for which mass loss values were below the performance criterion, with no statistically significant differences between each other, with a p-value of 0.1934 (i.e., greater than the significance level of 0.05). Overall, Sources 2 and 6 were statistically similar to each other. In addition, recall from Table 1 that R2 showed the greatest high-temperature grade; R2 had a PGH of 106°C, and the remaining RAP binders (i.e., R1, R4, R5, and R6) had high-temperature grades ranging from 82°C to 94°C. The higher temperature PG for R2 resulted in an asphalt mixture with lower abrasion resistance and, therefore, less durability. Sources 2 and 6 also required lowering the asphalt content during mix design verification to meet the BMD special provision design air-void content of 3 to 4.5%. Thus, the poor durability can be partially attributed to the RAP source and the lower asphalt content in these mixtures opposed to the asphalt binder incompatibility or the RAs' inefficiency in restoring the aged binder rheological properties.

Rutting Assessment of Asphalt Mixtures (APA Test Results)

Figure 9 shows the mean APA rut depth values for Source 2, 4, 5, and 6 mixtures. The rut depth values for all blends are below the rut depth performance criterion of 8.0 mm, as prescribed in the VDOT BMD special provision. This finding suggests that these mixtures are not rut-susceptible, including different component materials such as virgin binders, RAP stockpiles, and RAs. The letters above the bars convey the statistical groupings of mixtures within a given source with statistically equivalent means based on the pairwise Games-Howell test at a 95% confidence level. Although the data met the assumptions of normal distribution, the Games-Howell test was conducted because the equal variance assumption was not met. The analysis showed no significant differences in the mean rut depth values among different mixtures at a 95% confidence level.

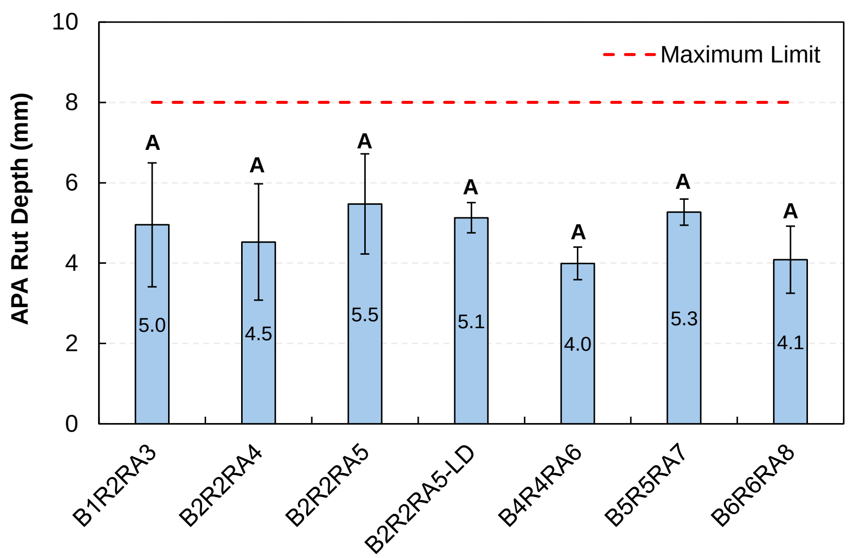

Figure 9. Rut Depth from APA Test for Source 2 Mixtures. I-bars indicate rut depth variability and correspond to ±1 standard deviation. Uppercase letters represent Games-Howell statistical groupings. APA = Asphalt Pavement Analyzer; B = virgin binder; LD = lower dosage of recycling agent; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent. Red dashed line = balanced mix design special provision limit for asphalt surface mixtures with A and D designations.

Cracking Assessment of Asphalt Mixtures (IDT-CT Test Results)

Indirect Tensile Cracking Test at Shot-Term Oven Aging

Figure 10 presents the CT index results at the STOA condition. A one-way ANOVA was conducted at a 95% confidence level to assess the differences in CT index for mixtures with the same RAP source. The ANOVA demonstrated statistical differences among mixtures with the same RAP source, with a p-value of less than 0.0001 for both Source 1 and Source 2. To identify the mixtures with significantly different CT index values, the Tukey's HSD test was performed at a 95% confidence level. The letters above the bars convey the statistical groupings of mixtures within a given source with statistically equivalent means based on the pairwise Tukey's HSD test at a 95% confidence level. The data evaluated met the assumptions of normal distribution and equal variance. The Source 1, 4, and 5 mixtures surpass VDOT's established minimum CT index requirement of 70, whereas Source 2 and Source 6 mixtures fail this requirement. Interestingly, the observations on CT index values match the Cantabro mass loss results (Figure 8). Source 2 and 6 mixtures also failed the BMD performance criteria, and Sources 1, 4, and 5 met the maximum allowed mass loss limit. The Source 2 and Source 6 mixtures notably have lower asphalt contents than the other mixtures, possibly contributing to their lower CT index values than the other mixtures, despite an overlapping span in binder blend GRP values. In addition, the binder content of Source 2 and Source 6 mixtures had to be lowered from the binder content reported on the job mix formula during mixture verification to yield air-void contents within the tolerance range selected for this project (3.0 to 4.5%).

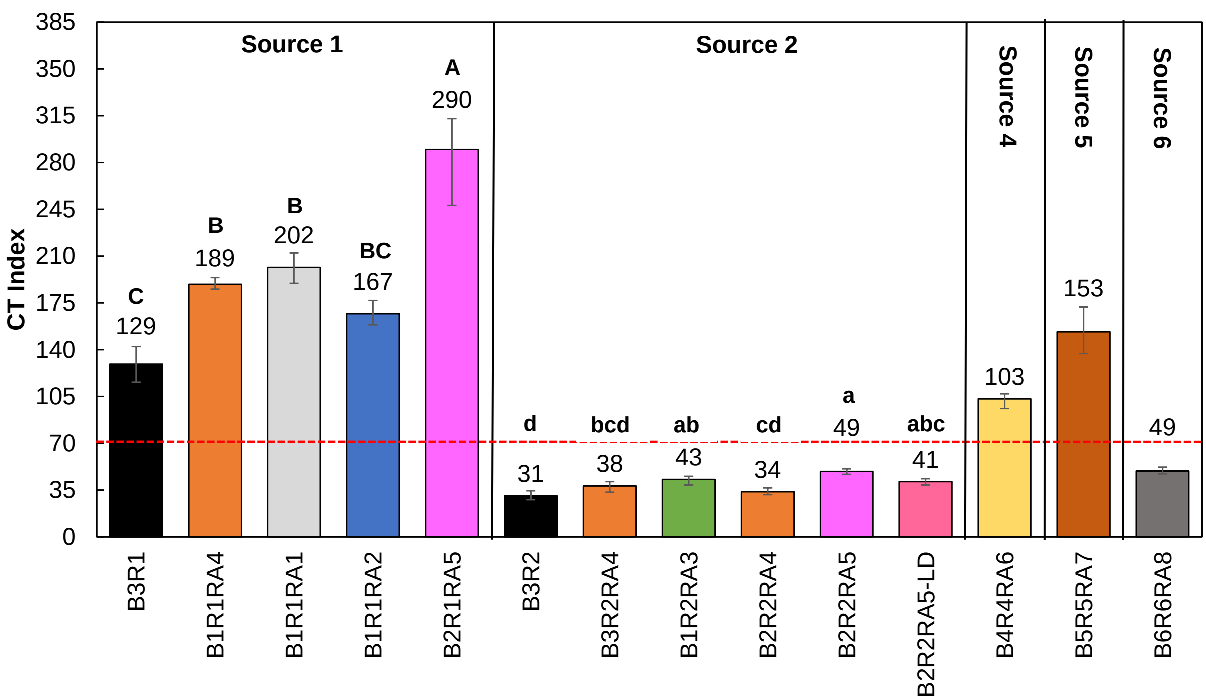

Figure 10. CT Index Results at the Short-Term Oven Aging Condition. I-bars correspond to ±1 standard deviation. Uppercase letters represent Tukey's Honest Significant Difference statistical groupings for Source 1, and lowercase letters represent the groupings for Source 2. B = virgin asphalt binder; CT = cracking tolerance; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

For both Sources 1 and 2, where comparative reference mixtures with PG 58-28 virgin binder and no RA are available, it is evident that the mixtures with RAs have similar or better CT index values compared with the respective reference mixtures (B3R1 and B3R2). Source 1 mixtures, with higher asphalt content (6.4%) and the PG 94-04 RAP binder, generally exhibit more substantial increases in CT index with the addition of RAs. Source 2 mixtures, with lower asphalt content (5.7%) and the PG 106+02 RAP binder, achieved a more moderate level of improvement, indicating that RAP binder properties and asphalt content play critical roles in the effectiveness of RAs.

Indirect Tensile Cracking Test at Long-Term Oven Aging

Figure 11 shows the CT index results at the LTOA condition. Similarly, a one-way ANOVA was conducted at a 95% confidence level to assess the differences in CT index for mixtures with the same RAP source. The ANOVA showed statistical differences among mixtures with the same RAP source, with p-values of less than 0.0001 for both Sources 1 and 2. To identify the mixtures with significantly different CT index values, the Tukey's HSD test was performed at a 95% confidence level. The letters above the bars convey the statistical groupings of mixtures within a given source with statistically equivalent means based on the pairwise Tukey's HSD test at a 95% confidence level. The data evaluated met the assumptions of normal distribution and equal variance. The LTOA CT index value for each mixture is less than that at the STOA condition, which is expected because of the stiffening and embrittlement effect of oven aging. Notably, the performance trends or rankings among the mixtures after LTOA conditioning remained similar to the rankings observed after the STOA conditioning. The Source 1, 4, and 5 mixtures show higher CT index values than the Source 2 and Source 6 mixtures, and B2R1RA5 shows the highest CT index.

At the LTOA condition, the RA-modified mixtures demonstrated statistically equal or significantly higher CT index values than the corresponding reference mixture for Sources 1 and 2, using Tukey's HSD tests with a 95% confidence level. Interestingly, the B1R1RA1 and B1R1RA2 mixtures retained a higher CT index than the B3R1 despite showing comparatively high GRP values at the PAV-20 condition. Differences in the long-term age state and/or interactive effects between the mixture constituents not captured in the binder blend experiments (e.g., aggregate absorption, partial mixing of virgin and recycled binders) may have contributed to this discrepancy. For both Sources 1 and 2, the number of statistically distinct groups is the same at the STOA and LTOA levels, indicating that the LTOA conditioning did not diminish the sensitivity of the CT index results to the binder variables.

