Recycled Binder Availability of Virginia RAP Materials and Its Effects on Asphalt Mixture Composition and Performance

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In Virginia, most asphalt mixtures contain reclaimed asphalt pavement (RAP), which may pose some challenges regarding asphalt pavement durability if these mixtures are not properly designed. One of the concerns is the uncertainty in the amount of RAP binder that is available, active, and effectively contributing to the total asphalt content of the mixture. Although the balanced mix design (BMD) approach may help overcome some of these concerns, not all RAP asphalt mixtures produced in Virginia have a BMD framework available. In fact, VDOT's existing BMD framework still requires mixtures to comply with volumetrics specifications, which may be more challenging for mixtures containing higher amounts of RAP.

The objective of this study was to characterize the asphalt binder availability, activity, and contribution from different RAP materials and asphalt mixtures in Virginia; evaluate the effectiveness of recycling agents (RAs) at activating the available binder for improved blending with virgin binder; and, collectively, assess their effect on asphalt mixture volumetrics and performance. The scope of work included a literature review; characterization of recycled binder availability (RBA) and degree of activity (DoA) of RAP materials; characterization of the recycled binder contribution (RBC) of selected asphalt surface mixtures; laboratory performance tests using VDOT's BMD and advanced test methods for reference and study mixtures incorporating RBA or RA, or both; and pavement performance simulations.

The literature review revealed knowledge gaps related to the lack of a practical method to estimate RBC, limited comparisons across RBA, DoA, and RBC, as well as limited evaluation of the effect of RAs on binder activation and contribution. The sieve analysis method showed that RBA ranged from 41.4% to 73.5% and an average of 59.5% for nine RAP sources in Virginia, with finer gradations associated with higher RBA values. A strong agreement was observed between RBA from RAP materials and RBC from corresponding mixtures, indicating that the RBA sieve analysis method could be used as a practical, simple, and low-cost method to estimate RBC. Mixture composition analysis showed that assuming 100% RBA overestimates asphalt content, voids in mineral aggregate, and voids filled with asphalt and may incorrectly suggest compliance with the volumetric requirements, especially at higher RAP contents. BMD tests showed that incorporating RBA and/or RA can substantially improve mixture durability and cracking without adversely affecting the rutting resistance. Mechanistic-based pavement performance simulations showed substantial improvement in the fatigue cracking predictions of asphalt mixtures, including RBA and/or RA compared with reference or control mixtures.

This study recommends that VDOT should consider (1) incorporating RBA in the design of dense-graded asphalt surface mixtures with 9.5- and 12.5-mm nominal maximum aggregate size with up to 40% RAP content by total mixture weight; (2) incorporating the sieve analysis method into VDOT's specification as a practical and low-cost method to quantify RAP materials RBA; and (3) evaluating, along with VTRC, additional RAP stockpiles and corresponding asphalt mixtures with RAP content above 30% to verify RBC consistency among additional mixtures and evaluate the effect of RBA on mixture performance.

Supplemental materials can be found at **https://library.vdot.virginia.gov/vtrc/supplements**.

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FINAL REPORT

RECYCLED BINDER AVAILABILITY OF VIRGINIA RAP MATERIALS AND ITS EFFECTS ON ASPHALT MIXTURE COMPOSITION AND PERFORMANCE

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In Cooperation with the U.S. Department of Transportation
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ABSTRACT

In Virginia, most asphalt mixtures contain reclaimed asphalt pavement (RAP), which may pose some challenges regarding asphalt pavement durability if these mixtures are not properly designed. One of the concerns is the uncertainty in the amount of RAP binder that is available, active, and effectively contributing to the total asphalt content of the mixture. Although the balanced mix design (BMD) approach may help overcome some of these concerns, not all RAP asphalt mixtures produced in Virginia have a BMD framework available. In fact, VDOT's existing BMD framework still requires mixtures to comply with volumetrics specifications, which may be more challenging for mixtures containing higher amounts of RAP.

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The literature review revealed knowledge gaps related to the lack of a practical method to estimate RBC, limited comparisons across RBA, DoA, and RBC, as well as limited evaluation of the effect of RAs on binder activation and contribution. The sieve analysis method showed that RBA ranged from 41.4% to 73.5% and an average of 59.5% for nine RAP sources in Virginia, with finer gradations associated with higher RBA values. A strong agreement was observed between RBA from RAP materials and RBC from corresponding mixtures, indicating that the RBA sieve analysis method could be used as a practical, simple, and low-cost method to estimate RBC. Mixture composition analysis showed that assuming 100% RBA overestimates asphalt content, voids in mineral aggregate, and voids filled with asphalt and may incorrectly suggest compliance with the volumetric requirements, especially at higher RAP contents. BMD tests showed that incorporating RBA and/or RA can substantially improve mixture durability and cracking without adversely affecting the rutting resistance. Mechanistic-based pavement performance simulations showed substantial improvement in the fatigue cracking predictions of asphalt mixtures, including RBA and/or RA compared with reference or control mixtures.

This study recommends that VDOT should consider (1) incorporating RBA in the design of dense-graded asphalt surface mixtures with 9.5- and 12.5-mm nominal maximum aggregate size with up to 40% RAP content by total mixture weight; (2) incorporating the sieve analysis method into VDOT's specification as a practical and low-cost method to quantify RAP materials RBA; and (3) evaluating, along with VTRC, additional RAP stockpiles and corresponding asphalt mixtures with RAP content above 30% to verify RBC consistency among additional mixtures and evaluate the effect of RBA on mixture performance.

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INTRODUCTION

Most asphalt mixtures produced in Virginia contain reclaimed asphalt pavement (RAP) because of the economic and environmental benefits. However, given the industry's growing interest in increasing the RAP content in asphalt mixtures, challenges regarding durability may arise if these mixtures are not properly designed. One of the main challenges is the uncertainty regarding the amount of RAP binder that is mobilized and blended with the virgin binder. This issue may be particularly critical at higher RAP contents, given that the volumetric requirements established under the Superpave mix design method were not originally developed to accommodate elevated levels of recycled asphalt.

The balanced mix design (BMD) protocol, 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, helps mitigate some of these challenges for BMD mixtures (Diefenderfer et al., 2021). Although performance tests and corresponding acceptance criteria are available to help screen out bad-performing mixtures, mixtures designed following VDOT's BMD framework still need to comply with volumetric specifications. In addition, other asphalt mixtures containing RAP and typically produced in Virginia do not have performance-related specifications that can be used during design. These mixtures include dense-graded surface mixtures with unmodified binders (e.g., 4.75-mm and 9.0-mm NMAS), polymer-modified dense-graded surface mixtures, intermediate and base mixtures, and gap-graded asphalt mixtures. Instead, they rely solely on the Superpave volumetrics-based method, which may be inaccurate for higher RAP contents.

In literature, different terminologies exist to describe the amount of aged RAP binder that is either available and/or active. In this present study, the recycled binder availability (RBA), degree of activity (DoA), and recycled binder contribution (RBC) concepts are described later in subsequent sections. Briefly, RBA and DoA are properties of RAP, and RBC is a property of the recycled asphalt mixture. RBA is an inherent property of a specific RAP source that refers to the proportion of total recycled binder available to blend with virgin asphalt. Binder inside agglomerated particles that do not separate during the mixing process is considered "unavailable". DoA is the portion of the available binder within a RAP source that is mobilized during mixing. RAP binder that remains solid and rigidly adhered to RAP agglomerates throughout the mixing and handling process is considered "inactive". Binder activity results from the interactions between RAP, additives such as recycling agents (RAs), and production conditions (e.g., mixing temperature, duration). RBC refers to the proportion of total recycled asphalt binder contained within the virgin binder matrix of an asphalt mixture resulting from both RBA and DoA, which are illustrated in Figure 1).

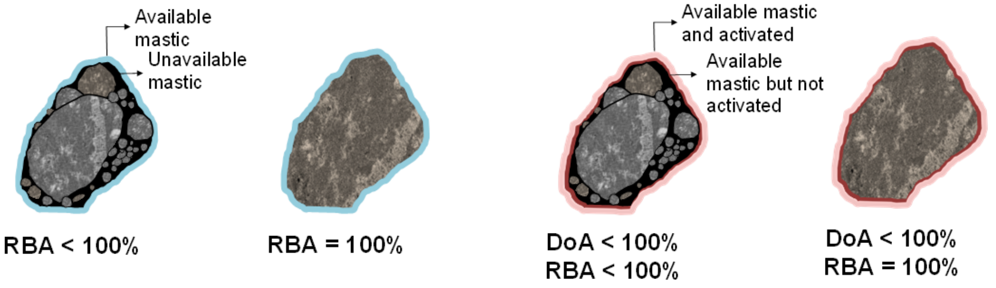


Figure 1. Illustration of RBA and DoA. DoA = degree of activity; RBA = recycled binder availability.

Crediting only the recycled binder that is both available and active during mix design and evaluation is crucial. Currently, VDOT's mix design specifications, as in many state highway agencies' specifications, assume that 100% of the RAP binder blends with the virgin binder, with a 0.4% correction factor applied to discount the fines lost in the ignition oven when determining RAP's asphalt content (AC). Although it is known that the assumption of partial availability (i.e., RBA < 100%) is more accurate than complete availability (RBA = 100%), the lack of test methods that can practically and more accurately estimate RBC often impairs the adoption of the partial availability concept during design. Giving full credit to the RAP binder, that is, considering the inactive binder encapsulated by or coating the RAP agglomerations as active binder, leads to a lower effective binder content (P_{be}) and, thus, lower voids in mineral aggregate (VMA) than what actually exists in the mixture. Consequently, mixtures designed under the assumption of complete availability and activity of the RAP binder (i.e., 100% RBA) may lack sufficient virgin asphalt, which may affect durability.

Therefore, a better understanding of the recycled binder availability and activity of RAP materials is especially important for mixtures that do not have a BMD framework yet developed, for mixtures with higher RAP content (e.g., more than 30% by total weight of mixture), and for RAP materials with low binder contribution. It is also important to evaluate how RAs influence recycled binder activity. Accounting for a more accurate estimate of the RAP binder availability in mix design may improve asphalt mixtures' durability, while verifying and/or leveraging the benefits associated with BMD.

PURPOSE AND SCOPE

The purpose of this project was to characterize the asphalt binder availability, activity, and contribution from different RAP materials and asphalt mixtures in Virginia; evaluate the effectiveness of RAs at activating the available binder for improved blending with virgin binder; and, collectively, assess their effect on asphalt mixture volumetrics and performance. The scope of work included a literature review; characterization of RBA and DoA from RAP materials; characterization of RBC from selected asphalt mixtures; BMD and advanced laboratory performance test methods using mixtures incorporating RBA or RA, or both, as well as reference mixtures; and pavement performance predictions. Supplemental materials that accompany this final report can be found at VDOT research library website.

METHODOLOGY

Literature Review on Recycled Binder Availability

A literature review was conducted to identify methods used to characterize RBC, RBA, and DoA. The literature review built on the recent review conducted under National Cooperative Highway Research Program (NCHRP) Project 09-68 (Yin et al., 2026), which evaluated approaches for characterizing RAP quality and the mobilization and blending of RAP binders with and without additives. NCHRP Project 09-68 adopted the terminology proposed by RILEM Technical Committee 264 (TC264-RAP) Task Group 5 (TG5) (Lo Presti et al., 2020; Tebaldi and Dave, 2025), which emphasizes RAP binder mobilization and its contribution to mixture performance in the presence or absence of additives. In contrast, the present review focused on categorizing methods by underlying mechanisms that inhibit blending, specifically agglomeration and partial activation, and therefore employs alternative terminology aligned with these mechanisms. Relevant references were selected using transportation engineering-related databases and search engines, including Transportation Research Information Services (TRID), Scopus, Catalog of Worldwide Libraries, Google Scholar, ProQuest, and Web of Science.

Methods for characterizing RBC, RBA, and DoA were first reviewed, followed by a comparison of approaches based on practical applicability and theoretical considerations. These considerations included:

- Reliance on standard laboratory equipment, thereby minimizing cost and training requirements for implementation.
- Dependence on direct testing of RAP versus methods that require mixture preparation or supplementary specimens to infer the property of interest.
- Whether solvent extraction is required.
- The extent to which each method has been applied in the literature.
- Whether the approach provides a clear basis for interpreting RBC, RBA, or DoA based on known reference conditions corresponding to 100% effectiveness.

The findings were used to identify the most promising methods for characterizing each property in both research and practice. In addition, results across studies are synthesized to identify key material and production variables influencing these properties and to highlight remaining knowledge gaps.

Experimental Program Overview

Nine RAP source materials were sampled across the state of Virginia and subjected to RBA and DoA characterization. Fourteen mixture compositions obtained from different combinations of virgin binder performance grade (PG), RAs, and RBA assumptions were evaluated using component materials from six source locations. The evaluation included both BMD and advanced test methods to assess the asphalt mixtures' laboratory performance and the potential influence of RAs and RBA assumptions. Pavement performance predictions were conducted using AASHTOWare® Pavement ME Design and FlexPAVE™ computer simulations.

To accomplish the study objectives, the following component materials were evaluated:

- Four virgin asphalt binders, including three PG 64S-22 (B4, B5, and B6) and one PG 58-22 (B7).
- Six sources of virgin aggregates (Sources 4, 5, 6, 7, 11, and 12) were selected for mix verification and further asphalt mixture performance assessment.
- Nine RAP materials (R4 to R12) from various locations in Virginia were selected to encompass a wide range of geographical locations and producers.
- Three RAs (RA6, RA7, and RA8) were used to evaluate their potential effect on RBA.

Regarding the aforementioned materials, three virgin asphalt binders (B4, B5, and B6), three aggregates sources (Source 4, 5, and 6), three RAP materials (Sources 4, 5, and 6), and the RAs were obtained during Phase I of this project (Kuchiishi et al., 2025). The following sections present details regarding the materials, test methods, and pavement performance predictions. Figure 2 summarizes the experimental program for this study.

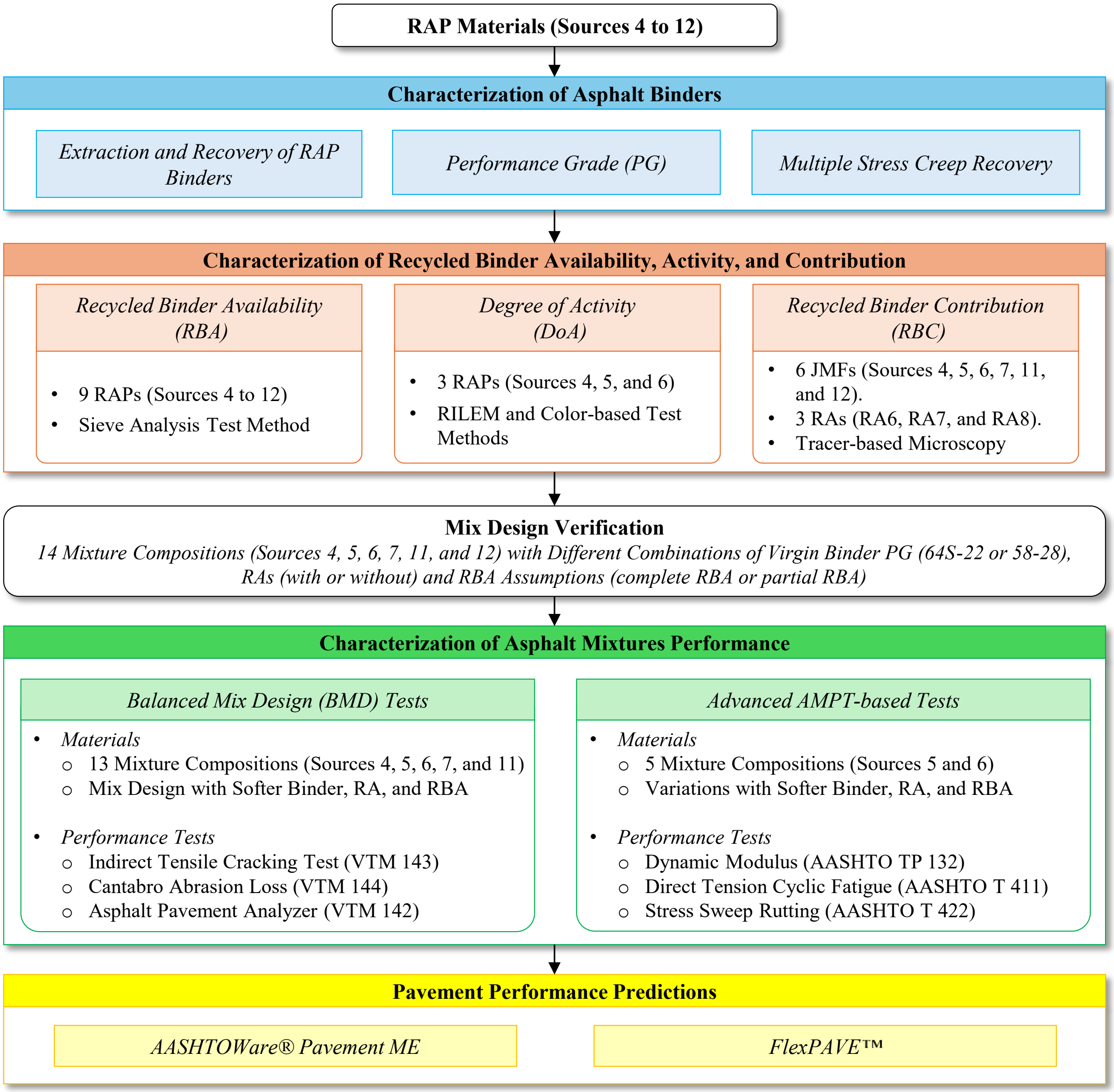


Figure 2. Experimental Program Overview, Including Laboratory Testing and Pavement Performance Simulations. AMPT = asphalt mixture performance tester; BMD = balanced mix design; DoA = degree of activity; JMF = job mix formula; ME = mechanistic-empirical; PG = performance grade; RA = recycling agent; RAP = reclaimed asphalt pavement; RBA = recycled binder availability; RBC = recycled binder contribution; VTM = Virginia test method.

Selection and Sampling of RAP and Component Materials

Reclaimed Asphalt Pavement Materials

In this study, nine RAP source materials were selected and sampled in accordance with Virginia Test Method 48 (VDOT, 2025) across Virginia to represent different producers and geographical locations. The RAP materials are identified as Source 4 to Source 12 to keep consistency with the naming convention used in Phase I of this project (Kuchiishi et al., 2025).

Besides testing the extracted and recovered asphalt binders, the RAP materials were subjected to further laboratory tests to determine their corresponding RBA and DoA values. Figure 3 presents the approximate locations of the asphalt plants from which the RAP materials were sampled.

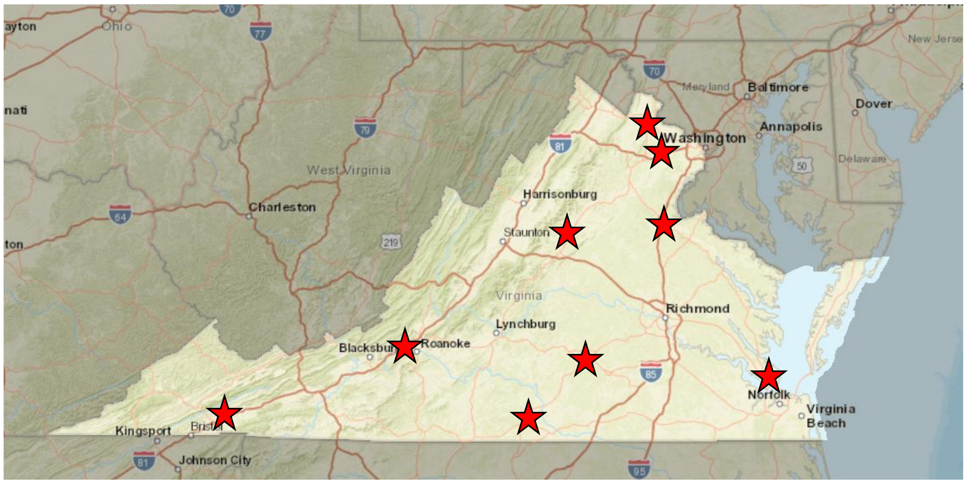


Figure 3. Approximate Locations of Asphalt Plants where Reclaimed Asphalt Pavement Materials Were Sampled

Asphalt Mixtures

Six job mix formulas (JMFs) were selected from Sources 4, 5, 6, 7, 11, and 12 for RBC characterization, mix verification, and performance testing. These JMFs were selected to encompass a wide variety of asphalt mixtures with different NMAS, geographical location, volumetrics parameters, gradation properties, as well as RAP content, and RA usage. Virgin aggregates were sampled in accordance with VDOT's specifications (VDOT, 2020) and combined with virgin binders obtained in Phase I of this project. Notably, Sources 4 to 6 asphalt mixtures are the same ones evaluated in Phase I, which included 40% RAP content by weight of total mixture and RA. Table 1 summarizes the mix design information for the six JMFs selected for this study.

Table 1. Mix Design Information for Asphalt Mixtures from Sources 4, 5, 6, 7, 11, and 12

Mix Source	Source 4^a	Source 5^a	Source 6^a	Source 7	Source 11	Source 12
Mixture Composition Information						
Mix Type	SM-9.5A	SM-9.5A	SM-12.5D	SM-12.5D	SM-9.5D	SM-12.5A
Design Type	BMD P+VO	BMD P+VO	BMD P+VO	BMD P+VO	Superpave	Superpave
District	Northern Virginia	Northern Virginia	Hampton Roads	Salem	Lynchburg	Bristol
NMAS (mm)	9.5	9.5	12.5	12.5	9.5	12.5
RAP Content (%)	40	40	40	26	30	30
Virgin Binder PG	64S-22	64S-22	64S-22	64S-22	64S-22	64S-22
Recycling Agent	RA6	RA7	RA8	None	None	None
Volumetrics Parameters						
Asphalt Content (%)	5.5	5.6	5.5	5.5	6.0	5.4
Rice SG, G_{mm}	2.673	2.668	2.493	2.547	2.506	2.495
VTM (%)	3.2	4.0	3.5	3.7	3.8	3.9
Gradation Parameters (Percent Passing)						
¾ in. (19.0 mm)	-	-	100	100	-	100

Mix Source	Source 4[a]	Source 5[a]	Source 6[a]	Source 7	Source 11	Source 12
½ in. (12.5 mm)	100	100	97	97	100	95
⅜ in. (9.5 mm)	94	96	87	88	95	88
No. 4 (4.75 mm)	65	64	-	-	62	57
No. 8 (2.36 mm)	44	42	43	42	44	35
No. 30 (0.6 mm)	-	-	-	-	-	16
No. 200 (0.075 mm)	6.2	6.2	5.0	6.1	5.0	6.6

- = data not available; BMD = balanced mix design; NMAS = nominal maximum aggregate size; PG = performance grade; P+VO = performance plus volumetrics optimized; RAP = reclaimed asphalt pavement; SG = specific gravity; SM = surface mixture; VTM = voids in total mixture. [a] Obtained in Phase I.

BMD and advanced laboratory tests were conducted to evaluate the performance of asphalt mixtures with respect to durability, cracking resistance, and rutting potential. Different mixture compositions were subjected to the laboratory tests and were obtained from varying combinations of virgin binder PG (64S-22 or 58-22), RAs (with or without), and RBA assumptions (complete RBA or partial RBA). Table 2 summarizes the different mixture compositions subjected to laboratory performance tests.

Table 2. Mix Designs Evaluated for Material Each Source

Mix Source	Mix Name	Virgin Binder Grade	RBA	RA	Mix Verif.	Balanced Mix Design Tests				Advanced Tests		
						IDT-CT at STOA	IDT-CT at LTOA	CML	APA	DM	CF	SSR
4	B7R4[a]	58-22	C	No	✓	✓	✓	✓	✓	-	-	-
	B4R4RA6[a]	64S-22	C	Yes	✓	✓	✓	✓	✓	-	-	-
5	B7R5[a]	58-22	C	No	✓	✓	✓	✓	✓	✓	✓	✓
	B5R5RA7[a]	64S-22	C	Yes	✓	✓	✓	✓	✓	✓	✓	✓
6	B7R6[a]	58-22	C	No	✓	✓	✓	✓	✓	✓	✓	✓
	B7R6_RBA	64S-22	P	No	✓	✓	-	✓	-	-	-	-
	B6R6RA8[a]	64S-22	C	Yes	✓	✓	✓	✓	✓	✓	✓	✓
	B6R6RA8_RBA	64S-22	P	Yes	✓	✓	✓	✓	✓	✓	✓	✓
7	B5R7	64S-22	C	No	✓	✓	✓	✓	✓	-	-	-
11	B7R11_RBA	58-22	P	No	✓	✓	-	-	-	-	-	-
	B5R11	64S-22	C	No	✓	✓	-	✓	✓	-	-	-
	B5R11_RBA	64S-22	P	No	✓	✓	-	✓	✓	-	-	-
	B5R11RA6_RBA	64S-22	P	Yes	✓	✓	-	-	-	-	-	-
12	B5R12	64S-22	C	No	✓	-	-	-	-	-	-	-

- = test was not conducted in this study; ✓ = test was conducted in this study; APA = asphalt pavement analyzer; B = virgin binder; C = complete RBA (100%); CF = cyclic fatigue; CML = Cantabro mass loss; DM = dynamic modulus; IDT-CT = indirect tensile cracking test; LTOA = long-term oven aging; P = partial RBA (<100%); R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability; SSR = stress sweep rutting; STOA = short-term oven aging; Verif. = verification. [a] Obtained from Phase I.

Characterization of Asphalt Binders

Extraction and Recovery

The RAP binder was extracted following American Association of State Highway and Transportation Officials (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 (AASHTO, 2024). The asphalt binder was then recovered from the solvent using the Rotary evaporator recovery method in accordance with AASHTO T 319, *Standard Method of*

Test for Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures (AASHTO, 2022).

Asphalt Binder Aging Methods

For virgin binder, the rolling thin-film oven was used for short-term aging following 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, 2023). The pressurized aging vessel was used for a 20-hour long-term aging protocol in accordance with AASHTO R 28, *Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)* (AASHTO, 2022). For the RAP material, the extracted and recovered asphalt binders were tested as extracted for high-temperature grading but subjected to PAV aging for both intermediate and low-temperature grading to keep consistency with Phase I efforts (Kuchiishi et al., 2025).

Performance Grading and Multiple Stress Creep Recovery

Asphalt binder performance grading was conducted following AASHTO M 320, *Standard Specification for Performance-Graded Asphalt Binder* (AASHTO, 2023), and AASHTO M 332, *Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test* (AASHTO, 2023).

Characterization of Reclaimed Asphalt Pavement

Recycled Binder Availability

The sieve analysis method proposed by Pape and Castorena (2022) and refined by Fonseca da Costa et al. (2024) was used to determine the RBA of the acquired RAP samples. This method subjects RAP samples to an experimental procedure to obtain and compare the particle size distribution of the RAP sample (black curve [BC]) and the recovered RAP aggregate (white curve [WC]). The gradation curves, combined with the RAP's AC and effective aggregate specific gravity (G_{se}), are used to calculate RBA.

RAP samples were dried at 60°C and then reduced to 1,500-g samples using a mechanical splitter following AASHTO R 76, *Standard Practice for Reducing Samples of Aggregate to Testing Size* (AASHTO, 2023). G_{se} was calculated using the theoretical maximum specific gravity (G_{mm}) of RAP obtained according to ASTM D6857M, *Standard Test Method for Maximum Specific Gravity and Density of Asphalt Mixtures Using Automatic Vacuum Sealing Method* (ASTM International, 2023).

To determine the BC, the separated samples underwent mechanical washing for 10 minutes following AASHTO T 11, *Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Aggregates by Washing* (AASHTO, 2024), and the weight of the washed fines was added to the final mass passing 0.075 mm. Then, the samples were dried at 100°C, and while still hot, weak RAP agglomerations were manually broken for processing G_{mm} samples following the same method outlined in AASHTO T 209, *Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Asphalt Mixtures* (AASHTO, 2025). Once the samples cooled to room temperature, the first sieve analysis was performed to obtain the BC according to AASHTO T 27, *Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates* (AASHTO, 2023).

The WC and RAP asphalt binder content were obtained using the ignition oven method in accordance with AASHTO T 308, *Standard Method of Test for Determining the Asphalt Binder Content of Asphalt Mixtures by the Ignition Method* (AASHTO, 2024). The VDOT correction factor of 0.4% was not applied to the ignition oven results given that prior research demonstrated that when the RAP was washed and no correction was applied, the binder content results from the ignition oven were, in general, similar to those from solvent extraction-based methods (Fonseca da Costa et al., 2024). Similarly, to determine the gradation of the WC, the samples were washed, dried at 110°C, and then sieved in accordance with AASHTO T 30, *Standard Method of Test for Mechanical Analysis of Extracted Aggregate* (AASHTO, 2021). The sieve analysis procedure was performed for two replicates to obtain the difference of RBA between the sample's results.

Following the methodology from Fonseca da Costa et al. (2024), RBA was calculated based on the assumption that binder confined inside RAP agglomerations is unavailable to blend with virgin asphalt, whereas the available mastic on the periphery of agglomerations is available. The parameters to calculate RBA are obtained from the gradation curves, the RAP's AC, and G_{se} of the RAP aggregate.