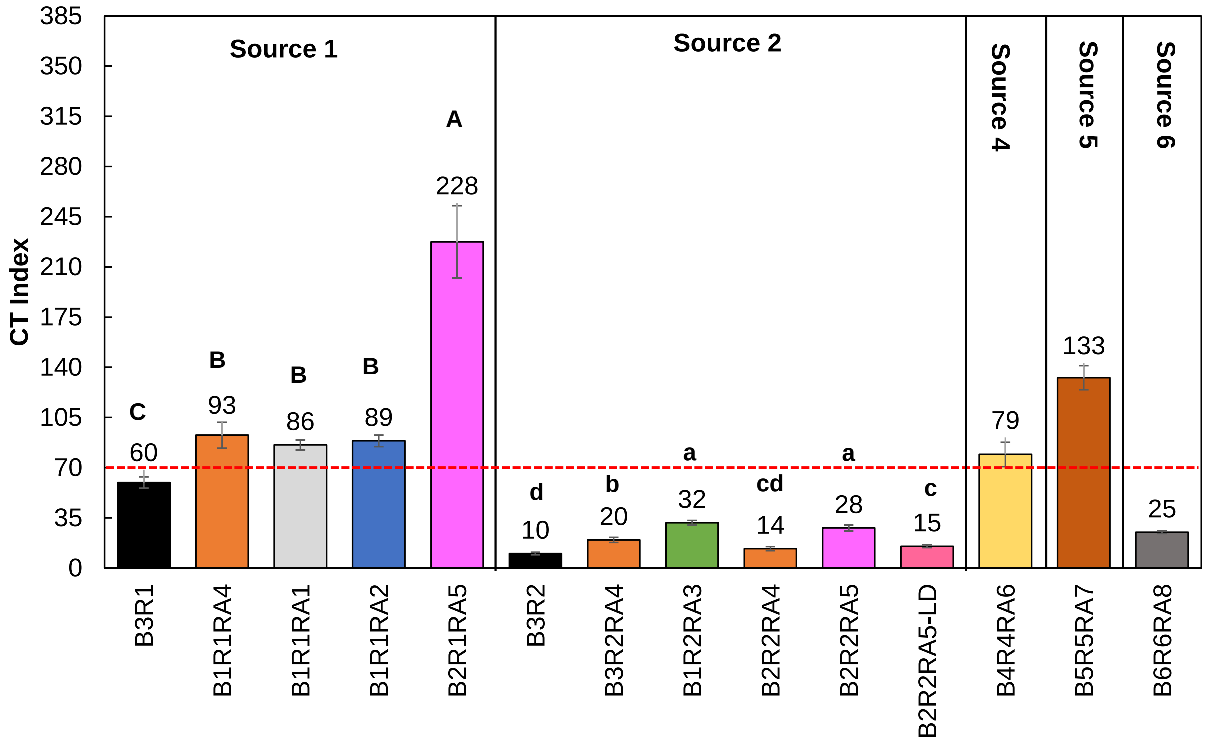

Figure 11. CT Index Results at the Long-Term Oven Aging Condition. I-bars correspond to ±1 standard deviation. Uppercase letters represent Tukey's Honest Significant Difference statistical groupings for Source 1, and lowercase letters represent the groupings for Source 2. B = virgin asphalt binder; CT = cracking tolerance; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

Aging Sensitivity Assessment of Asphalt Mixtures

Figure 12 shows the CTAS results for each mixture. The standard deviation of CTAS was obtained from the nine possible pairs of individual trimmed CT index results at the STOA and LTOA conditions. The trimmed results were used to keep consistency with VDOT Project No. 117566. A one-way ANOVA was conducted at a 95% confidence level to assess the differences in CTAS for mixtures with the same RAP source. The ANOVA demonstrated statistical differences among mixtures with the same RAP source, with a p-value of 0.0029 for Source 1 and less than 0.0001 for Source 2. To identify the mixtures with significantly different CT index values, the Tukey's HSD test was performed at a 95% confidence level. The letters above the bars convey the statistical groupings of mixtures within a given source with statistically equivalent means based on the pairwise Tukey's HSD test at a 95% confidence level. The data in Figure 12 met the assumptions of normal distribution and equal variance.

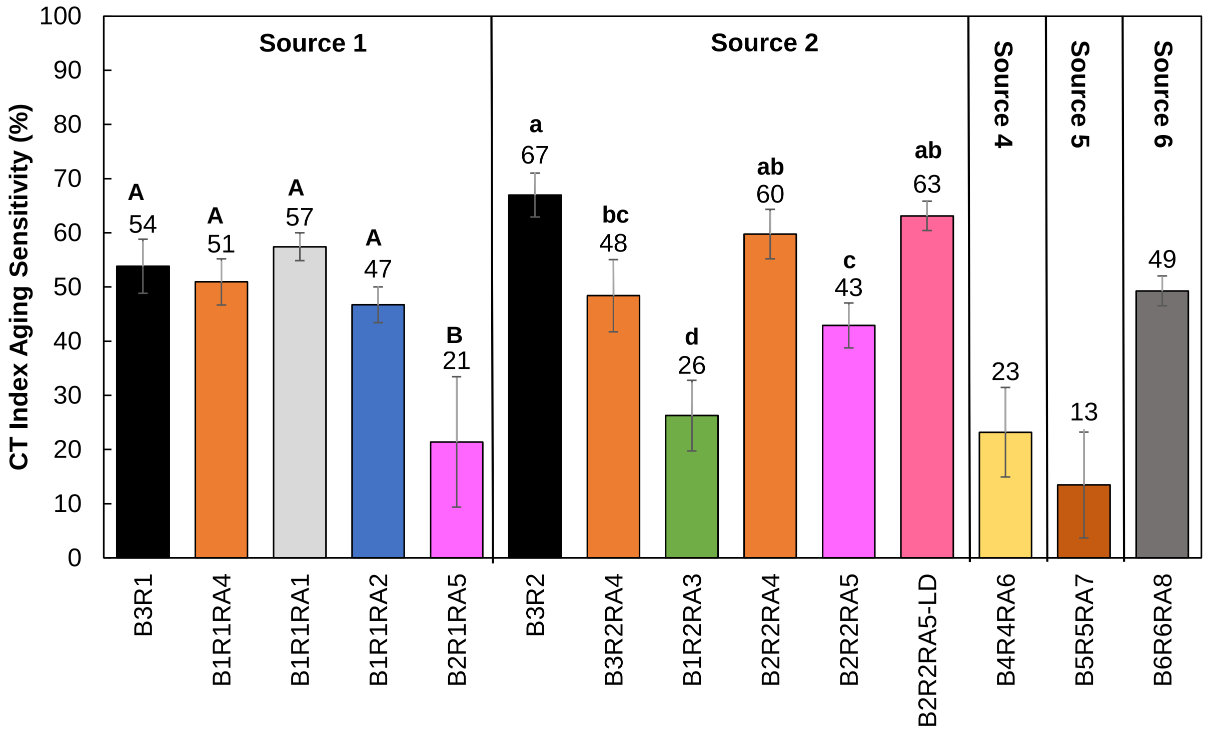

Figure 12. CT Index Aging Sensitivity. I-bars correspond to ±1 standard deviation. Uppercase letters represent Tukey's Honest Significant Difference statistically distinct groupings for Source 1, and lowercase letters represent the groupings for Source 2. B = virgin asphalt binder; CT = cracking tolerance; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent.

The distinction between the sources evident in the CT index results at a given age level is not as apparent in the aging sensitivity results. For example, the mean Source 1 and Source 2 aging sensitivity values do not differ greatly despite different CT index values at a given age level. All Source 1 and Source 2 RA-modified mixtures show a lower or statistically similar aging sensitivity compared with reference mixtures. Notably, the effect of the RA dosage is evident by the statistically significant differences in the B2R2RA5 and B2R2RA5-Lower Dosage cases, with the lower dosage yielding poorer aging sensitivity. The B2R1RA5, B1R2RA3, B4R4RA6, and R5R5RA7 mixtures stand out as having lower aging sensitivities compared with the other mixtures, falling below the preliminary threshold of 45% established in a previous study (Habbouche et al., 2023).

Spearman's rank correlation coefficients (r) were determined to further understand the relationships between CT index values at the STOA and LTOA levels and aging sensitivity across the collective mixtures at a 95% confidence level. An r value closer to 1 or -1 signifies a strong correlation, whereas a value closer to 0 indicates a weak correlation. The analysis revealed a strong positive monotonic and significant relationship between CT index values for STOA and LTOA (r = 0.9373). This finding indicates that the relative rankings of the study mixtures based on CT index values at the two age levels were similar. However, the correlation coefficients between CT index values at the two age levels and aging sensitivity reveal more marginal associations with r values of -0.4532 and -0.6703 for STOA and LTOA conditions, respectively. These coefficients indicate that the aging sensitivity parameter may provide unique insights when screening the relative performance of mixtures compared to the CT index values at a specific age level.

To help understand the inferences from the correlation coefficients, Figure 13 shows the relationship between the CT index at the STOA versus LTOA conditions. When aggregated, the collective results show an exponential relationship between CT index values after STOA and LTOA, explaining Spearman's high correlation coefficient. Mixtures with higher CT index values at STOA generally maintain or improve their performance after LTOA, indicating better overall durability. This overarching relationship is largely driven by the distinction between the different mixture sources. Source 1, 4, and 5 mixtures are predominantly distributed toward the higher end of the CT index spectrum for both STOA and LTOA, indicating better initial and aged cracking performance. Moreover, Source 2 and Source 6 mixtures cluster toward the lower end of the CT index spectrum.

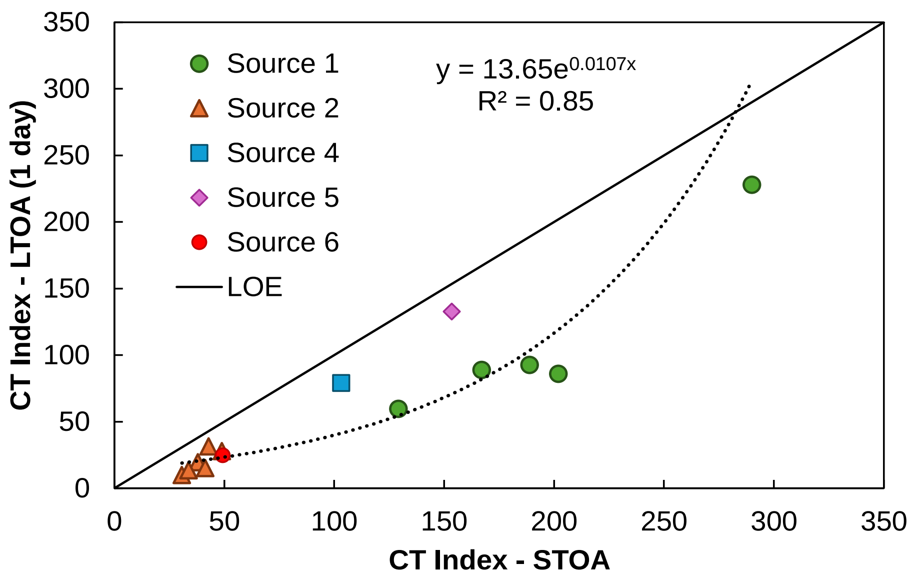

Figure 13. Comparison of the CT Index Values at the STOA and LTOA Conditions. CT = cracking tolerance; LTOA = long-term oven aging; LOE = line of equality; STOA = short-term oven aging.