The total volume of mastic in a sample of RAP containing 100 g of aggregate was calculated using Equation 1.

$$V_{mastic} = \frac{P_b\left(1+\frac{P_b}{(100-P_b)}\right)}{G_b} + \frac{P_{200}}{G_{se}} \qquad \text{[Eq. 1]}$$

Where:

V_{mastic} = volume of mastic in a mix with 100 g of aggregate (cm^3)

P_b = RAP AC (%),

G_b = binder specific gravity,

G_{se} = effective specific gravity of the RAP aggregate, and

P_{200} = filler content of the mastic, equal to the percent passing the No. 200 (0.075 mm) sieve of the WC minus that of the BC previously determined.

The average mastic film thickness in the RAP was determined via least squared error optimization to minimize the absolute difference between the volume of mastic calculated using Equation 2 and the total known volume of mastic calculated in Equation 1.

$$V_{mastic} = \sum_{i=1}^{n-1} \frac{P_{i+1}-P_i}{G_{se}\times\rho_{water}\times\frac{\pi}{6}\times\left(\frac{d_{i+1}+d_i}{2}\right)^3} \times \frac{\pi}{6}\left[\left(\frac{d_{i+1}+d_i}{2}+2t\right)^3 - \left(\frac{d_{i+1}+d_i}{2}\right)^3\right] \qquad \text{[Eq. 2]}$$

Where:

n = number of sieve sizes,

N_i = number of particles of size i,

P_i = WC percent passing sieve size i (%),
G_{se} = aggregate effective specific gravity,
d_i = sieve size (cm), and
t = mastic film thickness (cm).

Lastly, a similar equation to Equation 2 was used to calculate the volume of peripheral (i.e., available) mastic coating the RAP particle $V_{available\ mastic}$, with the t value previously obtained. However, Equation 3 uses the BC instead of WC; thus, the diameter of particles was adjusted.

$$V_{available\ mastic} = \sum_{i=1}^{n-1} \frac{RP_{i+1}-RP_i}{G_{se}\times\rho_{water}\times\frac{\pi}{6}\times\left(\frac{d_{i+1}+d_i}{2}-2t\right)^3} \times \frac{\pi}{6}\left[\left(\frac{d_{i+1}+d_i}{2}\right)^3 - \left(\frac{d_{i+1}+d_i}{2}-2t\right)^3\right] \quad \text{[Eq. 3]}$$

Where:
RP_i = RAP percent passing sieve size i, and
RP_{i+1} = RAP percent passing sieve size $i+1$.

RBA was then computed as defined in Equation 4.

$$RBA = \frac{V_{available\ mastic}}{V_{mastic}} \times 100\% \quad \text{[Eq. 4]}$$

Degree of Activity

The DoA of RAP binders (Sources 4, 5, and 6) was quantified using the indirect tensile strength (ITS) in accordance with ASTM D6931-17, *Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures* (ASTM International, 2017), with modifications based on the methodology proposed by Menegusso Pires et al. (2021) and adopted by the RILEM TC 264-RAP Task Group 5 (Tebaldi and Dave, 2025). The original method involves conditioning 100% RAP specimens for 4 hours at different temperatures to induce varying levels of binder activation. This approach assumes that increased binder activation leads to enhanced mixture cohesion, which can be captured through ITS measurements.

In this study, 100% RAP specimens were thermally conditioned following the same conceptual framework as Menegusso Pires et al. (2021). However, a conditioning time of 2 hours was adopted to limit oxidative aging impacts. For this study, conditioning temperatures of 140°C, 155°C, and 170°C were evaluated because they span the temperature range most representative of production conditions in Virginia for different types of asphalt mixture. A fourth temperature of 120°C was also included to explore the limits of DoA measurements. Sources 4, 5, and 6 were selected for DoA measurements for two reasons. First, the asphalt mixtures containing these RAP sources had the highest RAP content (i.e., 40%). At these higher RAP contents, there is a greater potential to influence the interpreted mixture composition than in mixtures with lower RAP contents. Therefore, DoA becomes more critical. Second, asphalt mixtures from Sources 4, 5, and 6 contained RA. Determining DoA for these sources, together with RBA and RBC measurements, may help infer the influence of RAs on binder availability, especially for DoA values below 100%.

After thermal conditioning, the RAP material was manually mixed to promote binder redistribution and compacted using a Superpave gyratory compactor with 30 gyrations. All specimens were prepared with a consistent compaction effort to minimize variability in specimen preparation. At least five replicate specimens were produced and tested for each RAP source and conditioning temperature.

Indirect tensile tests were conducted at 25°C, and the resulting ITS values were used to quantify binder activation. The degree of activation was calculated as the ratio of ITS measured at a given conditioning temperature to the maximum ITS across all conditioning temperatures for the same RAP source, which was assumed to represent the condition of 100% binder activation. DoA was calculated using Equation 5.

$$DoA = \frac{X_{RAP}(T)}{\max X_{RAP}} \times 100\% \qquad \text{[Eq. 5]}$$

Where:

$X_{RAP}(T)$ = ITS of a compacted RAP sample at a given conditioning temperature T, and

max X_{RAP} = maximum ITS of a compacted RAP sample observed among all the conditioning temperatures evaluated.

In addition to mechanical testing, surface color measurements were conducted to support the evaluation of binder activation. This approach was adopted following the general methodology proposed by Fonseca da Costa and Castorena (2025), in which color measurements were used as indicators of DoA as an alternative to ITS testing. The Asphalt Compatibility Tester (ACT) was used to measure the light intensity of loose asphalt mixture samples. However, the authors noted segregation in the loose samples may have affected measurements. Therefore, the lightness parameter (L*) was measured in this study using a CR-400 colorimeter on samples after compaction. Measurements were taken directly on the surface of the compacted specimens, with five readings per face and 10 measurements per specimen. This procedure was adopted to account for surface heterogeneity and ensure representative color characterization of the RAP mixtures. Although compacted samples were expected to limit segregation impacts, the results showed a bias in the L* values between the top and bottom of compacted samples, consistent across the three RAP sources analyzed. The L* at the top is reported unless noted otherwise. A comprehensive summary showing the bias between top and bottom L* measurements is provided in the Supplemental Materials File.

Recycled Binder Contribution

Tracer-based microscopy was used to measure the RBC in asphalt mixtures. Asphalt mixture sample fabrication and the tracer-based microscopy analysis followed the general recommendations of Fonseca da Costa and Castorena (2024). Accordingly, gyratory-compacted samples, each with an approximate mass of 4,500 g, were prepared with tracer-modified virgin binder. The tracer was titanium dioxide nanoparticles (TiO_2). A high-shear mixer was used to blend 10% of TiO_2 by mass of virgin binder for 10 minutes. The blending began at 1,000 rpm for the first minute, and then the speed was gradually increased to 5,000 rpm for the remaining time. The virgin binder was heated at the specified mixing temperature as per VDOT specification (VDOT, 2020). A sample of the virgin blended binder was poured into 25-mm diameter silicone molds, frozen, and subsequently analyzed in a microscope using energy dispersive spectroscopy (EDS) to determine the sulfur content. Similarly, extracted RAP binder was heated and prepared in the same manner as the blended virgin binder to determine the RAP binder sulfur content using the microscope-based method described in the following.

RAP was added to the heated aggregate 30 minutes prior to mixing. After mixing, the samples were conditioned at the compaction temperature specified by each JMF for 2 hours and then compacted using 100 gyrations to minimize voids, which can cause issues during the EDS-scanning electron microscopy (SEM) analysis. After cooling, the gyratory samples were cut in half using a saw, and a smaller prism sample was obtained from each half. The samples were then polished.

Similarly, a virgin mixture was also prepared for each RAP mixture to determine the change in titanium-to-sulfur (Ti:S) concentration when RAP is introduced in the mix. Accordingly, virgin mixtures were prepared using the same stockpile proportions as the corresponding recycled asphalt mixtures and were mixed using the remainder virgin binder previously blended with the tracer. This approach was chosen to preserve the elemental composition of the binder and aggregates used in the RAP mixture.

EDS-SEM measurements of the mixture and binder samples were then used to quantify RBC. SEM emits primary electrons with a focused beam to scan across the sample and produce an image based on the secondary and backscattered electrons that were in contact with the sample's surface. The interaction between the primary electron beam and the sample generates energy emission of X-rays specific to the elements in the sample, which EDS detects and quantifies. Thus, it is possible to map the distribution and relative concentrations of sulfur and TiO_2 in a compacted asphalt mixture sample. Sulfur is used to infer binder concentrations, and TiO_2 is incorporated into the virgin binder to differentiate it from RAP. TiO_2 can be used for this purpose because asphalt mixtures generally do not contain titanium, and so the binder bound in the RAP agglomerations lacks titanium. Thus, areas with sulfur but no titanium are used to identify agglomerations in RAP mixtures. Titanium and sulfur concentrations are measured in binder-rich areas without agglomerations and also in binder-rich areas of the virgin mixture. Furthermore, sulfur concentrations are measured in the virgin and RAP binders. Together, these values provide the information needed to assess RBC.

In this study, 20 microscopy measurements of the elemental composition were acquired for each mixture, including 10 measurements from each of the two sawn and polished samples collected at different locations. A sensitivity analysis, presented in the Supplemental Materials file, was conducted to evaluate the average RBC and associated standard error as a function of the number of measurements. The results demonstrated that using 20 measurements yields stable estimates of both the mean RBC and the standard error. The RBC at each RAP mixture location was then calculated using Equation 6. Results from each location were averaged to obtain the representative RBC for the mixture.

$$Local\ RBC\ (\%) = \left(\frac{Virgin_{Ti:S}}{Mixture_{Ti:S}} - 1\right) \times \frac{(AC - RAP_{AC})}{RAP_{AC}} \times \frac{S_V}{S_R} \times 100\% \quad \text{[Eq. 6]}$$

Where:
$Virgin_{Ti:S}$ = average titanium to sulfur (Ti:S) concentration ratio in the virgin mixture,
$Mixture_{Ti:S}$ = Ti:S concentration ratio in the RAP mixture,
AC = asphalt content of the mixture,
RAP_{AC} = RAP binder content,
S_v = sulfur content of the virgin binder blended with TiO_2, and
S_R = sulfur content of the recycled binder obtained from solvent extraction.

Characterization of Asphalt Mixtures

Reference Mixture Verification

The mixture designs specified in present VDOT-approved JMFs are termed "reference mixtures" herein. The reference mixtures were verified by determining the air void contents of specimens compacted at optimum binder content (OBC) and two additional asphalt contents (OBC – 0.5% and OBC + 0.5%) at an N_{design} of 50 gyrations (VDOT, 2020). The results were used to obtain a relationship between air void and binder content. A mix design was considered verified if the air void content at the OBC fell within the range of 3.0 to 4.5% (Habbouche et al., 2023). In cases when OBC did not yield an air void content within the acceptable range, the OBC was adjusted to achieve an acceptable air void content.

Mixtures Adjustments

The volumetric properties of each verified reference mixture were evaluated using two approaches: (1) assuming complete RBA (100%), consistent with VDOT's current practice and aligned with AASHTO R 35, *Standard Practice for Superpave Volumetric Design for Asphalt Mixtures* (AASHTO, 2022), and (2) incorporating the actual partial RBA (< 100%). In the latter approach, the virgin asphalt binder content was held constant and equal to the verified OBC from the corresponding mix design. The actual RBA was incorporated by treating the unavailable portion of the recycled binder as part of the aggregate structure. For example, for a RAP with an RBA of 60%, 60% of the RAP binder was included in the total binder mass and volume, and the remaining 40% was treated as unavailable and incorporated into the aggregate mass and volume when calculating volumetric properties, AC, and recycled binder ratio (RBR). It is noted that no adjustments were made to the aggregate specific gravity when attributing unavailable binder to the bulk aggregate volume.

The resulting volumetric properties were then compared with VDOT specifications. If a mixture failed to meet VDOT's minimum requirements for AC and VMA when the actual RBA was applied, an adjusted mixture design was developed by adding a virgin AC equivalent to the unavailable RAP binder and modifying the virgin aggregate stockpile proportions to increase VMA and achieve compliance with both volumetric and minimum AC requirements. Notably, increasing the virgin binder content without adjusting the gradation may not result in compliant mixtures because air voids may fall below the minimum specification limit.

Once the volumetric requirements were satisfied when accounting for RBA, the mixtures were subjected to short-term oven aging (STOA) and evaluated using the indirect tensile cracking test (IDT-CT) per VDOT specifications. Adjusted mixtures achieving a cracking tolerance index (CT_{Index}) greater than or equal to 70 were considered satisfactory. If the cracking resistance criterion was not met, RAs or softer virgin binders were incorporated using the adjusted virgin stockpile proportions as an additional means to improve cracking performance, followed by reverification of volumetric properties and subsequent performance testing. If a STOA CT_{Index} greater than or equal to 70 was achieved through the adjustment process, subsequent Cantabro mass loss (CML), Asphalt Pavement Analyzer (APA), and long-term oven aging (LTOA) IDT-CT testing was conducted. Figure 4 illustrates the described workflow.

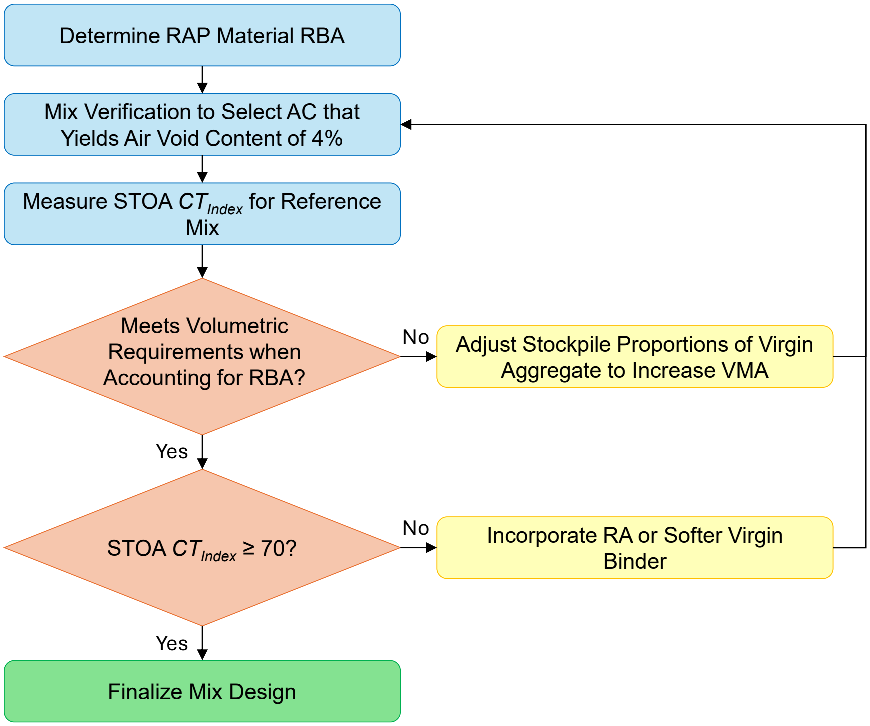


Figure 4. Mix Design Adjustment Flowchart. AC = asphalt content; AV = air voids; CT = cracking tolerance; RA = recycling agent; RAP = reclaimed asphalt pavement; RBA = recycled binder availability; STOA = short-term oven aging; VMA = voids in mineral aggregate.

Asphalt Mixture Aging Methods

The asphalt mixtures were aged under STOA and LTOA methods. For STOA, the asphalt mixtures were placed in the oven at compaction temperature for 2 hours (mix design and rutting performance specimens) and 4 hours (cracking performance characterization). For LTOA, the protocol proposed and verified for mixtures containing RA was conducted (Habbouche et al., 2023; Kuchiishi et al., 2025), which specified 24 hours at 95°C following the 4-hour STOA protocol.

Balanced Mix Design Tests

Indirect Tensile Cracking Test

IDT-CT was conducted following Virginia Test Method 143, *Determination of Cracking Tolerance Index for Asphalt Mixture Using the Indirect Tensile Cracking Test (IDT-CT) at Intermediate Temperature* (VDOT, 2025). The test was performed on five replicate specimens that were 150 mm in height and 62 mm in diameter and compacted at 7.0 ± 0.5% air void content. The CT_{Index} was then calculated, with higher CT_{Index} values suggesting improved cracking resistance.

Cantabro Abrasion Loss

The Cantabro abrasion loss test was conducted following Virginia Test Method 144, *Cantabro Abrasion Loss of Asphalt Mixture Specimens* (VDOT, 2025), with three replicates tested. The CML values were then calculated, with lower CML values suggesting improved durability.

Asphalt Pavement Analyzer

The APA test was conducted in accordance with Virginia Test Method 142, *Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt Using the Asphalt Pavement Analyzer (APA)* (VDOT, 2025). The test was performed on four replicate specimens that were 150 mm in diameter and 75 mm in height and compacted at 7.0 ± 0.5% air voids. Lower APA rut depth corresponds to improved rutting resistance.

Advanced Tests

Dynamic Modulus

The dynamic modulus (DM) test was conducted to characterize the asphalt mixtures' resistance to deformation following AASHTO TP 132, *Standard Method of Test for Determining the Dynamic Modulus for Asphalt Mixtures Using Small Specimens in the Asphalt Mixture Performance Tester (AMPT)* (AASHTO, 2025). Cylindrical test specimens of 38 mm in diameter and 100 mm in height with a target 5.0% ± 0.5% were tested with three replicates per mix. The measured stresses and strains were used to compute dynamic modulus ($|E^*|$) and phase angle isotherms, which were then shifted to a reference temperature of 21.1°C using the FlexMAT™ Cracking v2.2 program to create the master curves (Federal Highway Administration [FHWA], 2025). The two springs, two parabolic elements, and one dashpot model (2S2P1D) were used to fit the mastercurves (Olard and Di Benedetto, 2003).

Direct Tension Cyclic Fatigue

The cyclic fatigue (CF) test was conducted to characterize the asphalt mixtures' resistance to fatigue cracking following AASHTO T 411, *Standard Method of Test for Determining the Damage Characteristic Curve and Failure Criterion Using Small Specimens in* *the Asphalt Mixture Performance Tester (AMPT) Cyclic Fatigue Test* (AASHTO 2024). Cylindrical test specimens of 38 mm in diameter and 100 mm in height with a target 5.0% ± 0.5% air voids were tested with three replicates per mix. The pseudo-energy-based failure criterion (D^R) and the fatigue index parameter (S_{app}) were determined. The S_{app} parameter was used to compare the asphalt mixtures' fatigue cracking resistance with higher S_{app} values indicating improved fatigue damage resistance. All analysis was performed using the FlexMAT™ Cracking v2.2 program (FHWA, 2025).

Stress Sweep Rutting

The stress sweep rutting (SSR) test was conducted to characterize the asphalt mixtures' resistance to rutting following AASHTO T 422, *Standard Method of Test for Stress Sweep Rutting (SSR) Test Using Asphalt Mixture Performance Tester (AMPT)* (AASHTO, 2025). Cylindrical test specimens of 100 mm in diameter and 150 mm in height with a target 5.0% ± 0.5% were tested at two temperatures, with two replicates per temperature per mix. Test temperatures included one high temperature (T_H) of 48°C and one low temperature (T_L) of 23°C that reflects Virginia's climate condition based on LTPPBind Online and is consistent with temperatures adopted in previous Virginia Transportation Research Council (VTRC) projects. The rutting strain index (RSI) was used to compare asphalt mixtures' rutting resistance, with lower RSI values indicating improved rutting resistance. All analysis was performed using the FlexMAT™ Rutting v2.2 program (FHWA, 2025).

Analysis of the Effects of Recycled Binder Availability on Mixture Composition

Selected Reclaimed Asphalt Pavement Sources

The JMFs for mixtures incorporating the selected RAP sources were analyzed to evaluate the implications of adopting RBA factors under different scenarios on the interpreted volumetric properties of asphalt mixtures. The scenarios evaluated included the adoption of a fixed RBA equal to the average across all nine sources and the adoption of the source-specific RBA, either through direct measurement or predicted from a regression model. The method, introduced by Mocelin and Castorena (2022), was applied to analyze the effect of RBA on the interpreted volumetric properties of the asphalt mixtures. This method accounts for the presence of RAP agglomerations and associated RBA on the aggregate structure and volumetric composition of asphalt mixtures. The approach modifies volumetric calculations by explicitly including the volume of unavailable binder within the aggregate bulk volume, thereby adjusting the inferred aggregate bulk specific gravity and binder content. Although the method also infers the RAP gradation as its BC rather than its WC, this effect was not considered herein because the focus was on the evaluation of volumetric properties.

When reporting the results of this analysis, mixtures are identified using a notation based on RAP source and RAP content (e.g., R5-40 refers to the mix containing RAP from Source 5 at 40% content by weight of total mixture). This naming convention differs from that used in other sections of this report because the mixture information was obtained directly from the approved JMFs rather than from mixtures prepared in the laboratory with a specific virgin binder and subjected to the mix verification process. As a result, minor differences in the interpreted volumetric properties may exist compared with mixtures evaluated through laboratory verification procedures.

VDOT Statewide 2024 Balanced Mix Design Production Data

To assess the potential influence of RBA assumptions on volumetric interpretation and mixture performance indicators, VDOT statewide 2024 BMD production data were analyzed. The dataset included JMFs and production data from both producers and VDOT districts. Each record in the database represents a production sublot, including information regarding mixture composition, volumetrics parameters, gradation properties, and BMD performance test results. The database consists exclusively of VDOT dense-graded surface mixtures with 9.5- and 12.5-mm NMAS and D-type designation. For the BMD data, only reheated specimen results were retained for analysis because this condition corresponds to one most typically used across the state. Prior to the analysis, a preprocessing step was performed to remove data that failed either the volumetrics and gradation process tolerance limits defined by VDOT specifications (VDOT, 2020), or the multilaboratory limits for volumetrics data, when comparing districts and producers, and single-operator precision limit for the IDT-CT (i.e., coefficient of variation greater than 18.3%). This step was important to remove potential confounding factors associated with plant-production issues, divergencies in material handling and testing between organizations, and highly variable IDT-CT results.

Analyses were conducted to evaluate the effects on mixture composition interpretation with different RBA assumptions, including (1) 100% RBA (reflecting VDOT's current assumption); (2) average RBA (average across the nine RAP materials); (3) lowest RBA among the nine RAP materials evaluated; and (4) highest RBA among the RAP materials evaluated. For each scenario, the virgin binder content was kept constant and equal to the source-specific optimum value from the corresponding JMF, whereas the unavailable fraction of recycled binder was incorporated into the aggregate structure for volumetric calculations analogous to the analysis of the selected RAP sources described previously. Because RAP binder content was not explicitly reported in the database, a representative value of 4.8% was assumed, equal to the average derived from experimental characterization of Virginia RAP stockpiles through the present and past research projects. Volumetric properties were recalculated under alternative RBA scenarios, and statistical comparisons were conducted to evaluate differences among scenarios. In addition, mixtures were classified based on specification compliance, and their corresponding IDT-CT results were analyzed to examine potential relationships between RBA assumptions, volumetric interpretation, and IDT-CT results.

Pavement Performance Predictions

AASHTOWare® Pavement ME

VDOT uses AASHTOWare® Pavement ME (referred herein as Pavement ME for brevity) to design new construction (new alignment, lane addition, and total reconstruction) of interstates, primary routes, and high-volume secondary roads. Pavement ME adopts a mechanistic-empirical (ME) design process that relies on mechanistic models to calculate pavement responses (i.e., stresses, strains, and deflections) and empirical relationships to predict pavement performance (i.e., rutting, fatigue cracking, etc.) for various traffic, climate, and material types.

In this study, Pavement ME was used to evaluate the effect of RBA and RA in pavement performance for Sources 5 and 6 asphalt mixtures. Two five-layer pavement structures consistent with the ones used in past VTRC studies were selected (Habbouche et al., 2025; Kuchiishi, 2025), corresponding to typical A- and D-type pavement structures designed to withstand 0 to 3 million equivalent single-axle loads (MESALs) and 3 to 10 MESALs, respectively. Table 3 summarizes the pavement structures used in the pavement performance predictions with Pavement ME.

Table 3. Pavement Structures Used in Pavement Performance Predictions

Pavement Layer	**Material**	**Thickness (inches)**		**Modulus (psi)**
		Structure A	**Structure D**	
SM	Source 5: B7R5, B5R5RA7 Source 6: B7R6, B6R6RA8, B6R6RA8_RBA	1.5	1.5	Obtained from Dynamic Modulus Test
IM	VDOT IM	2.0	2.0	VDOT IM
BM	VDOT BM	4.0	6.0	VDOT BM
Non-stabilized Base	VDOT Avg 21A/21B	6.0	6.0	21,000
Subgrade	VA A-7-6	Semi-infinite	Semi-infinite	14,000

B = virgin binder; BM = base mixture; IM = intermediate mixtures; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability; SM = surface mixture.

Pavement ME simulations were conducted assuming that each mixture could be used on A or D structures. The analyses included A structures modeled under 3 MESALs and a traffic speed of 35 mph, and D structures with 10 MESALs and a speed of 45 mph. For the climate condition, data from the North American Regional Reanalysis station database were used, with Herndon and Newport News locations selected for being the closest for Source 5 and Source 6 mixture field sections, respectively.

For each simulation, mixture-specific parameters were used as input, including $|E^*|$, volumetrics, and laboratory fatigue coefficients (k_{f1}, k_{f2}, and k_{f3}). Two densities were evaluated, 93% and 95%, with corresponding volumetric parameters determined for each case. Because the dynamic modulus test was conducted at 5.0% air void (95% density), the dynamic modulus values at 7.0% air void (93% density) were predicted using an artificial neural network model (Sakhaei Far, 2011), following a similar approach adopted in past VTRC studies (Habbouche et al., 2025; Kuchiishi et al., 2025). For the laboratory fatigue coefficients, an adjustment to the framework to obtain them from the cyclic fatigue test was proposed and used herein. Additional details to the updated framework can be found in the Supplemental Materials file.

The total rut depth at year 15 and the bottom-up fatigue cracking at year 30 (expressed in percent lane area) were determined and compared with VDOT's *AASHTOWare Pavement ME User Manual* thresholds (VDOT, 2017), that include a maximum 0.26-inch total rut depth at year 15 and a maximum 6% cracked lane area at year 30.

FlexPAVE™

FlexPAVE™ is a specialized program designed to predict the performance of asphalt pavement throughout its lifespan, specifically regarding fatigue and rutting (FHWA, 2025). To achieve accurate predictions, the program considers various factors, including the three-dimensional response of moving loads, viscoelastic material properties, and climate data. In addition, the program imports data from FlexMAT™ Cracking (DM and CF tests), FlexMAT™ Rutting (SSR test), volumetric information, and details on unbound materials and subgrade. FlexPAVE™ also integrates a pavement temperature database, which accommodates site-specific weather conditions (FHWA, 2025).

FlexPAVE v2.1.6 simulations were conducted on the same structures used in Pavement ME and highlighted in Table 3. Mixture performance properties were defined using DM, CF, and SSR test results. A Virginia-specific Level 3 aging model was used to determine the aging parameters required for FlexPAVE™ aging analysis (Habbouche et al., 2025).

Other than the surface mixtures, all layers had characteristics representative of typical VDOT materials and were kept the same for all simulations. For climate selection, the closest North American Regional Reanalysis station was used for each mixture. FlexPAVE™ analysis results in Total %Damage, Top %Damage, Bottom %Damage, Total Rut Depth, and the Rut Depth for each layer separately. The %Damage is computed as the ratio of the damaged area to the total effective area, where the Top %Damage is confined to the damage only in the top one-third of the asphalt layer structure, whereas Bottom %Damage focuses on the bottom two-thirds of the asphalt layer structure (Kim et al., 2024).

The simulation results were used to investigate the predicted performance of the surface mixtures under representative structure, climate, and traffic. The assessment for rutting performance was consistent with VDOT's *AASHTOWare Pavement ME User Manual*, which adopts a 0.26-inch limit on the total rutting at year 15 (VDOT, 2017). Cracking performance was evaluated by comparing the predicted damage with that of typical VDOT control mixtures benchmarked under the same factors (Habbouche et al., 2025). The Top %Damage was chosen for this analysis because it mostly corresponds to the damage incurred by the surface mixture.

RESULTS AND DISCUSSION

Literature Review

Table 4 summarizes the comparison of methods identified in the literature for determining RBC, RBA, and DoA across several key considerations. The first consideration is whether the approach provides a clear basis for interpreting results relative to a known reference condition corresponding to 100% RBC, RBA, or DoA. The next three considerations relate to practical implementation. From an adoption standpoint, a method is advantageous if it (1) relies on standard laboratory equipment, thereby minimizing cost and training requirements; (2) emphasizes direct testing of RAP rather than requiring the preparation of mixtures or supplementary specimens, which increases sample preparation effort; and (3) avoids solvent extraction because of associated time, cost, and hazardous disposal concerns. Lastly, the method with the most references in each property category was identified and used as an evaluation metric. Other relevant considerations are also noted in Table 4.

Methods reported in the literature for determining RBC can be grouped into three categories: tracer-based techniques, volumetric mixture design comparisons, and performance-based approaches. Tracer-based methods most directly quantify the fraction of recycled binder that blends with virgin binder; however, their reliance on solvent extraction, the preparation of multiple mixtures, and specialized equipment limit practical implementation. Volumetric mixture design comparisons infer RBC by comparing the asphalt contents required to achieve a target air void level at a fixed compaction effort for virgin and RAP mixtures, with differences attributed to incomplete RAP binder contribution. Performance-based approaches estimate RBC by comparing measured RAP mixture performance with that of mixtures representing known or assumed RBC conditions, using fabricated mixtures or model predictions. Volumetric and performance-based approaches also impose extensive mixture sample preparation requirements and rely on less direct measures to infer RBC. Collectively, these limitations indicate that a method that is both reliable and readily implementable for the routine determination of RBC does not currently exist. Among available approaches, tracer-based microscopy has been most widely applied and is considered the most promising research tool despite its limited practicality for routine use.