Cross-Scale Binder and Mixture Evaluation and Analysis

The relationship between GRP and CT index was investigated to further assess the role of binder properties on the mixture cracking performance. To this end, GRP and CT index results were paired at the short-term (i.e., rolling thin-film oven and STOA) and long-term (i.e., PAV-20 and LTOA) conditions. Despite a few inconsistent trends in the GRP and CT index results noted previously, Figure 14 reveals that source-specific logarithmic relationships are evident. Source 1, 4, and 5 mixtures show a similar negative logarithmic correlation between GRP and the CT index, indicating that the CT index generally decreases as GRP increases, with a consistent relationship across STOA and LTOA conditions. Recall that these mixtures had comparatively high asphalt contents compared with the Source 2 and Source 6 mixtures. The dependence of the CT index on GRP is attenuated at higher GRP values, where it is evident that further increases in GRP do not coincide with a reduction in the CT index. Source 2 and Source 6 mixtures exhibit a weaker negative logarithmic correlation between GRP and the CT index, indicating more variability and a weaker association.

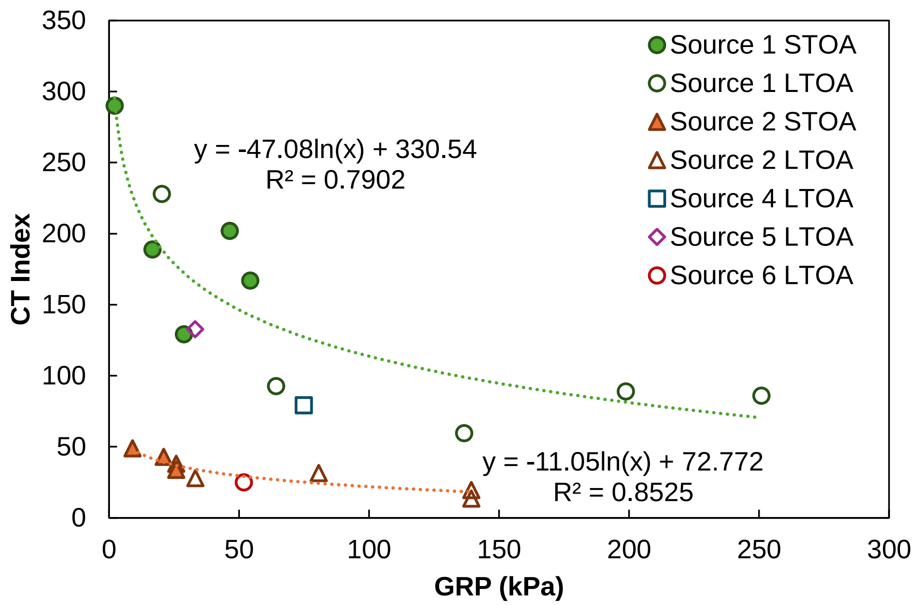

Figure 14. Relationship between CT Index and GRP. CT = cracking tolerance; GRP = Glover-Rowe parameter; LTOA = long-term oven aging; STOA = short-term oven aging.

The consistent negative correlation between GRP and the CT index supports the role of the binder blend properties in determining the mixture performance. However, the sensitivity of the mixture's CT index in relation to binder properties varies significantly between the sources and binder age levels.

The relationships between CTAS and GRP at the PAV-20 age level was also evaluated because a strong association between the two parameters was reported for the three mixtures evaluated in a previous study (Habbouche et al., 2023). Figure 15 shows the resultant source-independent relationship ($R^2 = 0.39$). Analyzing the best fit line to the relationship between CTAS and GRP shows that the commonly accepted GRP threshold of 180 kPa for the onset of cracking coincides with CTAS of approximately 50%, which closely aligns with the 45% threshold determined through similar means in a previous study (Habbouche et al., 2023). However, some mixtures (e.g., Sources 5 and 6 and certain Source 1 mixtures) exhibit aging sensitivities above this threshold while maintaining a CT index greater than 70 at the LTOA condition. These mixtures are expected to perform well based on the CT index, despite their higher aging sensitivities, highlighting the need for a mix acceptance criteria that account for both the CT index at the LTOA condition and aging sensitivity.

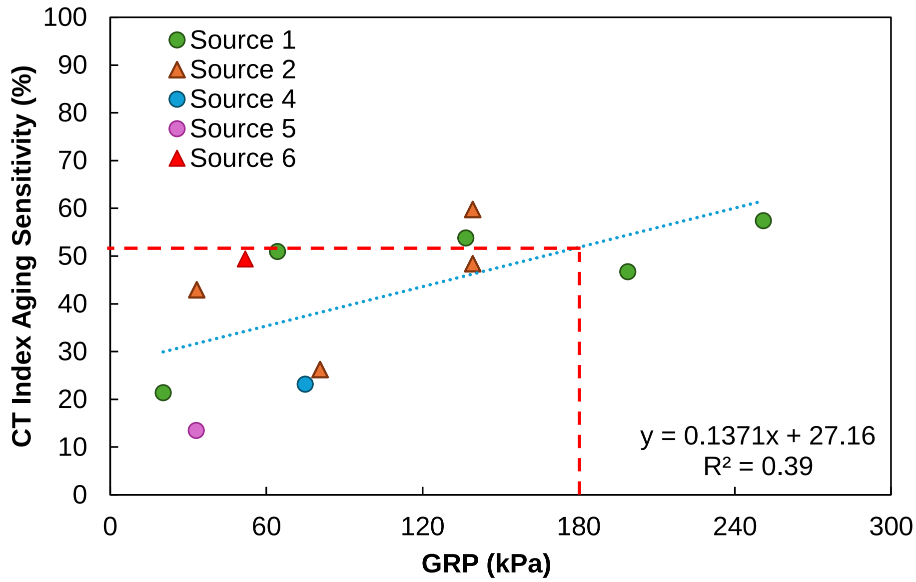

Figure 15. Relationship between CT Index Aging Sensitivity and GRP at the PAV-20 Age Level. CT = cracking tolerance; GRP = Glover-Rowe parameter. PAV-20 = pressurized aging vessel for 20 hours.

Building on the collective results and existing VDOT specifications, the proposed mixture design acceptance framework, depicted in Figure 16, was developed. The framework ensures that the RA effectively restores binder properties, achieves CT index requirements, and minimizes the risk of approving highly aging-susceptible mixtures with RA. Accordingly, the proposed mix design framework is composed of four steps, as follows:

- ***Step 1: RA effectiveness in restoring the low-temperature PG of the recycled binder blend***. The RA must be verified to ensure the RA-modified binder blend in the mixture meets or exceeds the climatic low-temperature PG of -22ºC. This step is initially accounted for during the evaluation process of a given RA product and its potential inclusion into VDOT's APL (framework 1). Only RAs added to VDOT's APL should be selected for mix design considerations because these RAs would have been considered acceptable in terms of their ability to restore the low-temperature rheological properties of the recycled binder blend. However, additional verification of the RA-modified system shall be conducted to ensure the effectiveness of the RA given the variability that the asphalt mixture component materials may experience between the evaluation of the RA (framework 1) and the mix design (framework 2). If the RA of interest is considered acceptable by restoring the low-temperature PG of -22ºC of the RA-modified system, then the cracking resistance of the mixture with such RA should be evaluated (Step 2).
- ***Step 2: IDT-CT at STOA.*** The IDT-CT test shall be conducted at STOA for the asphalt mixture with the selected RA. The CT index must achieve a minimum value of 70 as prescribed in the BMD special provision requirements for asphalt surface mixtures with A and D designations. If the CT index is less than 70 at STOA, the mix is rejected and should be redesigned. If the CT index is greater than or equal to 70 at STOA, the asphalt mixture cracking resistance should be evaluated at LTOA condition (Step 3).
- ***Step 3: IDT-CT at LTOA.*** The IDT-CT test shall be conducted at LTOA, which corresponds to 1 day (24 hours) at 95ºC. If the CT index is greater than or equal to 70

after LTOA, the mix design shall be accepted because the mixture is able to meet the BMD special provision requirements for STOA condition, even at a more severe aging level (LTOA). If the CT index is less than 70 after LTOA, then the aging susceptibility of the mix should be evaluated by calculating CTAS (Step 4).

- ***Step 4: CT index aging sensitivity***. CTAS shall be calculated as the percent difference between the CT index after STOA and the CT index after LTOA. CTAS represents the percentage reduction in the CT index after LTOA compared with the STOA condition. If CTAS is less than or equal to 45%, the mix design shall be accepted. If CTAS is greater than 45%, the mix shall be considered susceptible to aging and, thus, should be rejected and redesigned, either by selecting other component materials or using softer binder grades with the given RA.

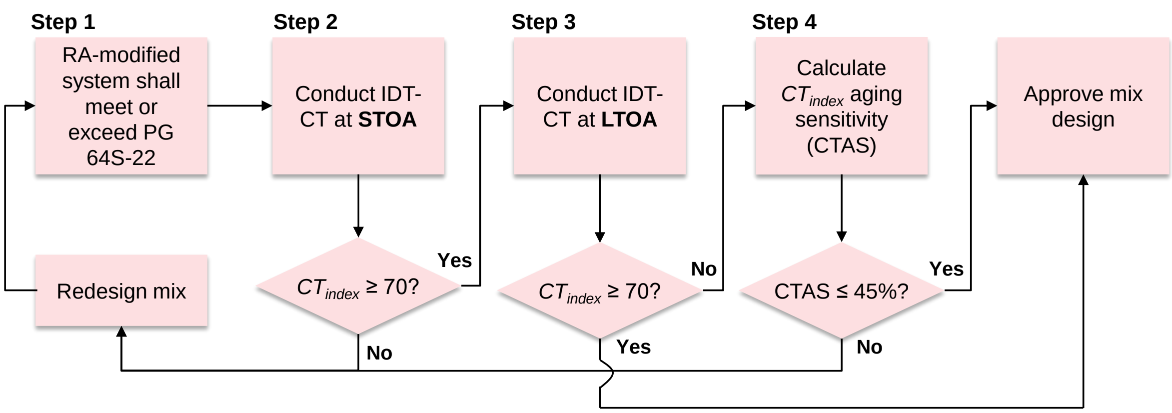

Figure 16. Proposed Mixture Design Acceptance Framework. CT = cracking tolerance; IDT-CT = indirect tensile cracking test; LTOA = long-term oven aging; PG = performance grade; RA = recycling agent; S = standard traffic; STOA = short-term oven aging.

Table 7 presents a risk assessment conducted for the study mixtures according to the proposed mixture design acceptance framework in Figure 16. The acceptance rates were calculated at each step considering the number of available mixtures in a given step or the total number of mixtures evaluated in this study. Two of the 12 binder systems evaluated failed to meet the low-temperature PG requirement of -22ºC, indicating 83% of the binder systems met the requirement. Five of the remaining 10 mixtures (50%) that met the low-temperature grade acceptance criterion exceeded a STOA CT index of 70. The relatively low acceptance rate based on the STOA CT index requirement may be partially attributed to the need for lower binder contents than those binder contents reported on the job mix formula for these mixtures to meet the air-void verification criteria adopted specifically for the research project. Four of the five mixtures (80%) that met both binder grade and STOA CT index requirements passed either the LTOA criteria of a minimum CT index of 70 or a maximum CTAS of 45%. Under the same conditions, the acceptance rate regarding the total number of mixtures is 33%. This relatively low acceptance rate highlights the effectiveness of the proposed framework in filtering out unsuitable asphalt mixtures, specifically those asphalt mixtures including improper binder PG, low cracking resistance, and/or high aging susceptibility.