Only one method was identified for quantifying RBA as defined in this review. This approach uses comparative sieve analysis of RAP and recovered RAP aggregate to infer the proportion of binder bound in agglomerated particles. The method requires testing of RAP alone, relies on standard laboratory equipment, and does not require solvent extraction, making it more practical than existing RBC methods. Moreover, studies report strong correlations between RBA and RBC at typical hot-mix production temperatures, supporting the potential use of RBA as a practical surrogate for RBC under certain conditions.

Methods for determining DoA fall into two categories: property changes with temperature and color-based approaches. The former evaluates changes in RAP characteristics, most commonly ITS, as a function of conditioning temperature. These methods are relatively practical, require testing of RAP alone, and avoid solvent extraction; however, they lack a clear reference condition corresponding to full activation. Color-based methods partially address this limitation by incorporating a reference condition for 100% activation, but they require the preparation of additional samples using recovered RAP aggregate and virgin binder and are subject to concerns related to segregation or subjectivity, depending on the specific approach used.

Table 4. Comparison of Laboratory Methods to Estimate Recycled Binder Contribution, Recycled Binder Availability, and Degree of Activity [a]

Method		Consideration					
		100% Condition Known	Relies on Standard Equipment	Requires Only RAP	Requires Solvent Extraction	Most References ?	Other
Recycled Binder Contribution							
Tracer-Based	Microscopy	Y	N	N	Y	Y	Requires variable pressure SEM equipped with EDS
	Aggregate	Y	Y	N	N	N	Only single size of RAP
	Glass Bead	Y	Y	N	Y	N	Limited glass size, content
Volumetric Design Comparisons		Y	Y	N	N	N	Assumes compactability is indicative of recycled binder contribution
Performance -Based	BMD Testing	Y	Y	N	Y	N	Extensive extraction and recovery
	Hirsch Model	Y	N	N	Y	N	Hirsch model is uncertain
Recycled Binder Availability							
Sieve Analysis		Y	Y	Y	N	Y	Assumes agglomerations sieved match those after mixing
Degree of Activation							
ITS		N	Y	Y	N	Y	Complementary use of ITS in NCHRP IDEA 245
DWT		N	N	Y	N	N	Pine compactors can perform with standard equipment
Fragmentation Tendency		N	Y	Y	N	N	Not correlated with binder properties
COAC	COAC	Y	Y	N	N	N	Used by GDOT to establish COAC
	Greyscale Analysis	N	N	Y	N	N	Sensitivity to scanner used unknown
	Light Intensity	Y	N	N	N	N	Loose samples segregate

BMD = balanced mix design; COAC = corrected optimum asphalt content; DWT = Dongre workability test; EDS = energy dispersive spectroscopy; GDOT = Georgia Department of Transportation; ITS = indirect tensile strength; N = no; NCHRP = National Cooperative Highway Research Program; RAP = reclaimed asphalt pavement; SEM = scanning electron microscopy; Y = yes. [a] Cells highlighted in red indicate a negative attribute to the test method, and cells highlighted in green indicate a positive attribute to the test method.

The literature review was also used to identify material and processing factors that affect RBC, RBA, and DoA. Across the literature, finer RAP gradations and processing practices that reduce agglomeration, such as crushing and abrasion, generally increase RBA, although such processing practices may also generate excessive dust. DoA consistently increases with temperature up to an apparent optimum, beyond which excessive thermal exposure may reduce effective activation because of oxidative aging. Prolonged conditioning and mixing can further enhance activation if oxidation is controlled. Higher RAP binder PGs are generally associated with lower activation under a given set of mixture production conditions. Although some studies suggest that gradation, AC, and RAs influence activation, trends are inconsistent and somewhat sparsely documented, indicating potentially marginal effects or strong interactions with other mixture variables. Consistent with these findings, higher mixing temperatures, softer virgin and RAP binders, reduced RAP agglomeration, and the use of RAs generally promote higher RBC, whereas the effects of RAP content and RAP binder content remain inconsistent across studies.

Based on the literature review, several key knowledge gaps relevant to this project were identified:

- **Lack of a practical method to determine RBC:** A practical and readily implementable method to determine RBC was not identified in the literature. Most existing approaches require specialized equipment, extensive sample preparation, and, in many cases, solvent extraction and binder recovery. In contrast, methods for determining RBA and DoA are generally more practical. Consequently, a more viable strategy for mixture design may be to use RBA and/or DoA measurements as predictors of RBC.
- **Limited comparisons across RBA, DoA, and RBC measurements:** Direct comparisons among RBA, DoA, and RBC for the same mixtures are scarce. Although some studies report good agreement between RBA and RBC, these investigations are largely limited to laboratory-prepared hot-mix asphalt mixtures without RAs. Additional research is needed to better quantify the relationships and interactions among RBA, DoA, and RBC across a broader range of materials and production conditions.
- **Limited evaluation of the effects of recycling agents:** A small number of studies suggest that RAs may enhance binder activation and contribution. However, given the wide variety of RAs available and the potential for complex interactions among RAs, RAP materials, and virgin binders, further research is needed to further evaluate their effects.

Laboratory Evaluation of Component Materials

Virgin and Extracted and Recovered Asphalt Binders

Table 5 presents the PG results for the virgin and RAP binders evaluated. For the virgin binder B7, relatively high continuous PG results were observed, with a high continuous high-temperature performance grade (HPG_c) of 62.5°C nearing the 64°C PG, and the continuous low-temperature PG of –27.7°C nearing the requirements for a –28°C binder. For the RAP binders, HPG_c ranged from 83.3°C to 99.5°C. It is worth noting that, although VDOT specification assumes a HPG of 88°C for RAP binders for mix design purposes, the average HPG_c for the RAP binders in Table 5 is equal to 91°C. Notably, previous VTRC studies with different RAP sources showed that RAP binder HPG$_c$ ranged from 78.0°C to 111.2°C, with an average of 98.2°C (Boz et al., 2025).

Table 5. Virgin and Reclaimed Asphalt Pavement Binders Performance Grade Results

Binder	HPG$_c$	IPG$_c$	LPG$_c$	PG (AASHTO M 320)
B4[a]	66.7	20.4	– 24.9	64–22
B5[a]	65.8	19.9	– 25.1	64–22
B6[a]	66.3	21.1	– 23.7	64–22
B7	62.5	13.8	– 27.7	58–22
R4[a]	86.6	32.0	– 11.4	82–10
R5[a]	99.5	34.3	– 3.3	94+02
R6[a]	94.2	35.3	– 9.7	94–04
R7	83.3	32.0	– 15.0	82–10
R8	90.7	38.8	– 12.6	88–10
R9	88.5	32.6	– 15.7	88–10
R10	93.4	37.7	– 11.1	88–10
R11	86.5	33.8	– 13.7	82–10
R12	96.4	42.7	– 8.1	94–04

B = virgin binder; HPG$_c$ = continuous high-temperature performance grade; IPG$_c$ = continuous intermediate-temperature performance grade; LPG$_c$ = continuous low-temperature performance grade; PG = performance grade; R = reclaimed asphalt pavement. [a] Obtained from Phase I of this study.

Gradation of Reclaimed Asphalt Pavement Recovered Aggregates

Figure 5a presents the RAP BC gradations for the nine RAP stockpiles in Virginia, and Figure 5b shows the corresponding RAP WC gradations. Substantial variability is observed among the RAP stockpiles. Furthermore, a comparison of Figures 5a and 5b shows that the BC gradations are notably coarser than the WC gradations. A more detailed analysis of these gradation differences is presented in the next section.

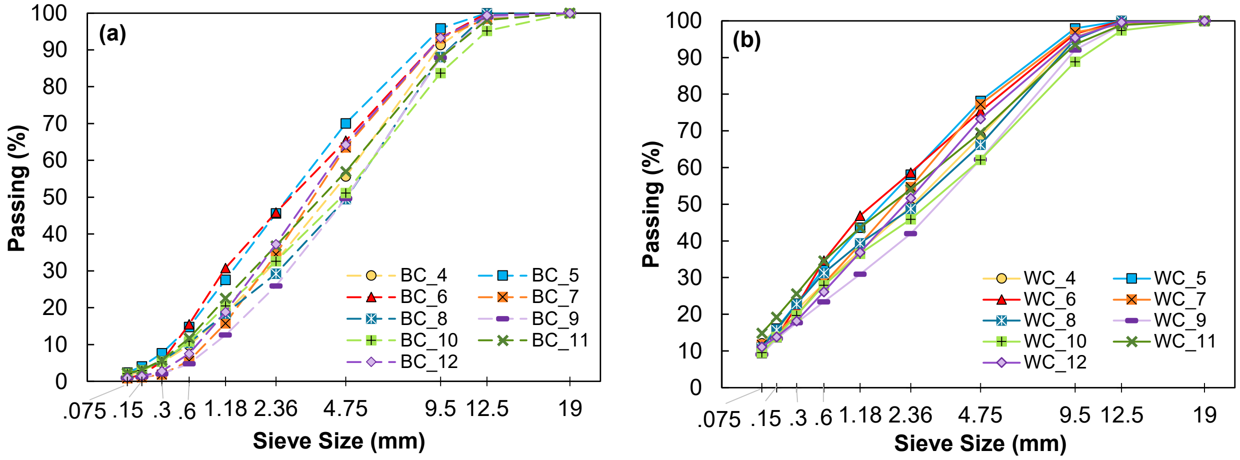


Figure 5. Reclaimed Asphalt Pavement Gradations (a) Black Curves and (b) White Curves. BC = black curve; WC = white curve.

Quantification of Recycled Binder Availability, Activity, and Contribution

Recycled Binder Availability

Figure 6 shows the RBA results obtained through the sieve analysis method and the AC for each RAP source. The overall average RBA across all sources was 59.5%, and the variability between replicate RBA results ranged from 0.5% (Source 8) to 2.8% (Source 11). Among the nine sources, Source 5 exhibited the highest RBA (73.5%), and Source 9 showed the lowest RBA (41.4%).

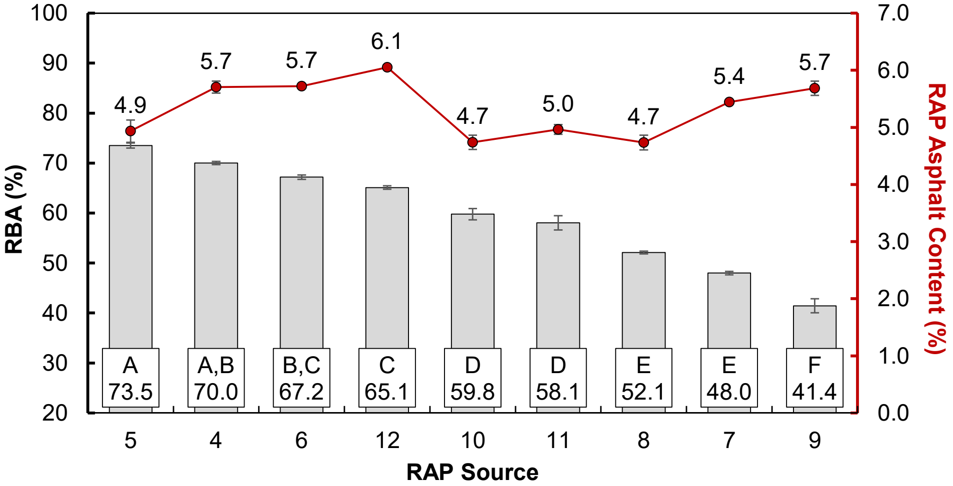


Figure 6. RBA and Asphalt Content Results for RAP Materials with Post-hoc Tukey-Kramer's Honestly Significant Difference Grouping Results for RBA. Error bars indicate the maximum and minimum values among replicates. RAP = reclaimed asphalt pavement; RBA = recycled binder availability.

Statistical tests were conducted at a significance level of 0.05 to assess the significance of differences in RBA results among RAP sources. Bartlett's test indicated no significant difference in variance among the sources (p-value = 0.723). A one-way analysis of variance (ANOVA) revealed that the RAP source has a statistically significant effect on the mean RBA. To further distinguish differences among sources, a post-hoc Tukey-Kramer Honestly Significant Difference (HSD) test was conducted at a 0.05 significance level. Six distinct groups were identified (A to F), and a partial overlap was observed among Groups A, B, and C. These findings highlight notable variability in RBA among RAP stockpiles in Virginia. Although some group averages align closely with the overall mean RBA of 59.5%, others differ substantially. Notably, Group F exhibits an RBA approximately 18% less than the overall average RBA, suggesting potential limitations of applying a fixed RBA factor for all mixtures containing RAP.

For better visualization, the WC and BC gradation curves of the RAP materials in Figure 5 were further clustered in accordance with the Tukey-Kramer's HSD statistical groupings (A to F), as shown in Figures 7a through 7e. The maximum density line for the maximum aggregate size of the WC is also shown as a point of reference. Note that in some cases, the maximum aggregate size of the BC and WC for a given RAP differs. Group B, from the Tukey-Kramer's HSD analysis, is omitted because the sources in Group B are also covered in either Group A or C. The RBA results of each source are conveyed in parentheses within the graph legends.

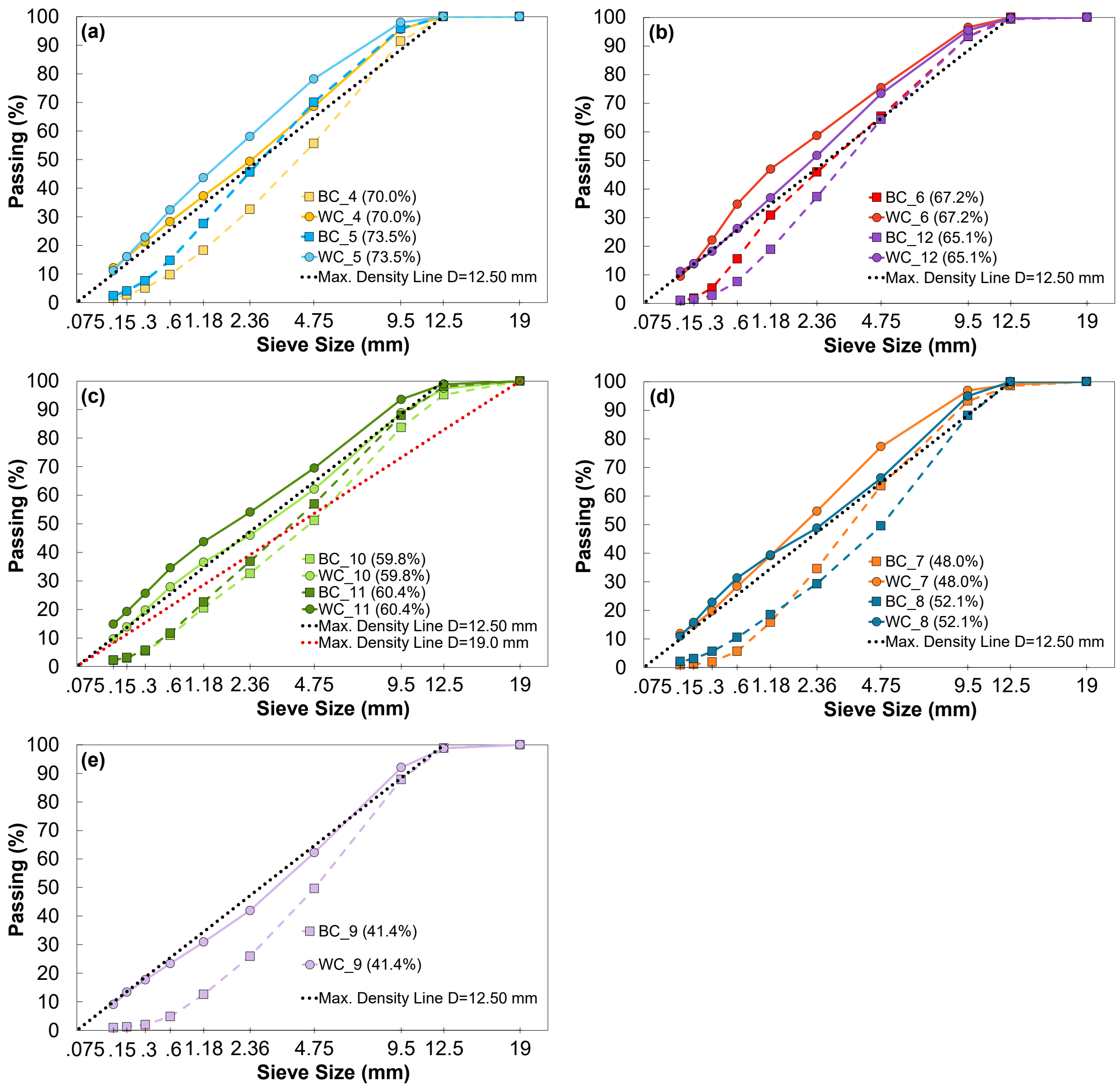


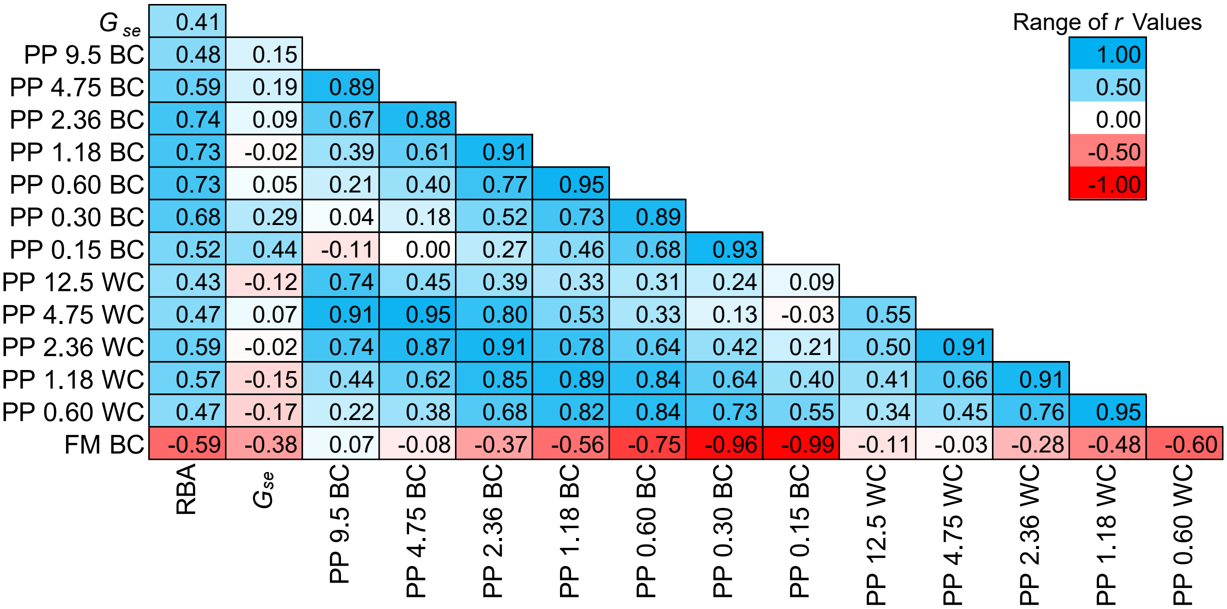
Figure 7. Black Curve and White Curve Gradations Organized by Post-hoc Tukey-Kramer's Honestly Significant Difference Groupings: (a) Group A; (b) Group C; (c) Group D; (d) Group E; (e) Group F. BC = black curve; WC = white curve.

For an individual RAP stockpile, the closer the BC and WC are, the less agglomerated the RAP is, an indicator typically associated with higher RBA. Figure 7 shows that although the overall gradations within a given group may vary, the differences between BC and WC across sieve sizes tend to be more similar within each group. However, comparing the proximity of BC and WC across different RAP sources does not reliably indicate RBA because RBA is influenced not only by particle agglomeration but also by the overall RAP gradation.

BCs tend to converge to 100% passing as the sieve sizes approach the NMAS (9.5 mm or 12.5 mm depending on the source) and maximum aggregate size. For finer sieve sizes, groups with higher RBA (A, B, and C) tend to exhibit higher percent passing values, indicating overall finer gradations. In contrast, the groups with lower RBA (D, E, and F) generally coincide with overall coarser gradations. Similar to past studies (Pape et al., 2022; Fonseca da Costa et al., 2024), the results herein suggest that BCs exhibit relatively little material passing the 0.075-mm sieve, suggesting that RAP particles maintain a peripheral mastic coating. In contrast, WCs show considerable variability in percent passing the 0.075-mm sieve.

A correlation analysis was conducted to investigate the relationship between RAP composition and RBA. The RAP compositional parameters evaluated included AC, G_{se}, HPG, and gradation parameters. Gradation parameters from both BC and WC were considered, including fineness modulus (FM), uniformity coefficient (C_u), percent passing (PP) at each sieve size, and individual percentage retained on each sieve (IR). FM was determined in accordance with AASHTO T 27, *Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates* (AASHTO, 2023). Both Pearson's correlation coefficient and Spearman's rank correlation coefficient were calculated. Pearson's correlation coefficient (r) assesses linear relationships, whereas Spearman's correlation coefficient evaluates monotonic relationships regardless of linearity. The results from both methods were generally consistent. For brevity, Spearman's correlation coefficient results are shown in the Supplemental Materials file.

Figure 8 presents Pearson's r values, including correlations among the compositional parameters with RBA. The r value ranges from −1 (negative correlation) to +1 (positive correlation), with zero suggesting no correlation between parameters. Figure 8 includes only parameters with r values of 0.4 or greater with RBA, commonly considered the threshold for a moderate association (Dancey and Reidy, 2017). In addition, because the percent passing and individual percentage retained at most sieve sizes are highly correlated, Figure 8 shows only the percent passing results.



	RBA	G_{se}	PP 9.5 BC	PP 4.75 BC	PP 2.36 BC	PP 1.18 BC	PP 0.60 BC	PP 0.30 BC	PP 0.15 BC	PP 12.5 WC	PP 4.75 WC	PP 2.36 WC	PP 1.18 WC	PP 0.60 WC
G_{se}	0.41													
PP 9.5 BC	0.48	0.15												
PP 4.75 BC	0.59	0.19	0.89											
PP 2.36 BC	0.74	0.09	0.67	0.88										
PP 1.18 BC	0.73	-0.02	0.39	0.61	0.91									
PP 0.60 BC	0.73	0.05	0.21	0.40	0.77	0.95								
PP 0.30 BC	0.68	0.29	0.04	0.18	0.52	0.73	0.89							
PP 0.15 BC	0.52	0.44	-0.11	0.00	0.27	0.46	0.68	0.93						
PP 12.5 WC	0.43	-0.12	0.74	0.45	0.39	0.33	0.31	0.24	0.09					
PP 4.75 WC	0.47	0.07	0.91	0.95	0.80	0.53	0.33	0.13	-0.03	0.55				
PP 2.36 WC	0.59	-0.02	0.74	0.87	0.91	0.78	0.64	0.42	0.21	0.50	0.91			
PP 1.18 WC	0.57	-0.15	0.44	0.62	0.85	0.89	0.84	0.64	0.40	0.41	0.66	0.91		
PP 0.60 WC	0.47	-0.17	0.22	0.38	0.68	0.82	0.84	0.73	0.55	0.34	0.45	0.76	0.95	
FM BC	-0.59	-0.38	0.07	-0.08	-0.37	-0.56	-0.75	-0.96	-0.99	-0.11	-0.03	-0.28	-0.48	-0.60

Figure 8. Pearson's Correlation Coefficients (*r*). BC = black curve; FM = fineness modulus; G_{se} = effective aggregate specific gravity; PP = percent passing; RBA = recycled binder availability; WC = white curve.

The parameter most strongly correlated with RBA is the BC percent passing the 2.36-mm sieve, with r = 0.74. Notably, this sieve is the primary control for the RAP materials evaluated because all have NMAS values of 9.5 mm or 12.5 mm. Moderate to strong positive correlations are also observed for the BC percent passing at other sieve sizes. These positive correlations indicate finer gradations are generally associated with higher RBA. The BC fineness modulus shows a moderate and statistically significant negative correlation with RBA ($r = -0.59$), reinforcing that coarser RAP gradations are associated with lower RBA. This relationship is attributed to the presence of RAP agglomerations that coarsen the BC gradation and simultaneously trap RAP binder, making it unavailable for blending.

Correlations between RBA and the WC parameters are generally weaker than those observed with the corresponding BC parameters, highlighting the importance of BC measurements in characterizing RBA variation among stockpiles. AC showed a weak correlation with RBA ($r = 0.20$), whereas G_{se} showed a moderate, positive correlation with RBA ($r = 0.41$). These findings suggest that BC gradation characteristics are influential compositional variables affecting RBA.

Asphalt plant producers were surveyed to document their RAP stockpiling, crushing, and screening practices. The survey responses were compiled in Table 6 and subsequently analyzed. Plants reported accepting various RAP sources, including secondary roads (Source 6), interstates (Source 12), private facilities (Source 7), and unused plant mix (Sources 8, 9, and 11). The plants also reported that after obtaining the RAP materials that they homogenized their RAP stockpiles in most cases by mixing their material with excavators before initiating any crushing process. Only Sources 6 and 9 reported mixing RAP again after crushing, and Source 10 did not specify. Crushing frequency varied, with some plants performing it daily (Sources 4, 5, 7, and 8), and others crushed RAP as needed or depending on storage capacity. All sources that specified their crushing method use a horizontal impact crusher. Sources 6 and 12 did not specify their crushing method. Crushing was either performed in house or outsourced. Sources 4, 5, 7, and 8 conducted their own crushing, and the remaining plants outsourced or did not specify.

After crushing, plants reported that the RAP is screened to remove overly coarse RAP particles and impurities such as debris or organic matter. Material retained on the screen is then processed through the crusher again. The crushing screen size varied among plants: Sources 4 and 5 use a 12.5-mm screen; Sources 6, 10, 11, and 12 use a 14.3-mm screen; and the remaining plants use a 16.0-mm screen. In addition, Sources 8 and 12 reported processing oversized RAP through a secondary belt that feeds into an inline crusher, which then reintroduces the further crushed RAP into the plant. Sources 6, 8, 9, and 11 reported post-crushing homogenization of the RAP whenever it is moved. Some plants also reported screening RAP upon feeding it into the plant to further mitigate oversized particles, with screen sizes ranging from 12.5 to 16.0 mm.

The influence of commonly shared practices among material suppliers on RBA, such as crushing method, could not be assessed because these practices exhibited little variability across producers. Similarly, information on post-crushing homogenization was insufficient to determine any relationship to RBA. A multiple linear regression analysis was performed incorporating the remaining variables, including homogenization with excavators prior to crushing, use of in-line crushers, crushing in house versus outsourcing, crushing frequency, and screen size. Among these variables, only the crusher screen size demonstrated a statistically significant relationship with RBA, with a p-value of 0.002 and below the 0.05 significance level.

Table 6. Summary of Producers' RAP Stockpiling, Crushing, and Screening Practices

Material/Process	Detail	RAP Source								
		4	5	6	7	8	9	10	11	12
RAP Source	Variable	✓	✓	✓	✓	✓			✓	
	Secondaries			✓						
	Private Works				✓					
	Plant Waste					✓	✓			
	Interstates									✓
Homogenization of Stockpiles with Excavators	Before Crushing	✓	✓	✓	✓	✓	✓		✓	✓
	After Crushing			✓			✓			
Crushing Frequency	Daily	✓	✓		✓					
	As Required			✓		✓				
	Once or Twice a Year						✓		✓	✓
Crushing Method	Horizontal Impact Crusher	✓	✓		✓	✓	✓	✓	✓	
Crushing Contractor	In house	✓	✓		✓	✓				
	Outsourced			✓			✓		✓	✓
Crushing Screen Size (mm)		12.5	12.5	14.3	16.0	16.0[a]	16.0	14.3	14.3	14.3[a]
Post-crushing Homogenization				✓		✓	✓		✓	
Screen Size Prior to Entering the Plant (mm)					25.0	14.3		25.0, 14.3[b]	9.5	31.5

✓ = activity conducted by producer; RAP = reclaimed asphalt pavement. [a] Oversized RAP is processed through a secondary belt that feeds into an inline crusher. [b] Source 10 uses an upper 25.0-mm screen and a bottom 14.3-mm screen. Blank cells represent either activity not conducted or information not provided by producer.

Figure 9 presents the RBA results as a function of post-crushing screen size, demonstrating that larger screen sizes are associated with lower RBA. Figure 9 also shows the Tukey-Kramer HSD groupings from Figure 6 to illustrate the alignment between screen size with RBA groups. RAP sources with higher RBA values (Group A) typically use a 12.5-mm screen size. Sources in Groups C and D, which exhibited intermediate RBA values, were processed with a 14.3-mm screen. Lastly, groups with the lowest RBA values used a screen size of 16.0 mm. These findings suggest that smaller screen sizes reduce the amount of agglomerated particles and, in turn, increase RBA.

Collectively, the analysis of producers' processing practices and RAP gradation characteristics indicates that larger post-crushing screen sizes generally yield coarser BC gradations that are associated with increased agglomeration and lower RBA. This finding might suggest that extensive crushing and screening could break down agglomerations and potentially increase RBA. However, crushing operations must be carefully controlled to limit aggregate degradation and excessive dust generation. These factors are critical to ensure that the processed RAP can still be incorporated into asphalt mixtures that meet gradation specifications and maintain an appropriate fines-to-asphalt (FA) ratio (West, 2015). Given that screen size varied among RAP sources, additional analyses are warranted with additional RAP materials to isolate the screen size effect and confirm its impact on RBA.

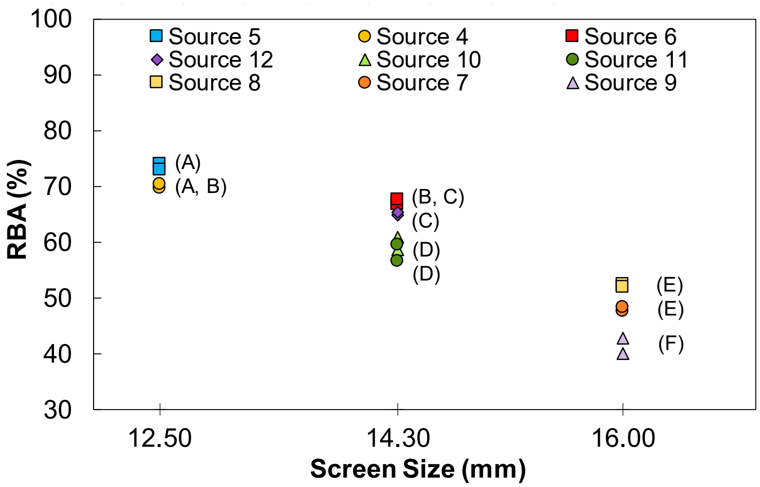


Figure 9. RBA as a Function of Crusher Screen Size. Letters in parentheses represent Tukey-Kramer's Honestly Significant Difference statistical groupings based on RBA values. RBA = recycled binder availability.

Multiple linear regression was conducted to assess the ability to estimate RBA from compositional variables and crusher screen size. Equation 7 presents the resulting predictive model. The predictor variables were selected from the RAP compositional and screen size attributes, with multicollinearity evaluated using a correlation matrix to ensure statistical independence. Several gradation parameters derived from the BC were initially considered, given their observed correlation with RBA. However, these variables exhibited strong collinearity with the crusher screen size and were excluded from the final model because they would require measuring the BC gradation, whereas crusher screen size would not impose any new characterization requirements. Among the resulting parameters considered, the G_{se} and the crusher screen size emerged as the most significant predictors of RBA. As previously discussed, G_{se} demonstrated a moderate positive correlation with RBA, suggesting that RAP with denser aggregates may enable greater mobilization of aged binder. However, Equation 7 suggests a negative relationship between RBA and G_{se}, suggesting that when screen size is accounted for, the effect of G_{se} is actually negative, implying lower aggregate density is associated with higher RBA. Similarly, finer crusher screen sizes, identified in previous sections as the only processing practice with a statistically significant effect, are associated with increased RBA.

$$RBA = 377.2 - 64.8 \times G_{se} - 10.4 \times Screen\ Size \qquad \text{[Eq. 7]}$$

Where:
RBA = recycled binder availability (%),
G_{se} = RAP effective specific gravity, and
$Screen\ Size$ = RAP crusher screen size (mm).

Figure 10 shows a strong agreement between measured and estimated RBA values with an adjusted R^2 of 92%. Note that all estimated RBA values are within ±10% of the line of equality. Although these results may highlight the potential for predicting RBA as a practical alternative to direct measurements, additional analysis including independent validation is needed to confirm the broader applicability of Equation 7, particularly given that the observed relationships may not extend to other crushing methods and RAP aggregate characteristics not included in this study.

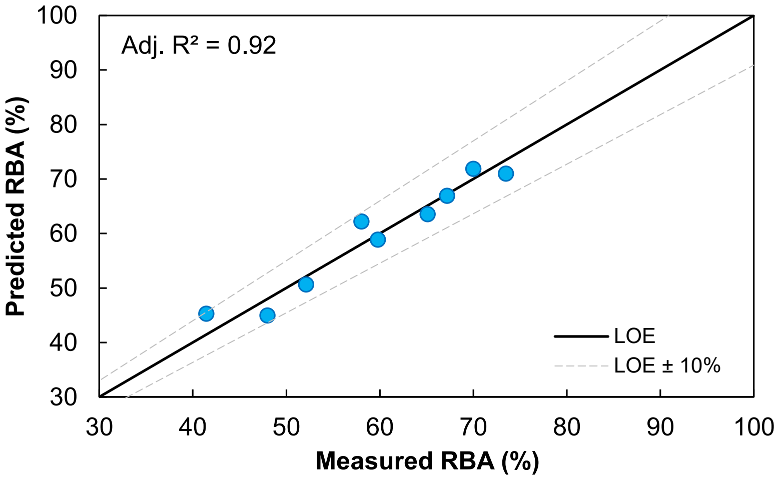


Figure 10. Measured versus Predicted Values of RBA from the Regression Models Using Aggregate Specific Gravity and Screen Size as Predictors. Adj. = adjusted; LOE = line of equality; RBA = recycled binder availability.

Recycled Binder Contribution

RBC measurements were obtained using tracer-based microscopy for nine mixtures, including six reference mixtures (B7R4, B7R5, B7R6, B5R7, B5R11, and B5R12) prepared with different RAP sources and three RA-modified mixtures (B4R4RA6, B5R5RA7, and B6R6RA8). Figure 11 shows the RBC results along with the corresponding RBA results for comparison.

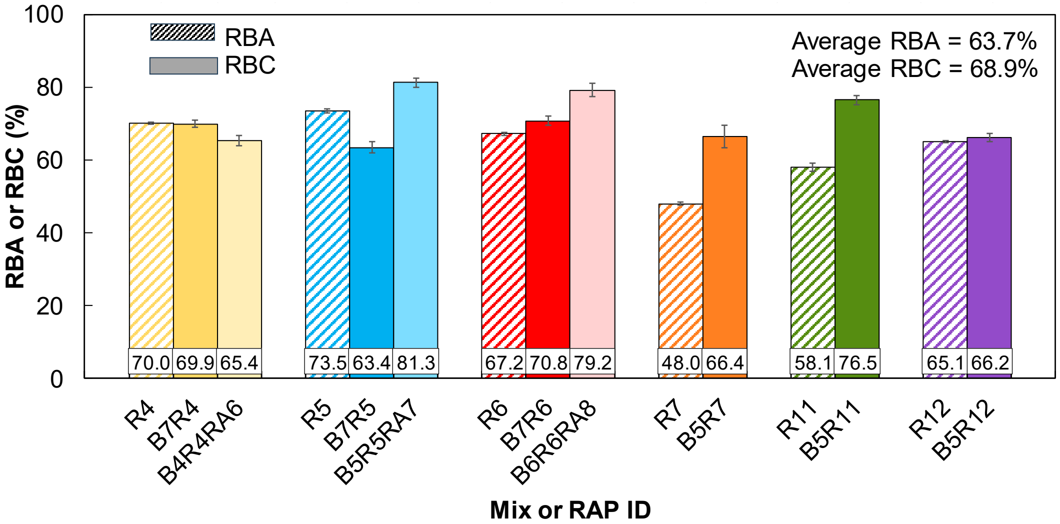


Figure 11. RBA and RBC Results for Mixtures B7R4, B4R4RA6, B7R5, B5R5RA7, B7R6, B6R6RA8, B5R7, B5R11, and B5R12. B = binder; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability; RBC = recycled binder contribution.

The RBC values of the reference mixtures spanned from 63.4% to 76.5%, representing a narrower range than the corresponding RBA values, which spanned from 48.0% to 73.5%. In general, the RBC values of the reference mixtures were higher than the corresponding RBA values, with the exception of RAP Sources 4 and 5. On average, RBA across the RAP sources was 63.7%, whereas the average RBC of the reference mixtures was 68.9%. Note that, given that RBC was not calculated for all RAP sources, the average RBA in this section refers to the six RAP sources for which RBC was also measured (63.7%) rather than the previously calculated average among all nine RAP sources (59.5%). For Sources 4, 6, and 12, the differences between reference mixture RBC values and RAP RBA values differ by less than 4%. However, differences are notably larger for Sources 5, 7, and 11.

The RA-modified mixtures prepared with RAP Sources 5 and 6 exhibited higher RBC values than their respective reference mixtures, suggesting that RA7 and RA8 may have increased RBC. In contrast, the RA-modified mixture prepared with RAP Source 4 exhibited an RBC value less than the measured RBA and the corresponding reference mixture RBC. Given that the reference and the RA-modified mixtures include different virgin binder grades (i.e., PG 58-22 for B7 and PG 64S-22 for B4, B5, and B6), differences between reference and RA-modified mixtures' RBC values cannot be attributed solely to the presence of RA. It is worth noting that the reference mixtures used for RBC determination were selected because they represent a potential mix design strategy using a softer virgin binder that would be more likely considered in practice. This observation is based on anecdotal evidence that suggests that a reference mixture with a softer virgin binder may help offset the effects of the recycled asphalt from the 40% RAP content compared with a control mix with PG 64S-22 virgin binder. For this reason, the experimental plan did not include a control mix with 40% RAP, PG 64S-22, and no RA.

Additional analyses were conducted to evaluate the practical effect on the interpreted mixture AC when different binder availability parameters are used. To quantify this effect, the available RAP binder content was calculated by multiplying the RAP AC measured by solvent extraction by the corresponding binder availability measure (RBA or RBC). This available RAP binder content was then converted to an equivalent percentage of the total mixture mass based on the RAP proportion in each mixture. For instance, for a RAP with RBA of 60%, 60% of the RAP binder was added to the virgin binder mass and volume to determine the total mixture binder content, and the remaining 40% of the RAP binder was considered unavailable and incorporated into the aggregate mass and volume when calculating volumetric properties, AC, and RBR.

Absolute differences between the interpreted mixture AC (termed ΔAC) using different binder availability measures were calculated using Equation 8 under three different scenarios: source-specific RBA versus mixture-specific RBC (Scenario 1); average RBC versus mixture-specific RBC (Scenario 2); and reference mixture RBC versus RA-modified mixture RBC (Scenario 3). Scenario 1 aims to evaluate the potential practical impact of using either source-specific RBA or RBC on the interpreted mixture composition. Scenario 2 aims to compare the effect of source-specific or fixed RBC values on the interpreted mixture composition given the narrower range of RBC values across different mixtures. Scenario 3 aims to assess whether the differences in RBC measurements between reference and RA-modified mixtures have a significantly practical impact on the interpreted mixture composition.

$$\Delta AC = |AC_{Measure\ X} - AC_{Measure\ Y}| \qquad \text{[Eq. 8]}$$

Where:

ΔAC = absolute difference between interpreted mixture AC,
$AC_{Measure\ X}$ = interpreted mixture AC using binder availability measure *X*,
$AC_{Measure\ Y}$ = interpreted mixture AC using binder availability measure *Y*, and
X, *Y* = RBA or RBC measures obtained under different scenarios (1 to 3).

Table 7 presents the corresponding ΔAC values for the three scenarios. For instance, RAP Source 5 has an RBA of 73.5% and a RAP binder content of 5.90%. These values indicate that 4.34% (RBA × RAP binder content = 0.735 × 5.90) of the RAP binder is added to the virgin binder mass and volume to determine the total mixture AC, whereas the remaining 1.56% of the RAP binder is considered unavailable and incorporated into the aggregate mass and volume when calculating volumetric properties, AC, and RBR. The effective RAP binder content is then recalculated as an equivalent percentage of the total mixture weight. For Scenario 1, assuming RBA (73.5%) results in a RAP binder content of 1.70%, whereas assuming RBC (69.9%) reduces the RAP binder content to 1.46%. The difference between these values is 0.24% (Table 7). Results highlighted with red shading represent ΔAC values exceeding 0.21%, which corresponds to the typical VDOT's process control tolerance limit for AC during production when eight tests are performed per 4,000-ton lot (VDOT, 2020). Therefore, ΔAC values below 0.21% were considered practically insignificant.

Table 7. Evaluation of the Practical Impact of Different Binder Availability Assumptions on the Interpreted Asphalt Content of the Mixture [a]

Source	Scenario 1			Scenario 2			Scenario 3		
	Source-specific RBA	Source-specific RBC	Absolute ΔAC	Average RBC	Source-specific RBC	Absolute ΔAC	Reference Mixture RBC	RA-Modified RBC	Absolute ΔAC
4	70.0	69.9	0.00	68.9	69.9	0.02	69.9	65.4	0.10
5	73.5	63.4	0.24	68.9	63.4	0.13	63.4	81.3	0.43
6	67.2	70.8	0.09	68.9	70.8	0.05	70.8	79.2	0.21
7	48.0	66.4	0.27	68.9	66.4	0.04	-	-	-
11	58.1	76.5	0.32	68.9	76.5	0.13	-	-	-
12	65.1	66.2	0.02	68.9	66.2	0.05	-	-	-

- = RA-modified mixture was not evaluated for these sources; ΔAC = absolute difference in the interpreted mixture asphalt content; RA = recycling agent; RBA = recycled binder availability; RBC = recycled binder contribution.

[a] Cells highlighted in red showed ΔAC values exceeding VDOT's process tolerance of 0.21% for eight tests.

For Scenario 1, the ΔAC values for three out of six mixtures (B7R4, B7R6, and B5R12) were below the practical significance threshold of 0.21%. The remaining mixtures (B7R5, B5R7, and B5R11) exhibited ΔAC values above 0.21% but below 0.33%, which represents the process tolerance limit for three tests performed during production per 4,000-ton lot. Despite the differences from the last three mixtures, previous studies reported high correlation with comparable values between RBA determined from sieve-based methods and RBC measured using tracer-based microscopy for mixtures incorporating the same RAP (Pape and Castorena, 2022a; Fonseca da Costa et al., 2024). Collectively, these studies include data from 18 RAP stockpiles: 14 from North Carolina and 4 from other states, including Maine, Texas, and Wisconsin.

To further evaluate the relationship between RBA and RBC in Scenario 1, the results obtained in this project were combined with the 18 data points from previous studies and plotted in Figure 12. A strong correlation was observed between RBA and RBC ($R^2 = 0.99$), supporting RBA as a predictor for RBC. The Virginia reference mixtures generally fall close to the envelope of variability established by prior studies, demonstrating consistency with past trends. The best-fit line across all data points has a slope of 1.07, suggesting that a central tendency for RBA values to be 7% less than RBC for a given RAP. It is speculated that the underprediction of RBC from RBA may be a consequence of the sieve analysis procedure failing to break all weak agglomerations that would likely break during mixture production. However, given the strong correlation between RBC and RBA, it may be feasible to calibrate a relationship to more accurately estimate RBC from RBA measurements. For instance, applying a multiplier of 1.07 to RBA values would reduce the average ΔAC value reported in Table 7. Nevertheless, because this study includes RBC measurements for mixtures incorporating only six RAP sources, development and validation of such a calibration approach requires evaluation using a broader and more diverse dataset within the state of Virginia before it can be recommended for practice.

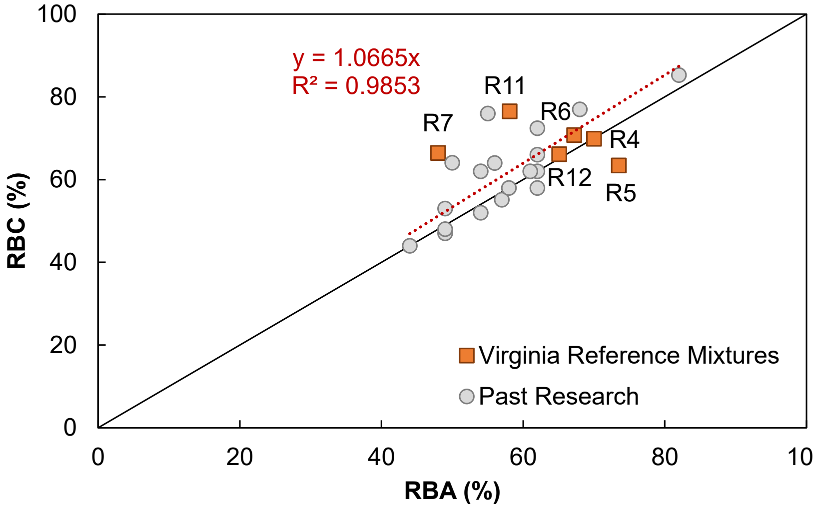


Figure 12. RBC versus RBA Measurements of Virginia Reference Mixtures and Past Research. R = reclaimed asphalt pavement; R^2 = coefficient of determination; RBA = recycled binder availability; RBC = recycled binder contribution.

For Scenario 2, ΔAC values were calculated to quantify the potential error associated with interpreting mixture AC using the average RBC across all reference mixtures (68.9%), rather than the mixture-specific RBC value. Table 7 shows that the ΔAC values are below the practical significance threshold of 0.21% for all mixtures. Although findings may suggest that adopting a fixed RBC may be reasonable, the RBC measurements in this study were limited to mixtures from only six different sources. Although promising, further evaluation using a broader and more diverse set of mixtures is warranted to confirm these findings.

For Scenario 3, the differences in RBC values between the reference and RA-modified mixtures were evaluated using the ΔAC values. Although Source 6 showed a ΔAC value equal to the practical significance threshold of 0.21%, Table 7 shows that Source 5 exceeded this limit. To verify whether these differences were significantly different, statistical analysis was conducted by comparing the RBC values between reference and RA-modified mixtures at a 0.05 significance level. First, Bartlett’s test was conducted to evaluate the homogeneity of variances in the RBC results. All mixtures met the equal variance assumption between reference and RA-modified mixtures, except for Source 6. For the statistical analysis, the mean RBC values between reference and RA-modified mixtures were compared using Student's t-tests (Sources 4 and 5) and Welch's t-test (Source 6). Although the mean RBC values for B7R4 and B4R4RA6 were statistically similar (p-value = 0.198), significantly different mean RBC values were observed for B7R5 versus B5R5RA7 and B7R6 versus B6R6RA, with p-values less than 0.001 in both cases. Despite the significant differences in RBC values for Sources 5 and 6 mixtures, the observed differences cannot be attributed solely to the RAs and may also reflect the influence of virgin binder properties.

Recycled Binder Degree of Activity

The degree of RAP binder activation was assessed for RAP Sources 4, 5, and 6. Figure 13 shows the corresponding ITS, DoA, and relationships to complementary L* color-based results for the 100% RAP samples. The reported conditioning temperatures correspond to the temperatures to which the RAP samples were preheated prior to mixing and compaction. All indirect tensile tests were conducted at 25°C. Recall, DoA is calculated as ITS at the temperature of interest normalized by the maximum individual ITS value observed among all replicates across all conditioning temperatures for the same RAP source. The maximum ITS values were 2,424 kPa, 2,977 kPa, and 2,280 kPa for Sources 4, 5, and 6, respectively. The letters in Figures 13a and 13b indicate the Tukey-Kramer's HSD groupings. Lowercase letters denote statistically significant differences among conditioning temperatures within a given RAP source, whereas uppercase letters identify significant differences in the mean values across all RAP sources at different conditioning temperatures.

Figure 13a shows that the ITS values increase with conditioning temperature for all RAP sources. This increase in ITS values could be associated with a higher DoA, but it may also be caused by binder stiffening due to aging at higher conditioning temperatures. Although differences in ITS values between specimens compacted at 120°C and those compacted at 155°C and 170°C were statistically significant, differences in ITS values across the compaction temperature span of 140°C to 170°C were often insignificant. In fact, the overall mean values across RAP sources did not differ significantly among 140°C, 155°C, and 170°C, suggesting a plateau in ITS and, thus, limited change in binder activation beyond 140°C. Source 5 consistently exhibited higher ITS values than the other sources, particularly at elevated temperatures, which may be attributed to its higher RAP binder HPG of 99.5°C and its lower binder content of 4.9% compared with those of Sources 4 and 6.

Figure 13b shows that the DoA values calculated based on the ITS results closely mirror the ITS trends, suggesting enhanced activation of the RAP binder at 155°C and 170°C compared with 120°C. Tukey-Kramer's HSD analysis demonstrates significant differences between the lowest and highest temperatures, with 120°C generally producing significantly lower DoA values than the higher conditioning temperatures. At 120°C, DoA values remained below 70% for all sources, whereas values exceeding 80% were generally observed at 155°C and 170°C. The main effect grouping indicates that 155°C and 170°C were statistically similar and yielded the highest degrees of activation. Source-dependent effects were also observed, with Source 6 generally exhibiting higher DoA values than Sources 4 and 5.

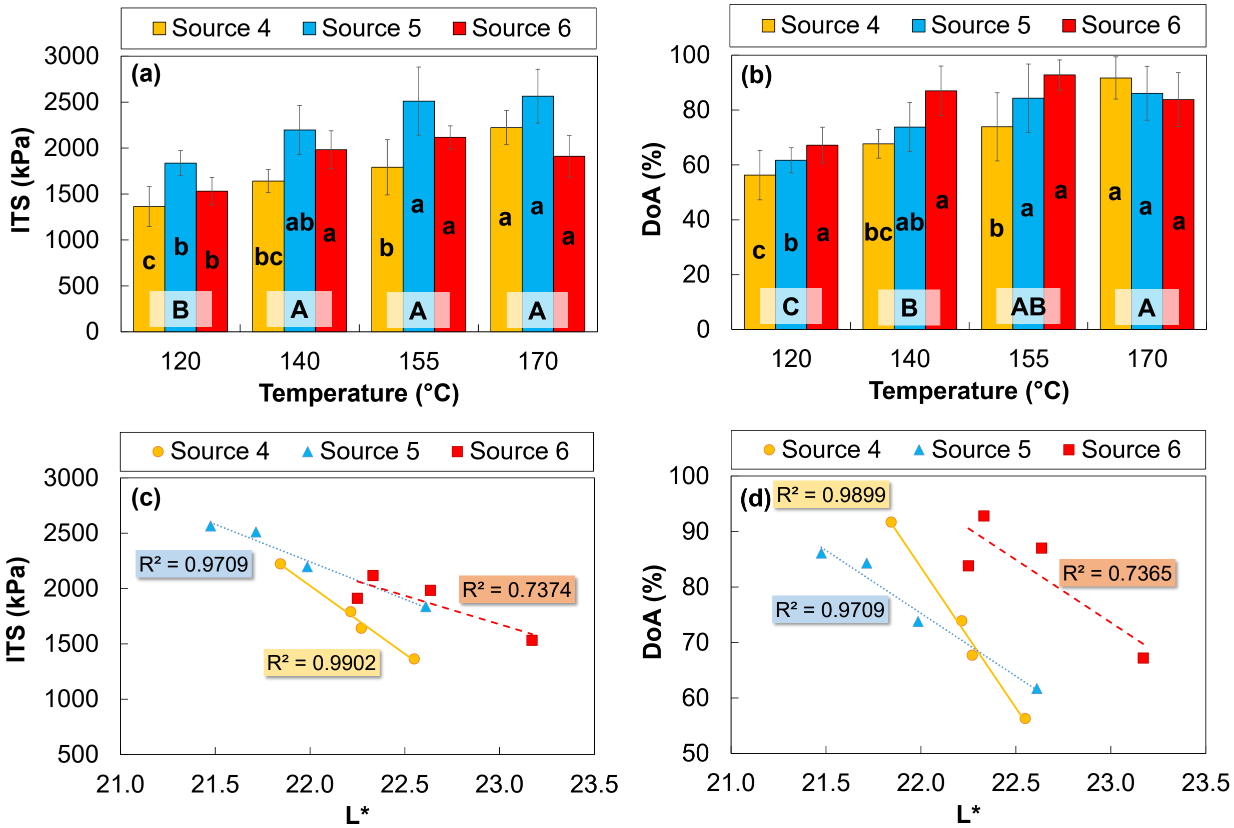


Figure 13. Results of: (a) ITS at Different Temperatures; (b) DoA at Different Temperatures; (c) Correlation between L* and ITS; (d) Correlation between L* and DoA for the 100% Reclaimed Asphalt Pavement Samples. Error bars represent ±1 standard deviation at each temperature. Lowercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for a given reclaimed asphalt pavement source at different temperatures. Uppercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for temperature means. DoA = degree of activity; ITS = indirect tensile strength; L* = lightness parameter.

Figures 13c and 13d show the relationships between the surface lightness parameter L* and the ITS and DoA values. Strong linear correlations are observed between L* and ITS for a given RAP source, particularly for Sources 4 and 5. Lower L* values correspond to darker colors associated with greater binder activation based on ITS and DoA results. Thus, the results suggest that increased surface brightness may be associated with incomplete coating, limited blending, or reduced contribution of the RAP binder to the effective binder phase. These results support the potential use of changes in L* with conditioning temperature as a practical surrogate indicator of RAP binder activation, providing complementary insight to the ITS results. However, it is noted that differences in L* measurements between the top and bottom of each sample are consistent across samples and sources, which may be attributed to the compaction equipment used and potential material segregation. Additional analysis on this regard is presented in detail in the Supplemental Materials file.

The collective results indicate that RAP binder activation is sensitive to conditioning temperature but is relatively stable between 140°C and 170°C. Because DoA is calculated by normalizing ITS values to the single highest specimen measurement rather than to a reference condition known to represent 100% activation, it is more appropriate to emphasize relative trends with temperature rather than absolute DoA values. Nonetheless, DoA may decrease at lower production temperatures, suggesting that increasing the conditioning temperature above 140°C does not result in additional effective activation of the RAP binder. Notably, past studies suggested that DoA can decrease from 140°C to 170°C (Abdelaziz et al., 2021; Sobieski et al., 2022), but they relied on a 4-hour conditioning period rather than the 2 hours used in this study. Findings in the literature indicate excessive temperatures may contribute to increased aging and potential performance degradation if subjected to prolonged exposure times.

Thus, given the consistently high DoA values between 140°C and 170°C and the strong correspondence between RBA and RBC measurements shown in previous sections of this report, the results suggest that an assumption of complete activation may be acceptable for hot mix asphalt, indicating that using RBA as an indicator of RBC is reasonable.

Effect of Recycled Binder Availability on Mixture Composition

Selected Reclaimed Asphalt Pavement Sources

The effect of RBA on the interpreted volumetric properties of the reference mixtures was evaluated across different RBA scenarios using JMF information. Six calculation scenarios were evaluated: (1) 100% RBA, reflecting VDOT's current practice and aligning with AASHTO R 35; (2) Average RBA (59.5%), calculated as the mean value obtained from the nine RAP stockpiles evaluated in this study and reflecting the potential adoption of a fixed RBA in practice; (3) Actual RBA per source, based on measured values for each RAP stockpile; (4) Calculated RBA, derived from multiple linear regression; (5) Minimum RBA, using the lowest RBA value of the stockpiles; and (6) Maximum RBA, using the highest RBA value of the stockpiles. In each scenario, virgin asphalt binder content was kept the same and equal to the source-specific OBC from the corresponding mix design. Recall that the RBA is accounted for by treating the unavailable portion of the recycled binder as part of the bulk aggregate structure.

Figure 14 shows the calculated AC, VMA, voids filled with asphalt (VFA), and RBR under the six different RBA scenarios. The mixture labels in Figure 14 reflect the RAP source and content. As an example, R5-40 corresponds to the JMF incorporating RAP from Source 5 at 40% content by weight of total mixture. The horizontal lines in Figure 14 represent the minimum and maximum limits specified by VDOT for each property and mix designation. The results indicate that assuming 100% RBA leads to an inflated interpretation of total AC, particularly in mixtures with higher RAP content (i.e., greater than 30%). This overestimation stems not from inherently lower RBA values in these sources but from the higher RAP content. In the 100% RBA scenario, all mixtures comply with the minimum AC tolerance limits; however, in the Actual RBA scenario, many mixtures are below the limit, such as R4-40, R6-40, R5-40, R7-26, and R12-30.