Table 7. Risk Assessment of the Proposed Mix Design Framework

Source	Mix	RA-Modified System PG	STOA CT Index	LTOA CT Index	CTAS (%)
Source 1	B3R1	PG 70-22	129.2	59.7	53.8
	B1R1RA4	**PG 70-22**	**188.9**	**92.7**	50.9
	B1R1RA1	PG 70-16	202.0	86.0	57.4
	B1R1RA2	PG 70-16	167.0	89.0	46.7
	B2R1RA5	**PG 64-28**	**290.0**	**228.0**	21.4
Source 2	B3R2RA4	PG 70-22	38.0	19.6	48.4
	B1R2RA3	PG 70-22	42.9	31.6	26.3
	B2R2RA4	PG 70-22	33.7	13.6	59.8
	B2R2RA5	PG 64-28	48.9	27.9	42.9
Source 4	**B4R4RA6**	**PG 64-22**	**103.2**	**79.2**	23.2
Source 5	**B5R5RA7**	**PG 64-22**	**153.4**	**132.8**	13.5
Source 6	B6R6RA8	PG 64-22	49.3	24.9	49.4
Acceptance Rate Based on Number of Mixtures at a Given Step		**83%**	**50%**	**80%**	
Acceptance Rate Based on Total Number of Mixtures		**83%**	**42%**	**33%**	

B = virgin binder; CT = cracking tolerance; CTAS = CT index aging sensitivity; LTOA = long-term oven aging; PG = performance grade; R = reclaimed asphalt pavement (RAP) binder; RA = recycling agent; STOA = short-term oven aging. Red highlighting = failed acceptance criteria; gray highlighting = not applicable because failed prior acceptance criteria; blue highlighting = mixture passed acceptance criteria.

CONCLUSIONS

- *The rejuvenation path index (SR_D) is independent of the RA dosage and could be used to assess different RAs for acceptance into VDOT's APL.* This finding was evidenced by the linearity in the slope between the logarithm of creep stiffness (*S*) and the creep relaxation (*m*), both obtained at 60 seconds of creep loading and at -12ºC, using additional component materials (virgin binder, RAP, and RA) that were not included in previous studies. Given the dosage-independence of RAs, the current study verified the ability to use SR_D as a single index to accept or reject a different RA by comparing the low-temperature rheological properties of the RA-modified system to the laboratory performance of reference virgin binders, PG 64S-22, commonly used in Virginia. Moreover, given the demonstrated independence of the SR_D with respect to the RA dosage, the last step (Step 6) of the first engineered framework (i.e., assessment of RAs into VDOT's APL) that required additional testing at 0.5 or 1.5 times the initial RA dosage could be removed.

- *The engineered framework proposed in the previous VDOT Project No. 117566 to optimize the RA dosage selection for a given recycled binder blend was verified using new virgin binders, RAP stockpiles, and RAs not initially included in the previous project.* This conclusion is supported by the effectiveness of the Mahalanobis distance concept in optimizing the RA dosage selection and restoring the low-temperature rheological properties of the recycled binder blend closer to VDOT's QA reference dataset for virgin PG 64S-22 binders. The analysis showed that the dosage for RA6, RA7, and RA8 recommended by the corresponding supplier was consistently higher than the optimized dosage using the Mahalanobis distance concept. This finding reinforces the ability of the engineered framework to optimize both performance and, potentially, the associated costs of mixtures containing high RAP content (30 to 45% by weight of total mixture) and RA.

- *The new combinations of virgin binder, RAP, and RA showed that mixtures containing high RAP contents (30 to 45% by weight of total mixture) with RAs can be designed such that their laboratory performance is equal to or better than the laboratory performance of reference mixtures containing high RAP content with softer binder grade (i.e., PG 58-28) but no RA.* This conclusion confirms and reinforces the findings obtained from the previous VDOT Project No. 117566.

- *The laboratory performance test results for asphalt mixtures (IDT-CT at STOA and LTOA) and asphalt binders (GRP derived from the temperature-frequency sweep test) verified the CTAS preliminary threshold of a maximum of 45%.* The verification of the threshold avoids the acceptance of potentially aging-susceptible asphalt mixtures, including high RAP content and RA. The CTAS criterion should be applied if the CT index after LTOA conditioning is less than 70.

- *The cross-scale binder and mixture evaluation highlighted the key role of the asphalt binder blend in determining the mixture laboratory performance.* This finding emphasizes the need and the importance of an objective framework that allows optimizing both the RA dosage selection process and, potentially, the associated costs while designing asphalt mixtures containing high RAP content and RA with similar or better laboratory performance than their counterparts—that is, mixtures with softer binder grade and no RA. The IDT-CT results also showed that RAP binder properties and asphalt content play critical roles in the effectiveness of RAs.

RECOMMENDATIONS

1. *VDOT's Materials Division should consider adopting the draft Virginia Test Method in Appendix B. This Virginia Test Method outlines the performance-based frameworks proposed in the previous VDOT Research Project No. 117566 and verified in the current project, which includes an objective methodology to evaluate RA products, assess their potential inclusion into VDOT's APL, and design asphalt surface mixtures with high RAP content and RA using the BMD approach.* The Virginia Test Method includes specific guidance on the testing and analysis of asphalt binder blends and mixtures with RA, specifically mixtures with RAP content greater than 30% and less than 45% by total weight of mixture. An Excel-based automated program developed in this study was designed to streamline the analysis of RA products. The program allows one to optimize RA dosage selection, aiming to restore the low-temperature rheological properties of the RA-modified system. The program compares the RA-modified system's properties against VDOT's QA reference dataset for virgin PG 64S-22 binders, ensuring that the modified binders achieve the desired performance standards through an objective framework. Appendix C presents

suggested modifications to VDOT's BMD special provision to incorporate the high RAP and RA mix design requirements proposed in this study.

2. *VDOT's Materials Division and VTRC should plan and execute field trials to validate the engineered framework.* The study will use field performance data from asphalt mixtures with high RAP and RA, followed by ongoing monitoring, to validate the performance criteria and the framework. In addition, the study will evaluate the engineered framework during production, including the effect of asphalt mixture conditioning (i.e., reheating versus nonreheating) on IDT-CT tests conducted at STOA- and LTOA-conditioned specimens for asphalt surface mixtures with high RAP (30 to 45% by total weight of mixture) and RA. Alternative accelerated LTOA protocols will also be evaluated to expedite the proposed asphalt mixture aging method (1 day, or 24 hours, at 95°C) under production conditions. This effort is critical considering the practical LTOA method proposed for inclusion in VDOT's BMD framework (Boz et al. 2025). Field trials will also allow testing additional high RAP (30 to 45% by total weight of mixture) and RA mixtures to benchmark their performance, considering the suggested changes in the VDOT BMD special provision regarding the IDT-CT performance criteria.

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 process 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, VDOT's Materials Division, by December 2027, will identify the most appropriate steps toward implementing the performance-based frameworks regarding the evaluation and acceptance of RA products into VDOT's APL and the design of asphalt surface mixtures with RAP (30 to 45% content by total weight of mixture) and RA. VTRC will also work with VDOT's Materials Division to develop a roadmap with specific guidance, needs, and activities to be addressed before the full implementation of mixtures with RA.

With regard to Recommendation 2, VTRC, with the help of VDOT's Materials Division and districts, will identify opportunities for field trials starting with the 2026 construction season to collect data for further evaluation of the mix design framework. Field trials will be constructed and monitored to validate the engineered frameworks and the performance criteria proposed in the previous VDOT Research Project No.117566 and verified in this current study. This effort will also allow researchers to evaluate the effectiveness of the proposed framework during production, including the effect of asphalt mixture conditioning (reheating versus nonreheating) and the exploration of alternative accelerated protocols to streamline LTOA conditioning of asphalt mixtures with high RAP (30 to 45% by total weight of mixture) and RA during production. The field trials will also allow for testing additional high RAP (30 to 45% by total weight of mixture) and RA mixtures to benchmark their performance, considering the suggested changes in the VDOT BMD special provision regarding the IDT-CT performance criteria.

Benefits

This study provided VDOT with a verified engineered framework for evaluating RA products and their potential acceptance into VDOT's APL. This study also provided VDOT with an objective methodology for the RA dosage selection by optimizing performance and associated cost. This optimization was demonstrated by comparing the lower RA dosages obtained using the proposed framework to the supplier-recommended dosage for new component materials not evaluated in the previous study. The framework also provides guidance on how to design asphalt mixtures with high RAP content (30 to 45% by total weight of mixture) and RA, ensuring conformity of the asphalt mixtures' performance with VDOT's BMD special provision requirements while minimizing the potential acceptance of aging-susceptible mixtures. Other benefits include a Virginia Test Method with specific guidance on the assessment of RA products and the design of asphalt mixtures with high RAP content and RA and an Excel-based program that can streamline the analysis of RA products through a user-friendly, automated interface.

Another benefit is that the proposed performance-based frameworks can be a potential solution when designing asphalt mixtures with lower RAP content (i.e., 26 to 30% by total weight of mixture) and without RA that fail the VDOT BMD performance criteria. Several factors can result in failure of the VDOT BMD performance criteria, including but not limited to RAP sources with overly stiff or aged binder or challenges meeting the LTOA threshold (Boz et al., 2025). To help mitigate these issues and meet the performance criteria, the engineered frameworks can be used to incorporate an RA into the mix design.

Using RAs through the proposed engineered frameworks can also enhance production efficiency at asphalt plants, particularly from a logistical perspective. When designing mixtures with a higher RAP content (e.g., 30 to 45% by total weight of mixture) and softer virgin binder grade (i.e., PG 58-28), producers often face the challenge of replacing their PG 64S-22 asphalt binder tanks with the softer binder. This practice can be time-consuming or lead to the supply of inadequate binder (i.e., blend of PG 64S-22 and PG 58-28) if proper protocols are not followed when replacing the asphalt binder type in the tanks. The proposed performance-based mix design acceptance framework addresses this issue by allowing producers to design mixtures that meet the VDOT BMD performance criteria while using PG 64S-22 binder, streamlining operations, and minimizing logistical disruptions.

To quantify the potential benefit, a *hypothetical* scenario was evaluated to estimate the cost avoidance of adopting the mix design framework for asphalt surface mixtures with high RAP content (30 to 45% by total weight of mixture) and RA. Based on Table 7, the framework allowed to screen out 67% of the mixtures evaluated with high RAP during design because these mixtures did not meet the performance criteria for the CT index at STOA and LTOA conditions. This finding emphasizes the framework's viability as a tool to remove potentially aging-susceptible mixtures, assuming that these mixtures would be placed in the field over a sound and good condition underlying pavement structure. To translate the 67% rejection rate into a cost-savings estimate for the agency, several conservative assumptions were made and are described next. Notably, these assumptions apply only to the hypothetical scenario presented herein.

First, the total 2024 tonnage of BMD SM-9.5D and SM-12.5D mixtures was obtained for the Fredericksburg, Hampton Roads, Northern Virginia, and Richmond districts, which are the districts with the greatest amount of available RAP in Virginia. A total of 917,275 tons of BMD SM-9.5D and SM-12.5D mixtures was produced in these districts in 2024. Second, although anecdotal evidence suggests that the vast majority of producers are likely to produce high RAP mixtures, it was conservatively assumed that only 50% of this total tonnage (i.e., 458,637.5 tons) would have been designed with high RAP content (30 to 45% by total mixture weight). Of this high RAP total, 25% (i.e., 114,659.4 tons) was assumed to incorporate RAs for use in high RAP and RA asphalt surface mixtures. Under this premise, it is assumed that the remaining 75% of the mixtures (i.e., 343,978.1 tons) would have been designed using different approaches, such as using a softer binder grade (i.e., PG 58-28) without RA, a PG 64S-22 binder with a higher virgin binder content, or even reducing the RAP content. Given that most BMDs with high RAP and RA sections in Virginia corresponds to field trials, the amount of cost data per ton available for this material is limited and, thus, not representative. Alternatively, the cost per ton for high RAP mixtures with RA was estimated as being 10% less than the average of the lowest bid price per ton for SM-9.5D and SM-12.5D in 2024, resulting in $74.77 per ton of high RAP with RA mixtures. The 10% reduction was conservatively estimated as the potential cost savings incurred by a mixture with 45% RAP content and 3% RA by total weight of recycled binder opposed to a mixture with 30% RAP content and no RA. This reduction was applied as a conservative approach and *applies only to the hypothetical scenario presented here*. Finally, considering that the proposed framework would have screened out 67% of the mix designs (Table 7) from being placed in the field, this scenario would result in a cost avoidance of $5.7 million in 2024 (calculated as 67% of 114,659.4 tons times $74.77 per ton). Given the conservative assumptions underlying this hypothetical analysis, the total cost avoidance is expected to be substantially higher.

ACKNOWLEDGMENTS

The authors are grateful to the following individuals who served on this study’s technical review panel: Mourad Bouhajja, Project Champion and Statewide Asphalt Program Manager; Amir Behravan, Research Scientist, VTRC; Angela Beyke, Assistant State Materials Engineer, VDOT Materials Division; David Shiells, District Materials Engineer, VDOT Northern Virginia District; Miranda Kidd, District Materials Engineer, VDOT Hampton Roads District; and Thomas Schinkel, District Construction Engineer, VDOT Richmond District. The contributions of the staffs of Associated Asphalt, Branscome, Kao Chemicals, Russell Standard, Sasol, Sripath Technologies, and Superior Paving Corp. are deeply appreciated.

The authors also thank Troy Deeds, Paxton Gunn, Derek Lister, Danny Martinez, Jacob Oliver, David McKee, and Jennifer Samuels, of VTRC, and Donnie Dodds and Reo Kunori, formerly of VTRC, for their outstanding efforts in sample collection and testing.

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APPENDIX A: SUMMARY OF FIELD TRIALS LOCATION INFORMATION

This appendix summarizes the information regarding high reclaimed asphalt pavement and recycling agent field trials, including route numbers, start and end coordinates, district locations, counties, and lanes (Table A1).

Table A1. Summary of High Reclaimed Asphalt Pavement and Recycling Agent Field Trial Information

Field Trial Number	Route Number	District	County	Lane	From	To	Coordinates from	Coordinates to
1	2401	Northern Virginia	Loudoun	Right	70 Feet East of County Line at Woodbridge Pkwy	166 Feet West of County Line at Ashburn Village Blvd	39.072611, -77.473389	39.076611, -77.476472
2	659	Northern Virginia	Loudoun	Single Lane	87 Feet North of County Line at Sudley Road	0.16 Miles South of County Line at Dawsons Corner Blvd	38.886639, -77.541500	38.845111, -77.545167
3	620	Hampton Roads	Isle of Wight	Both	Joint 0.163 Miles East of Route 680, Magnet Drive	Joint 120 Feet West of Route 258, Courthouse Hwy	36.96415, -76.68993	36.96132, -76.66515

APPENDIX B: DRAFT VIRGINIA TEST METHOD FOR RECYCLING AGENT PERFORMANCE EVALUATION

Virginia Test Method—XXX Evaluation of Recycling Agent Performance on Asphalt Binder Blends Rheology and Asphalt Surface Mixtures

Evaluation of Recycling Agent Performance on Asphalt Binder Blends Rheology and Asphalt Surface Mixtures

Month Day, Year

1. Scope

1.1. This standard describes the test methods and analyses required for evaluating recycling agent (RA) products for potential inclusion into the Virginia Department of Transportation (VDOT) Approved Product List (APL) and the mix design acceptance of asphalt surface mixtures with reclaimed asphalt pavement (RAP) content greater than 30% and less than 45% by weight of total mixture. These mixtures are designed with RA in accordance with VDOT's balanced mix design (BMD) special provision requirements for mixtures with A and D designations.

1.2. This standard describes two frameworks. Framework 1 presents a methodology to evaluate the effectiveness of the RA in restoring the rheological properties of the recycled binder blend (i.e., virgin binder and extracted and recovered binder from RAP) and the RA's potential inclusion into VDOT's APL. Framework 2 presents a methodology to evaluate the effectiveness of the RA (selected from VDOT's APL) on the performance of surface mixtures with 30 to 45% RAP content for mix design approval.

1.3. This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1. American Association of State Highway and Transportation Officials (AASHTO) Standards:

- AASHTO M 332—*Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test*.
- AASHTO T 164—*Quantitative Extraction of Asphalt Binder from Asphalt Mixtures.*
- AASHTO T 319—*Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures*.
- AASHTO T 240—*Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test).*
- AASHTO R 28—*Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV).*

- AASHTO T 350—*Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR).*
- AASHTO T 313—*Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR).*
- AASHTO T 315—*Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR).*
- AASHTO T 312—*Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor*.
- AASHTO T 166—*Bulk Specific Gravity (G_{mb}) of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens*.

2.2. Virginia Test Methods (VTMs):

- VTM-142—*Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt Using the Asphalt Pavement Analyzer (APA)*.
- VTM-143—*Determination of Cracking Tolerance Index for Asphalt Mixture Using the Indirect Tensile Cracking Test (IDT-CT) at Intermediate Temperature*.
- VTM-144—*Cantabro Abrasion Loss of Asphalt Mixture Specimens*.
- VTM-145—*Method of Test for Determining Rutting Susceptibility of Asphalt Mixtures Using the Indirect Tensile at High Temperature (IDT-HT) Test.*

2.3. VDOT Specification:

- VDOT. Special Provision for Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria, SQ315-000200-24, 2024.

3. Terminology

3.1. Definitions of Terms Specific to this Standard:

3.1.1. *Recycled binder blend*—Blend of virgin binder and the binder extracted and recovered from the RAP material.

3.1.2. *RA-modified system*—Blend of virgin binder, the binder extracted and recovered from the RAP material, and the RA.

3.1.3. *RA dosage*—Dosage of RA, expressed as a percentage of the total weight of recycled binder blend.

4. Summary of Test Method

4.1. *RA Approval Process*—For the evaluation of a given RA and potential inclusion into VDOT’s APL, the high-, intermediate-, and low-temperature rheological parameters specified in the AASHTO M 332 standard shall be determined for the recycled binder blend and the RA-modified system. The RA shall be selected from a batch produced within one (1) year of the evaluation period. The RA-modified system shall be produced using the RA initial dosage recommended by the supplier to produce a blended binder system with a low-temperature performance grade (PG) of at least -22℃. The resulting RA-modified system shall have a PG that meets or exceeds the PG 64S-22 requirements (AASHTO M 332). The RA dosage shall not exceed 10% by weight of the total binder. The work shall be completed by an accredited third-party laboratory. The "RA Assessment Tool" program can be used for the RA approval analysis. The tool is available upon request from the VDOT's Materials Division.

4.2. *Asphalt Mixture Design with RA*—For the mix design acceptance of BMD mixtures with more than 30% and less than 45% RAP content by total weight of mixture, only RA products included in VDOT's APL shall be considered. Mixtures shall be designed in accordance with VDOT's BMD special provision for asphalt surface mixtures with A and D designations, except for long-term oven aging (LTOA) condition. For LTOA, the asphalt mixture shall be conditioned in the oven at 95°C for 1 day (24 hours) after completing short-term oven aging (STOA) for 4 hours at compaction temperature. The mixture CT index aging sensitivity (CTAS) shall be determined to screen out aging-susceptible mixtures. The work shall be completed through collaboration among producer, RA supplier, and an accredited third-party laboratory.

5. Significance and Use

5.1. This method is designed to provide an objective methodology with detailed guidance on asphalt binder and asphalt mixture testing for the assessment of RA products and their potential acceptance into VDOT's APL and mix designs. This method is developed for asphalt surface mixtures with RAP content greater than 30% and less than 45% by total weight of mixture and RA and designed in accordance with VDOT's BMD special provision, with the exception of the asphalt mixture LTOA conditioning.

6. Apparatus

6.1. Dynamic shear rheometer to obtain the high- and intermediate-temperature performance-graded properties of the virgin asphalt binder, recycled binder blend, and RA-modified system in accordance with AASHTO T 315 and M 332.

6.2. Equipment required to obtain the binder from the RAP material using solvent-extraction and to recover the asphalt binder from the solvent for further testing in accordance with AASHTO T 164 and T 319, respectively.

6.3. Bending beam rheometer to obtain the low-temperature performance-graded properties of the asphalt binder in accordance with AASHTO T 313.

6.4. Rolling thin-film oven to conduct short-term aging of asphalt binders in accordance with AASHTO T 240.

6.5. Pressurized aging vessel to conduct long-term aging of asphalt binders in accordance with AASHTO R 28.

6.6. Ovens to conduct STOA and LTOA of asphalt mixtures.

6.7. Mixing tools (e.g., spoons, spatulas, pans, bowls, etc.).

6.8. Superpave gyratory compactor and associated equipment and tools (including ovens) to prepare specimens in accordance with AASHTO T 312.

6.9. Balance, water bath, and associated equipment required to determine the bulk specific gravity (G_{mb}) or compacted asphalt mixtures in accordance with AASHTO T 166.

6.10. Test equipment required to conduct the BMD tests specified in VDOT's BMD special provision (SQ315-000200-24).

7. RA Approval Process (Framework 1)

7.1. Procedure

7.1.1. The work described in Section 7.1.3 to Section 7.1.12, with the exception of Section 7.1.4, shall be conducted by a third-party accredited laboratory (i.e., AASHTO-accredited lab) and subject to approval by VDOT's Materials Division. The work described in Section 7.1.2 and Section 7.1.4 shall be conducted by the RA supplier.

7.1.2. Select a sample of a virgin PG 64S-22 asphalt binder, found on VDOT's Approved List 50.

7.1.3. Obtain the properties of the virgin PG 64S-22 asphalt binder listed in **Table B1**.

Table B1. Properties of Interest of Asphalt Binder

Parameter	Specification
$\|G^*\|/\sin(\delta)$ at 64°C	AASHTO T 315 and M 320
High-temperature PG (PGH)	AASHTO T 315 and M 320
$\|G^*\|\times\sin(\delta)$ at 25°C	AASHTO T 315 and M 320
Intermediate-temperature PG (PGI)	AASHTO T 315 and M 320
ΔT_c	AASHTO T 313 and M 320
Low-temperature PG (PGL)	AASHTO T 313 and M 320
Creep stiffness (*S*)	AASHTO T 313 and M 320
Creep relaxation (*m*-value)	AASHTO T 313 and M 320
$J_{nr,3.2}$ at 64°C	AASHTO T 350 and M 332

$|G^*|$ = dynamic shear modulus; δ = phase angle, $J_{nr,3.2}$ = nonrecoverable creep compliance at 3.2 kPa. PG = performance grade.