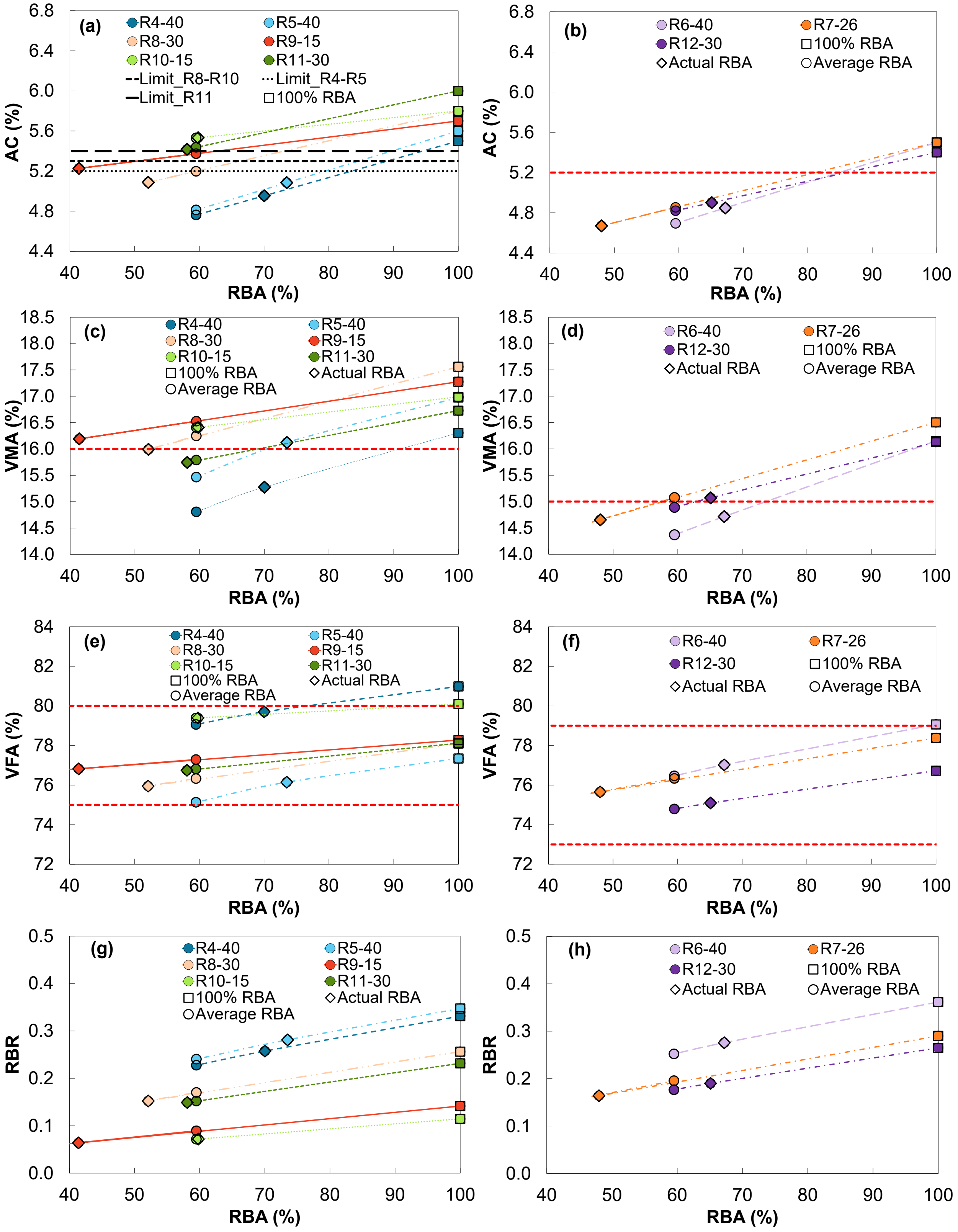


Figure 14. Effect of Reclaimed Asphalt Pavement RBA on Mixture Composition for: (a) AC for 9.5-mm NMAS Mixtures; (b) AC for 12.5-mm NMAS Mixtures; (c) VMA for 9.5-mm NMAS Mixtures; (d) VMA for 12.5-mm NMAS Mixtures; (e) VFA for 9.5-mm NMAS Mixtures; (f) VFA for 12.5-mm NMAS Mixtures; (g)

RBR for 9.5-mm NMAS Mixtures; (h) RBR for 12.5-mm NMAS Mixtures. Red dashed lines represent volumetric limits in accordance with VDOT specifications (VDOT, 2020). AC = asphalt content; NMAS = nominal maximum aggregate size; RBA = recycled binder availability; RBR = recycled binder ratio; VFA = voids filled with asphalt; VMA = voids in the mineral aggregate.

The decrease in total AC when considering the Actual RBA consequently lowers the calculated VFA values compared with the 100% RBA scenario, bringing them closer to or below the specification thresholds in some cases. This reduction in the calculated VFA suggests that when accounted for the actual RBA, the mixture may contain inadequate binder to fill voids between aggregates, which could increase susceptibility to cracking or raveling. VMA also shows sensitivity to RBA assumptions, especially in the 9.5-mm NMAS mixtures, with actual RBA scenarios resulting in a reduction in the calculated VMA values compared with the 100% RBA. When the Actual RBA values are used, some mixtures fail the minimum specification limits, such as R4-40, R5-40, R6-40, R9-15, R10-15, and R12-30. This failure in the calculated VMA with Actual RBA is a result of the fact that the effective binder volume calculated with 100% RBA is larger than with the Actual RBA. In terms of RBR, the RBR values under the 100% RBA assumption are substantially greater than the other scenarios, suggesting that a larger fraction of binder in the mix is derived from RAP. However, when the Actual RBA is used, RBR values decrease, indicating that a significantly smaller proportion of the total binder is being contributed by the RAP. Mixtures with 9.5-mm NMAS exhibited greater sensitivity to RBA than those with 12.5 mm, with more pronounced VMA reductions attributed to increased surface area and AC.

The Average RBA scenario generally yielded calculated volumetric properties closer to those using the Actual RBA condition than the 100% RBA condition, resulting in the same assessment as passing or failing established requirements as the Actual RBA scenario in most cases. However, although this average value can serve as a practical alternative to reduce the risk of significantly overestimating RBA, it does not consistently yield accurate results because the variability across different RAP sources is not captured.

To further compare the RBA scenarios, Figure 15 shows the absolute differences in the volumetric parameter values when calculated using the 100% RBA, Average RBA, and Calculated values relative to Actual RBA. Recall that the Calculated values are the ones estimated from the RBA predictive equation. It can be seen that the AC increase from the 100% RBA to the Actual RBA assumption ranged from 0.27% to 0.83%, with an average of 0.56%. In addition, the results demonstrate that the 100% RBA assumption consistently leads to the largest differences across all evaluated volumetric parameters. These deviations are especially pronounced in mixtures with 30% or higher RAP content, for which assuming 100% RBA results in a significantly higher estimation of total AC and correspondingly lower estimate of aggregate content. Although mixture R9-15 contains a lower RAP content, it still showed considerable differences in calculated properties, particularly VMA. This result can be attributed to its very low RBA value and highlights that even low-RAP mixtures can be sensitive to RBA.

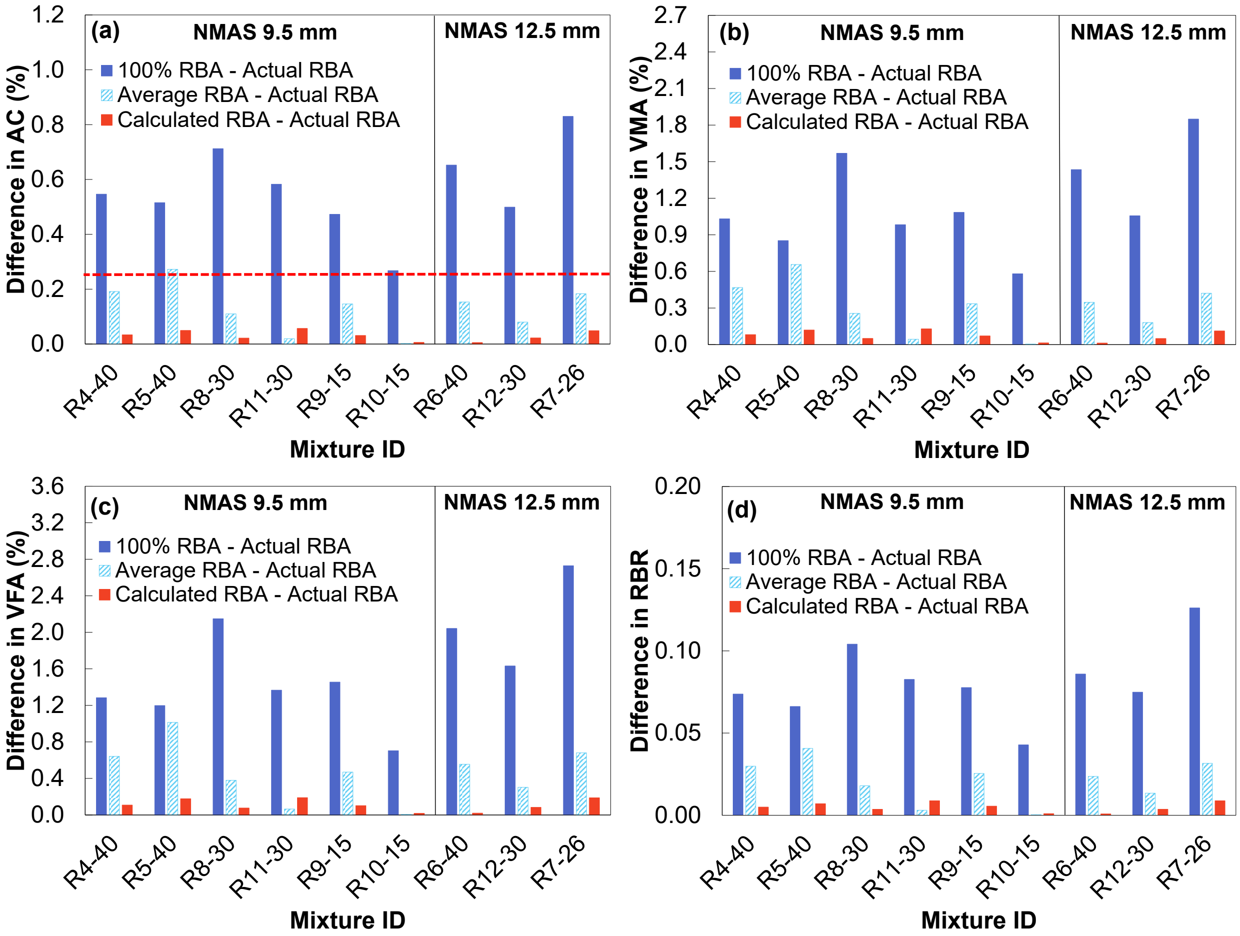


Figure 15. Absolute Differences in Volumetric Parameters when Calculated Using the 100% RBA, Average RBA, and Calculated Values Relative to Actual RBA for: (a) AC; (b) VMA; (c) VFA; (d) RBR. AC = asphalt content; NMAS = nominal maximum aggregate size; RBA = recycled binder availability; RBR = recycled binder ratio; VFA = voids filled with asphalt; VMA = voids in mineral aggregate.

The absolute differences in properties calculated using the Calculated versus Actual RBA values are minimal. These results suggest that the regression model offers a potential alternative to source-specific RBA measurements. However, the reported differences may underestimate potential deviations in practice because they were derived from the same sources used to calibrate the regression model. Therefore, further evaluation is warranted to validate the model using an independent dataset.

In contrast, the use of a fixed RBA equal to the average across all sources, or the Average RBA scenario, results in notably lower differences. For both NMAS levels, the average RBA approach shows errors in the interpreted AC that falls below 0.21%, with the exception of the mixture R5-40 case. Recall that 0.21% corresponds to the VDOT's process control tolerance for AC during production when eight tests are performed from each 4,000-ton lot, indicating the differences are generally practically insignificant for the study mixtures. However, it is important to note that mixture R9-15 includes the RAP source with the greatest deviation from the average RBA, yet it has a relatively low RAP content.

Figure 16 presents the absolute differences in key volumetric properties calculated when using the Minimum (41.4%) and Maximum (73.5%) RBA values relative to the Average RBA for each mixture. The results indicate that mixtures with higher RAP content and larger NMAS tend to exhibit greater potential differences in the interpreted volumetric properties from assuming the Average RBA across all properties. Differences are negligible for the mixtures with 15% RAP content (i.e., R9-15 and R10-15). For AC, the differences remain below 0.4% with some exceeding the 0.21% threshold used in process control noted previously. Similar patterns are observed for VMA and VFA, with differences observed as high as 0.8% and 1.4%, respectively, suggesting the potential risks of adopting the Average RBA in practice. In contrast, the potential differences in the RBR if the Average RBA is used are relatively small and below 0.1%, suggesting a limited effect on these specific properties.

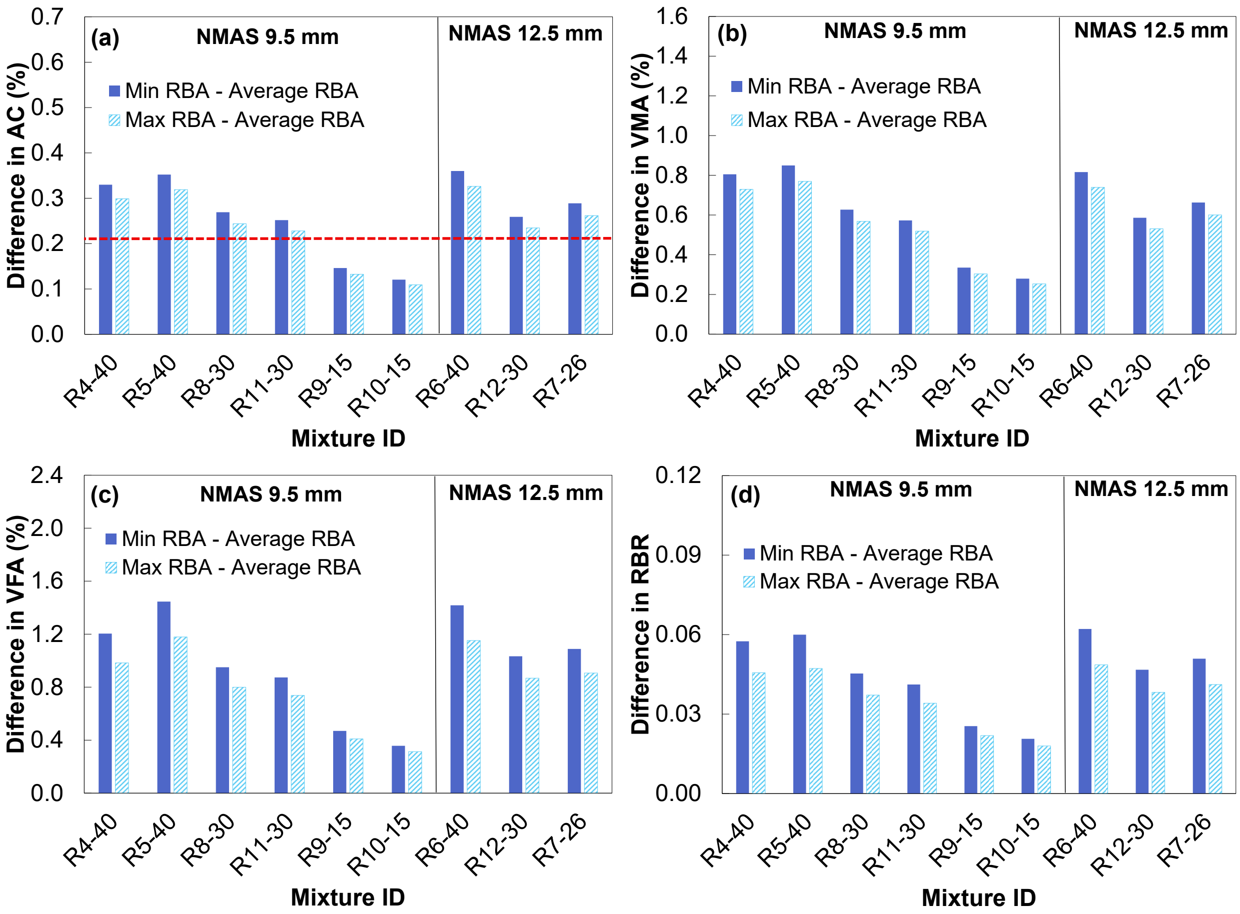


Figure 16. Absolute Differences between Minimum RBA and Maximum RBA Assumptions versus Actual RBA for: (a) AC; (b) VMA; (c) VFA; (e) RBR. AC = asphalt content; RBA = recycled binder availability; RBR = recycled binder ratio; VFA = voids filled with asphalt; VMA = voids in mineral aggregate.

These findings underscore that while adopting a fixed RBA for mixtures with relatively low RAP content (15%) may lead to negligible differences, it may lead to considerable differences in mixtures with higher RAP content (e.g., greater than 30%). In addition, because aggregate stockpile proportions may have up to 5% variation between design and production stages without a new mix design being requested, adopting a fixed RBA may pose challenges during production, especially when variation to these proportions occurs. These observations indicate that accounting for RBA variability among stockpiles may be beneficial for asphalt mixtures with higher RAP content. RBA has direct relevance to volumetric mixture design and VDOT's current BMD protocol, which still requires volumetrics compliance. Adopting a fixed RBA may lead to considerable errors in the interpreted mixture composition, especially at higher RAP contents.

VDOT Statewide 2024 Balanced Mix Design Production Data

The effect of adopting different RBA assumptions was further evaluated using a VDOT statewide 2024 BMD production dataset. The database yielded 207 and 52 records for producers and districts, respectively. The database was further used to evaluate the effect of different RBA scenarios on the interpreted volumetric properties distribution and their relationship to IDT-CT outcomes.

Tables 8 and 9 show the percentage of mixtures from the producer and district datasets that meet the volumetric requirements (i.e., AC, VMA, VFA, and FA ratio) under the different RBA assumptions for mixtures with 9.5- and 12.5-mm NMAS. The percentage of mixtures that meet all volumetric properties (all criteria) is also shown for reference purposes. To illustrate the data distribution for each volumetric parameter and different RBA assumptions, Figures 17 through 20 present boxplots for AC, VMA, VFA, and FA ratio, respectively. The information in Tables 8 and 9 and Figures 17 through 20 is discussed throughout this section for each volumetric parameter.

Asphalt Content

Figure 17 shows the distributions of AC for producer and district results under the four RBA scenarios. A clear and systematic effect of RBA on the distribution of AC values is observed, with the highest values corresponding to those calculated under the 100% RBA scenario and the lowest calculated under the Minimum RBA scenario, and Average and Maximum RBA exhibit intermediate levels. Tukey-Kramer's HSD test revealed significant differences across all scenarios for both the producer and district datasets. The similar patterns observed for producers and districts suggest consistent data and interpretations across datasets.

Higher assumed binder availability increases the interpreted binder content of the mixture. Consequently, the current practice of assuming 100% RBA may overestimate AC by an average of approximately 0.5%, based on the comparison between the 100% RBA and average RBA scenarios in Figure 17. The magnitude of AC variation among RBA scenarios has important practical implications for mixture performance and reliability. Inaccurate assumptions regarding binder availability may lead to suboptimal designs, especially for mixtures containing higher recycled AC.

Table 8. Percentage of Production Sublots Meeting Volumetrics Requirements for 9.5-mm Nominal Maximum Aggregate Size Mixtures

Scenario (RBA)	AC (%)		VMA (%)		VFA (%)		FA Ratio (%)		All Criteria (%)[a]	
	Producer	District	Producer	District	Producer	District	Producer	District	Producer	District
100% RBA	97.6	100.0	97.6	100.0	100.0	100.0	100.0	95.8	95.1	95.8
Avg. RBA (59.5%)	26.8	25.0	76.8	66.7	100.0	100.0	85.4	66.7	19.5	8.3
Min. RBA (41.4%)	3.7	0.0	63.4	66.7	100.0	100.0	69.5	54.2	2.4	0.0
Max. RBA (73.5%)	57.3	41.7	85.4	87.5	100.0	100.0	87.8	83.3	43.9	33.3

AC = asphalt content; Avg. = average; FA = fines-to-asphalt; Max. = maximum; Min. = minimum; RBA = recycled binder availability; VMA = voids in mineral aggregate; VFA = voids filled with asphalt. [a] Represents the percentage of mixtures simultaneously satisfying the AC, VMA, VFA, and FA ratio specification requirements under each RBA scenario. Specification limits used were minimum VMA = 16%, VFA = 70–85%, FA ratio = 0.7–1.3, and minimum AC based on G_{sb} aggregates, according to VDOT Balanced Mix Design Special Provision.

Table 9. Percentage of Production Sublots Meeting Volumetrics Requirements for 12.5-mm Nominal Maximum Aggregate Size Mixtures

Scenario (RBA)	AC (%)		VMA (%)		VFA (%)		FA Ratio (%)		All Criteria (%)[a]	
	Producer	District	Producer	District	Producer	District	Producer	District	Producer	District
100% RBA	99.2	100.0	100.0	100.0	92.8	96.4	99.2	100.0	92.0	96.4
Avg. RBA (59.5%)	39.2	53.6	95.2	96.4	100.0	100.0	81.6	92.9	37.6	50.0
Min. RBA (41.4%)	12.8	21.4	81.6	85.7	100.0	100.0	70.4	89.29	12.0	21.4
Max. RBA (73.5%)	74.4	78.6	96.0	100.0	99.2	100.0	89.6	96.4	63.2	75.0

AC = asphalt content; Avg. = average; FA = fines-to-asphalt; Max. = maximum; Min. = minimum; RBA = recycled binder availability; VFA = voids filled with asphalt; VMA = voids in mineral aggregate. [a] Represents the percentage of mixtures simultaneously satisfying the AC, VMA, VFA, and FA ratio specification requirements under each RBA scenario. Specification limits used were minimum VMA = 15%, VFA = 68–84%, FA ratio = 0.7–1.3, and minimum AC based on G_{sb} aggregates, according to VDOT Balanced Mix Design Special Provision.

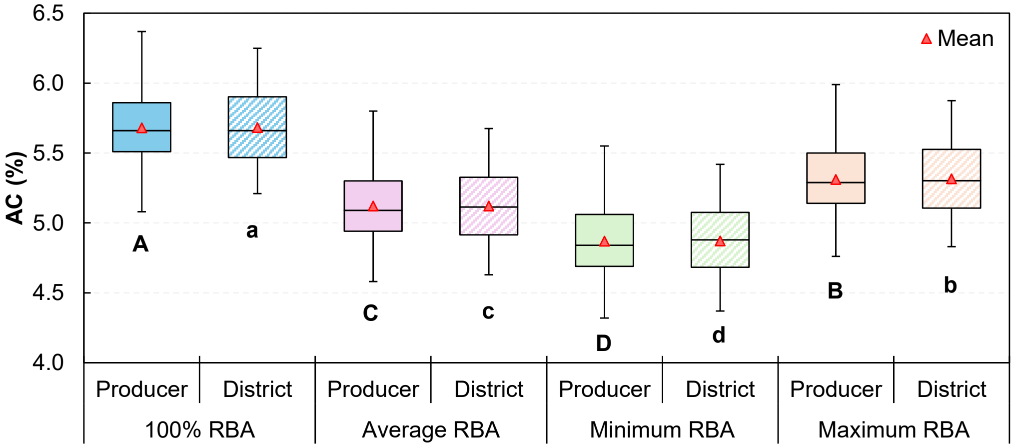


Figure 17. Boxplots of AC for Producer and District Mix Designs under Different RBA Scenarios. Lowercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for district data. Uppercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for producer data. Solid and hashed boxplots represent producers and districts' data, respectively. Whiskers represent maximum and minimum AC values. AC = asphalt content; RBA = recycled binder availability.

Across both NMAS sizes, the percentage of mixtures meeting the minimum AC requirements decreased as more conservative RBA assumptions were applied, as shown in Tables 8 and 9. For the 9.5-mm mixtures, compliance decreased from approximately 97% to 100% under the 100% RBA scenario to as low as 0% to 4% under the Minimum RBA scenario, and intermediate compliance levels of 25% to 57% were observed under the Average and Maximum RBA scenarios. A similar trend was observed for the 12.5-mm mixtures, for which compliance ranged from approximately 99% to 100% at 100% RBA to a range of 13 to 21% under the Minimum RBA scenario. Despite these reductions, mixtures that satisfy AC requirements were observed across all evaluated RBA scenarios, demonstrating that some existing JMFs would remain volumetrically compliant even when partial RBA is considered.

Voids in Mineral Aggregate

Figure 18 shows the distributions of VMA values as a function of RBA scenario, revealing trends similar to AC. Assumptions of lower RBA lead to lower interpreted VMA values, which is the result of the unavailable binder being attributed to the bulk aggregate volume. Tukey-Kramer's HSD test results indicate statistically significant differences among the RBA scenarios evaluated, with partial overlap observed in district data. The observed variation has potentially important implications for durability and performance because lower VMA may reduce binder film thickness and increase cracking susceptibility. VMA compliance exhibited trends consistent with those observed for AC. Table 8 showed that for the 9.5-mm mixtures, the percentage of compliant mixtures decreased from a range of approximately 98% to 100% under the 100% RBA scenario to a range of 63% to 67% under Minimum RBA, and the Average and Maximum scenarios showed intermediate compliance levels of 85% to 88%. For the 12.5-mm mixtures, Table 9 showed that VMA compliance remained comparatively high, generally exceeding 81% across all RBA scenarios. These results indicate that although VMA interpretation is influenced by RBA, a substantial proportion of existing mixtures satisfy specification limits even when accounting for less than 100% RBA.

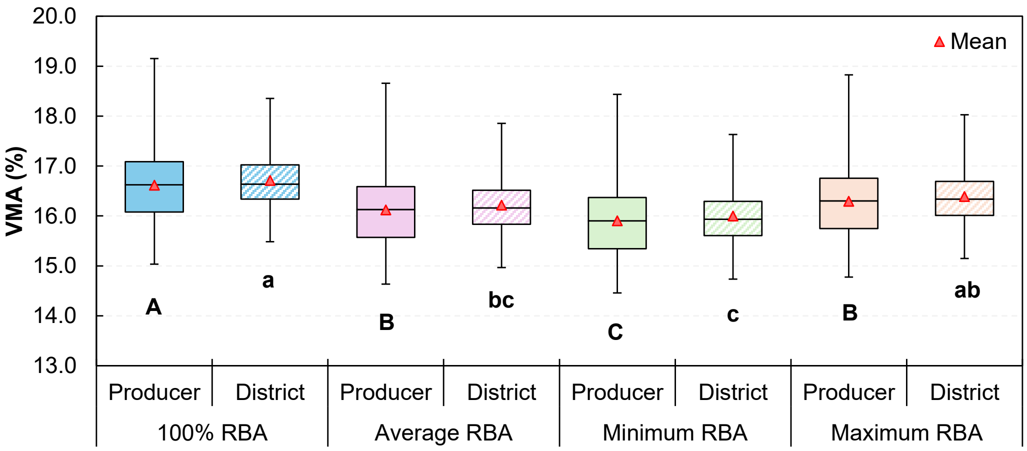


Figure 18. Boxplots of VMA for Producer and District Mix Designs under Different RBA Scenarios. Lowercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for district data. Uppercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for producer data. Solid and hashed boxplots represent producers and districts' data, respectively. Whiskers represent maximum and minimum VMA values. RBA = recycled binder availability; VMA = voids in mineral aggregate.

Voids Filled with Asphalt

Figure 19 presents the distribution of VFA values under the four RBA scenarios. VFA values show relatively small variation across the RBA scenarios, with most scenarios exhibiting similar central tendencies. Tukey-Kramer's HSD test results indicated limited statistical discrimination among RBA scenarios, particularly for the district data, suggesting that VFA is less sensitive to changes in RBA than AC and VMA. Specification compliance levels in Tables 8 and 9 remained consistently high across all scenarios, with most cases exhibiting 100% compliance for both NMAS sizes. Even under conservative RBA assumptions, VFA compliance generally exceeded 92% to 100%.

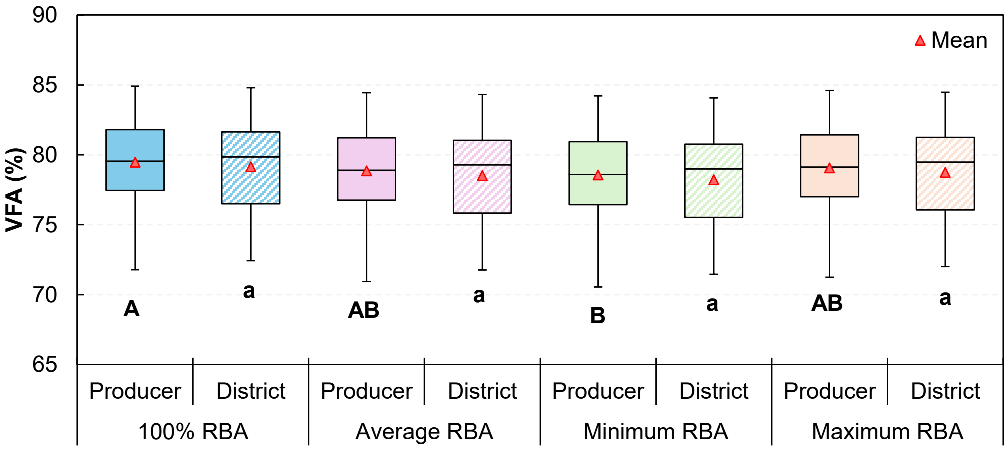


Figure 19. Boxplots of VFA for Producer and District Mix Designs under Different RBA Scenarios. Lowercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for district data. Uppercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for producer data. Solid and hashed boxplots represent producers and districts' data, respectively. Whiskers represent maximum and minimum VFA values. RBA = recycled binder availability; VFA = voids filled with asphalt.

Fines-to-Asphalt Ratio

Figure 20 shows the distributions of FA ratio values as a function of the RBA scenario. The data reveal sensitivity to the RBA scenario, with the lowest values corresponding to the 100% RBA scenario and the highest corresponding to the Minimum RBA condition. As RBA decreases, the FA ratio increases for a given mixture because of a decrease in the effective binder content. Tukey-Kramer's HSD results indicate significant differences across most RBA scenarios, confirming the FA ratio's sensitivity to the assumed RBA. Findings are generally consistent across the producers and districts' datasets. Specification compliance with FA ratio requirements in Tables 8 and 9 were moderately sensitive to RBA assumptions. For the 9.5-mm mixtures, compliance decreased from a range of approximately 96% to 100% under 100% RBA to a range of 54% to 70% under Minimum RBA, and the Average and Maximum scenarios ranged from 67% to 88%. For the 12.5-mm mixtures, compliance remained relatively high but decreased from approximately 99% to 100% to values ranging near 70% to 89% under reduced RBA assumptions. Notably, mixtures meeting FA ratio requirements were still present across all evaluated scenarios.

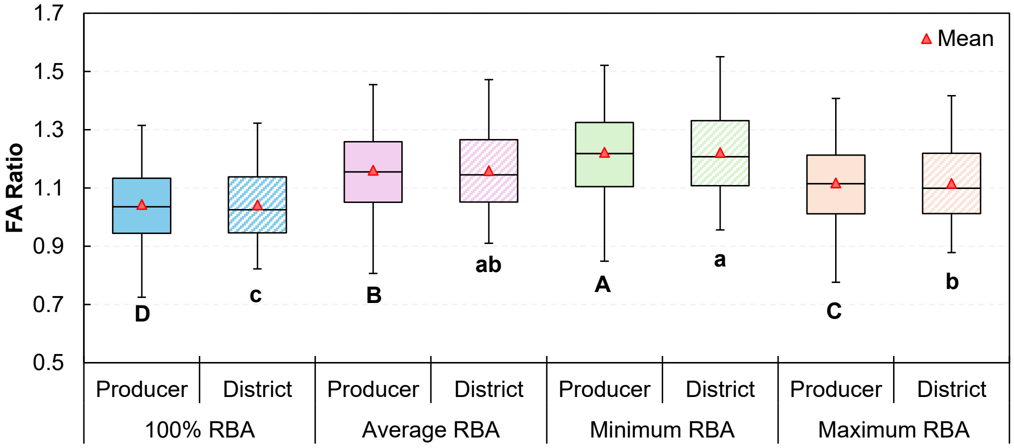


Figure 20. Boxplots of FA Ratio for Producer and District Mix Designs under Different RBA Scenarios. Lowercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for district data. Uppercase letters represent Tukey-Kramer's Honestly Significant Difference test groupings for producer data. Solid and hashed boxplots represent producers and districts' data, respectively. Whiskers represent maximum and minimum FA values. FA = fines-to-asphalt; RBA = recycled binder availability.

When all volumetric requirements were considered simultaneously, Tables 8 and 9 show that specification compliance decreased with increasingly conservative RBA assumptions but did not disappear. For the 9.5-mm mixtures, compliance ranged from approximately 95% to 96% under 100% RBA to a range of 0% to 2% under Minimum RBA, and intermediate scenarios yielded compliance between 8% and 44%. For the 12.5-mm mixtures, compliance varied from approximately 92% to 96% at 100% RBA to a range of 12% to 21% at Minimum RBA, with the Average and Maximum scenarios reaching 50% and 75%, respectively. These findings confirm that mixtures capable of meeting all volumetric requirements exist under every RBA scenario, emphasizing that adopting RBA in practice may not necessarily lead to changes to all VDOT mixture designs.

Relationship between Minimum Asphalt Content Compliance and IDT-CT Results

To evaluate the potential relationship between mixture volumetrics and performance results, CT_{Index} results for mixtures classified by compliance with the minimum AC requirement were compared across different RBA scenarios (Figure 21). Overall, the results indicate that when partial RBA is considered, mixtures that do not meet the minimum AC requirement tend to exhibit lower CT_{Index} values than those that do meet the minimum AC requirement. Statistical analysis further indicates that, for both producer and district datasets, the Minimum RBA scenario is the only condition in which no significant difference is observed in the mean CT_{Index} values between mixtures that pass and fail the minimum AC requirement. This result suggests that, under highly conservative assumptions of RBA, the interpreted effective AC is reduced, which may cause some mixtures to be classified as failing the minimum AC requirement despite exhibiting comparable cracking performance. For the remaining RBA scenarios, statistical differences were observed in mean CT_{Index} values between mixtures that passed or failed the minimum AC. This observation suggests that incorporating RBA may allow for an increase in virgin AC content, potentially improving the mixture's cracking resistance, provided that rutting tests confirm the mixtures are not susceptible to rutting. More information related to other volumetric parameters can be found in the Supplemental Materials file.

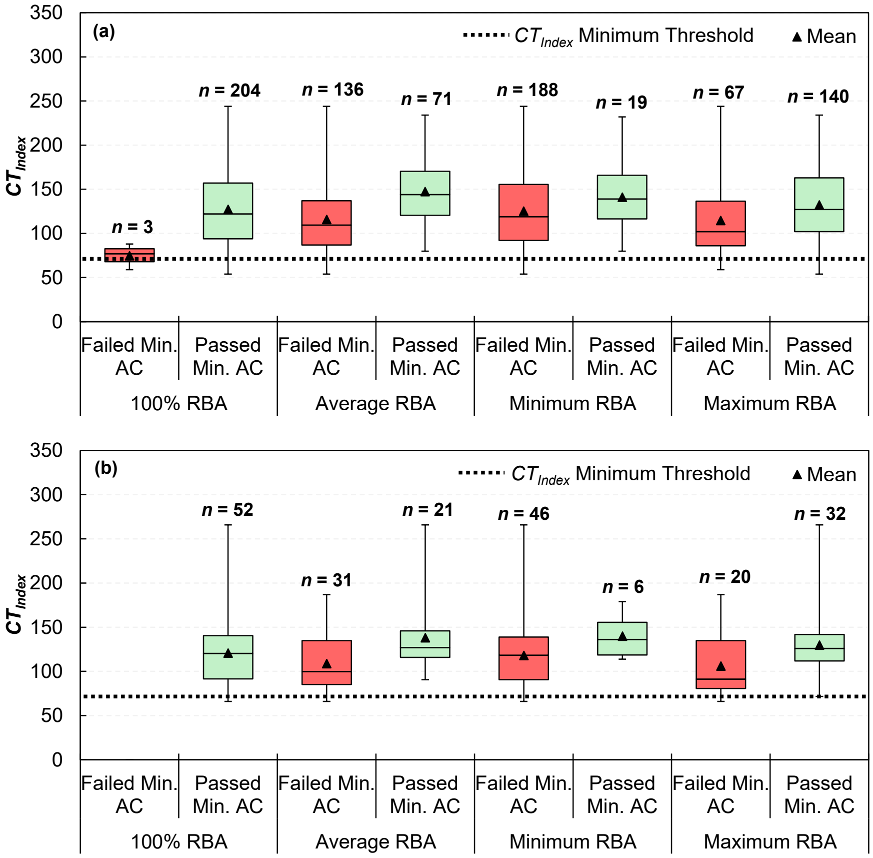


Figure 21. Boxplots of CT_{Index} for Mixtures Either Passing or Failing the Minimum AC Requirement under Different RBA Scenarios for (a) Producer and (b) District Data. Sample size (*n*) is shown for each group. Whiskers represent maximum and minimum CT_{Index} values. AC = asphalt content; CT = cracking tolerance; RBA = recycled binder availability.

Effect of Recycled Binder Availability on Asphalt Mixture Performance

Mixture Verification of Reference and Adjusted Mix Designs

Table 10 shows the reference and RA-modified mixture verification results for Sources 4, 5, and 7. Properties are shown under two RBA scenarios: 100% RBA and Actual RBA. The results indicate that mixtures from Sources 4, 5, and 7 satisfy the volumetric criteria under both RBA scenarios. Therefore, these mixtures did not require adjustment. Although the reference Source 4 and 5 mixtures did not fail volumetric criteria when RBA was applied, adjusted gradations were also tried for these mixtures to increase AC in an amount equal to the unavailable recycled binder content. However, the adjusted gradations yielded excessive VFAs that exceeded VDOT’s limits. This result suggests that not all VDOT mixtures may warrant adjustment for RBA. A detailed summary of the volumetric analyses for the adjusted Source 4 and 5 mixtures is provided in the Supplemental Materials file.

Tables 11 and 12 include the reference mixture verification results for Sources 6 (B7R6) and 11 (B5R11), respectively. These mixtures did not initially meet certain specified volumetric criteria in the Actual RBA scenario, including minimum AC for B7R6 and both minimum AC and FA ratio for B5R11. Therefore, alternative mixture designs incorporating gradation adjustments to increase VMA and AC were developed. Figure 22 presents comparisons of the reference and adjusted gradations. Finer and coarser gradations were selected for Sources 6 and 11, respectively. The adjusted mixture designs are included in Tables 11 and 12 (i.e., B7R6_RBA and B5R11_RBA) and demonstrate that adjusting the gradations resulted in mixtures meeting the volumetric requirements even when accounting for RBA. As presented later in the report, reference and adjusted Source 6 and 11 mixtures failed to meet minimum STOA CT_{Index} requirements. Therefore, RAs or softer virgin binders were incorporated using the adjusted gradations as an additional means to improve cracking performance. Tables 11 and 12 also include the properties of these mixtures (i.e., B6R6RA8_RBA, B5R11_RBA, and B5R11RA6_RBA). The binder adjustments had only marginal effects on volumetric properties. The B6R6RA8_RBA mixture incorporated the same RA8 dosage used in this project’s Phase 1 (Kuchiishi et al., 2025). For the B5R11RA6_RBA mixture, although the dosage and compatibility of RA6 were not evaluated in accordance with either the RA supplier’s recommendations or the performance-based methodology verified in this project’s Phase 1, it was used to further explore the potential improvement in asphalt mixture performance.

Table 10. Mixture Verification Results of Source 4, 5, and 7 Mixtures

Mixture ID	Limits for Sources 4 and 5/ Source 7[c]	B7R4		B4R4RA6[a]		B7R5		B5R5RA7[a]		B5R7	
Scenario		100% RBA	Actual RBA[b]	100% RBA	Actual RBA[b]	100% RBA	Actual RBA[b]	100% RBA	Actual RBA[b]	100% RBA	Actual RBA[b]
RBA, %	-	100.0	70.0	100.0	70.0	100.0	73.5	100.0	73.5	100.0	48.0
AC, %	Min. 5.2/5.1	5.9	5.4	5.9	5.4	5.9	5.4	5.9	5.4	6.0	5.2
Rice SG (G_{mm})	-	2.696	2.696	2.692	2.692	2.655	2.655	2.651	2.651	2.527	2.527
Agg. Effective SG (G_{se})	-	3.000	3.000	2.995	2.995	2.946	2.946	2.941	2.941	2.785	2.785
Agg. Bulk SG (G_{sb})	-	2.978	2.798	2.917	2.917	2.917	2.917	2.912	2.912	2.779	2.779
VTM, %	3.0–4.5%	3.9	3.9	3.9	3.9	4.0	4.0	3.9	3.9	4.2	4.2
VMA, %	Min. 16.0/15.0	18.1	17.6	18.1	17.6	17.8	17.3	17.7	17.3	18.1	17.4
VFA, %	75–80/73–79	78.7	78.1	78.7	78.1	77.5	76.9	78.0	77.1	76.8	75.9
Fines-to-Asphalt Ratio	0.7–1.3	1.01	1.12	1.01	1.12	1.08	1.19	1.08	1.19	0.98	1.13

AC = asphalt content; B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability; SG = specific gravity; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture. [a] Obtained in Phase I of this project. [b] Reclaimed asphalt pavement AC adjusted based on RBA. [c] Sources 4 and 5 correspond to SM-9.5A mixtures, and Source 7 corresponds to an SM-12.5D mixture type.

Table 11. Mixture Verification Results of Source 6 Mixtures

Mixture ID	Limits for Source 6	B7R6		B7R6_RBA		B6R6RA8[a]		B6R6RA8_RBA	
Scenario		100% RBA	Actual RBA[b]	100% RBA	Actual RBA[b]	100% RBA	Actual RBA[b]	100% RBA	Actual RBA[b]
RBA, %	-	100.0	67.2	100.0	67.2	100.0	67.2	100.0	67.2
AC, %	Min. 5.2	5.3	4.6	6.0	5.4	5.3	4.6	6.0	5.4
Rice SG (G_{mm})	-	2.489	2.489	2.464	2.464	2.486	2.486	2.465	2.465
Agg. Effective SG (G_{se})	-	2.703	2.703	2.704	2.704	2.700	2.700	2.706	2.706
Agg. Bulk SG (G_{sb})	-	2.700	2.700	2.701	2.701	2.697	2.697	2.703	2.703
VTM, %	3.0–4.5%	4.1	4.1	3.9	3.9	3.7	3.7	3.6	3.6
VMA, %	Min. 15.0	16.3	15.7	17.6	17.0	15.9	15.3	17.3	16.8
VFA, %	73–79	74.7	73.8	77.9	77.1	76.7	76.0	79.3	78.6
Fines-to-Asphalt Ratio	0.7–1.3	0.82	0.94	0.81	0.91	0.82	0.94	0.81	0.91

AC = asphalt content; Adj. = adjusted; B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability; SG = specific gravity; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture. [a] Obtained in Phase I of this project.
[b] Reclaimed asphalt pavement AC adjusted based on RBA.

Table 12. Mixture Verification Results of Source 11 Mixtures

Mixture ID	Limits for Source 11	B5R11		B5R11_RBA		B7R11_RBA		B5R11RA6_ RBA	
Scenario		**100% RBA**	**Actual RBA[a]**	**100% RBA**	**Actual RBA[a]**	**100% RBA**	**Actual RBA[a]**	**100% RBA**	**Actual RBA[a]**
RBA, %	-	100.0	58.1	100.0	58.1	100.0	58.1	100.0	58.1
AC, %	Min. 5.3	5.7	5.1	6.0	5.4	6.0	5.4	6.0	5.4
Rice SG (G_{mm})	-	2.525	2.525	2.514	2.514	2.510	2.510	2.515	2.515
Agg. Effective SG (G_{se})	-	2.768	2.768	2.769	2.769	2.764	2.764	2.770	2.770
Agg. Bulk SG (G_{sb})	-	2.735	2.735	2.736	2.736	2.731	2.731	2.737	2.737
VTM, %	3.0–4.5%	3.9	3.9	3.6	3.6	2.0	2.0	3.7	3.7
VMA, %	Min. 16.0	16.3	15.8	16.8	16.2	15.3	14.7	16.8	16.2
VFA, %	75–80	76.2	75.3	78.3	77.5	87.1	86.6	78.2	77.5
Fines-to-Asphalt Ratio	0.7–1.3	1.38	1.57	1.19	1.34	1.19	1.34	1.19	1.34

AC = asphalt content; Adj. = adjusted; B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability; SG = specific gravity; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture. [a] Reclaimed asphalt pavement AC adjusted based on RBA.

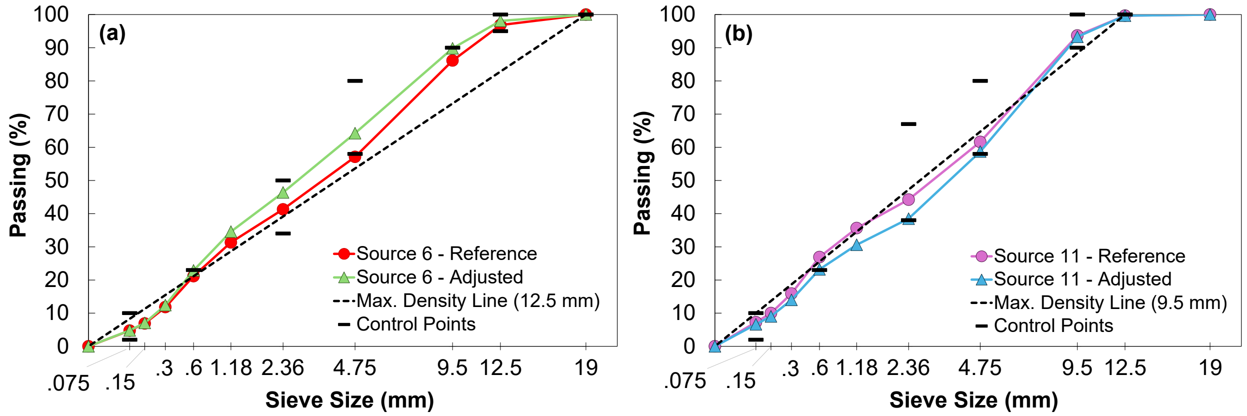


Figure 22. Mixtures Combined Gradations for (a) Source 6 and (b) Source 11

For Source 7 and 12 mixtures, challenges during mix verification were encountered that impaired adopting the RBA concept to adjust these mixtures. For Source 7, discrepancies were observed between the laboratory-measured G_{mm} and the value reported in the JMF, resulting in air void contents falling outside the specified range, potentially attributed to material variability between the time the mixture was designed and the component materials were sampled for this study. For Source 12, the mixture did not meet the verification criteria because the measured air void content remained outside the acceptable limits without making an excessive increase to the virgin AC. This difference may be attributed to the relatively high absorption of the virgin aggregates in the acquired materials compared with the JMF, which may have affected the effective binder content and volumetric response.

Balanced Mix Design Tests

Indirect Tensile Cracking Test

Figure 23 presents the STOA CT_{Index} results for Source 4, 5, and 7 mixtures. All mixtures passed the CT_{Index} design criterion of 70, although B7R5 is at the threshold. Notably, these mixtures also satisfied VDOT's minimum AC and volumetric property requirements when accounting for partial RBA. For Source 4, the reference and RA-modified mixtures exhibited similar CT_{Index} values. In contrast, incorporating PG 64S-22 with RA7 for Source 5 increased the CT_{Index} by more than 50% compared with the reference B7R5 mixture, highlighting the effectiveness of RA7 in mitigating the stiffening effects of aged RAP binder. Moreover, reference mixture B5R7 has a lower RAP content (26%) than Sources 4 and 5 and a slightly higher AC (6.0%), which may have contributed to its higher CT_{Index} compared with the other reference B7R4 and B7R5 mixtures.

Figure 24 presents the STOA CT_{Index} results for the Source 6 and 11 mixtures. In both cases, the B7R6 and B5R11 reference mixtures exhibited low CT_{Index} values of 22 and 18, respectively. Notably, these mixtures failed to meet VDOT's minimum asphalt binder contents when RBA is accounted for. The B6R6RA8, which had the same gradation and AC as the reference B7R6 mixture, yielded a higher CT_{Index}, but it still did not meet the design performance criterion of 70.

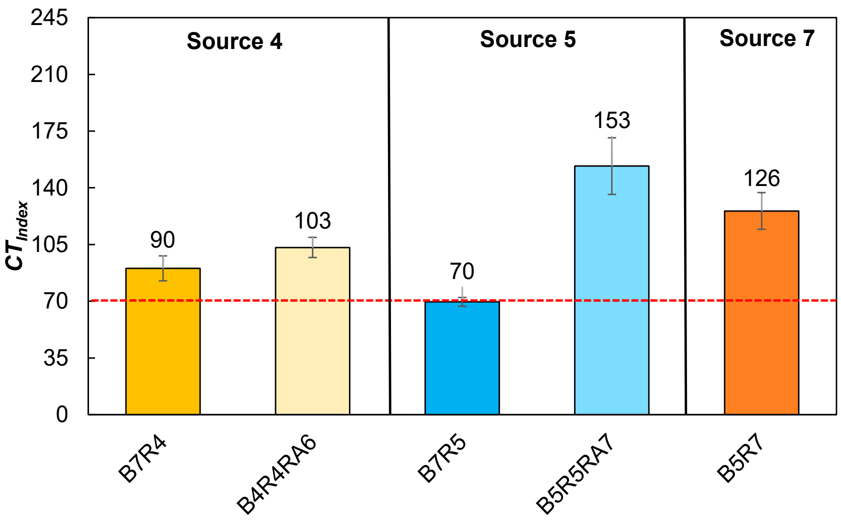


Figure 23. CT_{Index} **Results at the STOA Condition for Sources 4, 5, and 7. I-bars correspond to ± one standard deviation. Red dashed line represents** CT_{Index} **minimum threshold at STOA condition. B = virgin asphalt binder;** CT_{Index} **= cracking tolerance index; R = reclaimed asphalt pavement; RA = recycling agent; STOA = short-term oven aging.**

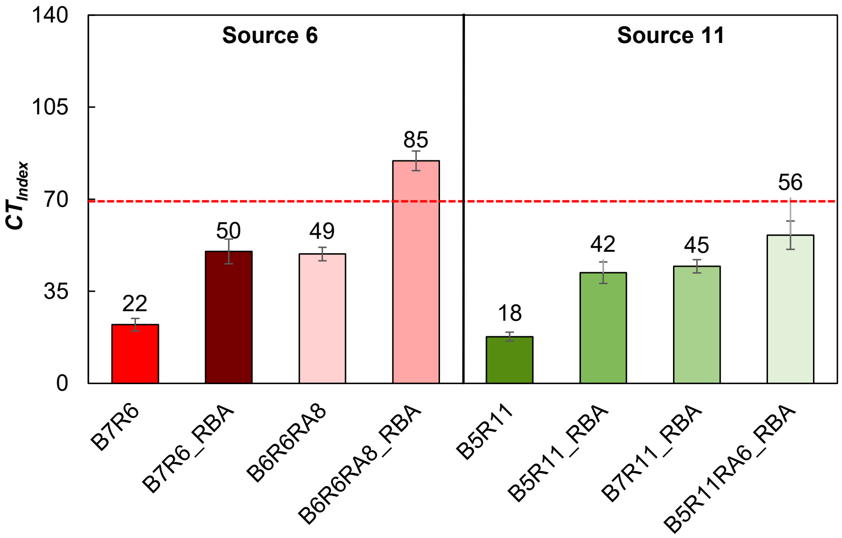


Figure 24. CT_{Index} **Results at the Short-Term Oven Aging Condition for Sources 6 and 11. I-bars correspond to ± one standard deviation. Red dashed line represents** CT_{index} **minimum threshold at short-term oven aging condition for RA-modified mixtures. B = virgin asphalt binder;** CT_{Index} **= cracking tolerance index; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability.**

Because the Source 6 and 11 reference mixtures did not satisfy all volumetric requirements when accounting for RBA, adjustments to the aggregate gradation and AC were made to achieve mixture designs that comply with the specifications. For Source 6, a finer gradation was selected to increase VMA, allowing for the increase in AC from 5.3% to 6.0% by adding virgin AC in an amount equivalent to the unavailable Source 6 RAP binder. Under these conditions, the resultant B7R6_RBA mixture exhibited a CT_{Index} of approximately 50, indicating an improvement of 127% in the cracking resistance. However, because the minimum CT_{Index} threshold was still not achieved, the combined use of RA and RBA was evaluated. The resulting mixture, B6R6RA8_RBA, reached a CT_{Index} of 85, passing the minimum requirement and demonstrating the effectiveness of this integrated approach to improving cracking resistance.

For Source 11, a coarser gradation was selected to increase VMA and allow for the increase in AC from 5.7% to 6.0% by adding virgin AC in an amount equivalent to the unavailable Source 11 RAP binder. The resultant B5R11_RBA mixture exhibited a STOA CT_{Index} of 42. Because this mix did not meet VDOT's thresholds, a softer virgin binder (PG 58-22) was used, maintaining the adjusted gradation. The resultant B7R11_RBA yielded a similar CT_{Index} to B5R11_RBA, which may be attributed to the relatively high continuous high grading temperature of the B7 binder of 62.5°C. Consequently, the combination of B5 (PG 64-22) and RA6 was evaluated, again maintaining the adjusted gradation. The resultant B5R11RA6_RBA achieved a CT_{Index} of 56, representing a 24% increase in the cracking resistance, but still failing to meet the threshold of 70.

These results demonstrate that incorporating RBA into the mixture design process improves the CT_{Index} of asphalt mixtures. However, accounting for RBA in the volumetric mixture design does not always yield CT_{Index} values that surpass BMD performance criterion. RAs offer an additional means to increase the CT_{Index}. When RBA is integrated into mixture design combined with RA, performance improvements become even more pronounced than when using a single mitigation strategy.

Figure 25 shows the LTOA CT_{Index} results. All mixtures experienced a reduction in CT_{Index} at the LTOA condition relative to the STOA condition. Although all mixtures experienced reductions in CT_{Index} after LTOA, the relative ranking among mixtures was preserved in many cases. Sources 4 and 5 RA-modified mixtures continued to show the highest CT_{Index} values after LTOA, whereas Source 6 mixtures showed the lowest CT_{Index} values after LTOA. Nonetheless, Figure 25 suggests that, at a higher RAP content, the use of RA combined with PG 64S-22 virgin binder (i.e., B4R4RA6, B5R5RA7, and B6R6RA8) outperforms the reference mixtures without RA but with a softer virgin binder.

Figure 26 shows the CT_{Index} aging sensitivity results, which generally support the performance trends observed in the STOA and LTOA CT_{Index} results. Mixtures that exhibited relatively high CT_{Index} values under both aging conditions also showed reduced sensitivity to long-term aging. For example, mixtures incorporating RAs such as B4R4RA6 and B5R5RA7 demonstrated substantially lower aging sensitivity compared with their corresponding reference mixtures B7R4 and B7R5, indicating improved resistance to aging-induced embrittlement. In contrast, mixtures associated with Source 6, particularly B7R6, exhibited the highest aging sensitivity values, reflecting the significant reduction in CT_{Index} observed after LTOA and confirming their greater susceptibility to long-term aging. Intermediate behavior was observed for mixtures such as B6R6RA8 and B5R7, which showed moderate aging sensitivity. It should be noted that only three mixtures met the recommended 45% threshold established in the previous project, VDOT Project No. 117566, and verified in Phase I of the present study. Nonetheless, the results indicate that despite failing the 45% aging sensitivity threshold, B6R6RA8_RBA showed an improvement of 68% in the LTOA CT_{Index}, with a negligible effect on the aging sensitivity compared with B6R6RA8. This observation suggests that RBA may improve cracking performance under both STOA and LTOA conditions without adversely affecting the aging sensitivity of RA-modified mixtures. Because data from only one mixture were available for such comparison, further evaluation is warranted to confirm this observation.

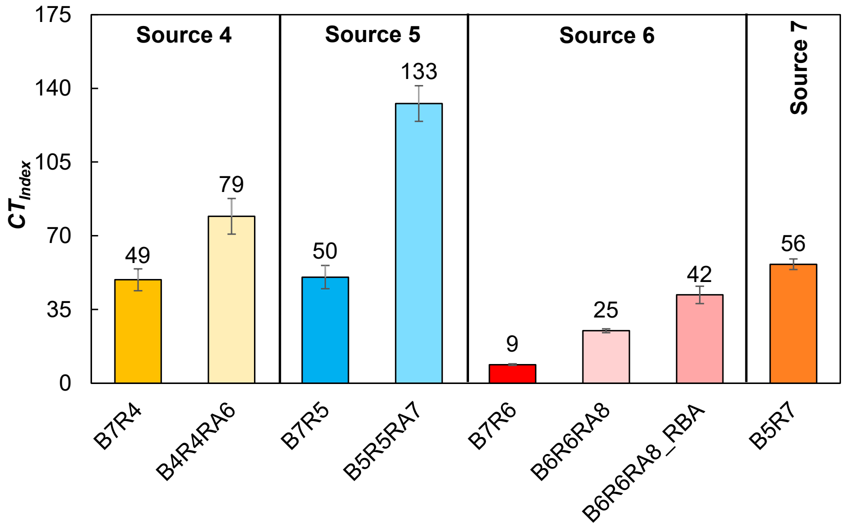


Figure 25. CT_{Index} **Results at the Long-Term Oven Aging Condition for Sources 4, 5, 6, and 7. I-bars correspond to ± one standard deviation. B = virgin asphalt binder;** CT_{Index} **= cracking tolerance index; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability.**

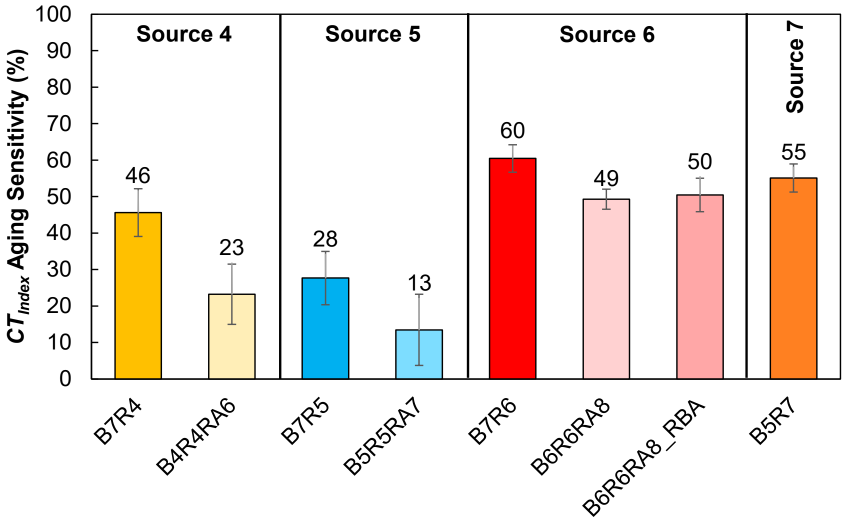


Figure 26. CT_{Index} **Aging Sensitivity for Sources 4, 5, 6, and 7. I-bars correspond to ± one standard deviation. B = virgin asphalt binder;** CT_{Index} **= cracking tolerance index; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability.**

Cantabro Mass Loss

Figure 27a shows the CML results for Sources 4, 5, and 7 mixtures. All mixtures, except B5R7, passed the maximum CML threshold of 7.5%. For Sources 4 and 5, the reference mixtures containing softer PG 58-22 virgin binder (B7R4 and B7R5) resulted in passing CML values, with similar results compared with the RA-modified mixtures and PG 64S-22 virgin binder for the same source materials.