7.1.4. Sample a representative source of RAP material from Virginia. The RAP material shall be selected such that the extracted and recovered binder has a PGH ranging from 82°C to 106°C and a PGL ranging from -10°C to +2°C.

7.1.5. Extract and recover the asphalt binder from the RAP material in accordance with AASHTO T 164 and T 319, respectively. The binder content of the RAP shall be reported.

7.1.6. Obtain the properties of the extracted and recovered RAP binder as listed in **Table B1**, except for $J_{nr,3.2}$.

7.1.7. Collect a sample of the RA to be evaluated from a batch produced within 1 year of the evaluation period.

7.1.8. Produce a recycled binder blend composed of virgin binder (PG 64S-22 as described in Section 7.1.2) and RAP binder equivalent to 40% RAP by total weight of mixture. The virgin and RAP binder shall be preheated to 140°C and 165°C, respectively, and blended using a power drill with a paddle attachment for two (2) minutes.

7.1.9. Obtain the properties of the recycled binder blend as listed in **Table B1**.

7.1.10. Select an initial dosage of RA to produce an RA-modified system that meets or exceeds a PGL of -22°C. The initial dosage shall be selected by the RA supplier based on the information provided in Sections 7.1.3 and 7.1.6.

Note 1: The RA dosage shall not exceed 10% of the total weight of the binder blend.

7.1.11. Produce an RA-modified system composed of the recycled binder blend produced in Section 7.1.8 and the RA at the initial dosage recommended in Section 7.1.10. The virgin and RAP binder shall be preheated to 140°C and 165°C, respectively, and blended using a power drill with a paddle attachment for two (2) minutes, resulting in the recycled binder blend. The recycled binder blend shall return to the oven at 165°C for five (5) minutes. The RA at the initial dosage shall be added to the recycled binder blend and blended for an additional two (2) minutes.

7.1.12. Obtain the properties of the RA-modified system as listed in **Table B1**.

7.2. Calculation

7.2.1. Calculate the rejuvenation path index (SR_D) using the binder properties obtained in Sections 7.1.9 and 7.1.12. The SR_D (Equation 1) is the absolute value of the slope between the recycled binder blend and the RA-modified system in a two-dimensional plot of the logarithm of creep stiffness (S) and creep relaxation (m-value) obtained from bending beam rheometer testing.

$$SR_D = \frac{[log(S)]_1 - [log(S)]_2}{m_1 - m_2} \qquad \text{Equation 1}$$

Where:
SR_D = rejuvenation path index.
$\log(S)_1$ = logarithm of creep stiffness of the recycled binder blend obtained at 60 seconds of creep loading and at -12°C (MPa),
$\log(S)_2$ = logarithm of creep stiffness of the RA-modified system obtained at 60 seconds of creep loading and at -12°C (MPa),
m_1 = creep relaxation of the recycled binder blend obtained at 60 seconds of creep loading and at -12°C, and
m_2 = creep relaxation of the RA-modified system obtained at 60 seconds of creep loading and at -12°C.

Note 2: The SR_D can be calculated automatically using the RA Assessment Tool program by entering the binder properties obtained in Sections 7.1.9 and 7.1.12 of the RA Approval Process (Framework 1). Appendix B1 includes a snapshot of the program interface to illustrate the SR_D calculation method. The tool is available upon request from the VDOT's Materials Division.

8. Asphalt Mixture Design with RA (Framework 2)

8.1. Procedure

8.1.1. The work described in Section 8.1.3 to Section 8.1.10, with the exception of Sections 8.1.4, 8.1.7, and 8.1.8, shall be conducted by a third-party accredited laboratory (i.e., an AASHTO-accredited lab) and subject to approval by VDOT's Materials Division. The work described in the remaining sections (i.e., 8.1.2, 8.1.4, 8.1.7, 8.1.8, and 8.1.11 to 8.1.17) shall be conducted by the producer.

8.1.2. Sample a representative source of PG 64S-22 virgin asphalt binder for the mix being designed and send to the RA supplier.

8.1.3. Obtain the properties of the virgin PG 64S-22 asphalt binder as listed in **Table B1**.

8.1.4. Sample a representative source of RAP material comparable with the material to be used during production and send the sample to the RA supplier.

8.1.5. Extract and recover the asphalt binder from the RAP material in accordance with AASHTO T 164 and T 319, respectively. The binder content of the RAP shall be reported.

8.1.6. Obtain the properties of the extracted and recovered RAP binder as listed in **Table B1**, with the exception of $J_{nr,3.2}$.

8.1.7. Select an RA from VDOT's Approved List [add number once available] to be used in the mix design.

8.1.8. Select an RA dosage to produce an RA-modified system that meets or exceeds a PGL of -22°C. The dosage shall be selected by the RA supplier based on the information provided in Sections 8.1.3 and 8.1.6.

Note 3: The RA dosage shall not exceed 10% of the total weight of the binder blend.

8.1.9. Produce 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 Section 8.1.8. The virgin and RAP binder shall be preheated to 140°C and 165°C, respectively, and blended using a power drill with a paddle attachment for two (2) minutes, resulting in the recycled binder blend. The recycled binder blend shall return to the oven at 165°C for five (5) minutes. The RA at the dosage recommended in Section 8.1.8 shall be added to the recycled binder blend and blended for an additional two (2) minutes.

8.1.10. Obtain the properties of the RA-modified system as listed in **Table B1**.

Note 4: The RA Assessment Tool program can be used to determine the optimized RA dosage that produces an RA-modified system that meets or exceeds a PGL of -22°C. The input data required are the properties of the recycled binder blend (follow the blending and testing procedure in Sections 7.1.8 and 7.1.9 of the RA Approval Process (Framework 1) using the RAP from Section 8.1.4 of the Asphalt Mixture Design with RA (Framework 2), the RA-modified system (Section 8.1.9 of Framework 2), and the RA dosage recommended by the supplier (Section 8.1.8 of Framework 2). Appendix B1 includes a snapshot of the program interface to illustrate the determination of the RA dosage. The tool is available upon request from the VDOT's Materials Division.

Note 5: The RA dosage selection shall be conducted to restore the low-temperature rheological properties for asphalt surface mixtures with high RAP content produced in Virginia. The software also permits the optimization of the RA dosage based on the high temperature, intermediate temperature, or global (high, intermediate, and low) rheological properties of the RA-modified system.

8.1.11. Produce the asphalt mixture with the selected RA and corresponding component materials. The quantity of asphalt mixture shall be enough to fabricate two sets of indirect tensile cracking test (IDT-CT) specimens: one set of specimens subjected to STOA only (Section 8.1.12 to 8.1.13) and another set subjected to STOA followed by LTOA (Section 8.1.14 to 8.1.16).

8.1.12. Conduct STOA of the asphalt mixture in accordance with VDOT's BMD special provision for four (4) hours ± 5 minutes at compaction temperature.

8.1.13. Fabricate five (5) test specimens using the asphalt mixture subjected to STOA obtained in Section 8.1.12 for IDT-CT in accordance with AASHTO T 312, with the following exceptions: test specimens shall be compacted to 7.0 ± 0.5% air-void content, at a height of 62 ± 1 mm and a diameter of 150 ± 2 mm.

8.1.14. Conduct STOA followed by LTOA of an additional quantity of asphalt mixture. The LTOA of the asphalt mixture shall be conducted in the oven at 95°C for one (1) day (24 hours) after completion of STOA. During LTOA, the asphalt mixture shall be uniformly placed in a pan such that the layer thickness is approximately equal to the nominal maximum aggregate size of the mixture.

8.1.15. Cool the asphalt mixture to room temperature and then reheat it to compaction temperature for specimen fabrication upon completion of LTOA.

8.1.16. Fabricate five (5) test specimens in addition to the specimens in Section 8.1.13 using the asphalt mixture subjected to STOA followed by LTOA obtained in Section 8.1.14 for IDT-CT in accordance with AASHTO T 312, with the following exceptions: the test specimens shall be compacted to 7.0 ± 0.5% air-void content, at a height of 62 ± 1 mm and a diameter of 150 ± 2 mm.

8.1.17. Conduct the IDT-CT test on the STOA specimens (Section 8.1.13) and the LTOA specimens (Section 8.1.16) in accordance with the VTM-143.

8.2. Calculation

8.2.1. Verify the rheological properties of the RA-modified system (Section 8.1.10). The RA-modified system shall meet the AASHTO M 332 requirements for creep stiffness (i.e., S less than or equal to 300 MPa) and creep relaxation (i.e., m-value greater than or equal to 0.300) obtained at 60 seconds of creep loading and at -12°C in accordance with AASHTO T 315.

8.2.2. Calculate the average CT index for the specimens subjected to STOA conditioning (i.e., $(CT_{Index})_{STOA}$) in accordance with VTM-143.

8.2.3. Calculate the average CT index for the specimens subjected to both STOA and LTOA conditioning (i.e., $(CT_{Index})_{LTOA}$) in accordance with VTM-143.

8.2.4. Calculate CTAS using the $(CT_{Index})_{STOA}$ and the $(CT_{Index})_{LTOA}$ obtained in Section 8.2.2 and Section 8.2.3, respectively. CTAS (Equation 2) is the percent difference in CT index between the LTOA and STOA test results.

$$CTAS = \left[\frac{(CT_{Index})_{STOA} - (CT_{Index})_{LTOA}}{(CT_{Index})_{STOA}}\right] \times 100 \qquad \text{Equation 2}$$

Where:
CTAS = CT index aging sensitivity (percent),
$(CT_{Index})_{STOA}$ = average CT index of five (5) specimens subjected to STOA, and
$(CT_{Index})_{LTOA}$ = average CT index of five (5) specimens subjected to LTOA after STOA conditioning.

8.2.5. Example calculation of CTAS.

$(CT_{Index})_{STOA}$ = 115,

$(CT_{Index})_{LTOA}$ = 65.

$$CTAS = \left[\frac{115 - 65}{115}\right] \times 100 = 43.5\%$$

9. Report

9.1. RA Approval Process (Framework 1):

9.1.1. Properties of the virgin PG 64S-22 binder listed in **Table B1** (Section 7.1.3).

9.1.2. Source of RAP stockpile.

9.1.3. Asphalt binder content in RAP (Section 7.1.5).

9.1.4. Properties of the extracted and recovered RAP binder listed in **Table B1**, with the exception of $J_{nr,3.2}$ at 64°C (Section 7.1.6).

9.1.5. Properties of the recycled binder blend listed in **Table B1** (Section 7.1.9).

9.1.6. Initial dosage of the RA provided by the supplier (Section 7.1.10).

9.1.7. Properties of the RA-modified system listed in **Table B1** (Section 7.1.12).

9.1.8. Rejuvenation path index (SR_D) (Section 7.2.1).

9.1.9. Optimum RA dosage (Section 7.2.2).

9.2. Asphalt Mixture Design with RA (Framework 2):

9.2.1. Properties of the virgin PG 64S-22 binder listed in **Table B1** (Section 8.1.3).

9.2.2. Source of RAP stockpile.

9.2.3. Asphalt binder content in RAP (Section 8.1.5).

9.2.4. Properties of the extracted and recovered RAP binder listed in **Table B1**, with the exception of $J_{nr,3.2}$ at 64°C (Section 8.1.6).

9.2.5. Dosage of the RA provided by the supplier (Section 8.1.8).

9.2.6. Properties of the RA-modified system listed in **Table B1** (Section 8.1.10).

9.2.7. Average CT index after STOA (Section 8.2.2).

9.2.8. Standard deviation and range (maximum minus minimum) of CT index values after STOA.

9.2.9. Average CT index after LTOA (Section 8.2.3).

9.2.10. Standard deviation and range (maximum minus minimum) of CT index values after STOA followed by LTOA.

9.2.11. CT index aging sensitivity, or CTAS (Section 8.2.4).

10. Precision and Bias

10.1. The precision estimates and statements for this test method are not available yet.

10.2. No information can be presented on bias of the procedure in this test method because no material having true reference value is available for comparison.

Appendix B1

The RA Assessment Tool v.1.0 was developed to expedite the calculation of the rejuvenation path index (SR_D), for the evaluation of an RA product for potential inclusion into VDOT's APL, and for optimizing the RA dosage targeting to restore the low-, intermediate-, or high-temperature rheological properties of the RA-modified system while meeting the requirements of AASHTO M 332 specification. The program also allows the RA dosage optimization to be conducted by evaluating the rheological properties of the RA-modified system at all three temperatures (i.e., low, intermediate, and high).

Determination of SR_D

Figure B1.1 presents the input and output data involved in calculating the SR_D. Input data include the date, RA name, RA initial dosage provided by the supplier, and the properties of interest for both recycled binder blend and RA-modified system. The selection of database years is used in the similarity analysis and is not needed for the SR_D calculation. The output data include the similarity scores of the RA-modified system at the RA initial dosage and the SR_D value. The similarity scores correspond to the Mahalonobis distance (MD^2) between the RA-modified system at the initial dosage and the centroid of VDOT's quality assurance dataset of virgin PG 64S-22 binders for the selected years. The MD^2 can be determined for low-temperature, intermediate-temperature, high-temperature, or global rheological properties. More details on the MD^2 concept can be found in VTRC Report 24-R3.

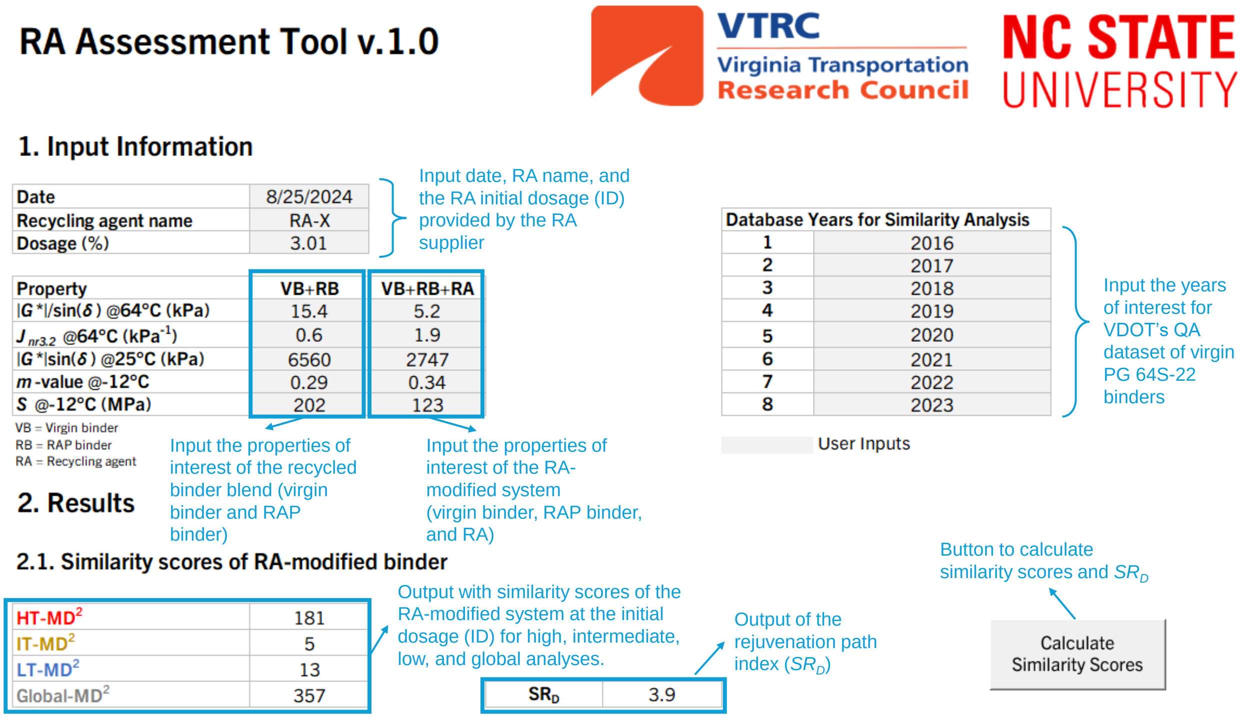

Figure B1.1. Calculation of SR_D Using the RA Assessment Tool Program. HT = high temperature; IT = intermediate temperature; LT = low temperature; MD^2 = Mahalanobis distance; RA = recycling agent; RB = reclaimed asphalt pavement (RAP) extracted and recovered binder; VB = virgin binder.

Figure B1.2 shows an example of an acceptable and nonacceptable RA product for inclusion into VDOT's APL. An acceptable RA product is the product that produces an RA-modified system that: (1) meets the low-temperature PG of -22°C, (2) exhibits *S* and *m* values that meet the AASHTO M 332 requirements, and (3) crosses VDOT's quality assurance reference data cluster for PG 64S-22 virgin binders with the line that connects the recycled binder blend to the RA-modified system. Note that the rheological properties shown in Figure B1.2 are fictional and were created to illustrate the analysis method of an RA product.

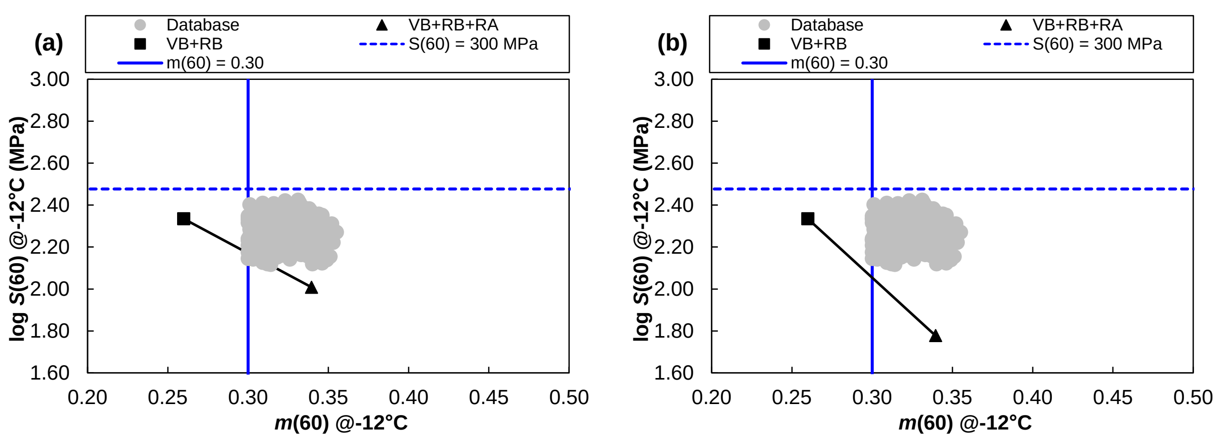

Figure B1.2. Example of (a) Acceptable and (b) Nonacceptable RA Product to be Included in VDOT's Approved Product List. RA = recycling agent; RB = reclaimed asphalt pavement (RAP) binder; VB = virgin binder.

Recycling Agent Dosage Analysis

Figure B1.3 shows the output data for the optimization analysis to obtain the RA dosage. Input data include the RA initial dosage provided by the supplier, the properties of interest for both recycled binder blend and RA-modified system, and the years in VDOT's quality assurance database for PG 64S-22 virgin binders. Output data include the optimum RA dosage (by weight of total asphalt binder) targeting low-temperature, intermediate-temperature, high-temperature, or global rheological properties, and the corresponding MD^2 in each case. The program also includes a graphical representation of the MD^2 values and a user-friendly interface to run the dosage analysis, clear the data (input and output), and save the information as a PDF or a printed document.

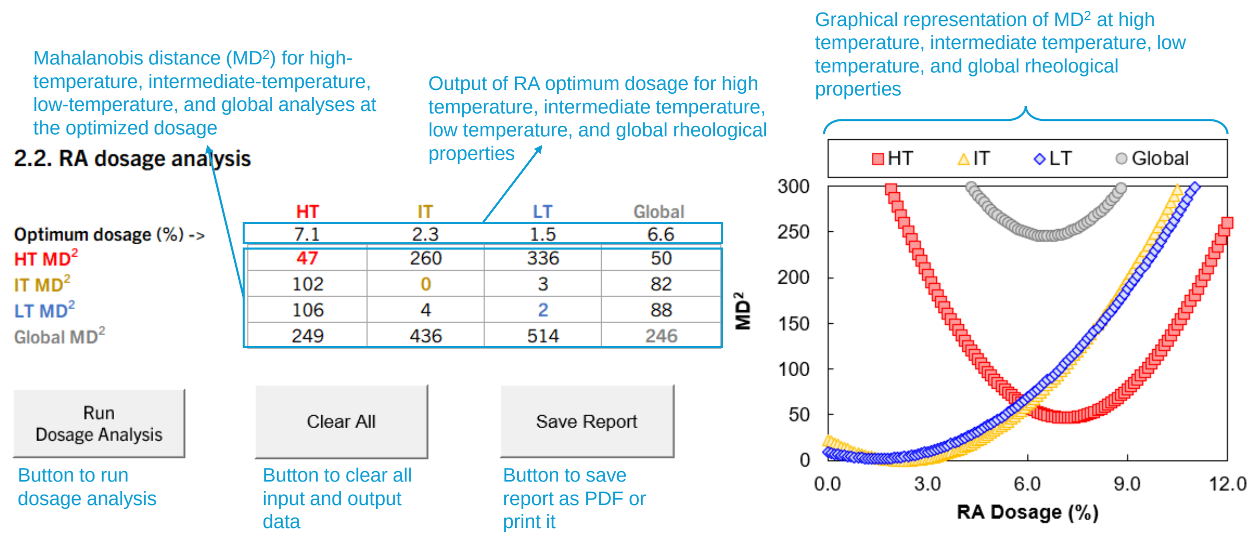

Figure B1.3. Optimization Analysis of RA Dosage. HT = high temperature; IT = intermediate temperature; LT = low temperature; MD^2 = Mahalanobis distance; RA = recycling agent.

APPENDIX C: BALANCED MIX DESIGN SPECIAL PROVISIONS WITH TENTATIVE MODIFICATIONS

This appendix presents the suggested modifications to the Virginia Department of Transportation's (VDOT) balanced mix design (BMD) special provision to include the mix design requirements for mixtures with high reclaimed asphalt pavement content (greater than 30% and less than 45% by total weight of mixture) and RA. Proposed modifications are highlighted in cyan. No other changes were made to the BMD special provision.

SQ315-000200-24

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
BALANCED MIX DESIGN (BMD) SURFACE MIXTURES DESIGNED USING PERFORMANCE CRITERIA

April 24, 2023

I. Description

This Specification covers the requirements and materials used to produce surface mixtures designed using performance criteria. Balanced Mix Design (BMD) surface mixtures shall be designed, produced, and placed as required by this Special Provision and Sections 211 and 315 of the Specifications.

II. Materials

All materials shall conform to Section 211.02 of the Specifications with the following exceptions:
a) **Recycled Asphalt Shingles (RAS)** will not be allowed in these mixes.
b) **Recycling agents (RA)** shall be selected from VDOT's Approved List XX.

III. Job-Mix Formula (JMF)

Mix Types SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D shall be designed to meet the Performance + Volumetric Optimized (BMD P+VO) criteria included in this section. Each mix type used shall conform to Section 211 of the Specifications. The Contractor shall submit the mix design at least two weeks before the mix is produced. Approval from the Engineer is required if the Contractor uses a binder with a PG grade not recommended by Table II-14A of Section 211 of the Specifications.

Mixes with high reclaimed asphalt pavement (RAP) content (greater than 30% and less than 45% by total weight of asphalt mixture) and recycling agent (RA) shall conform to Section 211 of the Specifications and to this Special Provision, except for the asphalt mixture long-term oven aging (LTOA) protocol and the corresponding performance test. Refer to VTM-143 for details on LTOA and corresponding performance test. The dosage rate of the RA shall be determined in accordance with the VTM-143.

Type Performance + Volumetric Optimized (BMD P+VO) asphalt mixtures shall be designed to conform to Section 211.03 of the Specifications as well as Table 1 herein, except that the following table shall replace Table II-13 in Section 211.03 of the Specifications:

Asphalt Concrete Mixtures: Design Range

Mix Type	Percentage by Weight Passing Square Mesh Sieves							
	¾ in	**½ in**	**3/8 in**	**No. 4**	**No. 8**	**No. 30**	**No. 50**	**No. 200**
SM-9.5 A,D		100[1]	90-100	90 max.	32-67			2-10
SM-12.5 A,D	100	90-100	90 max.		28-58			2-10

The design binder content shall be selected within a range of 3.0% --4.5% air voids.

This mix shall conform to Table 1 at the design binder content.
The results of supplementary performance testing at different binder contents (informational purposes) in addition to the design binder content shall be reported as follows:

1. Asphalt Pavement Analyzer (APA) rut testing (VTM-142): at design binder content and at 0.5% above the design binder content
2. Indirect Tensile Test at High Temperature (IDT-HT) (VTM-145): at design binder content and at 0.5% above the design binder content
3. Cantabro testing (VTM-144): at design binder content and at 0.5% below the design binder content
4. Indirect Tensile Cracking Test at intermediate temperature (IDT-CT) (VTM-143): at design binder content, at 0.5% above, and at 0.5% below the design binder content

The minimum design asphalt binder contents shall be based on the following unless otherwise approved by the Engineer:

Bulk Specific Gravity of the Total Aggregate	**Minimum Design Binder Content Mix Type (%)**	
	SM-9.5	**SM-12.5**
Less Than 2.65	5.5	5.3
2.65 - 2.74	5.4	5.2
2.74 - 2.85	5.3	5.1
Greater Than 2.85	5.2	5.0

For the BMD P+VO mixtures, a set of five IDT-CT pills with the final design JMF (only at the design binder content) shall be fabricated from long-term aged loose mix and tested in accordance with ASTM D8225. Test results shall be submitted with the JMF for the mix design review. Long-term aging shall be performed by aging loose laboratory produced mix for 8 hours at 135ºC, after short term oven aging is performed as required by Table 1. During long-term aging, the mix shall be uniformly placed in a pan such that the height of the loose mix shall not exceed the mixture nominal max aggregate size. Opening of the oven door shall be minimized during long-term aging. Specimens shall be heated to compaction temperature following aging and then compacted. The heating to compaction temperature shall not exceed 75 minutes.

The JMF shall meet the nominal max aggregate size of the designated mix type. The JMF shall establish a single percentage of aggregate passing each required sieve, a single percentage of binder to be added to the mix, the SUPERPAVE volumetric properties defined by AASHTO R 35 and a temperature range at which the mixture is to be produced.

The Contractor shall have a Department-certified Asphalt Mix Design Technician with the BMD training certification approved by the Department for designing and adjusting mixes. The Asphalt Mix Design Technician or an Asphalt Plant Level II Technician with the BMD training certification approved by the Department shall be capable of conducting necessary performance tests. The Asphalt Mix Design Technician shall be responsible for producing a mixture that complies with the requirements of this Specification.

Table 1
Performance Testing Requirements for Mix Design
(RAP content less than or equal to 30% by total weight of mixture)

Performance Property	**Performance Test**	**Test Method**	**Criteria**
Rutting	APA Rut depth	VTM-142	≤ 8.0mm
	IDT-HT	VTM-145	Strength ≥ 100 kPa
Durability	Cantabro Mass Loss	VTM-144	Mass loss ≤ 7.5%
Cracking	IDT-CT	VTM-143	CT_{index} ≥ 70 COV ≤ 18.3%[1]

1. Single operator testing tolerance: Coefficient of Variance (COV) shall be applied for the mix design IDT-CT test for all short-term aged specimens. For the long-term aged specimen test during design the COV shall be reported only for informational purposes.

Table 2
Performance Testing Requirements for Mix Design
(RAP content greater than 30% and lower than or equal to 45% by total weight of mixture)

Performance Property	Performance Test	Test Method	Criteria
Rutting	APA Rut depth	VTM-142	≤ 8.0mm
	IDT-HT	VTM-145	Strength ≥ 100 kPa
Durability	Cantabro Mass Loss	VTM-144	Mass loss ≤ 7.5%
Cracking	IDT-CT	VTM-143	$CT_{index, STOA} \geq 70$ $CT_{index, LTOA} \geq 70$ (LTOA) If $CT_{index, LTOA} < 70$ then CTAS ≤ 45% COV ≤ 18.3%[1]

1. Single operator testing tolerance: Coefficient of Variance (COV) shall be applied for the mix design IDT-CT test for all short-term aged specimens. For the long-term aged specimen test during design the COV shall be reported only for informational purposes.

The JMF shall indicate which type of specimen preparation will be used during production for Indirect Tensile Cracking at intermediate temperature (IDT-CT) testing for the mix: non-reheat or reheated mixture. Throughout the production of the approved JMF, the indicated method shall be followed for every IDT-CT sample, unless otherwise approved by the Engineer.

Mixes with high RAP content (greater than 30% and less than 45% by total weight of asphalt mixture) and RA shall conform to the performance requirements in Table 1. In addition, the mix design shall be accepted if (1) the CT index after LTOA is greater than or equal to 70 or (2) the CT index after LTOA is less than 70 but the CT index aging sensitivity (CTAS) is less than or equal to 45%. The CTAS criterion is not applicable for mixtures that conform to the performance requirements in Table 1 and have a CT index greater than or equal to 70. Details to the LTOA protocol and CTAS calculation for mixtures with high RAP content and RA can be found in VTM-XXX.

IV. Production Testing

Lot sizes defined by Sections 211 and 315 of the Specifications shall be followed for all production testing.

The Contractor shall conduct testing as required by Sections 211.05 and 211.06 of the Specifications for both A and D designated mixes. If less than 300 tons of asphalt mixture is produced under a single JMF in a day, SUPERPAVE testing will not be required on that day. That day's tonnage shall be added to subsequent production. When the accumulated tonnage exceeds 300 tons, minimum testing frequency for SUPERPAVE testing shall apply and results shall be reported.

In addition to all of the testing requirements for SUPERPAVE mixes, performance testing shall also be conducted on D designated mixes by the Contractor**,** in accordance with Table 3 and at the frequency shown in Table 4. The Contractor shall report BMD performance test results within 48 hrs of sampling to the Department unless otherwise approved by the appropriate District Materials Engineer
The approved asphalt concrete mixture shall also produce a tensile strength ratio (TSR) of not less than 0.80 in accordance with Section 211 of the Specification and as verified by the Contractor during the first lot of production.

Table 3
Performance Testing Requirements for Production

Performance Property	Performance Test	Test Method	Criteria
Rutting	APA Rut depth[1]	VTM-142	≤ 8.0mm
	IDT-HT	VTM-145	Report only COV report only
Durability	Cantabro Mass Loss	VTM-144	Mass loss ≤ 7.5%
Cracking	IDT-CT	VTM-143	CT_{index}[2] ≥ 70, reheated CT_{index}[2] ≥ 95, non-reheated COV report only

1. APA Rut will be performed during production by VDOT with specimens made by the Contractor at the request of the Engineer.
2. IDT-CT specimens shall be prepared (reheat or non-reheat) in accordance with the method indicated on the JMF and VTM-143.

Table 4
Performance Testing Frequency

Property/Test	Frequency (tons)
IDT-CT	2,000
Cantabro Mass Loss	2,000
IDT-HT[1]	4,000
APA Rut depth	As requested by Engineer[2]

1. IDT-HT shall be performed on the same sample as IDT-CT.
2. APA test will be performed by VDOT, however, specimens shall be made by the Contractor at the request of the Engineer.

V. Acceptance

Lot acceptance for BMD P+VO shall be as required by Section 211.08 of the Specifications.

Although acceptance will be based on Section 211, should any performance test results (based on the average of required number of specimens tested) fail to meet the criteria as specified in Table 3, the Department may require that production be stopped until corrective actions are taken by the Contractor. The Engineer will investigate and determine the acceptability of material placed and represented by failing performance test results.

Field density shall be determined in accordance with Section 315 of the Specifications.

VI. Adjustment System

The Department will determine adjustment points in accordance with Section 211.09 of the Specifications except for the following:

- If the total adjustment is 25 points or less and the Contractor does not elect to remove and replace the material, the unit price for the material will be reduced 3% of the unit price bid for each adjustment point the material is outside of the process tolerance.
- The Engineer will reduce the unit bid price by 1.0 % for each adjustment point applied for standard deviation.
- The Engineer will increase the unit bid price by 5% if the following criteria are met: 1) the standard deviation of the binder content is within the ranges of 0.0 – 0.15; 2) there are no adjustment points assigned for any sieve sizes as noted in Table II-16; and 3) the average binder content is no less than 0.10% below and no more than 0.20% above the approved mix design binder content.

VII. Initial Production

Mix type BMD P+VO shall be subject to Section 211.15 of the Specifications at the Engineer's discretion.

VIII. Measurement and Payment

Asphalt Concrete BMD P+VO will be measured in tons and will be paid for at the Contract ton price. Net weight information shall be furnished with each load of material delivered in accordance with Section 211 of the Specifications. Batch weights will not be permitted as a method of measurement unless the Contractor's plant is equipped in accordance with Section 211 of the Specifications, in which case the cumulative weight of the batches will be used for payment. This price shall include all labor, equipment, and materials necessary to furnish, install, and finish the work described herein.

Payment will be made under:

Pay Item	Pay Unit
Asphalt Concrete BMD P+VO (mix type)	Ton