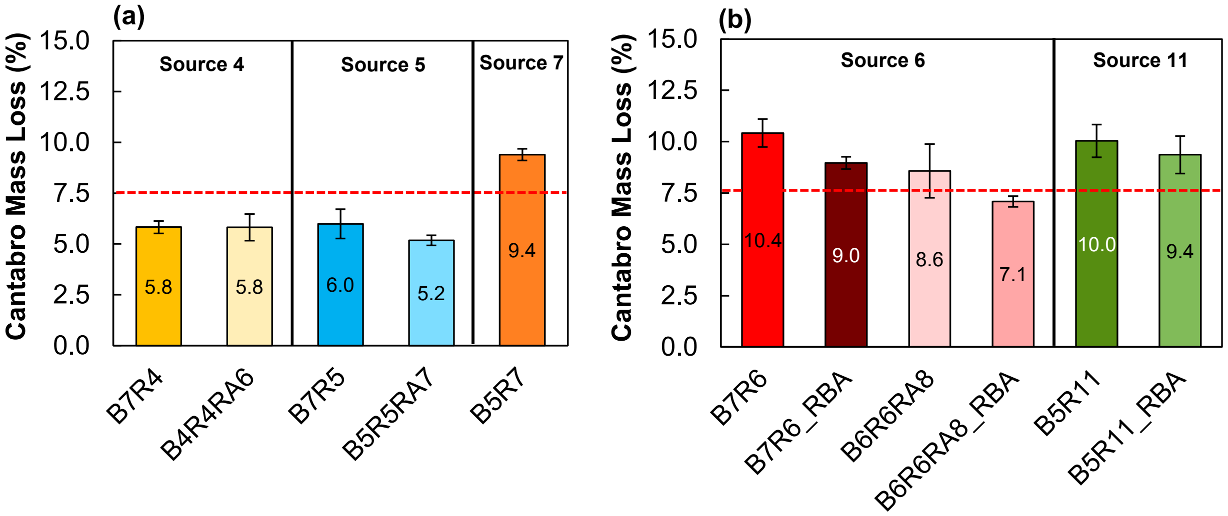


Figure 27. Cantabro Mass Loss Results for Mixtures from (a) Sources 4, 5, and 7 and (b) Sources 6 and 11. I-bars correspond to ± one standard deviation. Red dashed line represents Cantabro mass loss maximum threshold. Results from B4R4RA6, B5R5RA7, and B6R6RA8 were obtained from Phase I of this study. B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent.

Figure 27b shows the CML values for Source 6 and 11 mixtures. For Source 6, the reference B7R6 mixture containing a softer virgin binder (B7) showed higher CML values compared with B6R6RA8, which includes a PG 64S-22 virgin binder and RA in its composition. To account for RBA, B7R6 mix design was modified to become B7R6_RBA asphalt mixture, with a finer gradation and higher AC. Figure 27 shows that CML values decreased from B7R6 to B7R6_RBA but still failed the performance criteria. The B6R6RA8 design was then further modified to account for RBA, with the resulting B6R6RA8_RBA exhibiting CML values below the 7.5% maximum threshold. These observations suggest that the combination of different design strategies for the B6R6RA8_RBA, which includes 40% RAP content, converted an originally failing mix into a passing mix in terms of both durability and cracking resistances from Cantabro and IDT-CT results, respectively.

For Source 11, the B5R11 mixture failed the maximum CML threshold. Although reduced CML values from 10.0% to 9.4% were obtained by coarsening the mix and increasing AC, the resulting B5R11_RBA still failed the durability criterion. Cantabro tests on Source 11 RBA-adjusted asphalt mixtures with a softer virgin binder (B7R11_RBA) or RA (B5R11RA6_RBA) were not included because they failed the CT_{Index} criterion at STOA condition, as shown in Figure 24.

Asphalt Pavement Analyzer

Figure 28a shows the APA rut depth values for Sources 4, 5, and 7 mixtures. Overall, similar rut depth values were observed across RA-modified and reference mixtures containing softer virgin binder grade, with all mixtures passing the performance criterion of a maximum of 8.0 mm. Figure 28b shows the APA rut depth results for Source 6 and 11 mixtures. For Source 6, it can be seen that the reference mixture (B7R6) showed equivalent rutting performance compared with the RA-modified one (B6R6RA8). In addition, the RBA-modified mixture (B6R6RA8_RBA), which consisted of a finer mix with more AC compared with the B6R6RA8, showed increased rut depth values but was still below the APA threshold. Similar observations can be made regarding the Source 11 mixture, with the RBA-modified mixture (B5R11_RBA) showing higher rut values than B5R11 but still below the threshold.

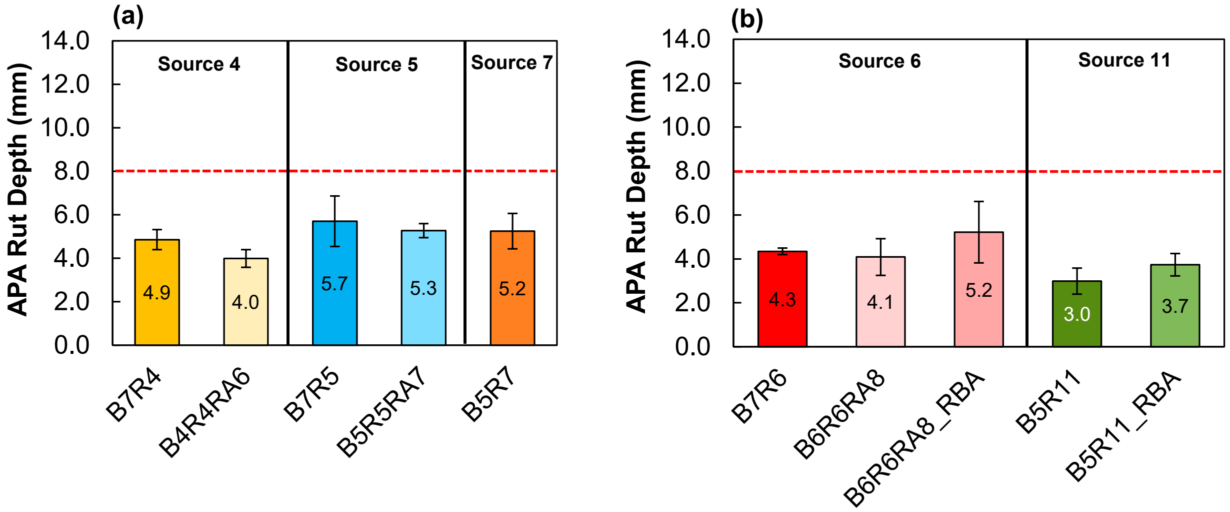


Figure 28. APA Test Results for Mixtures from (a) Sources 4, 5, and 7 and (b) Sources 6 and 11. I-bars correspond to ± one standard deviation. Red dashed line represents APA rut depth maximum threshold. Results from B4R4RA6, B5R5RA7, and B6R6RA8 were obtained from Phase I of this study. APA = asphalt pavement analyzer; B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent.

Figure 29 shows the interaction plots combining the results from Cantabro, IDT-CT, and APA tests. Collectively, it is observed that asphalt surface mixtures adopting RBA, RA, or a combination of both can still be designed to meet APA rutting performance criterion while improving asphalt mixtures' durability and cracking resistances compared with reference mixtures. Therefore, in addition to confirming that VDOT's current BMD protocol is appropriate for evaluating mixtures adopting RBA and/or RA, these observations suggest that an originally failing reference mix may still pass VDOT's BMD performance criteria when incorporating RBA and/or RA design strategies.

Advanced Tests

Dynamic Modulus

Figure 30 shows the $|E^*|$ master curves for the Source 5 and 6 mixtures at a reference temperature of 21.1°C. For Source 5, the RA-modified mixture (B5R5RA7) showed lower moduli values (in average 31.3% lower) compared with the reference mixture (B7R5). For Source 6, the reference B7R6 mixture showed the highest modulus, whereas B6R6RA8_RBA showed the lowest modulus. Compared with the reference mixture B7R6, the B6R6RA8 and B6R6RA8_RBA mixtures had average modulus reductions of 29.4% and 50.1%, respectively.

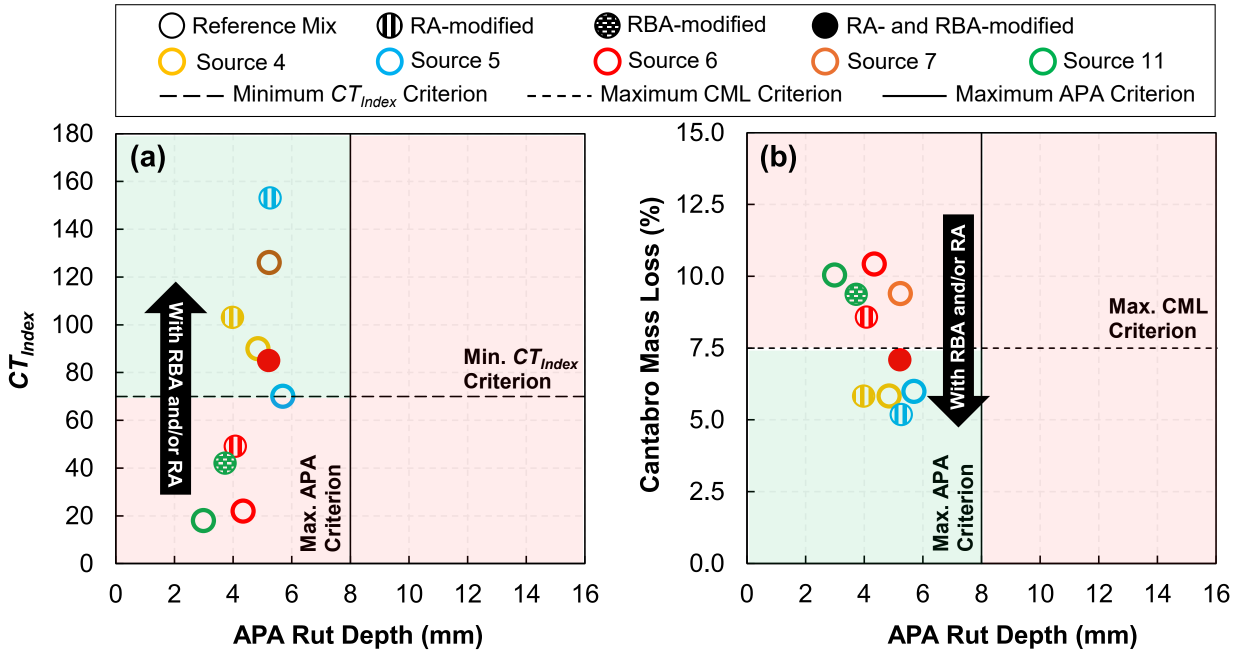


Figure 29. Balanced Mix Design Interaction Plots for (a) CT_{Index} and APA Rut Depth and (b) CML and APA Rut Depth. Green and red highlighted areas represent the area containing passing and failing balanced mix design results, respectively. APA = asphalt pavement analyzer; CML = Cantabro mass loss; CT_{Index} = cracking tolerance index; Max. = maximum; Min. = minimum; RA = recycling agent; RBA = recycled binder availability.

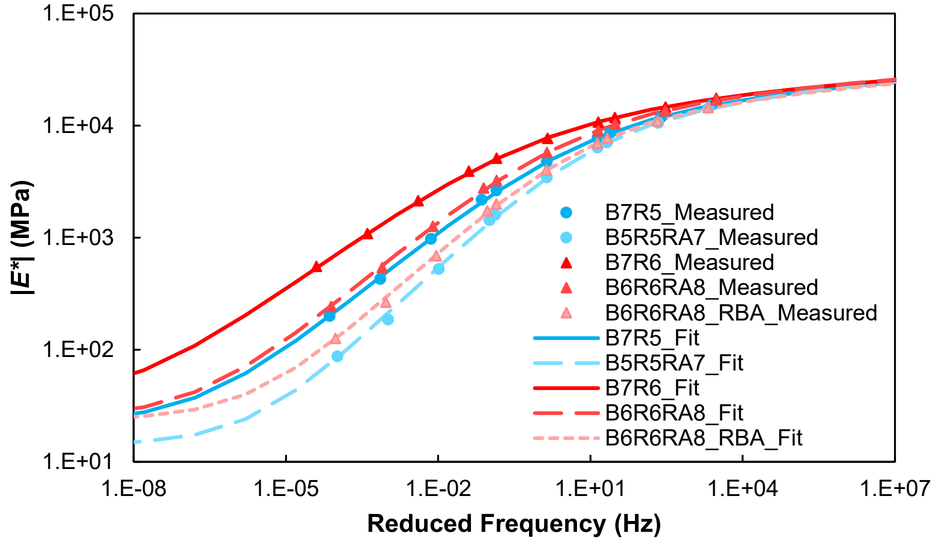


Figure 30. Dynamic Modulus (|E*|) Master Curves at 21.1°C Reference Temperature. B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability.

In addition, the |E*| results were used to calculate the mixture Glover-Rowe parameter (G-R_m) at 20°C and 5 Hz. This parameter is an indicator of cracking resistance and aging susceptibility at intermediate temperatures, for which lower G-R_m values indicate better cracking performance (Mensching et al., 2017; Ogbo et al., 2019; Zhang et al., 2020). The results were used for relative comparisons among mixtures and to examine consistency with the CT_{Index}. As shown in Figure 31, the high R^2 value suggests that the cracking performance for the tested mixtures based on G-R_m is consistent with the CT_{Index}, with mixtures B7R6 and B5R5RA7 having the lowest and highest G-R_m values, respectively.

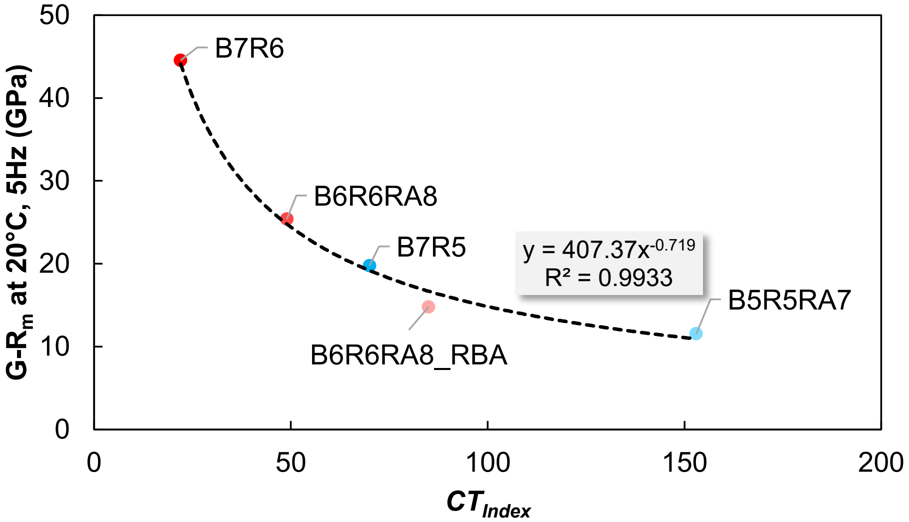


Figure 31. Correlation between Mixture Glover-Rowe Parameter (G-R_m) and CT_{Index}. B = virgin asphalt binder; CT_{Index} = cracking tolerance index; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability.

Direct Tension Cyclic Fatigue

Figure 32 shows the results of the CF test in terms of D^R and S_{app} at the climatic regions where the mixtures were placed in the field. Figure 32 shows that the use of RAs with PG 64S-22 virgin binder yielded statistically similar S_{app} and D^R values compared with the reference mixtures with the softer PG 58-22 virgin binder and no RA. On the other hand, accounting for RBA in the B6R6RA8_RBA mixture led to a statistically significant increase in both S_{app} and D^R. In addition, considering that the tested mixtures are surface mixtures with A and D designations used for 0 to 3 MESALs and 3 to 10 MESALs, respectively, the S_{app} values conformed with current nationally calibrated guidance with a minimum S_{app} value of 8 for traffic levels up to 10 MESALs (Wang et al., 2020).

Figure 33 shows the predicted number of cycles to failure (N_f) as a function of strain at 10°C and 27°C for all tested mixtures. Figure 33a shows that at the lower temperature, the RA mixtures have lower N_f compared with the reference mixtures, opposing the IDT-CT results. However, Figure 33b shows that at a temperature closer to that of IDT-CT, the performance ranking agrees with the IDT-CT results because the RA mixtures perform better than the reference mixtures at 27°C. Notably, accounting for RBA led to a better fatigue performance at both 10°C and 27°C.

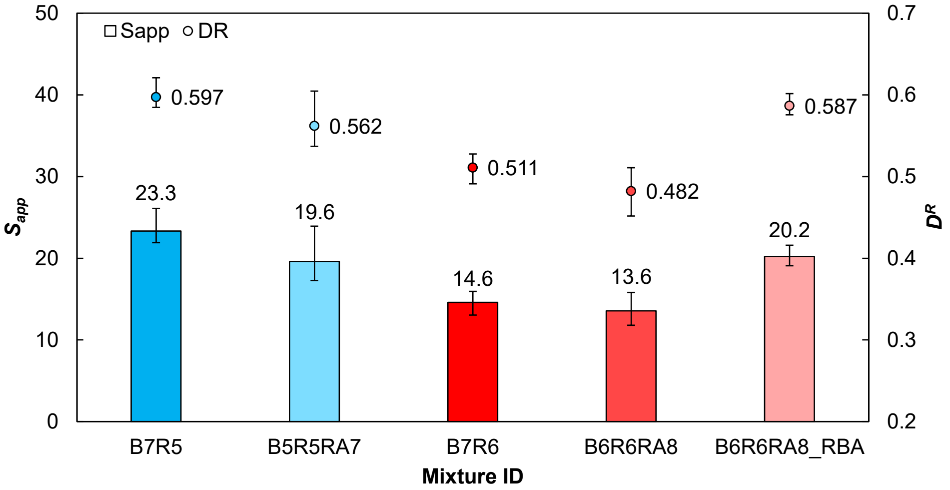


Figure 32. Cyclic Fatigue Performance Test Data for Mean S_{app} and D^R. Error bars indicate the range of minimum and maximum values. B = virgin asphalt binder; D^R = pseudo-energy-based failure criterion; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability; S_{app} = fatigue index parameter.

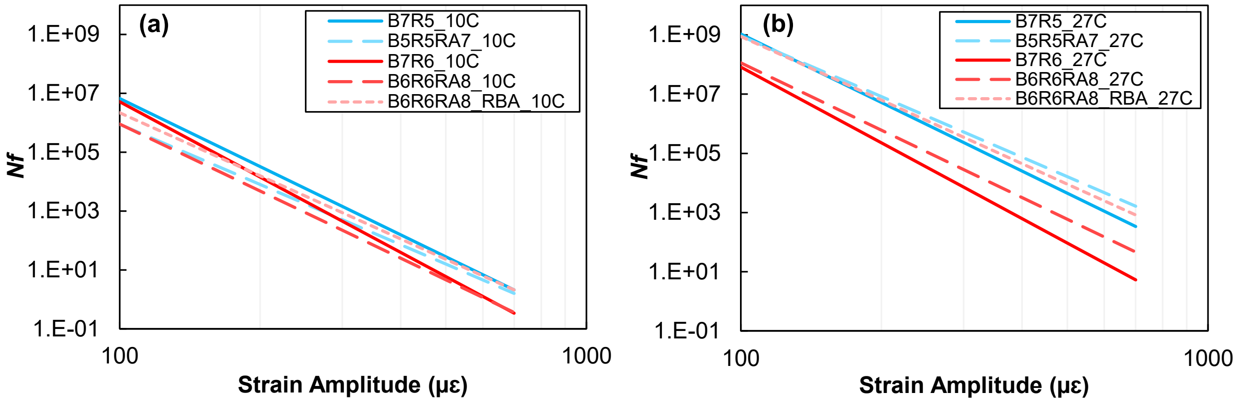


Figure 33. Cyclic Fatigue N_f versus Strain at (a) 10°C and (b) 27°C. B = virgin binder; N_f = number of cycles to failure; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability.

Stress Sweep Rutting

Figure 34 shows the RSI values at the climatic regions where the mixtures were placed in the field. For Source 5 mixtures, both B7R5 and B5R5RA7 ranked suitable for standard traffic levels (i.e., less than 10 MESALs) and had statistically similar RSI values. For Source 6 mixtures, B7R6, B6R6RA8, and B6R6RA8_RBA had RSI values suitable for very heavy (greater than 30 MESALs), heavy (between 10 and 30 MESALs), and standard traffic (less than 10 MESALs), respectively. Although the reference B7R6 mixture outperformed the RA and RBA mixtures, all mixtures had RSI values less than 12, which is the recommended value for mixtures with A and D designations designed for traffic less than 10 MESALs (Ghanbari et al., 2020).

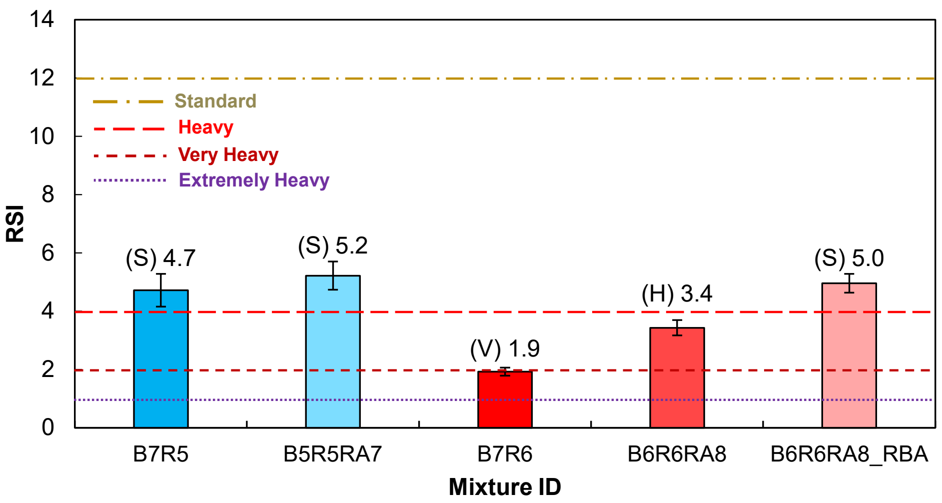


Figure 34. Stress Sweep Rutting Performance Test Data for Mean RSI. Error bars indicate the 95% confidence interval from four RSI values obtained from permutations of temperature combinations. B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability; RSI = rutting strain index.

Effect of Recycled Binder Availability on Pavement Performance Predictions

AASHTOWare® Pavement ME

For Source 5 mixtures, the bottom-up fatigue cracking predictions at year 30 were marginally lower for the B5R5RA7 mixture (average 6.2% cracked lane area) compared with the reference B7R5 mixture (average 7.3% cracked lane area). For Source 6 mixtures, B6R6RA8_RBA showed slightly higher fatigue cracking levels (average 6.3% cracked lane area) than B6R6RA8 (average 6.1% cracked lane area), followed by the reference B7R6 mixture (average 5.5% cracked lane area). In terms of rutting performance, the B7R5 mixture showed a lower total rutting at year 15 (average of 0.14 inch) compared with the B5R5RA7 (average of 0.15 inch) structure. For Source 6 mixtures, B6R6RA8_RBA showed slightly higher total rut depths (average of 0.15 inch) than B6R6RA8 (average of 0.14 inch), followed by the reference B7R6 mixture (average of 0.13 inch). In all cases, the rutting values were below the 0.26-inch maximum limit. For brevity, details of the Pavement ME simulation results are included in the Supplemental Materials file.

It is worth noting that the fatigue cracking predictions showed counterintuitive trends with respect to the laboratory performance test results. In fact, a weak correspondence was observed between CT_{Index} values and Pavement ME bottom-up fatigue cracking predictions, with a similar observation reported by Habbouche et al. (2025). This lack of correspondence may be attributed to the fact that bottom-up fatigue cracking is typically associated with the asphalt base mixture properties, suggesting that changes in the surface mixture properties may have only a marginal effect in the overall fatigue cracking performance, potentially contributing to the lack of correlation. For this reason, analysis using the FlexPAVE™ program was conducted by isolating the damage that occurs at the top one-third of the asphalt layer structure.

FlexPAVE™

Figure 35 shows the total rut depth at year 15 for the Source 5 and 6 mixtures under structures A and D, along with VDOT's 0.26-inch limit. Figure 35 shows that all mixtures resulted in total rut depths less than 0.26 inch, indicating acceptable rutting performance. Accounting for RBA in the B6R6RA8_RBA mixture results in slightly higher rut depth compared with its B6R6RA8 reference mixture (B7R6), with an increase of 0.02 to 0.03 inch but still within the 0.26-inch limit.

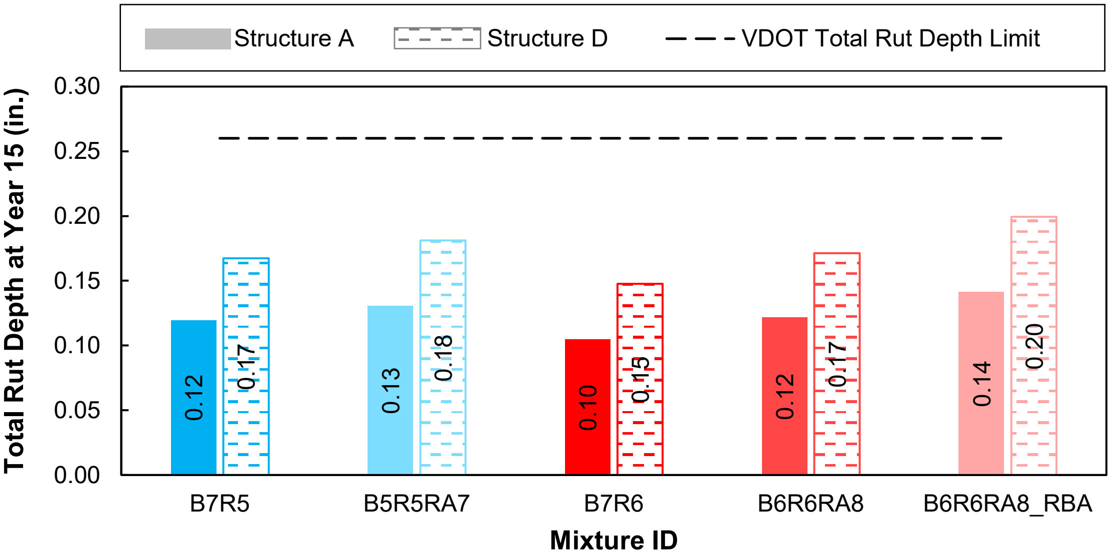


Figure 35. FlexPAVE™ Total Rut Depth at Year 15 for A and D Structures. B = virgin asphalt binder; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability.

Figure 36 shows the predicted Top %Damage at year 30 for the Source 5 and 6 mixtures under structures A and D and the average Top %Damage observed from typical VDOT control mixtures at the same conditions. The typical VDOT control mixtures were assessed as part of VTRC Report No. 26-R08, which compared control VDOT mixtures with alternative ones using different BMD strategies (Habbouche et al., 2025). The 2025 project included six control dense-graded mixtures, which were characterized in a similar manner to the mixtures investigated in this study and then incorporated into FlexPAVE™ to predict the Top %Damage at the end of the 30-year simulation. The Top %Damage results of these control mixtures were averaged for each structure type, and the resulting values are referred to in Figure 36 as "Avg. BMD ME Control."

Figure 36 shows that the use of RA with PG 64-22 virgin binder led to higher Top %Damage for Source 5 mixtures compared with the mixture with a softer virgin binder and no RA. An opposite trend was observed for the Source 6 mixtures, with the RA-modified mix with PG 64S-22 outperforming the one with PG 58-22 and no RA. A sensitivity study was carried out to quantify these differences in Top %Damage by characterizing each mixture using all combinations of DM and CF test results from individual specimens (nine combinations from three tested specimens per test per mixture). The analysis showed that these differences in Top %Damage are marginal given the test variability, especially considering that the difference in predicted damage ranged between 0.9% and 2.5% within a given source. Nonetheless, all mixtures had Top %Damage values less than the average of the typical VDOT control mixtures with corresponding values of 23.7% and 26.5% for A and D structures, respectively.

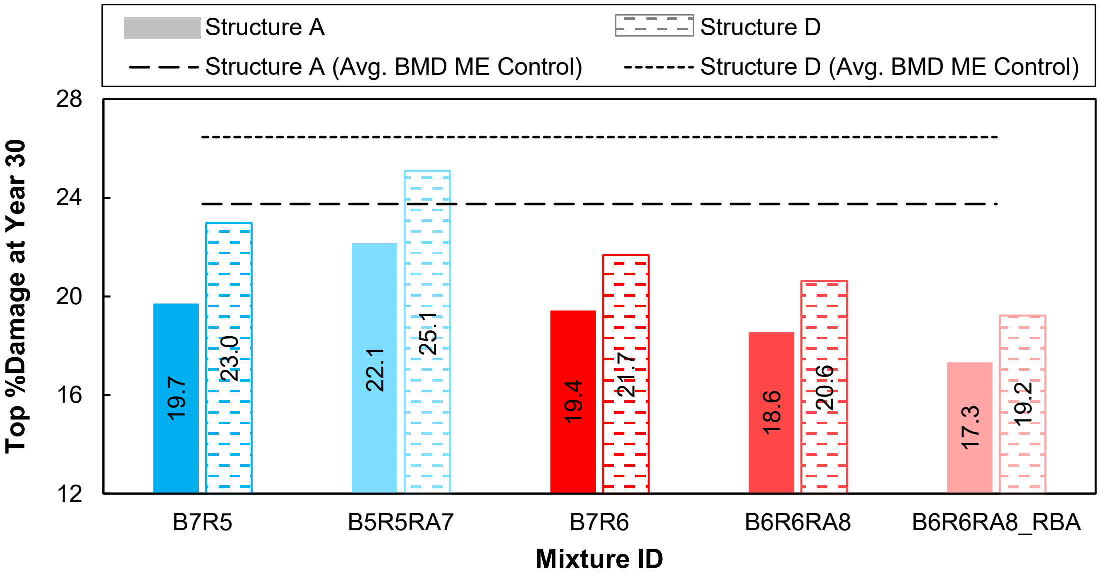


Figure 36. FlexPAVE™ Top %Damage at Year 30 for A and D Structures

For Source 6, accounting for RBA in the B6R6RA8_RBA mixture further improved the cracking performance compared with its B6R6RA8 control mixture. Table 13 presents the relative reduction in Top %Damage of R6B6RA8_RBA compared with other Source 6 mixtures at year 30. A substantial improvement can be observed in fatigue cracking performance predictions, with reductions in Top %Damage ranging from 7.0% to 7.3% and 33.0% to 33.4% compared with B6R6RA8 and the average BMD ME control mixtures, respectively.

Table 13. Relative Reduction in Top %Damage of R6B6RA8_RBA at Year 30 Compared with Other Mixtures

Mixture	Relative Reduction in Top %Damage of B6R6RA8_RBA at Year 30 Compared with Other Mixtures (%)	
	Structure A	Structure D
B6R6RA8	7.0	7.3
B7R6	11.3	11.9
Average BMD ME Control	33.0	33.4

B = virgin binder; BMD = balanced mix design; ME = mechanistic-empirical; R = reclaimed asphalt pavement; RA = recycling agent; RBA = recycled binder availability.

CONCLUSIONS

- *The literature review revealed some knowledge gaps, including the lack of a practical method to estimate RBC, limited comparisons across RBA, DoA, and RBC measurements, and limited evaluation of the effect of RAs on binder activation and contribution.*

- *RBA values determined by the sieve analysis method for nine RAP sources in Virginia ranged from 41.4% to 73.5%, with an average of 59.5%, highlighting that RBA is a source-*

dependent parameter. Correlations between RBA and black curve parameters were stronger than those with white curve parameters. The effective specific gravity of RAP and the RAP processing crusher screen size were found to be significant factors in RBA estimation. Overall, finer gradations were typically associated with higher RBA values.

- *Overall, a strong agreement was observed between RAP materials RBA (determined using the sieve analysis method) and corresponding asphalt mixtures RBC (determined using the tracer-based microscopy method)*. In addition, DoA results suggested that the assumption of complete activation of the available RAP binder may be acceptable for typical production temperatures for A and D asphalt surface mixtures. These observations indicate that the RBA sieve analysis method can be used as a practical, simple, and low-cost protocol to determine source-specific RBA during design and to estimate mixtures RBC.

- *Consistent RBC measurements were observed among asphalt mixtures, suggesting that a fixed value may be acceptable*. The adoption of a fixed RBA for all RAP materials is more accurate than assuming 100% RBA but may have detrimental effects on asphalt mixtures volumetrics and performance due to (1) allowable variation in stockpile proportions during production (typically limited to 5% maximum per stockpile without requiring redesign); (2) inaccurate volumetrics determination, potentially leading to sub-optimal AC, especially for higher RAP contents (i.e., higher RBR); and (3) inability to capture RAP variability between design and production and even throughout production. The RBA sieve analysis method can help overcome these limitations. Given that six asphalt mixtures were evaluated in this study for RBC determination, further investigation is warranted to confirm consistency in RBC measurements.

- *Assuming 100% RBA overestimates AC, VMA, and VFA values and may incorrectly suggest that the mix is compliant with the volumetric requirements*. This effect may be more pronounced at mixtures with higher RAP content (i.e., higher RBR). Some mixtures showed that incorporating RBA while meeting current volumetric requirements is possible after design adjustments to increase VMA, accommodate the additional virgin AC (equivalent to the unavailable RAP binder), and ensure adequate voids in the total mixture. Mixtures that satisfied volumetric requirements when incorporating RBA without requiring design adjustments resulted in VFA values failing the limits, indicating that not all VDOT mixtures may warrant RBA adjustments.

- *Incorporating RBA or RA, or both, may allow one to convert an otherwise failing mix into a mix that passes VDOT's BMD design performance criteria*. BMD test results showed that incorporating RBA or RA, or both, led to CML values below the 7.5% threshold, CT_{Index} values above the 70 threshold, and APA results below the 8.0 mm maximum criterion. In addition, a good agreement in cracking and rutting laboratory test results was observed between the BMD test methods (i.e., IDT-CT and APA) and advanced test methods (i.e., DM, CF, and SSR).

- *Mechanistic-based pavement performance simulations showed substantial improvements in fatigue cracking predictions for mixtures accounting for RBA and RA compared with reference and control mixtures*. Although these trends were observed for Source 6 mixtures, opposite trends were found for Source 5 mixtures, with the mixture having a softer binder grade and no RA showing slightly better rutting and fatigue cracking resistances than the RA-modified mixture.

RECOMMENDATIONS

1. *VDOT should consider incorporating RBA as part of the design of dense-graded asphalt surface mixtures with 9.5- and 12.5-mm NMAS and with up to 40% RAP content by weight of total mixture (RBR ≤ 0.38)*. The Appendix outlines the RBA determination process using the sieve analysis method and the procedure adopted in this study to incorporate RBA during mix design.

2. *VDOT should consider incorporating the sieve analysis method outlined in this study into VDOT's specification to quantify the RBA of RAP materials and estimate asphalt mixtures RBC*. The RBA sieve analysis method may also be used as a practical and low-cost tool for RAP stockpile management practices, including RAP consistency evaluation (quantity based) throughout production.

3. *VDOT should evaluate additional RAP materials and asphalt mixtures designed with RAP contents greater than 30% by weight of total mixture to further evaluate RBC consistency across additional mixtures and investigate the effect of RBA on asphalt mixture performance*. Because appropriate RBA consideration is more critical at higher contents of recycled asphalt, this effort will focus on asphalt mixtures containing more than 30% RAP content by weight of total mixture.

IMPLEMENTATION AND BENEFITS

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and 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

Regarding Recommendations 1 and 2, VDOT's Materials Division, with the support of VTRC, will identify by December 2027 the most appropriate steps toward the potential adoption of RBA during the design of asphalt dense-graded 9.5- and 12.5-mm NMAS surface mixtures as determined using the sieve analysis method outlined in this study. This effort will involve developing a roadmap with specific steps, guidance, and logistic and research needs required prior to RBA implementation. A Virginia Test Method will be developed outlining the sieve analysis test method, RBA determination, and RBA incorporation into asphalt mix design.

Regarding Recommendation 3, VTRC, with the help of VDOT's Materials Division, will draft and submit a research needs statement (RNS) to the appropriate Pavement Research Advisory Committee subcommittee by no later than the fall of 2026. This RNS will include the evaluation of additional RAP materials and corresponding asphalt mixtures to further verify RBC consistency among additional mixtures and evaluate the effect of RBA incorporation on asphalt mixture performance.

Benefits

Implementing recommendations of this study has two main benefits. First, incorporating RBA during the design of asphalt surface mixtures containing RAP will support BMD implementation. Given the changes in 2026 regarding CT_{Index} production performance criteria from 70 to 100 (reheated) and 95 to 130 (non-reheated), some mix designs may need to be adjusted by increasing AC to meet the new CT_{Index} production thresholds. Allowing the use of RBA during design could assist producers in meeting the new CT_{Index} criteria in a more rational and objective manner. This procedure is especially critical for asphalt mixtures containing higher RAP content and RAP materials with lower binder availability. Second, incorporating RBA may extend asphalt pavements service life, which may allow the agency to defer future asphalt paving costs.

To quantify this potential cost-deferral benefit, an analysis was conducted using a ***hypothetical scenario*** comparing Source 6 surface mixtures B6R6RA8 and B6R6RA8_RBA pavement performance predictions. These mixtures were selected because they allow for isolating the effect of RBA for comparative purposes. It is worth noting that this analysis is applicable only to the conditions in the hypothetical scenario presented herein.

The pavement performance simulations using FlexPAVE™ were used to estimate the difference in performance between the two mixtures, assuming that complete failure occurs when Top %Damage reaches 10%. Evaluating the Top %Damage evolution over time, the B6R6RA8 mixture reaches the threshold of 10% after 10.3 years compared with the 12.6 years from B6R6RA8_RBA simulation, suggesting that incorporating RBA may improve service life by approximately 2 years. To estimate the cost deferral for the agency regarding the potential service-life improvement of BMD asphalt mixtures incorporating RBA, several assumptions were made and are described next. It is worth noting that these assumptions apply only to the hypothetical scenario described herein.

First, the total 2025 tonnage of BMD mixtures produced in the Fredericksburg, Hampton Roads, Northern Virginia, and Richmond districts was determined to be 1,072,644 tons. These districts were selected because they are the ones with the greatest amount of RAP in Virginia. Second, it was conservatively assumed that only 10% of the producers would adopt RBA as part of their mix design process. For the mix cost estimation, the weighted-average bid price for all A and D BMD surface mixtures produced in 2025 across the four selected districts was calculated to be $104 per ton. In terms of potential life extension, incorporating RBA in the mix design was conservatively assumed to increase the service life of asphalt pavements by 1 year, despite pavement performance simulations suggesting a 2-year extension. Thus, if adopting RBA extends asphalt pavements service life by 1 year, $11.2 million per year of paving would be deferred (i.e., 1,072,644 tons × 10% × $104 per ton). Given all the conservative assumptions underlying this hypothetical analysis, the total cost deferral is expected to be substantially higher.

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REFERENCES

Abdelaziz, A., Epps Martin, A., Arámbula-Mercado, E., and Sobieski, T. Study of the quantification of recycled binder activity in asphalt mixtures with RAP. *Construction and Building Materials*, Vol. 309, 2021, pp. 125–189.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing and AASHTO Provisional Standards*. Washington, DC, 2021.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing and AASHTO Provisional Standards*. Washington, DC, 2022.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing and AASHTO Provisional Standards*. Washington, DC, 2023.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing and AASHTO Provisional Standards*. Washington, DC, 2024.

American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing and AASHTO Provisional Standards*. Washington, DC, 2025.

ASTM International. *ASTM D6931-17: Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures*. West Conshohocken, PA, 2017.

ASTM International. *ASTM D6857M: Standard Test Method for Maximum Specific Gravity and Density of Asphalt Mixtures Using Automatic Vacuum Sealing Method*. West Conshohocken, PA, 2023.

Boz, I., Diefenderfer, S.D., Habbouche, J., Hajj, E.Y., Alam, I., and Hajj, H.E. *A Practical Oven-Aging Method for Evaluating Long-Term Cracking Performance of Asphalt Mixtures in Virginia.* VTRC 26-R04. Virginia Transportation Research Council, Charlottesville, VA, 2025.

Castorena, C., Costa, R., Alvis, M.C.A., Mocelin, D., Isied, M., and Kusam, A. *A Practical Method to Determine Reclaimed Asphalt Pavement (RAP) Binder Availability*. Final Report for National Cooperative Highway Research Program (NCHRP) Innovations Deserving Exploratory Analysis (IDEA) Project 236. Transportation Research Board, Washington, DC, 2024.

Dancey, C.P., and Reidy, J. *Statistics Without Maths for Psychology*. Seventh Edition. Pearson Education, Harlow, England, 2017.

Diefenderfer, S.D., Boz, I., and Habbouche, J. *Balanced Mix Design for Asphalt Surface Mixtures: 2019 Field Trials*. VTRC 21-R21. Virginia Transportation Research Council, Charlottesville, VA, 2021.

Federal Highway Administration. Federal Highway Administration Asphalt Material Analysis Tools Information and Downloads, 2025. https://highways.dot.gov/turner-fairbank-highway-research-center/software/flexmat. Accessed February 9, 2026.

Fonseca da Costa, R., Aparicio Alvis, M.C., and Castorena C. Validation of a Sieve Analysis Procedure to Quantify Reclaimed Asphalt Pavement (RAP) Binder Availability. *International Journal of Pavement Engineering*, Vol. 25, No. 1, 2024.

Fonseca da Costa, R., and Castorena, C. Assessing Recycled Binder Availability, Activity, and Contribution at Different Temperatures. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2678, No. 11, 2024, pp 40–55.

Fonseca da Costa, R., and Castorena, C. Using Color Measurements to Assess Reclaimed Asphalt Pavement Degree of Activity. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2679, No. 12, 2025, pp. 795–808.

Ghanbari, A., Underwood, B.S., and Kim, Y.K. Development of a Rutting Index Parameter Based on the Stress Sweep Rutting Test and Permanent Deformation Shift Model. *International Journal of Pavement Engineering*, Vol. 23, No. 2, 2020, pp. 387–399.

Habbouche, J., Boz, I., Diefenderfer, S.D., Underwood, B.S., and Othman, O. Mechanistic-Based Evaluation of Performance Thresholds for Balanced Mix Design Asphalt Surface Mixtures. VTRC 25-R12, Virginia Transportation Research Council, Charlottesville, VA, 2025.

Habbouche, J., Boz, I., Underwood, B.S., Castorena, C., Preciado, J., Gulzar, S., and Fried, A. Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures for Virginia. VTRC 24-R3. Virginia Transportation Research Council, Charlottesville, VA, 2023.

Kim, Y.R., Underwood, B.S., Guddati, M., Ghanbari, A., Keshavarzi, B., Wang, Y.D., Jeong, J., Mocelin, D., Pivetta, F.D.C., and Saleh, N.F. *Development of Balanced Mixture Design Index Parameters and the Flex Suite of Performance Analysis Tools for Asphalt Pavements–Volume I.* FHWA-HRT-24-112. Washington, D.C., 2024.

Kuchiishi, A.K., Habbouche, J., Boz, I., Castorena, C., Underwood, B.S., Turbay, E., and Preciado, J. Verification of Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures. VTRC 26-R09. Virginia Transportation Research Council, Charlottesville, VA, 2025.

Kuchiishi, A.K. Streamlining the Determination of Pavement ME Bottom-Up Fatigue Cracking Model Coefficients for Intermediate and Base Asphalt Mixtures. Technical Assistance Final Report. Virginia Transportation Research Council, Charlottesville, VA, 2025.

Lo Presti, D., Vasconcelos, K., Orešković, M., Pires, G.M., and Bressi, S. On the degree of binder activity of reclaimed asphalt and degree of blending with recycling agents. *Road Materials and Pavement Design*, Vol. 21, No. 8, 2020, pp. 2071–2090.

Menegusso Pires, G., Lo Presti, D., and Airey, G.D. A practical approach to estimate the degree of binder activity of reclaimed asphalt materials. *Road Materials and Pavement Design*, Vol. 22, No. 5, 2021, pp. 1093–1116.

Mensching, D.J., Rowe, G.M., and Sias, D.J. A Mixture-Based Black Space Parameter for Low-Temperature Performance of Hot Mix Asphalt. *Road Materials and Pavement Design*, Vol. 27, No. 1, 2017, pp. 404–425.

Mocelin, D.M., and Castorena, C. Impacts of Recycled Binder Availability on Volumetric Mixture Design and Performance. *International Journal of Pavement Engineering*, 2022, pp. 1–17. https://doi.org/10.1080/10298436.2022.2046276.

Ogbo, C., Kaseer, F., Oshone, M., Sias, J.S., and Martin, A.E. Mixture-Based Rheological Evaluation Tool for Cracking in Asphalt Pavements. *Road Materials and Pavement Design*, Vol. 20, No. Sup. 1, 2019, pp. S299–S314.

Olard, F., and Di Benedetto, H. General "2S2P1D" Model and Relation Between the Linear Viscoelastic Behaviours of Bituminous Binders and Mixes. *Road Materials and Pavement Design*, Vol. 4, No. 2, 2003, pp. 185–224.

Pape, S.E., and Castorena, C.A. Application of Sieve Analysis to Estimate Recycled Binder Availability. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2676, No. 6, 2022, pp. 170–181.

Sakhaei Far, M. S. *Development of New Dynamic Modulus (|E*|) Predictive Models for Hot Mix Asphalt Mixtures*. Ph.D. dissertation. North Carolina State University, Raleigh, NC, 2011.

Sobieski, T., Arámbula-Mercado, E., and Epps Martin, A. A Method for Characterising RAP Degree of Binder Activity. *Road Materials and Pavement Design*, Vol. 23, No. 10, 2022, pp. 2250–2270.

Tebaldi, G., and Dave, E.V., eds. *Recycling Asphalt Pavement: State-of-the-Art of the RILEM Technical Committee 264-RAP*. Springer, Cham, Switzerland, 2025.

Virginia Department of Transportation. *AASHTOWare Pavement ME User Manual*. Richmond, VA, 2017.

Virginia Department of Transportation. *Road and Bridge Specifications.* Richmond, VA, 2020.

Virginia Department of Transportation. *Virginia Test Methods.* Richmond, VA, 2025.

Wang, Y.D., Underwood, B.S., and Kim, Y.R. Development of a Fatigue Index Parameter, Sapp, for Asphalt Mixes Using Viscoelastic Continuum Damage Theory. *International Journal of Pavement Engineering*, Vol. 23, No. 2, 2020, pp. 438–452.

West, R.C. *Best Practices for RAP and RAS Management*. Quality Improvement Series 129. National Asphalt Pavement Association, Lanham, MD, 2015. https://www.asphaltpavement.org/uploads/documents/EngineeringPubs/QIP129_RAP_-_RAS_Best_Practices_lr.pdf.

Yin, F., Jimenez, J.A.G., Chen, C., Dixon, S., Bonnet, A.M., Tran, N., Rodezno, C., Epps Martin, A., Al-Shamayleh, R., Arámbula-Mercado, E. *Recycled Asphalt Materials: Binder Availability and Its Impact on Mix Performance*. Web-Only Document 450. National Cooperative Highway Research Program, Washington, DC, 2026.

Zhang, R., Sias, J.E., and Dave, E.V. Evaluation of the Cracking and Aging Susceptibility of Asphalt Mixtures Using Viscoelastic Properties and Master Curve Parameters. *Journal of Traffic and Transportation Engineering (English Edition)*, Vol. 9, No. 1, 2020.

APPENDIX
GUIDELINES TO INCORPORATE RECYCLED BINDER AVAILABILITY INTO MIX DESIGN

Scope

This appendix describes the test methods and analyses adopted in this study to incorporate recycled binder availability (RBA) into the mixture design process. The procedural steps are presented first, followed by sample results and example calculations illustrating implementation of the method. The procedure described assumes that the following properties are available: compacted asphalt mixture bulk specific gravity (G_{mb}), theoretical maximum specific gravity of the asphalt mixture (G_{mm}), bulk specific gravity of the aggregate blend (G_{sb}), virgin asphalt content of the mixture ($\%AC_{Virgin}$), and reclaimed asphalt pavement (RAP) content, expressed as a percentage of total mixture mass ($\%RAP_{mix}$). Asphalt mixtures incorporating RBA should also comply with VDOT's balanced mix design (BMD) design performance criteria outlined in the BMD special provision.

Procedure

Step 1: Measure RAP Recycled Binder Availability

RBA shall be performed using the sieve analysis procedure developed in the National Cooperative Highway Research Program IDEA Project 236 (Castorena et al., 2024). The procedure first determines the gradation of a RAP stockpile (black curve). The analysis also requires the RAP asphalt content and recovered aggregate gradation (white curve), obtained either from the same sample used to measure the black curve or from separate American Association of State Highway and Transportation Officials (AASHTO) T 164 or T 308 (asphalt content) and T 30 (gradation) tests. In addition, the RAP aggregate effective specific gravity, determined in accordance with AASHTO T 209 and Virginia Test Method 102 is required. The differences between the black and white curves along with the asphalt content and effective aggregate specific gravity are used to calculate RBA. The following sections provide detailed test procedure and calculations.

Part A: Dry and prepare the RAP.

- Dry the RAP in an oven at 60°C. While the RAP is still warm, skim to break up any lumps formed during the drying process.
- Reduce the RAP to obtain a sample according to AASHTO R 76 Method A to achieve the sample size required by Virginia Test Method 102.

Part B: Conduct a washed sieve analysis of the RAP to determine its black curve.

- Wash the RAP sample over nested 1.18-mm (No. 16) and 0.075-mm (No. 200) sieves using a mechanical washer. When the water coming out from under the sieves is clear, the material retained in both sieves can be dumped into a pan.
- Spread the material in the pan.
- Dry the sample to a constant weight in an oven at a temperature of 100°C. While the sample is still hot, separate the RAP particles by hand, taking care to avoid fracturing the

aggregate. If a sample is not sufficiently soft to be separated manually, return it to the oven until at 100°C it can be separated as described.

- Sieve the sample over sieve size 1.18-mm (No.16) and spread the retained material over a pan. Set the finer fraction aside. Separate the particles from the coarse fraction (retained over sieve size 1.18 mm) by hand like a G_{mm} sample, taking care to avoid fracturing the aggregate. Allow the sample to cool and then recombine it with the finer fraction.
- Sieve and record the gradation of the entire RAP test sample after drying it according to AASHTO T 30. Calculate the total weight and ensure it passes the verification requirements in AASHTO T 30. The gradation of RAP is termed the black curve.
- Add the mass of dry material passing the 0.075-mm (No. 200) sieve by dry sieving to the mass removed by washing to obtain the total passing the 0.075-mm (No. 200) sieve.
- Proceed to the Calculations instructions if the RAP asphalt content and recovered aggregate gradation results are already available. Otherwise, proceed to Part C.

Part C: Remove asphalt and recover aggregate.

- Recombine the washed and sieved sample and remove the asphalt according to Virginia Test Method 102, recording the measured asphalt content without applying the 0.4% correction factor.

Part D: Conduct a washed sieve analysis of the recovered aggregate to obtain the white curve.

- Determine the grading of the extracted aggregate according to AASHTO T 30. The recovered aggregate gradation is termed the white curve.
- If Parts C and D are used, add the mass of dry material passing the 0.075-mm (No. 200) sieve by dry sieving obtained in Part B to the mass removed by washing in Part D to obtain the total passing the 0.075-mm (No. 200) sieve.

Calculations

- Compute the total volume of mastic in a sample of RAP containing 100 g of aggregate using Equation A1.

$$V_{mastic} = \frac{P_b\left(1+\frac{P_b}{(100-P_b)}\right)}{G_b} + \frac{P_{200}}{G_{se}} \quad \text{[Eq. A1]}$$

Where:

V_{mastic} = volume of mastic in a mix with 100 g of aggregate (cm^3),

P_b = RAP asphalt content (%),

G_b = binder specific gravity,

G_{se} = effective specific gravity of the RAP aggregate, and

P_{200} = filler content of the mastic, equal to the percent passing the No. 200 (0.075 mm) sieve of the white curve minus that from the black curve previously determined.

- Calculate the average mastic film thickness in the RAP using a least squared error optimization to minimize the absolute difference between the volume of mastic calculated using Equation A2 and the total known volume of mastic calculated in Equation A1.

$$V_{mastic} = \sum_{i=1}^{n-1} \frac{P_{i+1}-P_i}{G_{se}\times\rho_{water}\times\frac{\pi}{6}\times\left(\frac{d_{i+1}+d_i}{2}\right)^3} \times \frac{\pi}{6}\left[\left(\frac{d_{i+1}+d_i}{2}+2t\right)^3 - \left(\frac{d_{i+1}+d_i}{2}\right)^3\right] \qquad \text{[Eq. A2]}$$

Where:
n = number of sieve sizes,
N_i = number of particles of size i,
P_i = white curve percent passing sieve size i (%),
G_{se} = aggregate effective specific gravity,
d_i = sieve size (cm), and
t = mastic film thickness (cm).

- Compute the volume of peripheral (i.e., available) mastic coating the RAP particles using Equation A3.

$$V_{available\ mastic} = \sum_{i=1}^{n-1} \frac{RP_{i+1}-RP_i}{G_{se}\times\rho_{water}\times\frac{\pi}{6}\times\left(\frac{d_{i+1}+d_i}{2}-2t\right)^3} \times \frac{\pi}{6}\left[\left(\frac{d_{i+1}+d_i}{2}\right)^3 - \left(\frac{d_{i+1}+d_i}{2}-2t\right)^3\right]$$

[Eq. A3]

Where:
RP_i = RAP percent passing sieve size i, and
RP_{i+1} = RAP percent passing sieve size $i+1$.

- Compute *RBA* using Equation A4.

$$RBA = \frac{V_{available\ mastic}}{V_{mastic}} \times 100\% \qquad \text{[Eq. A4]}$$

Step 2: Recalculate RAP Asphalt Content According to the Measured RBA

Recalculate RAP asphalt content by adjusting for the measured RBA using Equation A5.

$$\%AC_{RAP,Available} = \%AC_{RAP} \times \frac{RBA}{100} \qquad \text{[Eq. A5]}$$

Where:
$\%AC_{RAP,Available}$ = available RAP asphalt content, accounting for RBA (%),
$\%AC_{RAP}$ = RAP asphalt content determined according to Virginia Test Method 102 (%), and
RBA = recycled binder availability from Step 1.

Step 3: Recalculate Mixture Properties

Volumetric properties, including voids in total mix, voids in mineral aggregate (VMA), voids filled with asphalt, and the fines-to-asphalt ratio, shall be determined and reported in accordance with AASHTO R 35. When calculating VMA, voids filled with asphalt, and the fines-to-asphalt ratio, the mixture's asphalt content shall be determined using Equation A6, with one exception. The effective aggregate specific gravity (G_{se}) shall be calculated using the total asphalt content calculated according to Equation A7.

$$\%AC_{adj} = \frac{\%RAP_{mix}}{100} \times \%AC_{RAP,Available} + \%AC_{Virgin} \qquad \text{[Eq. A6]}$$

Where:
$\%AC_{adj}$ = total mixture asphalt content, adjusted for RBA (%),
$\%RAP_{mix}$ = percent RAP in mixture (%), and
$\%AC_{Virgin}$ = virgin asphalt content in mixture (%).

$$\%AC_{original} = \frac{\%RAP_{mix}}{100} \times \%AC_{RAP} + \%AC_{Virgin} \qquad \text{[Eq. A7]}$$

Where:
$\%AC_{original}$ = total mixture asphalt content without RBA (%).

Step 4: Check Volumetric Requirements

Compare the properties calculated in Step 3 with Table II-14 in VDOT's (2020) *Road and Bridge Specifications* and the minimum design binder contents specified in VDOT Special Provision for BMD surface mixtures. If the requirements are satisfied, the mixture shall be subjected to VDOT's BMD testing to verify its compliance with performance criteria. However, if the minimum binder content and VMA are not achieved, proceed to Step 5.

Step 5: Adjust Mixture

Adjust the mixture design as necessary to comply with Table II-14 and the minimum design binder requirements when calculating mixture properties according to Step 3. For mixtures that marginally fail to meet the minimum binder requirement but achieve satisfactory VMA, increasing the virgin binder content may produce a compliant mixture while still meeting voids in total mixture requirements. In cases in which this adjustment is insufficient, the aggregate gradation may need to be modified to increase VMA and achieve compliance.

Sample Results

Table A1 provides sample RAP property results, and Table A2 provides sample mixture property results, incorporating the RAP from Table A1.

Table A1. Example RAP Properties

Property	Value
$\%AC_{RAP}$	5.0
RBA (%)	70

AC = asphalt content; RAP = reclaimed asphalt pavement; RBA = recycled binder availability.

Table A2. Example Mixture Properties

Property	Value
G_{mb}	2.386
G_{mm}	2.489
G_{sb}	2.700
G_b	1.030
$P_{0.075}$	4.5
$\%AC_{Virgin}$	3.3
$\%RAP_{mix}$	40

AC = asphalt content; RAP = reclaimed asphalt pavement.

According to Equation A5, the $\%AC_{RAP,Available}$ is calculated using Equation A8.

$$\%AC_{RAP,Available} = 5.0 \times \frac{70}{100} = 3.5\% \qquad \text{[Eq. A8]}$$

Then, according to Equation A6, the adjusted asphalt content of the mixture is calculated as shown in Equation A9.

$$\%AC_{adj} = \frac{40}{100} \times 3.5 + 3.3 = 4.7\% \qquad \text{[Eq. A9]}$$

The total (original) asphalt content is calculated as shown in Equation A10 and used to calculate G_{se} from the G_{mm} and G_b values.

$$\%AC_{orginal} = \frac{40}{100} \times 5.0 + 3.3 = 5.3\% \qquad \text{[Eq. A10]}$$

This G_{se} combined with the adjusted asphalt content are used in combination with the other mixture and component material properties to calculate voids in total mix, VMA, voids filled with asphalt, and the fines-to-asphalt ratio according to AASHTO R 35. Table A3 summarizes the corresponding inputs to the AASHTO R 35 calculations, yielding the properties in Table A4.

Table A3. Inputs to AASHTO R 35

Property	Value
G_{mb}	2.386
G_{mm}	2.489
G_{sb}	2.700
G_{se}	2.703
G_b	1.030
$P_{0.075}$	4.5
$\%AC$	4.7

AC = asphalt content.

Table A4. Calculated Properties

Property	**Value**
VTM	4.1
VMA	15.8
VFA	73.8
FA	1.0
%*AC*	4.7

AC = asphalt content; FA = fines-to-asphalt ratio; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture.