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Surface Mixtures Incorporating Recycled Plastic and High Reclaimed Asphalt Pavement Contents: 2022 and 2023 Field Trials

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Final Report VTRC 26-R36

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Abstract:

Like many other state highway agencies, the Virginia Department of Transportation is extensively working to consider how to best incorporate recycled materials—such as recycled plastic, reclaimed asphalt pavement (RAP) at higher contents with and without the use of recycling agents (RAs), and other materials—into their roads while maintaining or improving durability. The purpose of the study was to determine if recycled plastic-modified (RPM) asphalt mixtures and high RAP (HRAP) mixtures with RAs require deviation from current practice. The first objective of this research was to evaluate whether the design, production, and paving of RPM asphalt mixtures require a change in current practice. The second objective was to ascertain if the production and paving of RPM mixtures result in the generation of hazardous emissions to the environment. The third objective of the study was to assess if higher RAP content mixtures (RAP content > 30%) containing RAs can be designed, produced, and paved to meet relevant performance specifications. Finally, the study evaluated the short-term performance of RPM mixtures and HRAP mixtures containing RAs.

Two control, five RPM, and three HRAP RA mixtures were evaluated during the six field trials. The mixtures included combinations of different RAP contents, five recycled plastic-based additives, and three RA products. Volumetric and gradation analyses were performed on the mixtures. The Cantabro mass loss test, the indirect tensile cracking test, and the Asphalt Pavement Analyzer test were performed on laboratory-produced design specimens and non-reheated and reheated plant-produced, laboratory-compacted specimens. Additional testing, which included the indirect tensile test at high temperature, the indirect rutting test, dynamic modulus, cyclic fatigue, and stress sweep rutting tests, was performed on reheated mixtures. All findings and conclusions are limited to the mixtures evaluated.

Based on the results for the mixtures tested in this study, modification of mixtures with engineered recycled plastics could provide similar or enhanced cracking performance properties and characteristics compared with unmodified control mixtures if designed properly. Long-term cracking performance data remain a critical key element to assess such types of mixtures. Emissions of polycyclic aromatic hydrocarbons, asphalt fumes, and volatile organic compounds generated from one of the evaluated RPM mixtures during paving operations were consistently low and below the reporting limits provided by the laboratory in many cases. Furthermore, mixtures containing 40% RAP contents and RAs can be designed and produced to meet current balanced mix design performance thresholds and current volumetric properties, gradation, and asphalt content requirements. Moreover, all RPM and HRAP sections are in very good condition. Because the sections were placed in 2022 and 2023, field performance data are preliminary.

It is recommended that the Virginia Department of Transportation districts and the Virginia Transportation Research Council continue to monitor the performance of the RPM and HRAP RA sections evaluated in this study. In addition, it is recommended that the Virginia Transportation Research Council work with the Materials Division and districts to consider conducting additional field trials using RPM and HRAP RA mixtures to assess long-term field performance.

FINAL REPORT

SURFACE MIXTURES INCORPORATING RECYCLED PLASTIC AND HIGH RECLAIMED ASPHALT PAVEMENT CONTENTS: 2022 AND 2023 FIELD TRIALS

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

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DISCLAIMER

ABSTRACT

Like many other state highway agencies, the Virginia Department of Transportation is extensively working to consider how to best incorporate recycled materials—such as recycled plastic, reclaimed asphalt pavement (RAP) at higher contents with and without the use of recycling agents (RAs), and other materials—into their roads while maintaining or improving durability. The purpose of the study was to determine if recycled plastic-modified (RPM) asphalt mixtures and high RAP (HRAP) mixtures with RAs require deviation from current practice. The first objective of this research was to evaluate whether the design, production, and paving of RPM asphalt mixtures require a change in current practice. The second objective was to ascertain if the production and paving of RPM mixtures result in the generation of hazardous emissions to the environment. The third objective of the study was to assess if higher RAP content mixtures (RAP content > 30%) containing RAs can be designed, produced, and paved to meet relevant performance specifications. Finally, the study evaluated the short-term performance of RPM mixtures and HRAP mixtures containing RAs.

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TABLE OF CONTENTS

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INTRODUCTION

Overview

During the past several decades, the Virginia Department of Transportation (VDOT) evaluated the use and performance of several technologies in asphalt mixtures that can help extend the performance life of roadways and reduce environmental burdens from transportation systems. For example, asphalt mixtures have incorporated the use of warm mix asphalt technologies, highly polymer-modified asphalt binders, and bio-binders. For instance, warm mix asphalt technologies can reduce temperatures and emissions at the plant (Diefenderfer at al., 2007), highly polymer-modified asphalt binders can extend asphalt material performance life (Habbouche et al., 2021), and bio-binders can reduce dependence on fossil fuels (Habbouche et al., 2023). Furthermore, like many other state highway agencies, VDOT is extensively working to determine how to best incorporate recycled materials—such as recycled plastic, reclaimed asphalt pavement (RAP) at higher contents with and without recycling agents (RAs), recycled tire rubber, and hybrid rubber—into roads to conserve virgin material use while maintaining or improving durability (Diefenderfer et al., 2021b, 2023; Habbouche et al., 2023; Habbouche and Nair, 2024).

Recycled Plastic-Modified Asphalt Mixtures

The concept of incorporating plastic waste, or recycled plastic, into asphalt mixtures has been on VDOT's radar for several years. The effort to address this concept promotes defining a sustainable solution for both improving the performance of asphalt pavements in Virginia and diverting waste plastic away from the landfill or incinerator and into a secondary use as a replacement for other raw materials. With the existence of multiple plastic types and major uncertainties due to variabilities in their chemical and physical properties, this approach will help the agency gain some knowledge about the types of recycled plastic waste that may be compatible with the paving materials typically used in Virginia (e.g., asphalt binders, aggregates, and others) and that are expected to result in longer lasting materials.

The Virginia Transportation Research Council (VTRC) in collaboration with the Richmond District completed one major benchmarking experiment and project during the 2021 paving season (Habbouche et al., 2025). The experiment included two recycled plastic-modified (RPM) 12.5-mm nominal maximum aggregate size (NMAS) dense-graded surface mixtures (SMs) (SM-12.5RPM P1 and SM-12.5RPM P2) alongside two typical VDOT reference dense-graded mixtures (SM-12.5D and SM-12.5E). The first RPM mixture featured the use of a mixture of recycled polyethylene-based polymers (hereafter, P1) designed for the extension and enhancement of asphalt binders used in road surfaces, introduced at a rate of 5% by total weight of the employed asphalt binder. The second plastic trial featured the use of recycled polyethylene terephthalate-based plastomeric amorphous polymers (hereafter, P2) designed to improve the overall performance introduced at a rate of 3% by total weight of the employed asphalt binder. The RPM mixtures were designed to meet the agency's specifications in terms of gradation and volumetric properties. Both RPM mixtures included 15% RAP and were produced using a performance grade (PG) 64S-22 asphalt binder, with "S" denoting standard traffic.

Habbouche at al. (2025) documented and assessed the RPM field trials constructed during the 2021 paving season in Virginia in terms of constructability, laboratory performance, and initial field performance. Along with the increased interest in the reuse of waste plastics, a growing concern has been raised regarding the topic of microplastics in the environment. Therefore, this effort also addressed detecting and quantifying the presence of microplastics in material generated from pavement wear that could potentially be mobilized via stormwater runoff.

Many lessons were learned from this trial regarding the mixture design and production stages, but more remains to be understood and addressed. Continuing to evaluate the RPM and reference mixtures is needed in the laboratory with a major focus on critical long-term aging and in the field through non-destructive testing. It is also necessary to evaluate the feasibility and process of recycling asphalt mixtures already containing recycled plastic to address the effect of further recycling on the properties and production of such mixtures, and the potential generation of hazardous emissions to the environment (Habbouche et al., 2025). To begin to address these concerns, multiple field trials were constructed during the 2022 paving season. These trials featured similar and new types of plastic waste.

High Reclaimed Asphalt Pavement Mixtures and Recycling Agents

Facilitating the increased durability of asphalt mixtures is a priority for VDOT. The balanced mix design (BMD) concept proposes to address this task through incorporating performance criteria into mixture design and acceptance (Diefenderfer et al., 2021a; Habbouche et al., 2022). In 2007, VDOT introduced specifications to allow higher percentages of RAP (i.e., up to 30%) in non-polymer modified SMs. By 2013, VDOT had begun to consider the feasibility of allowing the use of SMs containing up to 45% of RAP material. Several trial sections were constructed having mixtures with 20%, 30%, 40%, and 45% RAP for evaluation (Diefenderfer and Nair, 2014). In general, those trials found that mixtures incorporating up to 45% RAP could be designed, produced, and constructed if proper procedures were followed. Moreover, the challenges arising from the use of HRAP mixtures, such as the production of overly stiff mixtures, can be addressed through the use of softer binders. Therefore, VDOT has developed a special provision that uses BMD concepts to specify as-designed mixture performance for use with field trials of mixtures having higher (greater than 30%) RAP content (HRAP mixtures).

In 2019, another study was conducted to evaluate field trials of non-HRAP and HRAP asphalt mixtures with and without the use of RAs (Diefenderfer et al., 2021b). The HRAP mixtures were designed following the BMD special provision for VDOT's SMs. Nine mixtures were evaluated from two field trials. The first trial included a reference non-HRAP control mixture, a conventional non-HRAP mixture with a softer binder grade, an HRAP mixture, an HRAP mixture with a softer binder, and an HRAP mixture with a RA. The second trial included two control mixtures and two non-HRAP mixtures incorporating two different RAs. In 2020, Diefenderfer et al. (2023) evaluated 12 mixtures (four control and eight BMD HRAP mixtures) during five field trials. The mixtures incorporated various combinations of RAP contents, two binder grades, four RAs, one type of fiber, and two warm mix asphalt additives. Understanding and wanting to address the potential effects of HRAP on durability, VTRC developed and established two practical performance-based frameworks related to RAs (Habbouche et al., 2023). The first framework determines the acceptability of a specific RA product for inclusion in VDOT's approved product list. The second framework evaluates the short- and long-term effectiveness of RAs in improving the performance of asphalt mixtures, particularly those with HRAP contents (Habbouche et al., 2023).

PURPOSE AND SCOPE

The purpose of this study was to determine if using RPM asphalt mixtures and HRAP mixtures with RAs requires deviation from current practice. The study had four objectives:

- Determine if RPM asphalt mixtures produced using plastic waste and typical aggregates and asphalt binders available in Virginia necessitate a change in design, production, or paving practice.
- Determine if the production and paving of RPM mixtures result in the generation of excess polycyclic aromatic hydrocarbons, volatile organic compounds, and asphalt fume emissions to the environment.
- Determine if higher RAP content mixtures (RAP content > 30%) containing RAs can be designed, produced, and paved to meet relevant performance specifications.
- Evaluate the short-term performance of RPM asphalt mixtures and HRAP mixtures containing RAs.

The scope is limited to information learned from the three RPM and three HRAP field trials.

METHODS

The general approach for this study was to document the mixture design, production, and construction processes for each field trial. Producer-supplied design specimens, plant-produced mixture samples, and as-paved material (i.e., cores) were obtained. Testing was conducted on laboratory-produced design specimens, specimens fabricated from non-reheated and reheated plant-produced mixtures, and field cores. The steps required to execute this approach were to:

- Conduct field trials.
- Sample materials.
- Conduct laboratory evaluations of asphalt mixtures.
- Conduct laboratory evaluations of asphalt binders.
- Evaluate field cores.
- Conduct initial field performance.
- Evaluate emissions.

Field Trials

Previous field trials provided valuable insights into mixture design and production (Diefenderfer et al., 2021b, 2023; Habbouche et al., 2025), but further investigations were needed to fully understand and address the laboratory- and field-related attributes of mixtures with recycled materials. To that end, demonstration trials of three RPM and three HRAP with RA mixtures were constructed during the 2022 and 2023 construction seasons.

2022 and 2023 Recycled Plastic-Modified Field Demonstration Trials

The first RPM field trial, constructed by Colony Construction, Inc. (hereafter, Contractor A) in 2022 on State Route (SR) 630 Bull Hill Road and SR 645 River Road in Prince George County, included two RPM SMs alongside one reference SM-D mixture. The first RPM mixture had an NMAS of 9.5mm and incorporated recycled plastic P1 (5% by total weight of binder) by means of the dry process. The second RPM mixture, shown in Figure 1, was a 9.5mm NMAS HRAP mixture (40% RAP) that incorporated an engineered blend of polymers (P3) (8% by total weight of binder) by means of the dry process.

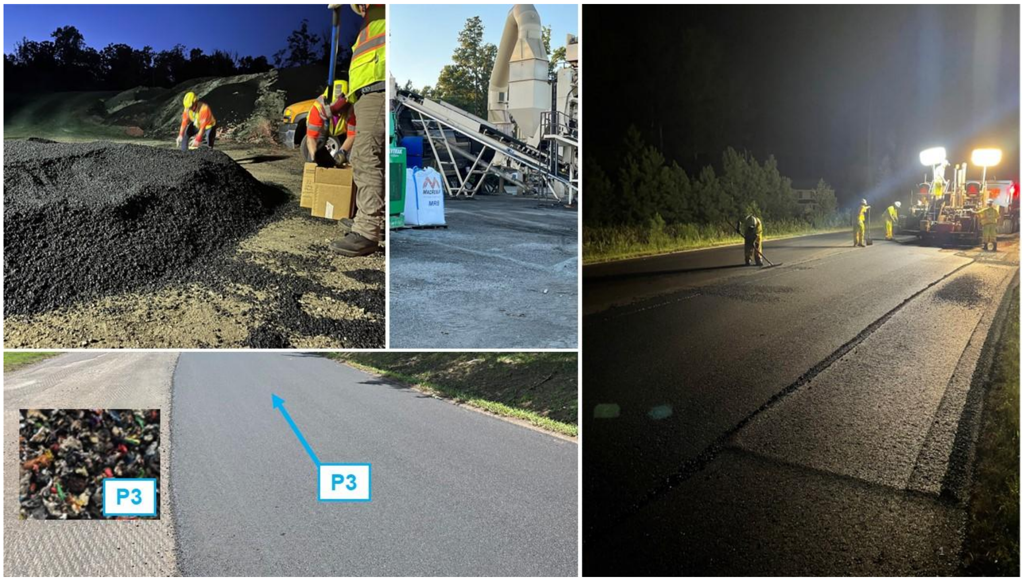


Figure 1. Production, Paving Operations, and Placement of Recycled Plastic-Modified Mixture with Plastic Additive P3

Similarly, the second RPM trial, constructed by Allan Myers (hereafter, Contractor B) in 2022 on SR 622, Dorset Road, in Powhatan County, included two RPM SMs, shown in Figure 2, alongside one SM-D reference mixture. The first RPM mixture was a 9.5-mm NMAS mixture that featured the use of highly engineered polymers (P4) made from post-consumer and post-commercial plastic (2% by total weight of binder) by means of the dry process. The second RPM mixture was a 9.5-mm NMAS mixture that used a plastic-based value-added wax and specialty polymers (P5) incorporated by means of the wet process (3% by total weight of binder).

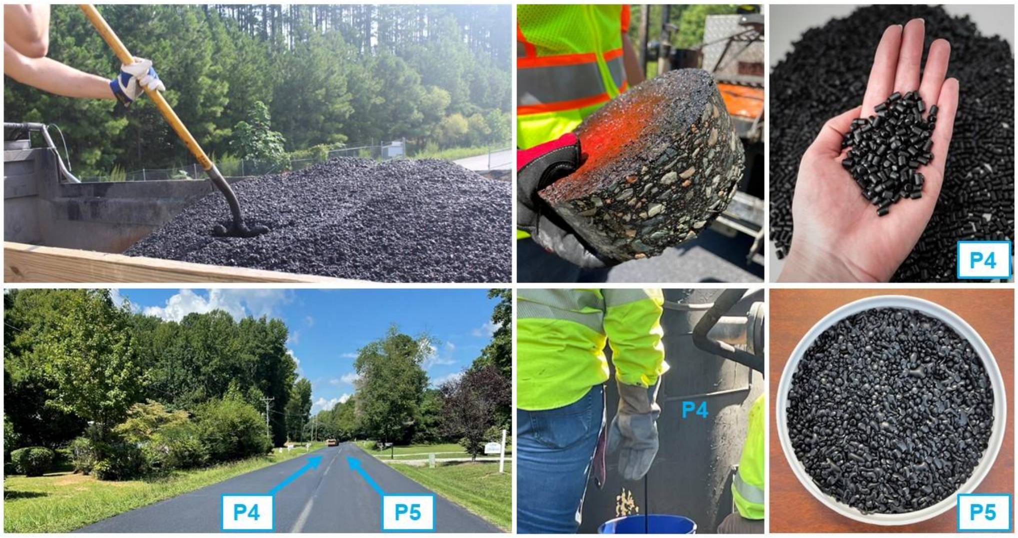


Figure 2. Production, Paving Operations, and Placement of Recycled Plastic-Modified Mixture with Plastic Additives P4 and P5

The third RPM trial, constructed by Boxley Materials Company (hereafter, Contractor C) in 2023 on SR 1220, Huntridge Road, in Roanoke, included one RPM SM with no control or reference mixture. The RPM mixture, shown in Figure 3, was a 9.5-mm NMAS mixture that incorporated a graphene-enhanced recycled plastic (P6) (5% by total weight of binder) via the dry process. The plastics used in this modifier were specifically selected as hard plastics and not sourced from plastic bottles, bags, or plasmix, a mixture of unclassified plastics. In addition, besides recycled plastics, other components, such as graphene nanomaterials and certain functional additives, were also incorporated in the additive. Graphene consists of a single monoatomic layer of carbon atoms arranged in a honeycomb structure. The graphene used in producing this asphalt modifier has undergone dermatological testing (Allen et al., 2024).

Figure 3. Production, Paving Operations, and Placement of Recycled Plastic-Modified Mixture with Plastic Additive P6

Table 1 summarizes the RPM field trials constructed during the 2021 (Habbouche et al., 2025), 2022, and 2023 paving seasons. The focus of this report is on the evaluation of the 2022 and 2023 field trials. The preconstruction condition of the roadway sites was determined from the VDOT pavement management system and with a field visit. Details relevant to the production and paving operations were thoroughly documented.

Table 1. 2021, 2022, and 2023 RPM Field Demonstration Projects

Year	Contractor	Mixture Type / Description	Locations
2021	A	**SM-12.5D1**: 30% RAP + PG 64S-22	--
		SM-12.5E1: 15% RAP + PG 64E-22	SR 732, Old Stage Road, Chester
		SM-12.5RPM P1: 15% RAP + PG 64S-22 + P1	
		SM-12.5RPM P2: 15% RAP + PG 64S-22 + P2	
2022	A	**SM-9.5D2**: 30% RAP + PG 64S-22	--
		SM-9.5RPM P1: 15% RAP + PG 64S-22 + P1	SR 645, River Road, Prince George
		SM-9.5RPM P3: 40% RAP + PG 64S-22 + P3	SR 630, Bull Hill Road, Prince George
	B	**SM-9.5D3**: 30% RAP + PG 64S-22	--
		SM-9.5RPM P4: 15% RAP + PG 64S-22 + P4	SR 622, Dorset Road, Powhatan
		SM-9.5RPM P5: 15% RAP + PG 64S-22 + P5	SR 622, Dorset Road, Powhatan
2023	C	**SM-9.5RPM P6**: 26% RAP + PG 64S-22 + P6	SR 1220, Huntridge Road, Roanoke

D and E = mixture designations; E = extremely heavy traffic; PG = performance grade; RAP = reclaimed asphalt pavement; RPM = recycled plastic-modified; S = standard traffic; SM = surface mixture; SR = State Route.

2022 and 2023 High Reclaimed Asphalt Pavement with Recycling Agent Field Demonstration Trials

The first HRAP with RA mixture, constructed in 2022 (SM-9.5HRAP RA1), was a 9.5-mm NMAS mixture with 40% RAP content that incorporated a green bio-based asphalt rejuvenator. This RA was expected to soften and restore the functional properties of the aged binder, aid the workability and compactability of the asphalt mixture, deliver the required roadway performance and durability, and reduce the need for virgin binder. Superior Paving Corporation (hereafter, Contractor D) produced the mixture during the course of 2 days, and it was placed on SR 2401, Riverside Parkway, and SR 2403, Woodridge Parkway, in Ashburn, Virginia (Figure 4).

Figure 4. Production, Paving Operations, and Placement of Mixture with High Content of Reclaimed Asphalt Pavement and Recycling Agent RA1

The second HRAP with RA mixture, constructed during the 2023 paving season (SM-9.5HRAP RA2), was a 9.5-mm NMAS mixture with 40% RAP content that incorporated a polyester oil-based asphalt rejuvenator. This RA was intended to improve mixture cracking without adversely affecting rutting performance, reduce mixture cost by incorporating higher RAP contents without performance issues, reduce viscosity and improve mixture workability, and reduce stiffness of the aged binder. Contractor D produced the mixture during the course of 2 nights, and it was placed on SR 621, Gum Spring Road, in Bull Run, Virginia (Figure 5).

The third HRAP with RA mixture, constructed during the 2023 paving season (SM-12.5HRAP RA3), was a 12.5-mm NMAS mixture with 40% RAP content that incorporated a high-purity petrochemical-based asphalt rejuvenator. Similar to other RAs, it was used to reduce the risk of cracking, enhance the durability of asphalt pavements, and increase the amount of RAP in asphalt mixtures without adversely affecting the final performance. Branscome Inc. (hereafter, Contractor E) produced the mixture during the course of 2 days, and it was placed on SR 620 Foursquare Road in Isle of Wight, Hampton Roads, Virginia.

Figure 5. Production, Paving Operations, and Placement of Mixture with High Content of Reclaimed Asphalt Pavement and Recycling Agent RA2

Table 2 summarizes the HRAP field trials constructed during the 2022 and 2023 paving seasons. Similarly, the preconstruction conditions of the selected roadway site were determined from the VDOT pavement management system and with a field visit. Details relevant to the production and paving operations were thoroughly documented.

Table 2. 2022 and 2023 HRAP RA Field Demonstration Projects

Year	Contractor	Mixture Type / Description	Locations
2022	D	**SM9.5HRAP RA1**: 40% RAP + PG 64S-22 + RA1	SR 2401, Riverside Parkway, Ashburn
2023	D	**SM9.5HRAP RA2**: 40% RAP + PG 64S-22 + RA2	SR 659, Gum Spring Road, Bull Run
	E	**SM12.5HRAP RA3**: 40% RAP + PG 64S-22 + RA3	SR 620, Foursquare Road, Isle of Wight

HRAP = high reclaimed asphalt pavement (RAP) content; PG = performance grade; RA = recycling agent; SM = surface mixture; S = standard traffic; SR = State Route.

All mixtures were designed using the BMD concept to provide equal or better performance than the associated control mixture (when available).

Material Sampling

Plant-produced loose mixtures were collected for each mixture type. Loose mixtures were sampled from an approximately 3- to 5-ton quantity of mixture dumped on the ground at the plant and struck off using a loader. Loose plant-produced mixture intended for specimens compacted without reheating at the plant was taken into the producer's laboratory and immediately compacted into specimens (non-reheat). Plant-compacted specimens were provided to VTRC for testing. Tables 3 and 4 summarize the sampling and testing matrix for the RPM and HRAP RA non-reheat mixtures and specimens, respectively.

The testing on non-reheat samples included testing for volumetric properties by the producer and the corresponding VDOT district (not provided in this report for the sake of brevity) and BMD tests (i.e., Cantabro test, Asphalt Pavement Analyzer [APA] rut test, and indirect tensile cracking test [IDT-CT]).

Table 3. Sampling, Compaction, and Laboratory Testing of Non-Reheat[a] RPM Mixture Specimens

Laboratory Tests, Production Details, and VTRC Log ID	Contractor A							Contractor B				Contractor C		
	SM-9.5D2	SM-9.5RPM P1			SM-9.5RPM P3			SM-9.5D3	SM-9.5RPM P4		SM-9.5RPM P5	SM-9.5RPM P6		
	1 Night	3 Nights			3 Nights			1 Night	1 Day		1 Day	3 Days		
	22-1072	Night 1 22-1048	Night 2 22-1054	Night 3 22-1057	Night 1 22-1065	Night 2 22-1069	Night 3 22-1073	22-1096	Set 1 22-1090	Set 2 22-1092	22-1098	Day 1 23-1075	Day 2 23-1080	Day 3 23-1083
Mix Design Verification														
Volumetric Properties	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Durability Assessment														
Cantabro Test	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Assessment of Rutting Performance														
APA Rut Test	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Assessment of Cracking Performance														
IDT-CT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

APA = Asphalt Pavement Analyzer; D = mixture designation; IDT-CT = indirect tensile cracking test; RPM = recycled plastic-modified; SM = surface mixture.

[a] Non-reheat refers to laboratory-compacted non-reheated specimens that were compacted on site without reheating the loose mixture sampled at the plant.

Table 4. Sampling, Compaction, and Laboratory Testing of Non-Reheat[a] HRAP RA Mixture Specimens

Laboratory Tests, Production Details, and VTRC Log ID	Contractor D						Contractor E	
	SM-9.5HRAP RA1				SM-9.5HRAP RA2		SM-12.5HRAP RA3	
	2 Days				2 Nights		2 Days	
	Day 1		Day 2		Night 1	Night 2	Day 1	Day 2
	Set 1 22-1078	Set 2 22-1080	Set 3 22-1083	Set 4 22-1085	23-1058	23-1059	23-1071	23-1073
Mix Design Verification								
Volumetric Properties	✓	✓	✓	✓	✓	✓	✓	✓
Durability Assessment								
Cantabro Test	✓	✓	✓	✓	✓	✓	✓	✓
Assessment of Rutting Performance								
APA Rut Test	✓	✓	✓	✓	✓	✓	✓	✓
Assessment of Cracking Performance								
IDT-CT	✓	✓	✓	✓	✓	✓	✓	✓

APA = Asphalt Pavement Analyzer; HRAP = high reclaimed asphalt pavement (RAP); IDT-CT = indirect tensile cracking test; RA = recycling agent; SM = surface mixture.

[a] Non-reheat refers to laboratory-compacted non-reheated specimens that were compacted on site without reheating the loose mixture sampled at the plant.

Furthermore, loose plant-produced mixtures were placed into boxes, taken to VTRC, and stored in a climate-controlled area until evaluated. Specimens were then fabricated by reheating the loose mixtures until they became workable, splitting the material into appropriate quantities, heating the material to the compaction temperature, and then compacting the material. Tables 5 and 6 summarize the testing matrix for the reheats. The evaluation included testing for volumetric properties and BMD tests. Additional testing of short-term aged specimens consisted of the indirect tensile test at high temperature (IDT-HT), indirect tensile rutting test (IDEAL-RT), dynamic modulus |E*| test, direct tension cyclic fatigue (CF) test, and stress sweep rutting (SSR) test.

Laboratory Evaluation of Asphalt Mixtures

Volumetric Properties and Aggregate Gradations of Mixtures

The theoretical maximum specific gravity of each mixture was determined in accordance with American Association of State Highway and Transportation Officials (AASHTO) T 209, *Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Asphalt Mixtures* (AASHTO, 2020). The asphalt binder content of each mixture was determined by the ignition method in accordance with Virginia Test Method 102, *Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Method* (VDOT, 2013). The size distribution (gradation) of the recovered aggregate was determined in accordance with AASHTO T 11, *Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing* (AASHTO, 2020), and AASHTO T 30, *Standard Method of Test for Mechanical Analysis of Extracted Aggregates* (AASHTO, 2021). Loose mixtures were conditioned at the compaction temperature and then compacted to N_{design} gyrations (i.e., 50 gyrations) using a Superpave gyratory compactor in accordance with AASHTO T 312, *Preparing and Determining the Density of Asphalt Mixtures Specimens by Means of the Superpave Gyratory Compactor* (AASHTO, 2019). Basic physical characteristics and volumetric parameters in terms of bulk specific gravity, voids in total mixture, voids in mineral aggregate, voids filled with asphalt, fines to aggregate ratio, aggregate effective specific gravity, aggregate bulk specific gravity, absorbed asphalt binder content, effective asphalt binder content, and effective film thickness were determined.

VDOT Balanced Mix Design Performance Tests

Cantabro Test

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

Table 5. Sampling, Compaction, and Laboratory Testing of Reheat[a] RPM Mixture Specimens

Laboratory Tests, Production Details, and VTRC Log ID	Contractor A							Contractor B				Contractor C		
	SM-9.5D2	SM-9.5RPM P1			SM-9.5RPM P3			SM-9.5D3	SM-9.5RPM P4		SM-9.5RPM P5	SM-9.5RPM P6		
	1 Night	3 Nights			3 Nights			1 Night	1 Day		1 Day	3 Days		
	22-1071	Night 1 22-1049	Night 2 22-1055	Night 3 22-1058	Night 1 22-1064	Night 2 22-1068	Night 3 22-1074	22-1095	Set 1 22-1089	Set 2 22-1091	22-1097	Day 1 23-1074	Day 2 23-1079	Day 3 23-1082
Mix Design Verification														
Volumetric Properties	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Durability Assessment														
Cantabro Test	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Determination of Mechanical Property														
Dynamic Modulus |E*| Test	✓		✓			✓		✓		✓	✓		✓	
Assessment of Rutting Performance														
IDT-HT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
IDEAL-RT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
APA Rut Test	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SSR Test	✓		✓			✓		✓		✓	✓		✓	
Assessment of Cracking Performance														
IDT-CT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CF Test	✓		✓			✓		✓		✓	✓		✓	
Evaluation of Extracted and Recovered Asphalt Binders														
Continuous PG	✓		✓			✓		✓		✓	✓		✓	

APA = Asphalt Pavement Analyzer; CF = cyclic fatigue; D = mixture designation; IDT-CT = indirect tensile cracking test; IDT-HT = indirect tensile test at high temperature; IDEAL-RT = indirect tensile rutting test; PG = performance grade; RPM = recycled plastic-modified; SM = surface mixture; SSR = stress sweep rutting.

[a] Reheat refers to laboratory-compacted reheated specimens that were compacted after reheating the loose mixture sampled at the plant.

Table 6. Sampling, Compaction, and Laboratory Testing of Reheat[a] HRAP RA Mixture Specimens

Laboratory Tests, Production Details, and VTRC Log ID	**Contractor D**						**Contractor E**	
	SM-9.5HRAP RA1				**SM-9.5HRAP RA2**		**SM-12.5HRAP RA3**	
	2 Days				**2 Nights**		**2 Days**	
	Day 1		**Day 2**		**Night 1**	**Night 2**	**Day 1**	**Day 2**
	Set 1 22-1077	**Set 2 22-1079**	**Set 3 22-1082**	**Set 4 22-1084**	**23-1045**	**23-1046**	**23-1070**	**23-1072**
Mix Design Verification								
Volumetric Properties	✓	✓	✓	✓	✓	✓	✓	✓
Durability Assessment								
Cantabro Test	✓	✓	✓	✓	✓	✓	✓	✓
Determination of Mechanical Property								
Dynamic Modulus |E*| Test		✓				✓	✓	
Assessment of Rutting Performance								
IDT-HT	✓	✓	✓	✓	✓	✓	✓	✓
IDEAL-RT	✓	✓	✓	✓	✓	✓	✓	✓
APA Rut Test	✓	✓	✓	✓	✓	✓	✓	✓
SSR Test		✓				✓	✓	
Assessment of Cracking Performance								
IDT-CT	✓	✓	✓	✓	✓	✓	✓	✓
CF Test		✓				✓	✓	
Evaluation of Extracted and Recovered Asphalt Binders								
Continuous PG		✓				✓	✓	

APA = Asphalt Pavement Analyzer; CF = cyclic fatigue; D = mixture designation; HRAP = high reclaimed asphalt pavement; IDEAL-RT = indirect tensile rutting test; IDT-CT = indirect tensile cracking test; IDT-HT = indirect tensile test at high temperature; PG = performance grade; RA = recycling agent; SM = surface mixture; SSR = stress sweep rutting.

[a] Reheat refers to laboratory-compacted reheated specimens that were compacted after reheating the loose mixture sampled at the plant.

Indirect Tensile Cracking Test

IDT-CT was conducted at 25°C in accordance with American Society for Testing Materials D8225-19, *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature* (ASTM International, 2019). All test specimens were 150 mm in diameter by 62 mm in height and were tested at 7.0 ± 0.5% air voids. The cracking tolerance (CT) index was calculated from the test load-displacement curve collected during testing. A higher CT index value indicates greater resistance to cracking.

Asphalt Pavement Analyzer Rut Test

The APA rut test was performed in accordance with AASHTO T 340, *Standard Method of Test for Determining the Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)* (AASHTO, 2019). All test specimens were 150 mm in diameter by 75 mm in height and were tested at 7.0 ± 0.5% air voids. After 8,000 cycles were applied at a temperature of 64°C, the deformation of the specimen was measured. A lower APA rut depth (RD) indicates greater resistance to rutting.

Indirect Tensile Test at High Temperature

IDT-HT was conducted by applying a constant rate of axial displacement on the diametrical plane of the test specimens. The test was conducted at 54.4°C and a loading rate of 50 ± 2 mm/minute (Boz et al., 2023). The specimens were fabricated at a diameter of 150 mm and a height of 62 mm at 7 ± 0.5% target air voids. The specimens were conditioned for 45 minutes in a water bath at the test temperature before being tested. Once testing was completed, the indirect tensile strength (S_t) of the specimens was determined. A higher S_t value indicates higher resistance to rutting.

Indirect Tensile Rutting Test

IDEAL-RT, also known as the rapid rutting test, is a monotonic loading rutting test that researchers at the Texas Transportation Institute developed. IDEAL-RT is conducted in a similar manner as IDT-HT except that a shear fixture is used in lieu of a typical IDT-HT fixture. The rutting potential of asphalt mixtures from IDEAL-RT is quantified through the rutting tolerance (RT) index. A higher RT index indicates higher resistance to rutting (Boz et al., 2023).

Advanced Performance Tests

Dynamic Modulus |E| Test*

The dynamic modulus |E*| test measures the stiffness of asphalt mixtures. Testing was conducted using the Asphalt Mixture Performance Tester in accordance with AASHTO TP 132*, Standard Method of Test for Determining Dynamic Modulus for Asphalt Mixtures Using Small Specimens in the Asphalt Mixture Performance Tester* (AASHTO, 2019). The test specimens were 38 mm in diameter by 110 mm in height and were cored from a Superpave gyratory compacted specimen 150 mm in diameter by 180 mm in height. All tests were conducted in the uniaxial mode without confinement. All test specimens were compacted to 7.0 ± 0.5% air voids.

Direct Tension Cyclic Fatigue Test

The simplified viscoelastic continuum damage test, known as the direct tension CF test, was performed at 21°C using the Asphalt Mixture Performance Tester in accordance with 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, 2023). The CF test was performed on specimens 38 mm in diameter by 110 mm in height cored from Superpave Gyratory samples 150 mm in diameter by 180 mm in height compacted from loose mixtures collected during construction. All test specimens were compacted to 7.0 ± 0.5% air voids. The developed damage characteristic curves were then used with the viscoelastic material properties (i.e., |E*|) to obtain the fatigue behavior of the asphalt mixtures. Three key test outcomes were obtained from the CF tests: (1) the damage characteristic curve, also referred to as the material integrity (C) versus damage (S) curve; (2) the pseudo-energy-based failure criterion D^R; and (3) the apparent damage capacity S_{app}. The last parameter measures the amount of fatigue damage the material can tolerate while considering the effect of the material's toughness and modulus. A higher S_{app} indicates higher fatigue cracking resistance. The calculation was conducted with FlexMAT^{TM} Cracking (Version 2.1.3b), an Excel-based tool provided by the Federal Highway Administration (FHWA) (FHWA, 2019).

Stress Sweep Rutting Test

The SSR test assesses the rutting susceptibility of asphalt mixtures by applying repeated cyclic loading to confined cylindrical test specimens at two location-specific temperatures, low (23°C) and high (48°C), in accordance with AASHTO TP 134, *Standard Method of Test for Stress Sweep Rutting (SSR) Test Using Asphalt Mixture Performance Tester (AMPT)* (AASHTO, 2021). The SSR test specimens were 100 mm in diameter by 150 mm in height and were cored from the center of a Superpave gyratory compacted specimen 150 mm in diameter by 180 mm in height. All test specimens were compacted to an air void level of 7.0 ± 0.5% air voids. The SSR test results were used to calculate the average percentage of permanent strain and produce the rutting strain index (RSI) parameter calculated by the FlexMAT^{TM} Rutting analysis (Version 2.1.4.3) (FHWA, 2021b). Test results were also used to generate a permanent strain shift model that can be used with FlexPAVE^{TM} analysis to model rutting in the pavement layer. A lower RSI indicates a relatively greater resistance to rutting (FHWA, 2021b).

Laboratory Evaluation of Asphalt Binders

Extraction and Recovery of Asphalt Binders

Testing was performed on extracted and recovered asphalt binders from the mixtures collected at the plant. Extraction of asphalt binder from collected mixtures was performed in accordance with AASHTO T 164, *Quantitative Extraction of Asphalt Binder From Hot Mix Asphalt (HMA), Method A* (AASHTO, 2018) using n-propyl bromide as the solvent. The asphalt binder was then recovered from the solvent using the rotavap recovery procedure specified in AASHTO T 319, *Quantitative Extraction and Recovery of Asphalt Binder From Asphalt Mixtures* (AASHTO, 2019).

Performance Grading and Multiple Stress Creep Recovery Testing

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

Difference in Critical Low-Temperature Performance Grade Limiting Temperatures (ΔT_c)

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

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

Evaluation of Field Cores

Field core samples were collected from the projects during construction for SM-9.5RPM P1, SM-9.5RPM P3, SM-9.5RPM P4, SM-9.5RPM P5, SM-9.5RPM P6, and SM-9.5HRAP RA1 mixtures. Core locations were randomly stratified along the length and width of the section. The following properties were measured for each core: in-place layer thickness, density, permeability in accordance with Virginia Test Method 120 (VDOT, 2000), and resistance to cracking by means of the IDT-CT in accordance with American Society for Testing Materials D8225-19 (ASTM International, 2019).

Initial Field Performance

The field demonstration sections were visited in 2024, and pictures were taken to show the performance of the mixtures evaluated in this study at that time.

Evaluation of Emissions

Asphalt vapor sampling of SM-9.5RPM P6 was conducted on October 17, 2023, in Roanoke, Virginia. Eight samples were collected for polycyclic aromatic hydrocarbon (PAH), asphalt fume (AF), and volatile organic compound (VOC) analysis. PAH samples were collected and analyzed according to National Institute for Occupational Safety and Health (NIOSH) methods 5506 (NIOSH, 1998b, 2003). NIOSH method 5042 was used for the analysis of AF samples (NIOSH, 1998a). Prior to sampling, all pumps were calibrated to ensure their proper function. Sampling rates ranged from 2.1 to 2.6 liters per minute, depending on the pump, and the total sampling duration was 100 minutes, collecting 210 to 260 liters per sample. These volumes are within the ranges required by NIOSH methods 5506 and 5042 (NIOSH, 1998b, 2003).

VOC samples were collected using 566 Organic Vapor Monitor badges produced by Assay Technology and ultimately analyzed via NIOSH method 1501 (NIOSH, 2003). As opposed to the active sampling methods used for PAH and AF, these passive sampling badges rely on natural diffusion of VOCs from the air into an absorbent media and are typically used for personal exposure monitoring. Because of this technique, longer sampling intervals, commonly 4 to 8 hours, are preferred to ensure the sample is representative of a typical working period. However, because of time constraints, VOC sampling was only able to be conducted for 100 minutes, limiting the amount of VOC constituents collected. The Results and Discussion section will discuss the effects of this limitation on the results. All collected PAH, AF, and VOC samples were shipped to a certified laboratory for analysis.

Table 7 provides a breakdown of the samples collected, analysis conducted, and locations where the samples were collected. AF1/VOC1 and AF2/VOC2 samples refer to the samplers attached to the paver operators working on the left and right sides of the paver, respectively. PAH1 was collected at the center back of the paver, directly between the two operators. These locations were selected based on the literature review, which indicated that paver operators typically receive the greatest exposure to airborne contaminants (McClean et al., 2004). All blank samples were collected from an equipment staging area at a sufficient distance to prevent influence from the paving operation.

Table 7. Emissions Sampling Locations

Analyte	Sample Name	Location
Polycyclic Aromatic Hydrocarbons (PAH)	PAH1	Back of paver
	PAH2 (blank)	Staging area
Asphalt Fumes (AF)	AF1	Paver operator (left)
	AF2	Paver operator (right)
	AF3 (blank)	Staging area
Volatile Organic Compounds (VOC)	VOC1	Paver operator (left)
	VOC2	Paver operator (right)
	VOC3 (blank)	Staging area

RESULTS AND DISCUSSION

For this study, assessing the field trials encompassed mixture, binder, and field core testing and emissions evaluation.

Testing and Characterization of Asphalt Mixtures

Volumetric Properties and Aggregate Gradations of Mixtures

This section presents and discusses the volumetric properties and gradations for each of the produced mixtures to assess their conformance to the design.

Recycled Plastic-Modified Mixtures

Table 8 shows the volumetric properties and gradations for mixtures SM-9.5D2, SM-9.5RPM P1, and SM-9.5RPM P3 for design and reheated samples tested by VTRC. The results compared with the job mix formula (JMF) and the quality control and acceptance data available from the producers/contractors and VDOT districts (not provided in this report for the sake of brevity). VDOT BMD specifications require that mixtures meet design criteria for volumetric properties (binder content, voids in total mixture, voids in mineral aggregate, voids filled with asphalt, and fines to aggregate ratio) and aggregate gradations for specific sieve sizes depending on the mixture type (Diefenderfer et al., 2023; VDOT, 2020). Table 8 indicates that the three mixtures from Contractor A met VDOT mixture design criteria as outlined in the specifications. Mixture acceptance during production is based on the determination of asphalt content, gradation, and temperature, along with in-place density. The production result means for asphalt content and gradation properties are checked against the allowable tolerance from the JMF as specified. The following is based on observations made by comparing VTRC's data to the JMF. Overall, during production, all mixtures compared with the JMF. The data for SM-9.5RPM P1 and SM-9.5RPM P2 compared very well across the 3 nights of production for each mixture. No major changes were noted among the three mixture types except a slight increase in the percentage passing the No. 200 sieve for SM-9.5D2 compared with SM-9.5RPM P1 and SM-9.5RPM P3 at various nights of production. Moreover, the addition of recycled plastics did not seem to affect the volumetric properties compared with the conventional D mixtures (SM-9.5D2). SM-9.5RPM P3 contains recycled plastic and is also an HRAP mixture, having 40% RAP content. The use of higher RAP contents for SM-9.5RPM P3 did not have any significant effects on the volumetric properties and aggregate gradation of the evaluated mixture compared with SM-9.5D2 and SM-9.5RPM P1.

Table 9 summarizes the volumetric properties and aggregate gradation for mixtures produced by Contractor B (SM-9.5D3, SM-9.5RPM P4, and SM-9.5RPM P5). Borderline failing voids in mineral aggregate and much higher values in the percentage passing the No. 200 sieve were observed for SM-9.5D3 compared to the JMF. In addition, much higher voids in total mixture were observed for SM-9.5RPM P4 during production compared to the JMF, despite both samples exhibiting a higher asphalt content than the JMF. A much lower value in the percentage passing the No. 200 sieve was observed compared to the JMF. Furthermore, a much lower value in the percentage passing the No. 200 sieve was observed for SM-9.5RPM P5. Overall, much higher asphalt content and much lower values in the percentage passing the No. 200 sieve were observed for SM-9.5RPM P4 and SM-9.5RPM P5 mixtures compared with the control SM-9.5D3.

Table 10 summarizes the volumetric properties and aggregate gradation for the mixture SM-9.5RPM P6 produced by Contractor C. It should be noted that no control mixture was sampled alongside the evaluated RPM mixture by Contractor C. Overall, much higher asphalt contents were observed throughout the 3 days of production compared to the JMF, which could be attributed to the added recycled plastic and not accommodating this addition as part of the calibration factor when performing furnace burns using an ignition oven. In addition, much higher values for the No. 200 sieve were observed throughout production compared to the JMF. It should be noted that, except for SM-9.5RPM P3, which was intentionally designed to be an HRAP mixture, all mixtures were designed and produced using a maximum RAP content of 15%. SM-9.5RPM P6 was the first mixture designed and produced using conventional RAP contents for D mixtures in Virginia (26% in this case), which could have led to the observed differences in the percentage passing the No. 200 sieve.

Table 8. VTRC Volumetric Properties and Gradations for SM-9.5D2, SM-9.5RPM P1, and SM-9.5 RPM P3 Produced by Contractor A

Mixture ID	**SM-9.5D2**			**SM-9.5RPM P1**					**SM-9.5RPM P3**				
Virgin Binder Grade	**PG 64S-22**			**PG 64S-22**					**PG 64S-22**				
RAP Content, %	**30**			**15**					**40**				
Additives	**WMA**			**WMA + Plastic P1**					**WMA + Plastic P3**				
Sample	**JMF**	**Process Tolerance[a]**	**Night 1 22-1071**	**JMF**	**Process Tolerance[a]**	**Night 1 22-1049**	**Night 2 22-1055**	**Night 3 22-1058**	**JMF**	**Process Tolerance[a]**	**Night 1 22-1064**	**Night 2 22-1068**	**Night 3 22-1074**
Property													
NMAS, mm	9.5	-	9.5	9.5	-	9.5	9.5	9.5	9.5	-	9.5	9.5	9.5
Asphalt Content, %	6.00	±0.61	6.23	6.10	±0.33	6.17	5.82	6.04	6.00	±0.33	6.23	6.14	6.33
Rice SG (G_{mm})	2.497	-	2.487	2.484	-	2.491	2.492	2.472	2.495	-	2.482	2.488	2.486
VTM, %	3.9	2.0–5.0	2.9	3.5	2–5	4.1	3.7	3.2	3.5	2–5	3.6	2.9	2.3
VMA, %	17.2	Min. 16	17.1	17.7	Min. 16	18.0	16.8	16.7	16.7	Min. 16	17.3	16.4	16.4
VFA, %	77.6	70–85	83.1	79.8	70–85	77.0	77.9	81.1	79.1	70–85	79.1	82.6	85.8
FA Ratio	1.1	0.7–1.3	1.20	1.1	0.7–1.3	1.01	1.18	1.13	1.2	0.7–1.3	1.11	1.13	0.70
Mixture Bulk SG (G_{mb})	-	-	2.415	-	-	2.388	2.400	2.394	-	-	2.392	2.417	2.428
Aggregate Effective SG (G_{se})	-	-	2.745	-	-	2.747	2.732	2.717	-	-	2.738	2.742	2.748
Aggregate Bulk SG (G_{sb})	-	-	2.733	-	-	2.732	2.717	2.702	-	-	2.711	2.715	2.721
Absorbed Asphalt Content (P_{ba}), %	-	-	0.16	-	-	0.21	0.21	0.21	-	-	0.37	0.37	0.37
Effective Asphalt Content (P_{be}). %	-	-	6.07	-	-	5.98	5.62	5.84	-	-	5.88	5.78	5.98
Effective Film Thickness (F_{be}), µm	-	-	6.07	-	-	10.8	9.5	9.7	-	-	10.1	9.6	12.4
Gradation, percent passing													
¾ in (19.0 mm)	100.0	±8.0	100.0	100.0	±4.4	100.0	100.0	100.0	100.0	±4.4	100.0	100.0	100.0
½ in (12.5 mm)	100.0	±8.0	99.7	100.0	±4.4	99.7	99.7	99.9	100.0	±4.4	99.2	99.4	99.5
3/8 in (9.5 mm)	95.0	±8.0	92.8	95.0	±4.4	93.8	94.2	94.6	97.0	±4.4	93.1	94.3	92.8
No. 4 (4.75 mm)	61.0	±8.0	55.9	65.0	±4.4	59.7	60.7	61.8	66.0	±4.4	58.7	61.4	60.1
No. 8 (2.36 mm)	39.0	±8.0	36.3	44.0	±4.4	39.1	39.3	40.9	45.0	±4.4	38.8	41.0	39.4
No. 16 (1.18 mm)	-	-	25.9	-	-	26.6	27.4	28.4	-	-	27.2	29.2	27.4
No. 30 (600 µm)	19.0	±6.0	18.7	20.0	±3.3	18.6	19.4	20.0	-	±3.3	19.4	20.7	18.8
No. 50 (300 µm)	-	±5.0	13.5	-	±2.8	12.7	13.7	14.1	-	±2.8	13.6	14.4	12.4
No. 100 (150 µm)	-	-	9.9	-	-	8.6	9.5	9.6	-	-	9.3	9.6	7.5
No. 200 (75 µm)	6.2	±2.0	7.3	6.3	±1.1	6.0	6.6	6.6	6.5	±1.1	6.5	6.6	4.2

D = mixture designation; FA = fines to aggregate; JMF = job mix formula; NMAS = nominal maximum aggregate size; PG = performance grade; RAP = reclaimed asphalt pavement; RPM = recycled plastic-modified; S = standard traffic; SG = specific gravity; SM = surface mixture; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture; WMA = warm mix asphalt.

[a] Process tolerance for one test from Table II-15 (VDOT, 2020).

Table 9. VTRC Volumetric Properties and Gradations for SM-9.5D3, SM-9.5RPM P4, and SM-9.5 RPM P5 Produced by Contractor B

Mixture ID	**SM-9.5D3**			**SM-9.5RPM P4**				**SM-9.5RPM P5**		
Virgin Binder Grade	**PG 64S-22**			**PG 64S-22**				**PG 64S-22**		
RAP Content, %	**30**			**15**				**15**		
Additives	**WMA**			**WMA + P4**				**WMA + P5**		
Sample	**JMF**	**Process Tolerance**[a]	**Night 1 22-1095**	**JMF**	**Process Tolerance**[a]	**Day 1, Set A 22-1089**	**Day 1, Set B 22-1091**	**JMF**	**Process Tolerance**[a]	**Day 1 22-1097**
Property										
NMAS, mm	9.5	-	9.5	9.5	-	9.5	9.5	9.5	-	9.5
Asphalt Content, %	5.70	±0.60	5.58	5.90	±0.43	6.31	5.98	5.90	±0.60	6.11
Rice SG (G_{mm})	2.505	-	2.508	2.485	-	2.488	2.488	2.489	-	2.496
VTM, %	4.0	2.0–5.0	2.8	4.0	2.0–5.0	4.9	6.4	4.0	2.0–5.0	4.0
VMA, %	17.3	Min. 16	15.9	17.6	Min. 16	19.4	19.9	17.5	Min. 16	18.0
VFA, %	76.6	70–85	82.7	77.5	70-85	74.6	67.6	77.1	70–85	78.0
FA Ratio	1.0	0.7–1.3	1.24	1.2	0.7–1.3	0.83	0.83	1.1	0.7–1.3	0.97
Mixture Bulk SG (G_{mb})	-	-	2.438	-	-	2.365	2.327	-	-	2.397
Aggregate Effective SG (G_{se})	-	-	2.740	-	-	2.750	2.734	-	-	2.751
Aggregate Bulk SG (G_{sb})	-	-	2.738	-	-	2.749	2.733	-	-	2.745
Absorbed Asphalt Content (P_{ba}), %	-	-	0.03	-	-	0.01	0.01	-	-	0.08
Effective Asphalt Content (P_{be}). %	-	-	5.55	-	-	6.29	5.96	-	-	6.03
Effective Film Thickness (F_{be}), µm	-	-	9.3	-	-	12.8	12.2	-	-	11.4
Gradation, percent passing										
¾ in (19.0 mm)	100.0	±8.0	100.0	100	±5.7	100.0	100.0	100.0	±8.0	100.0
½ in (12.5 mm)	100.0	±8.0	99.4	100	±5.7	99.4	99.9	100.0	±8.0	99.2
3/8 in (9.5 mm)	95.0	±8.0	90.8	96	±5.7	93.0	95.0	95.0	±8.0	88.9
No. 4 (4.75 mm)	61.0	±8.0	52.2	62	±5.7	55.6	60.0	60.0	±8.0	50.0
No. 8 (2.36 mm)	41.0	±8.0	35.5	39	±5.7	36.5	37.5	39.0	±8.0	34.3
No. 16 (1.18 mm)	-	-	26.0	-	-	25.1	25.0	-	-	24.7
No. 30 (600 µm)	20.0	±6.0	19.0	-	±4.3	17.0	17.1	-	±6.0	17.4
No. 50 (300 µm)	-	±5.0	13.7	-	±3.6	11.3	11.5	-	±5.0	12.3
No. 100 (150 µm)	-	-	9.7	-	-	7.4	7.5	-	-	8.5
No. 200 (75 µm)	5.8	±2.0	6.9	6.9	±1.4	5.2	5.0	6.5	±2.0	5.9

D = mixture designation; FA = fines to aggregate; JMF = job mix formula; NMAS = nominal maximum aggregate size; PG = performance grade; RAP = reclaimed asphalt pavement; RPM = recycled plastic-modified; S = standard traffic; SG = specific gravity; SM = surface mixture; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture; WMA = warm mix asphalt.

[a] Process tolerance for one test from Table II-15 (VDOT, 2020).

Table 10. VTRC Volumetric Properties and Gradations for SM-9.5 RPM P6 Produced by Contractor C

Mixture Type	**SM-9.5RPM P6**				
Virgin Binder Grade	**PG 64S-22**				
RAP Content, %	**26**				
Additives	**WMA + P6**				
Sample	**JMF**	**Process Tolerance**[a]	**Day 1 23-1074**	**Day 2 23-1079**	**Day 3 23-1082**
Property					
NMAS, mm	9.5	-	9.5	9.5	9.5
Asphalt Content, %	5.80	±0.33	6.38	6.30	6.21
Rice SG (G_{mm})	2.548	-	2.554	2.556	2.559
VTM, %	3.7	2.0–5.0	2.5	3.0	2.3
VMA, %	-	Min. 16	17.9	17.6	17.3
VFA, %	-	70–85	86.3	83.1	87.0
FA Ratio	-	0.7–1.3	1.07	1.32	1.13
Mixture Bulk SG (G_{mb})	-	-	2.492	2.480	2.501
Aggregate Effective SG (G_{se})	2.802	-	2.841	2.838	2.837
Aggregate Bulk SG (G_{sb})	-	-	2.841	2.820	2.837
Absorbed Asphalt Content (P_{ba}), %	-	-	0.00	0.23	0.00
Effective Asphalt Content (P_{be}). %	5.57	-	6.38	6.08	6.21
Effective Film Thickness (F_{be}), µm	-	-	10.0	8.6	9.7
Gradation, percent passing					
¾ in (19.0 mm)	100.0	±4.4	100.0	100.0	100.0
½ in (12.5 mm)	100.0	±4.4	99.7	99.7	99.7
3/8 in (9.5 mm)	94.0	±4.4	96.5	97.5	96.6
No. 4 (4.75 mm)	66.0	±4.4	67.1	71.1	67.0
No. 8 (2.36 mm)	48.0	±4.4	45.4	47.8	44.4
No. 16 (1.18 mm)	-	-	31.9	33.6	31.0
No. 30 (600 µm)	-	±3.3	23.1	24.4	22.6
No. 50 (300 µm)	-	±2.8	15.8	17.1	15.7
No. 100 (150 µm)	-	-	10.0	11.3	10.2
No. 200 (75 µm)	6.5	±1.1	6.8	8.1	7.0

FA = fines to aggregate; JMF = job mix formula; NMAS = nominal maximum aggregate size; PG = performance grade; RAP = reclaimed asphalt pavement; RPM = recycled plastic-modified; S = standard traffic; SG = specific gravity; SM = surface mixture; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture; WMA = warm mix asphalt.

[a] Process tolerance for one test from Table II-15 (VDOT, 2020).

High Reclaimed Asphalt Pavement Recycling Agent Mixtures

Table 11 shows the volumetric properties and gradations for mixtures SM-9.5HRAP RA1 and SM-9.5HRAP RA2 for design and reheated samples tested by VTRC. The results compared with the JMF and quality control and acceptance data available from the producers/contractors and VDOT districts (not provided in this report for the sake of brevity). During production, SM-9.5HRAP RA1 exhibited similar volumetric properties, including asphalt content and voids in total mixture, when compared to those of the JMF. However, higher values for the No. 200 sieve were observed during production compared to the JMF, possibly attributed to the fines generated from the HRAP content (40%). SM-9.5HRAP RA2 exhibited a much higher asphalt content compared to that of the JMF, resulting in much higher voids in mineral aggregate and voids filled with asphalt values. Moreover, no major differences were observed in terms of aggregate gradation except for the fines. The values for the No. 200 sieve were also higher during production compared to those of the JMF.

Table 12 summarizes the volumetric properties and aggregate gradation for SM-12.5HRAP RA3 produced by Contractor E. No major changes were observed in the volumetric properties or aggregate gradations except for percent passing of the No. 200 sieve. Lower values were observed during production compared to those of the JMF despite using higher RAP contents. Comparing the percent passing values of the No. 200 sieve in Table 11 and those in Table 12, although all mixtures were produced using higher RAP contents (40%), opposite observations were made for the mixtures produced by Contractor D and those produced by Contractor E. This result could be attributed to the difference in NMAS (9.5mm versus 12.5mm) or to the contractors' differing practices for processing RAP for SMs and specifically HRAP mixtures during production.

Balanced Mix Design Test Results and Discussions

This section presents and discusses BMD test results, including ML, CT index, APA RD, S_t, and RT index for design, non-reheat, and reheat specimens of all evaluated mixtures (whenever available).

Durability Assessment—Cantabro Mass Loss Test Results

RPM Mixtures. Figure 6 presents the Cantabro test results for design and non-reheat specimens for the control and RPM mixtures produced by Contractors A, B, and C (SM-9.5D2, SM-9.5RPM P1, SM-9.5RPM P3, SM-9.5D3, SM-9.5RPM P4, SM-9.5RPM P5, and SM-9.5RPM P6). The error bars indicate average values from three replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's maximum ML threshold of 7.5% for design and reheat specimens. No ML data were available for the control design specimens. However, all RPM mixtures exhibited ML values for non-reheat specimens comparable with those of typical D mixtures tested in Virginia (Diefenderfer et al., 2023). Higher ML values were observed for non-reheat specimens compared with design specimens for all RPM mixtures, except for mixture SM-9.5RPM P6, for which ML values were similar or less than those of the design specimens. Similar or lower ML values were observed for RPM mixtures compared with control mixtures. The use of recycled plastics in asphalt mixtures is expected to lead to greater ML values by means of Cantabro test. The reduced ML, indicating increased durability, highlights the effectiveness of using BMD to design well-balanced and engineered RPM mixtures. No control mixture was tested alongside mixture SM-9.5RPM P6. All design and non-reheat specimens exhibited ML values less than 7.5%, except for the non-reheat specimens of mixture SM-9.5RPM P5. The 7.5% threshold is only valid for design and reheat data for SMs with A and D designations and is provided here for informational purposes only.

Table 11. VTRC Volumetric Properties and Gradations for SM-9.5HRAP RA1 and SM-9.5HRAP RA2 Produced by Contractor D

Mixture Type	**SM-9.5HRAP RA1**						**SM-9.5HRAP RA2**			
Virgin Binder Grade	**PG 64S-22**						**PG 64S-22**			
RAP Content, %	**40**						**40**			
Additives	**WMA + RA1**						**WMA + RA2**			
Sample	**JMF**	**Process Tolerance[a]**	**Day 1 Set A 22-1077**	**Day 1 Set B 22-1079**	**Day 1 Set C 22-1082**	**Day 1 Set D 22-1084**	**JMF**	**Process Tolerance[a]**	**Day 1 Set A 23-1045**	**Day 1 Set B 23-1046**
Property										
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.50	±0.30	5.63	5.53	5.59	5.63	5.60	±0.43	6.03	6.14
Rice SG (G_{mm})	2.673	-	2.716	2.718	2.702	2.696	2.668	-	2.678	2.677
VTM, %	3.2	2.0–5.0	3.1	3.6	3.6	3.4	4.0	2.0–5.0	3.0	2.6
VMA, %	-	Min. 16.0	16.9	17.1	17.1	17.0	-	Min. 16.0	18.2	18.1
VFA, %	-	70.0–85.0	81.5	78.8	78.9	80.1	-	70.0–80.0	83.3	85.8
FA Ratio	-	0.70–1.30	1.22	1.21	1.18	1.18	-	0.70–1.30	1.07	1.15
Mixture Bulk SG (G_{mb})	-	-	2.631	2.619	2.604	2.605	-	-	2.597	2.608
Aggregate Effective SG (G_{se})	-	-	3.010	3.006	2.989	2.984	-	-	2.984	2.989
Aggregate Bulk SG (G_{sb})	-	-	2.988	2.984	2.967	2.962	-	-	2.984	2.989
Absorbed Asphalt Content (P_{ba}), %	-	-	0.25	0.25	0.26	0.26	-	-	0.00	0.00
Effective Asphalt Content (P_{be}). %	-	-	5.39	5.29	5.35	5.38	-	-	6.03	6.14
Effective Film Thickness (F_{be}), µm	-	-	8.8	8.7	8.9	9.0	-	-	9.5	9.2
Gradation, percent passing										
¾ in (19.0 mm)	100.0	±4.0	100.0	100.0	100.0	100.0	100.0	±5.7	100.0	100.0
½ in (12.5 mm)	100.0	±4.0	100.0	100.0	100.0	100.0	100.0	±5.7	100.0	100.0
3/8 in (9.5 mm)	94.0	±4.0	90.7	92.2	93.1	92.9	96.0	±5.7	96.6	96.1
No. 4 (4.75 mm)	65.0	±4.0	60.3	61.3	61.3	59.4	64.0	±5.7	66.5	66.8
No. 8 (2.36 mm)	44.0	±4.0	41.1	43.1	41.7	40.8	42.0	±5.7	44.9	45.6
No. 16 (1.18 mm)	-	-	29.1	30.4	29.2	28.9	-	-	31.9	32.8
No. 30 (600 µm)	-	±3.0	20.7	21.4	20.6	20.5	-	±4.3	22.9	23.7
No. 50 (300 µm)	-	±2.5	14.6	14.7	14.2	14.4	-	±3.6	15.9	16.6
No. 100 (150 µm)	-	-	9.9	9.8	9.5	9.7	-	-	10.4	11.0
No. 200 (75 µm)	5.5	±1.0	6.6	6.4	6.3	6.4	5.6	±1.4	6.4	7.0

FA = fines to aggregate; HRAP = high reclaimed asphalt pavement (RAP); JMF = job mix formula; NMAS = nominal maximum aggregate size; PG = performance grade; RA = recycling agent; S = standard traffic; SM = surface mixture; SG = specific gravity; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture; WMA = warm mix asphalt.

[a] Process tolerance for one test from Table II-15 (VDOT, 2020).

Table 12. VTRC Volumetric Properties and Gradations for SM-9.5HRAP RA3 Produced by Contractor E

Mixture Type	**SM-12.5HRAP RA3**			
Virgin Binder Grade	**PG 64S-22**			
RAP Content, %	**40**			
Additives	**WMA + RA3**			
Sample	**JMF**	**Process Tolerance[a]**	**Day 1 23-1070**	**Day 2 23-1072**
Property				
NMAS, mm	12.5	12.5	12.5	12.5
Asphalt Content, %	5.50	±0.43	5.64	5.61
Rice SG (G_{mm})	2.493	-	2.500	2.493
VTM, %	3.5	2.0–5.0	5.1	5.2
VMA, %	-	Min. 16	18.0	18.1
VFA, %	-	70.0–85.0	71.8	71.0
FA Ratio	-	0.70–1.30	0.82	0.71
Mixture Bulk SG (G_{mb})	-	-	2.373	2.362
Aggregate Effective SG (G_{se})	-	-	2.734	2.723
Aggregate Bulk SG (G_{sb})	-	-	2.731	2.723
Absorbed Asphalt Content (P_{ba}), %	-	-	0.04	0.00
Effective Asphalt Content (P_{be}). %	-	-	5.60	5.61
Effective Film Thickness (F_{be}), µm	-	-	11.5	12.7
Gradation, percent passing				
¾ in (19.0 mm)	100.0	±5.7	100.0	100.0
½ in (12.5 mm)	97.0	±5.7	97.9	97.3
3/8 in (9.5 mm)	87.0	±5.7	88.8	86.7
No. 4 (4.75 mm)	-	±5.7	57.4	54.4
No. 8 (2.36 mm)	43.0	±5.7	38.1	36.0
No. 16 (1.18 mm)	-	-	28.7	27.0
No. 30 (600 µm)	-	±4.3	19.9	18.5
No. 50 (300 µm)	-	±3.6	11.7	10.6
No. 100 (150 µm)	-	-	6.9	6.0
No. 200 (75 µm)	5.0	±1.4	4.6	4.0

FA = fines to aggregate; HRAP = high reclaimed asphalt pavement (RAP); JMF = job mix formula; NMAS = nominal maximum aggregate size; PG = performance grade; RA = recycling agent; S = standard traffic; SG = specific gravity; SM = surface mixture; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture; WMA = warm mix asphalt.

[a] Process tolerance for one test from Table II-15 (VDOT, 2020).

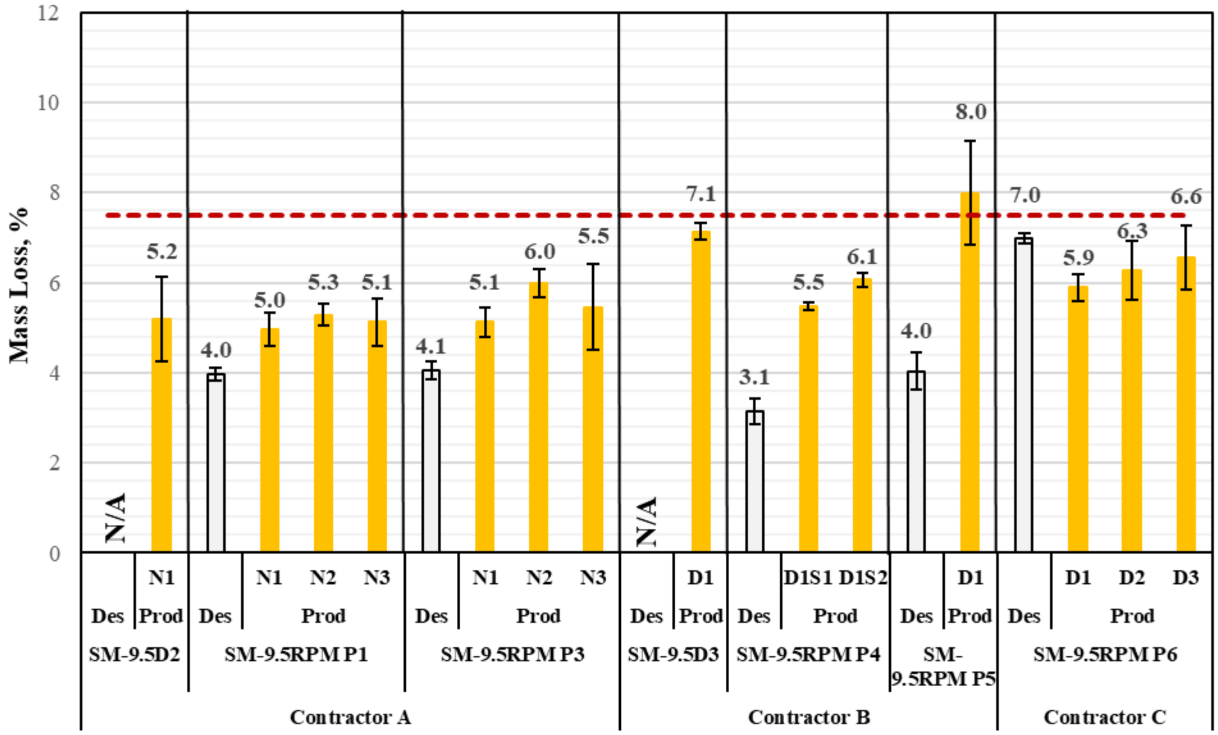


Figure 6. Performance Test Data for Mean Cantabro Mass Loss of Design and Non-Reheat Specimens for Control and RPM Mixtures Produced by Contractors A, B, and C. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D = mixture designation; D1, D2, and D3 = day 1, 2, and 3; D1S1 = day 1 sample 1; D1S2 = day 2 sample 2; Des = design; N1, N2, and N3 = night 1, 2, and 3; N/A = not available; Prod = production; SM = surface mixture; RPM = recycled plastic-modified.

Figure 7 presents the Cantabro test results for design and reheat specimens for the control and RPM mixtures produced by Contractors A, B, and C (SM-9.5D2, SM-9.5RPM P1, SM-9.5RPM P3, SM-9.5D3, SM-9.5RPM P4, SM-9.5RPM P5, and SM-9.5RPM P6). The error bars indicate the average values from three replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's maximum ML threshold of 7.5% for design and reheat specimens. Similarly, no ML data were available for the control design specimens. However, all RPM mixtures exhibited ML values for reheat specimens comparable with those of typical D mixtures tested in Virginia (Diefenderfer et al., 2023). Higher ML values were observed for reheat specimens compared with design specimens, except for mixture SM-9.5RPM P6, for which ML values were similar or less than those of the design specimens. Similar or higher ML values were observed for RPM mixtures compared with control mixtures. This outcome could be attributed to the greater effect of reheating on mixtures modified with recycled plastics. No control mixture was tested alongside mixture SM-9.5RPM P6. Mixtures produced by Contractors A and C (SM-9.5D2, SM-9.5RPM P1, SM-9.5RPM P3, and SM-9.5RPM P6) exhibited ML values similar to or less than the 7.5% VDOT BMD threshold. All mixtures produced by Contractor B (SM-9.5D3, SM-9.5RPM P4, and SM-9.5RPM P5) exhibited ML values higher than 7.5%, which may require further assessment in terms of durability. The 7.5% threshold is only valid for design and reheat data for SMs with A and D designations and is provided here for informational purposes only.

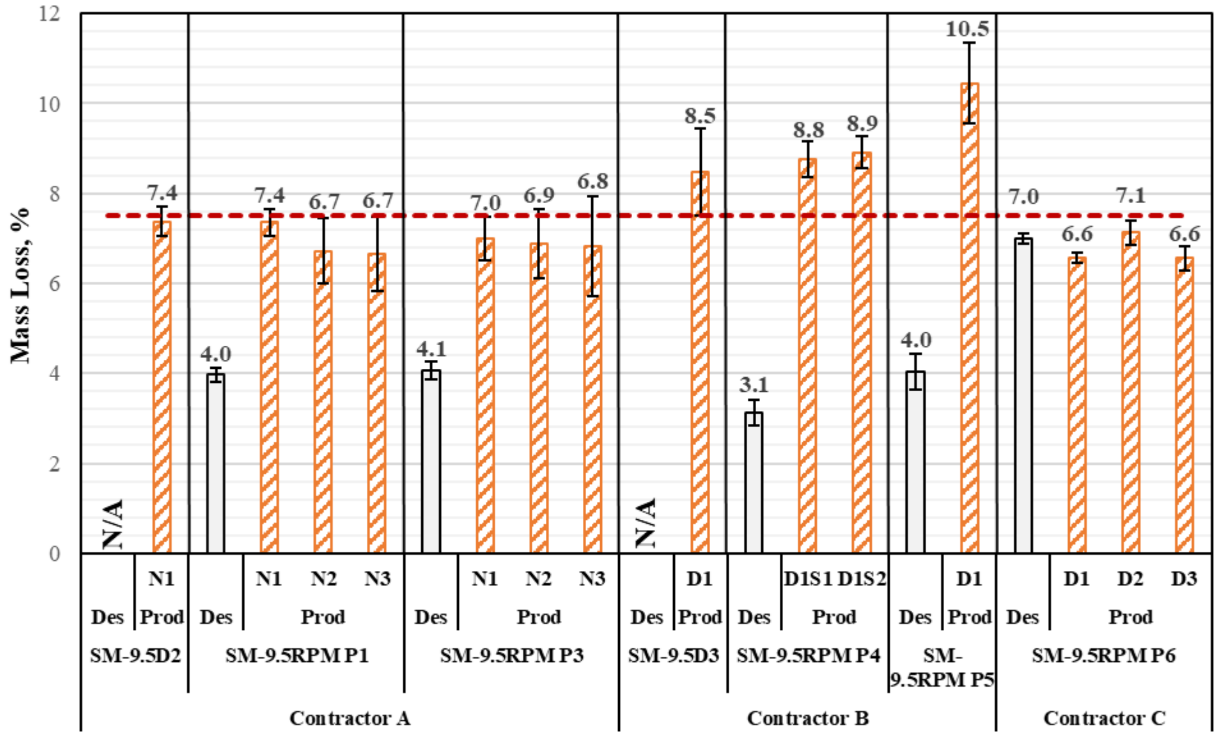


Figure 7. Performance Test Data for Mean Cantabro Mass Loss of Design and Reheat Specimens for Control and RPM Mixtures Produced by Contractors A, B, and C. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D = mixture designation; D1, D2, and D3 = day 1, 2, and 3; D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; Des = design; N1, N2, and N3 = night 1, 2, and 3; N/A = not available; Prod = production; RPM = recycled plastic-modified; SM = surface mixture.

No major differences in ML values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated RPM mixtures. In addition, greater ML values were observed for reheats compared with non-reheats, which is expected due to the negative effect of reheating on durability, regardless of the evaluated mixture. However, it was observed that reheating had a lesser effect on mixtures modified with recycled plastic P6, which could be attributed to the nanomaterials available in the plastic additive P6 structure.

HRAP RA Mixtures. Figure 8 presents the Cantabro test results for design, non-reheat, and reheat specimens for HRAP RA mixtures produced by Contractors D and E (SM-9.5HRAP RA1, SM-9.5HRAP RA2, and SM-12.5HRAP RA3). The error bars indicate the average values from three replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's maximum ML threshold of 7.5% for design and reheat specimens. No control mixtures were tested alongside these HRAP RA mixtures. Design specimens had the lowest ML values, followed by non-reheat specimens, and then reheat specimens. All design and non-reheat specimens exhibited ML values less than 7.5%. ML values of reheat specimens for SM-9.5HRAP RA1 and SM-12.5HRAP RA3 were greater than 7.5%, which may require further assessment in terms of durability.

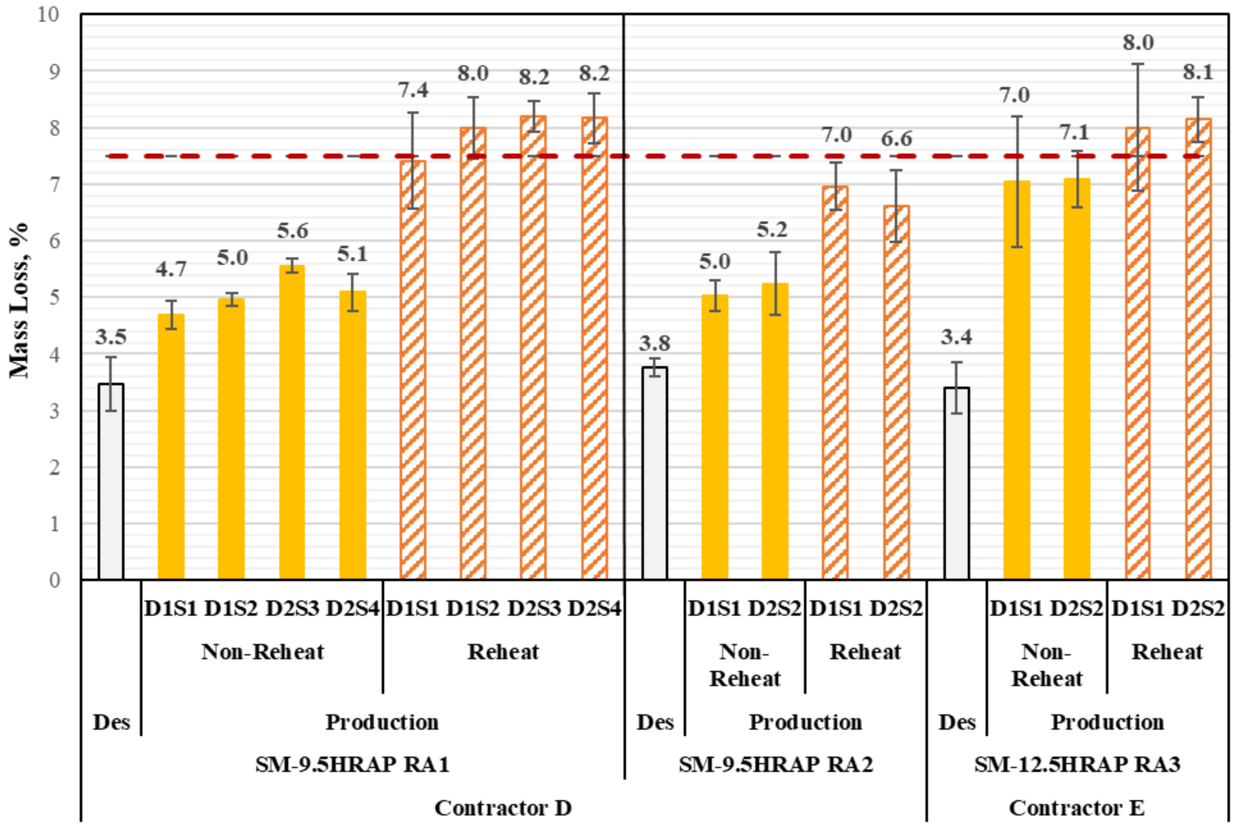


Figure 8. Performance Test Data for Mean Cantabro Mass Loss of Design, Non-Reheat, and Reheat Specimens for HRAP RA Mixtures Produced by Contractors D and E. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; D2S2 = day 2 sample 2; D2S3 = day 2 sample 3; D2S4 = day 2 sample 4; HRAP = high reclaimed asphalt pavement; RA = recycling agent; SM = surface mixture.

Similar to the observations made for RPM mixtures, no major differences in ML values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated HRAP RA mixtures. In addition, greater ML values were observed for reheats compared with non-reheats, which is expected due to the negative effect of reheating on durability, regardless of the evaluated mixture.

Cracking Assessment—Indirect Tensile Cracking Test Results

RPM Mixtures. Figure 9 presents the CT index results for design and non-reheat specimens for the control and RPM mixtures produced by Contractors A, B, and C (SM-9.5D2, SM-9.5RPM P1, SM-9.5RPM P3, SM-9.5D3, SM-9.5RPM P4, SM-9.5RPM P5, and SM-9.5RPM P6). The error bars indicate the average values from five replicates plus or minus 1 standard deviation. Dashed red and blue lines denote VDOT's maximum CT index thresholds of 70 and 95 for design and non-reheat specimens, respectively. No CT index data were available for the control design specimens. Similar or higher CT index values were observed for non-reheat specimens compared with design specimens, except for mixture SM-9.5RPM P6, for which CT index values were similar or less than those of the design specimens. Similar or lower CT index values were seen for the SM-9.5RPM P1 and SM-9.5RPM P3 mixtures compared with the control mixture, SM-9.5D2. Higher CT index values were observed for the SM-9.5RPM P4 and SM-9.5RPM P5 mixtures compared with the control mixture, SM-9.5D3. No control mixture was tested alongside mixture SM-9.5RPM P6. All design specimens exhibited CT index values greater than 70. All non-reheat specimens showed CT index values greater than 95, except for the N2 Production sample from mixture SM-9.5RPM P1 and the three Production samples (D1, D2, and D3) from mixture SM-9.5RPM P6. The 70 and 95 thresholds are only valid for SMs with A and D designations and are provided here for informational purposes only.

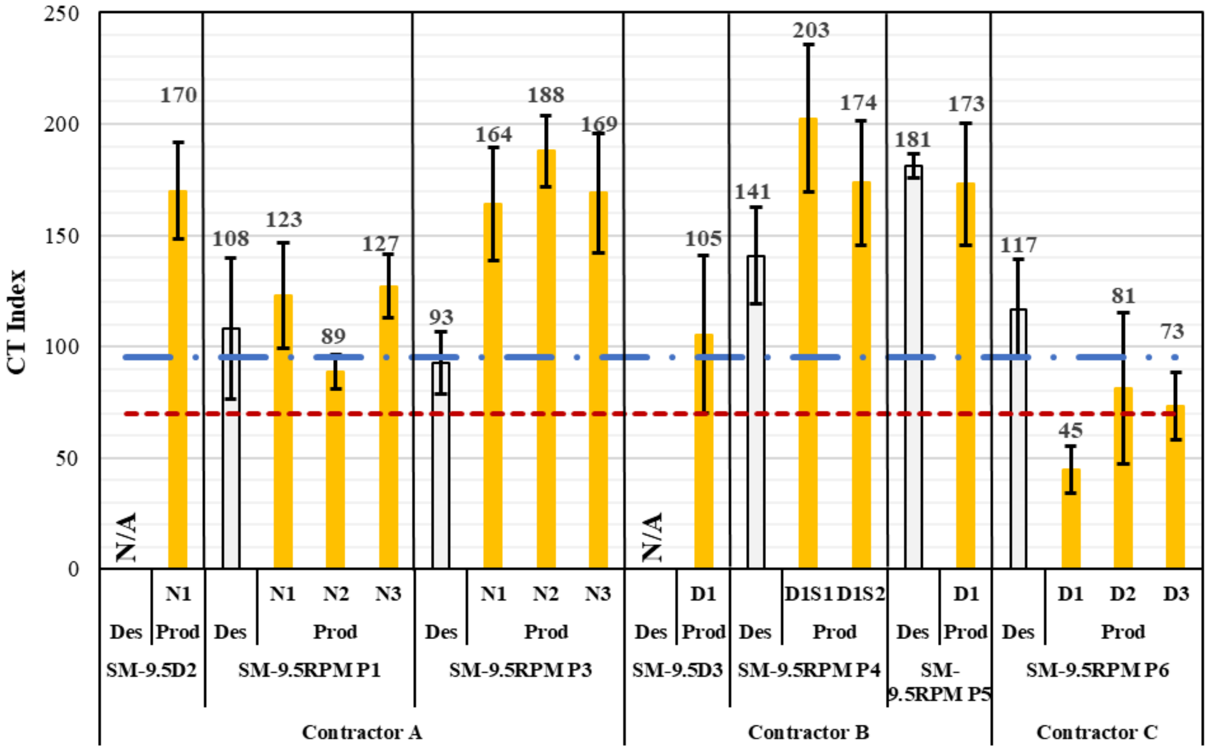


Figure 9. Performance Test Data for Mean CT Index of Design and Non-Reheat Specimens for Control and RPM Mixtures Produced by Contractors A and B. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design for reheat specimens for asphalt SMs with A and D designations. Dashed blue line denotes VDOT's balanced mix design limit for non-reheat specimens for asphalt SMs with A and D designations. CT = cracking tolerance; D = mixture designation; D1, D2, and D3 = day 1, 2, and 3; D1S1 = day 1 sample 1; D1S2 = day 2 sample 2; Des = design; N1, N2, and N3 = night 1, 2, and 3; N/A = not available; Prod = production; RPM = recycled plastic-modified; SM = surface mixture.

Figure 10 presents the CT index results for design and reheat specimens for the control and RPM mixtures produced by Contractors A, B, and C (SM-9.5D2, SM-9.5RPM P1, SM-9.5RPM P3, SM-9.5D3, SM-9.5RPM P4, SM-9.5RPM P5, and SM-9.5RPM P6). The error bars indicate the average values from five replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's maximum CT index threshold of 70 for design and non-reheat specimens. No CT index data were available for the control design specimens. Similar or higher CT index values were observed for reheat specimens compared with design specimens, except for mixture SM-9.5RPM P6, for which CT index values were less than those of the design specimens. Similar or lower CT index values were seen for RPM mixtures compared with control mixtures. The use of recycled plastics in asphalt mixtures is expected to lead to lower CT index values according to the IDT-CT. The similarity or increase in CT index, indicating increased flexibility, highlights the effectiveness of using BMD to design well-balanced and engineered RPM mixtures. No control mixture was tested alongside mixture SM-9.5RPM P6. All design and reheat specimens exhibited CT index values greater than 70, except for mixture SM-9.5RPM P6, for which CT index values for reheats were less than 70, a result that may require further investigation of this mixture for cracking resistance. The 70 threshold is only valid for SMs with A and D designations and is provided here for informational purposes only.

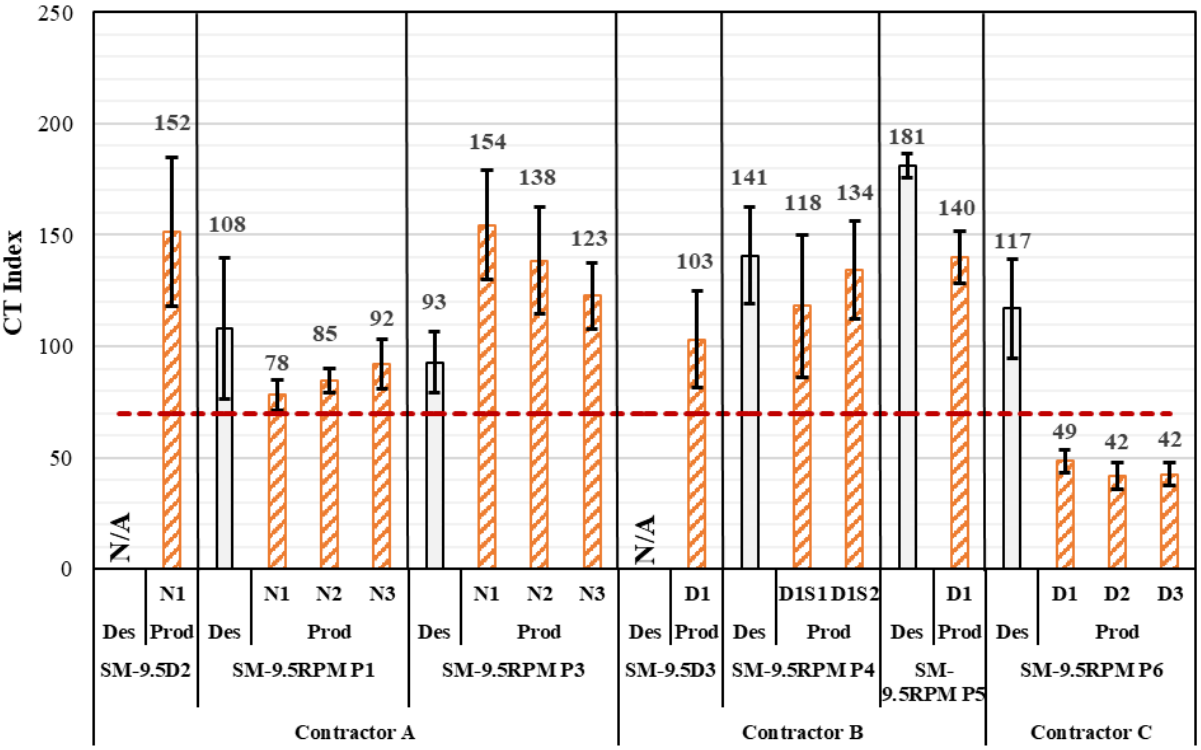


Figure 10. Performance Test Data for Mean CT Index of Design and Reheat Specimens for Control and RPM Mixtures Produced by Contractors A, B, and C. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. CT = cracking tolerance; D = mixture designation; D1, D2, and D3 = day 1, 2, and 3; D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; Des = design; ; N1, N2, and N3 = night 1, 2, and 3; N/A = not available; Prod = production; RPM = recycled plastic-modified; SM = surface mixture.

No major differences in CT index values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated RPM mixtures. In addition, similar or lower CT index values were observed for reheats compared with non-reheats, which is expected due to the negative effect of reheating on resistance to cracking, regardless of the evaluated mixture.

HRAP RA Mixtures. Figure 11 presents the CT index results for design, non-reheat, and reheat specimens for HRAP RA mixtures produced by Contractors D and E (SM-9.5HRAP RA1, SM-9.5HRAP RA2, and SM-12.5HRAP RA3). The error bars indicate the average values from five replicates plus or minus 1 standard deviation. Dashed red and blue lines denote VDOT's minimum CT index thresholds of 70 for design and reheat specimens and 95 for non-reheat specimens, respectively. No control mixtures were tested alongside these HRAP RA mixtures. Design specimens had the highest CT index values, followed by non-reheat specimens with similar or lower CT index values, and then reheat specimens with lower values. All design specimens exhibited CT index values greater than 70. All non-reheat specimens exhibited CT index values similar to or greater than 95. All reheat specimens exhibited CT index values greater than 70, except for SM-9.5HRAP RA1, which may require further assessment in terms of resistance to cracking.

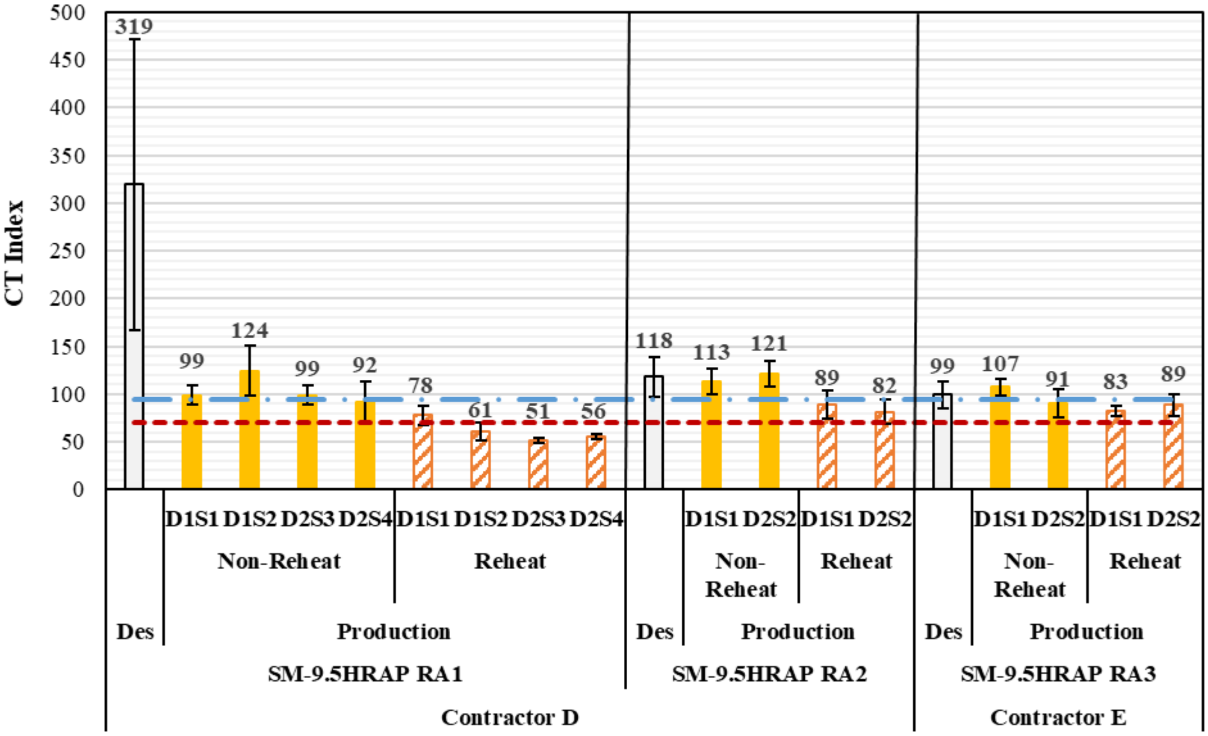


Figure 11. Performance Test Data for Mean CT Index of Design, Non-Reheat, and Reheat Specimens for HRAP RA Mixtures Produced by Contractors D and E. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. CT = cracking tolerance; D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; D2S2 = day 2 sample 2; D2S3 = day 2 sample 3; D2S4 = day 2 sample 4; Des = design; HRAP = high reclaimed asphalt pavement; RA = recycling agent; SM = surface mixture.

No major differences in CT index values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated HRAP RA mixtures. In addition, similar or greater CT index values were observed for non-reheat specimens compared with reheat specimens.

Rutting Assessment—Asphalt Pavement Analyzer Test Results

RPM Mixtures. Figure 12 presents the APA RD results for design and non-reheat specimens for the control and RPM mixtures produced by Contractors A, B, and C (SM-9.5D2, SM-9.5RPM P1, SM-9.5RPM P3, SM-9.5D3, SM-9.5RPM P4, SM-9.5RPM P5, and SM-9.5RPM P6). The error bars indicate the average values from four replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's maximum APA RD threshold of 8 mm. No APA RD data were available for the control design specimens. Similar APA RD values were observed for non-reheat specimens compared with design specimens, except for SM-9.5RPM P4 production samples, SM-9.5RPM P5 production samples, and the D2 production sample from mixture SM-9.5RPM P6, for which non-reheat specimens exhibited lower APA RD values compared with design specimens. Similar or lower APA RD values were observed for RPM mixtures produced by Contractors A and B compared with their respective control mixtures, which could be attributed to the stiffening effect induced by the use of recycled plastics. No control mixture was tested alongside mixture SM-9.5RPM P6. All design and non-reheat specimens exhibited APA RD values less than 8 mm. The 8-mm threshold is only valid for SMs with A and D designations and is provided here for informational purposes only.

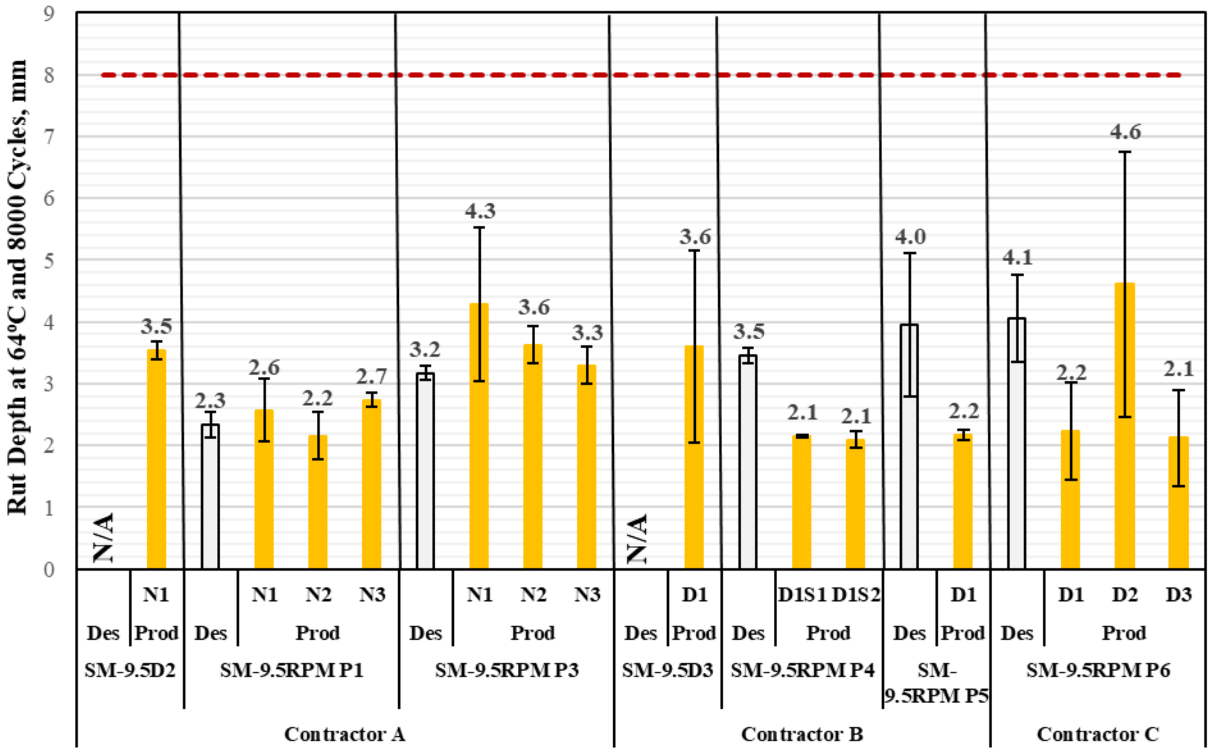


Figure 12. Performance Test Data for Mean Asphalt Pavement Analyzer Rut Depth of Design and Non-Reheat Specimens for Control and RPM Mixtures Produced by Contractors A, B, and C. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D = mixture designation; D1, D2, and D3 = day 1, 2, and 3; D1S1 = day 1 sample 1; D1S2 = day 2 sample 2; Des = design; N1, N2, and N3 = night 1, 2, and 3; N/A = not available; Prod = production; RPM = recycled plastic-modified; SM = surface mixture.

Figure 13 presents the APA RD results for design and reheat specimens for the control and RPM mixtures produced by Contractors A, B, and C (SM-9.5D2, SM-9.5RPM P1, SM-9.5RPM P3, SM-9.5D3, SM-9.5RPM P4, SM-9.5RPM P5, and SM-9.5RPM P6). The error bars indicate the average values from four replicates plus or minus 1 standard deviation. A dashed red line denoted VDOT's maximum APA RD threshold of 8 mm for design and reheat specimens. No APA RD data were available for the control design specimens. Similar or lower APA RD values were observed for reheat specimens compared with design specimens, regardless of the evaluated mixture. Similar or lower APA RD values were observed for RPM mixtures produced by Contractors A and B compared with their respective control mixtures. No control mixture was tested alongside mixture SM-9.5RPM P6. All design and reheat specimens exhibited APA RD values less than 8 mm.

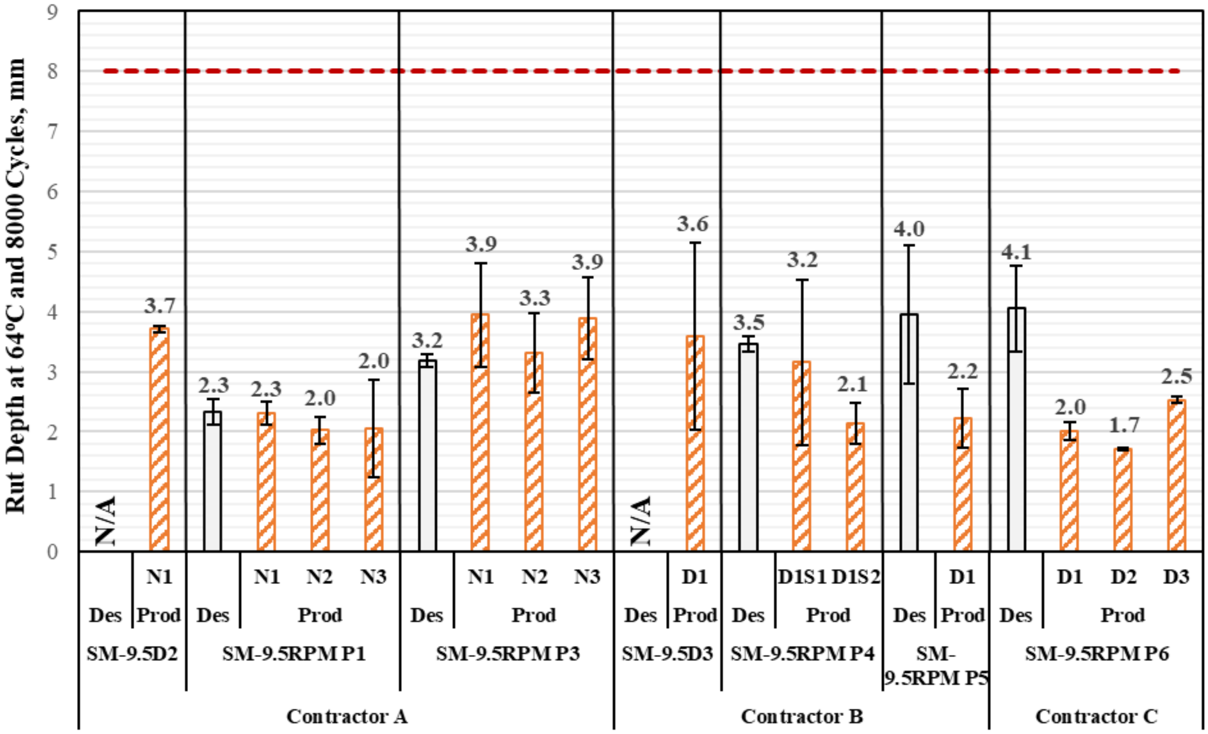


Figure 13. Performance Test Data for Mean Asphalt Pavement Analyzer Rut Depth of Design and Reheat Specimens for Control and RPM Mixtures Produced by Contractors A, B, and C. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D = mixture designation; D1, D2, and D3 = day 1, 2, and 3; D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; Des = design; N1, N2, and N3 = night 1, 2, and 3; N/A = not available; Prod = production; RPM = recycled plastic-modified; SM = surface mixture.

HRAP RA Mixtures. Figure 14 presents the APA RD results for design, non-reheat, and reheat specimens for HRAP RA mixtures produced by Contractors D and E (SM-9.5HRAP RA1, SM-9.5HRAP RA2, and SM-12.5HRAP RA3). The error bars indicate the average values from four replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's maximum APA RD threshold of 8 mm for design and reheat specimens. No control mixtures were tested alongside these HRAP RA mixtures. For SM-9.5HRAP RA1, design specimens exhibited an average APA RD value equal to the 8-mm threshold, which was higher than the APA RD values the non-reheat and reheat specimens exhibited. For SM-9.5HRAP RA2, design specimens exhibited APA RD values less than those of the non-reheat and reheat specimens. For SM-12.5HRAP RA3, design specimens exhibited APA RD values similar to those of the non-reheat and reheat specimens.

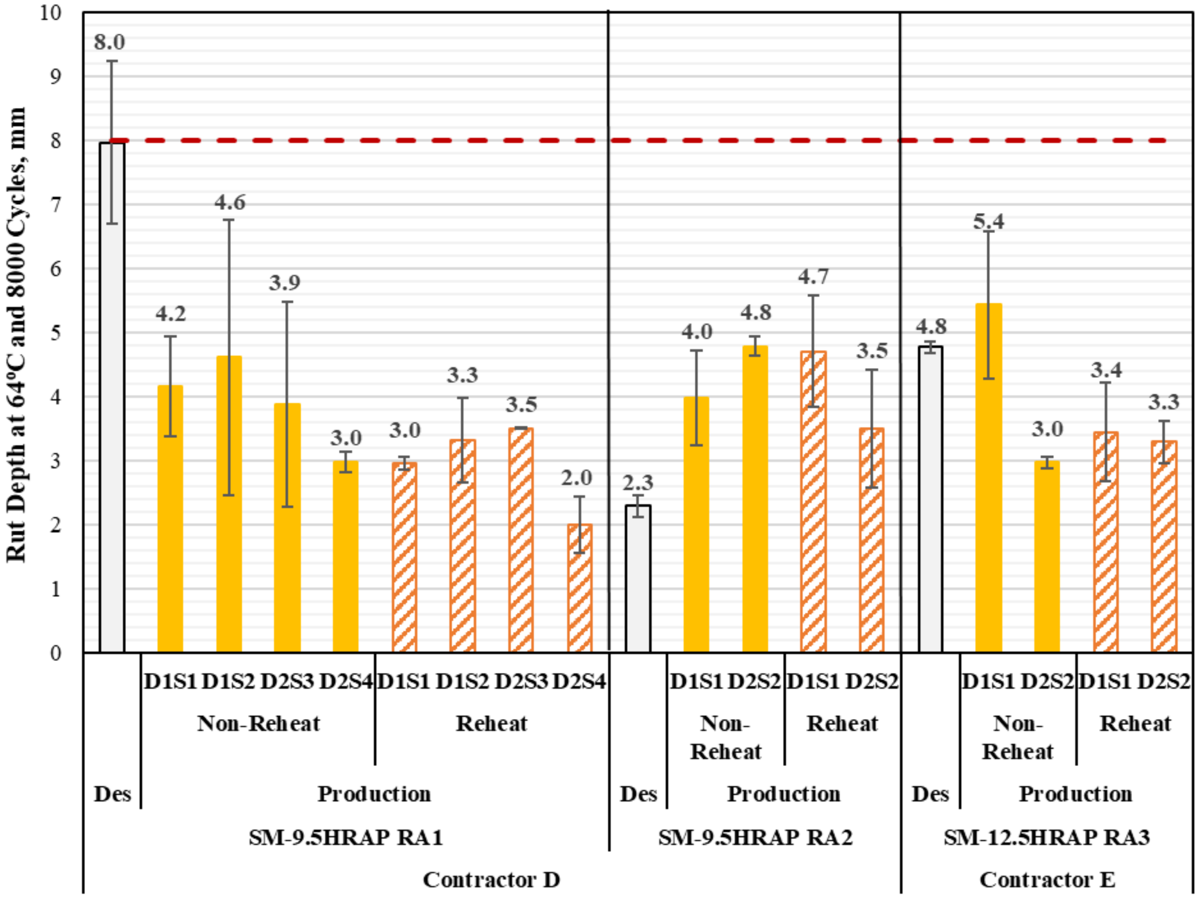


Figure 14. Performance Test Data for Mean Asphalt Pavement Analyzer Rut Depth of Design, Non-Reheat, and Reheat Specimens for HRAP RA Mixtures Produced by Contractors D and E. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; D2S2 = day 2 sample 2; D2S3 = day 2 sample 3; D2S4 = day 2 sample 4; HRAP = high reclaimed asphalt pavement; RA = recycling agent; SM = surface mixture.

No major differences in APA RD values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated RPM and HRAP RA mixtures. In addition, similar or lower APA RD values were observed for reheats compared with non-reheats, which is expected due to the effect of reheating on rutting resistance, regardless of the evaluated mixture.

Additional Testing on Reheats—IDT-HT and IDEAL-RT

RPM Mixtures. Figure 15 presents the S_t results of reheat specimens for the RPM mixtures and their corresponding controls (when available). The error bars indicate the average values from three replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's minimum S_t requirement of 100 kPa for design and reheat specimens. Overall, similar or higher S_t values were observed for RPM mixtures produced by Contractors A and B compared with their respective controls. SM-9.5RPM P6 exhibited the highest S_t among all RPM mixtures, which could be attributed to the graphene-enhanced plastic-based additive P6. All evaluated mixtures exhibited S_t greater than 100 kPa, indicating good resistance to rutting. No major differences in S_t values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated RPM mixtures.

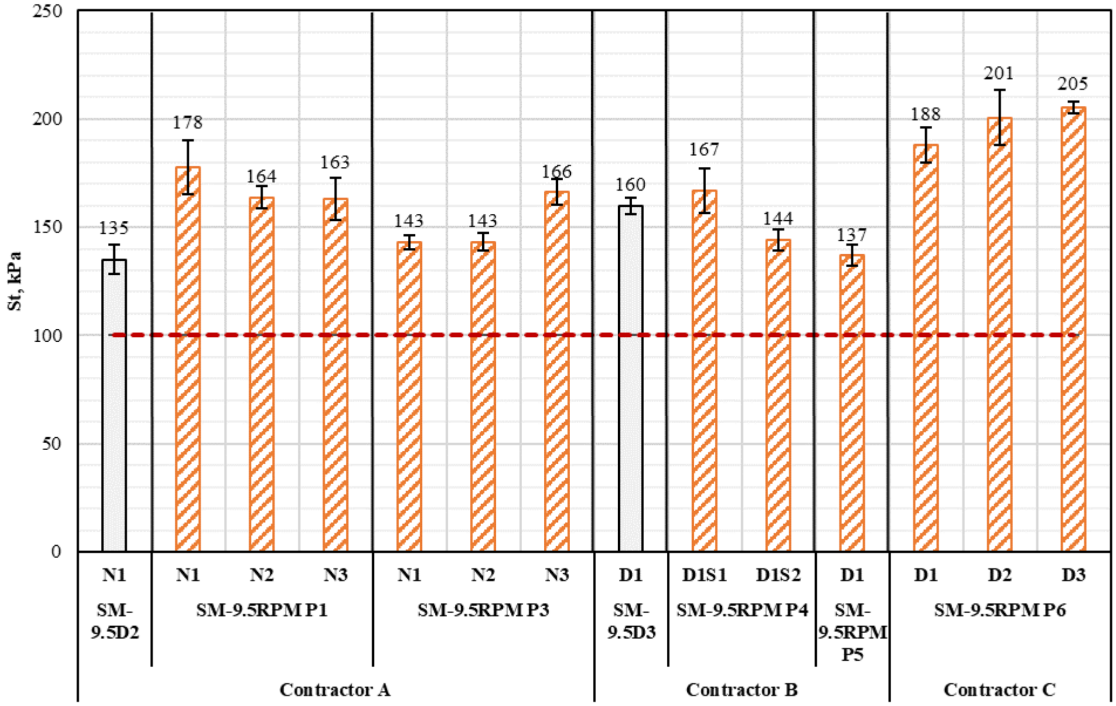


Figure 15. Performance Test Data for Mean Indirect Tensile Test at High Temperature Strength (S_t) of Reheat Specimens for Control and RPM Mixtures Produced by Contractors A and B. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D = mixture designation; D1, D2, and D3 = day 1, 2, and 3; D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; N1, N2, and N3 = night 1, 2, and 3; RPM = recycled plastic-modified; SM = surface mixture.

Figure 16 presents the RT index results of reheat specimens for the RPM mixtures and their corresponding controls (when available). The error bars indicate the average values from three replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's minimum RT index requirement of 72 for design and reheat specimens. Overall, similar or higher RT index values were observed for RPM mixtures produced by Contractors A and B compared with their respective controls. No major difference in RT index values was observed between SM-9.5RPM P3 and the other evaluated RPM mixtures. All evaluated mixtures exhibited RT index values greater than 72, indicating good resistance to rutting, except for sample N3 of SM-9.5RPM P3 taken during the third production night. No major differences in RT index values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated RPM mixtures.

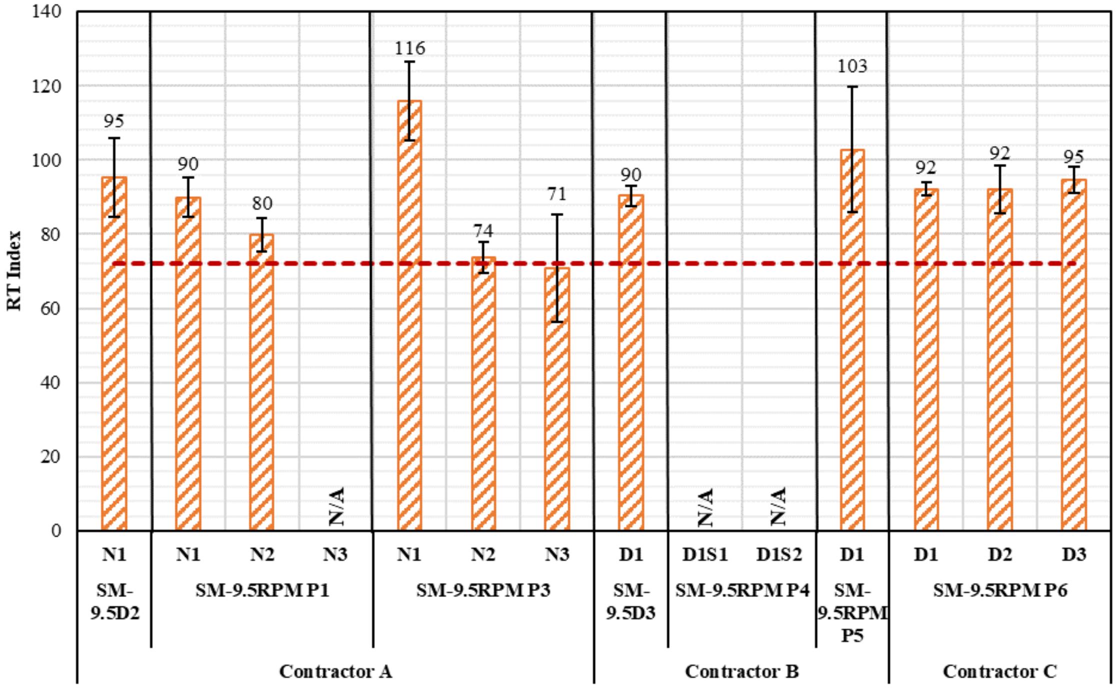


Figure 16. Performance Test Data for Mean RT Index of Reheat Specimens for Control and RPM Mixtures Produced by Contractors A and B. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D = mixture designation; D1, D2, and D3 = day 1, 2, and 3; D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; N1, N2, and N3 = night 1, 2, and 3; N/A = not available; RPM = recycled plastic-modified; RT = rutting tolerance; SM = surface mixture.

HRAP RA Mixtures. Figure 17 presents the S_t results of reheat specimens for the HRAP RA mixtures. The error bars indicate the average values from three replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's minimum S_t requirement of 100 kPa for design and reheat specimens. Overall, SM-9.5HRAP RA1 and SM-9.5HRAP RA2 produced by Contractor D exhibited similar S_t values, greater than those of SM-12.5HRAP RA3. All evaluated mixtures exhibited S_t values greater than 100 kPa, indicating good resistance to rutting, except for the SM-12.5HRAP RA3 sample collected during the second day of production, which was borderline. No major differences in S_t values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated RPM mixtures.

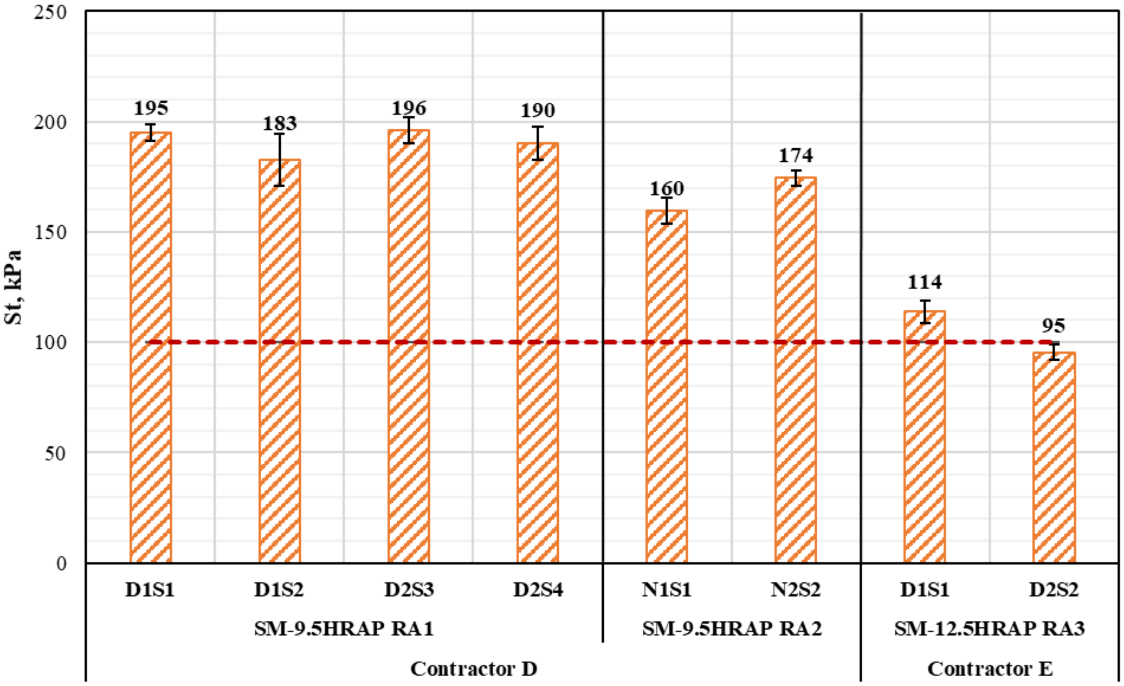


Figure 17. Performance Test Data for Mean Indirect Tensile Test at High Temperature Strength (S_t) of Reheat Specimens for HRAP RA Mixtures Produced by Contractors D and E. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; D2S1 = day 2 sample 1; D2S2 = day 2 sample 2; D2S3 = day 2 sample 3; D2S4 = day 2 sample 4; HRAP = high reclaimed asphalt pavement; N1S1 = night 1 sample 1; N2S2 = night 2 sample 2; RA = recycling agent; SM = surface mixture.

Figure 18 presents the RT index values of reheat specimens for the HRAP RA mixtures. The error bars indicate the average values from three replicates plus or minus 1 standard deviation. A dashed red line denotes VDOT's minimum RT index requirement of 72 for design and reheat specimens. Overall, SM-9.5HRAP RA1 exhibited RT index values greater than those of SM-9.5HRAP RA2, which were borderline. SM-12.5HRAP RA3 exhibited RT index values less than 72. These differences could be attributed to the various effects of the RA products used to produce these mixtures. No major differences in RT index values were observed across the various days or nights of production and the various samples tested per day and night of production (when available) for all evaluated HRAP RA mixtures.

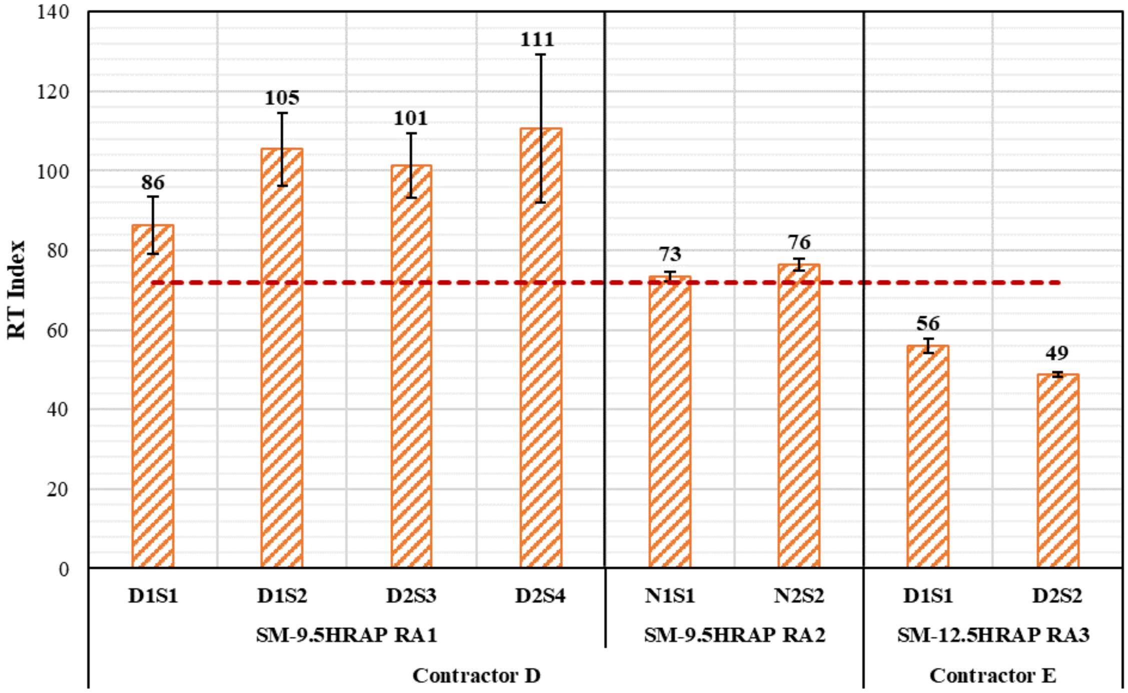


Figure 18. Performance Test Data for Mean RT Index of Reheat Specimens for HRAP RA Mixtures Produced by Contractors D and E. Error bars indicate ± 1 standard deviation. Dashed red line denotes VDOT's balanced mix design limit for asphalt SMs with A and D designations. D1S1 = day 1 sample 1; D1S2 = day 1 sample 2; D2S1 = day 2 sample 1; D2S2 = day 2 sample 2; D2S3 = day 2 sample 3; D2S4 = day 2 sample 4; HRAP = high reclaimed asphalt pavement; N1S1 = night 1 sample 1; N2S2 = night 2 sample 2; RA = recycling agent; RT = rutting tolerance; SM = surface mixture.

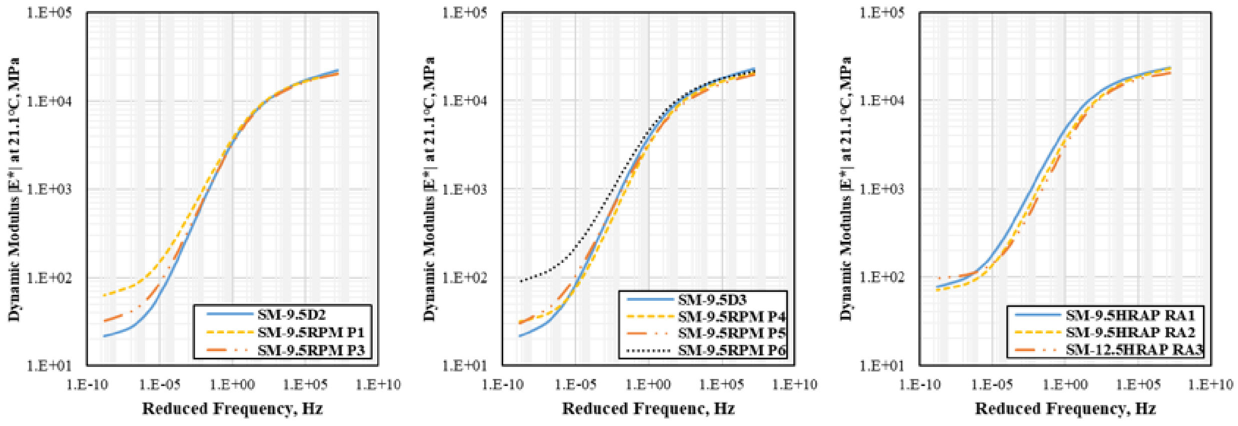
Advanced Performance Tests

The advanced performance tests (dynamic modulus |E*|, CF, and SSR tests) were performed on one reheat sample from each of the evaluated mixtures.

Stiffness Properties—Dynamic Modulus |E|*

Figures 19 and 20 show the dynamic modulus and phase angle master curves for all tested mixtures at a reference temperature of 21.1°C. Figures 19a and 20a give the results for control and RPM mixtures produced by Contractor A. Figures 19b and 20b show the results for control and RPM mixtures produced by Contractors B and C. Figures 19c and 20c present the results for HRAP RA mixtures produced by Contractors D and E.

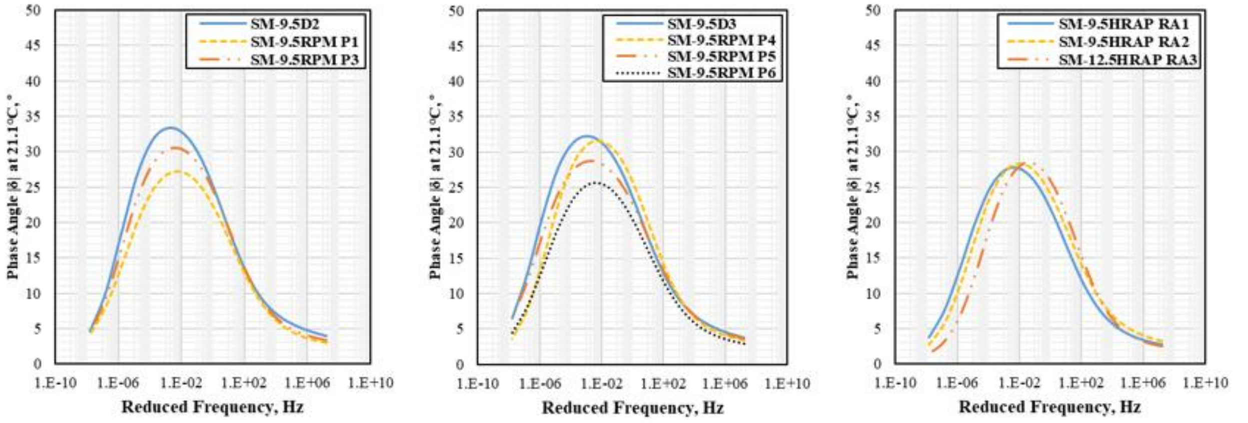
Based on the data presented in Figure 19a, the control and RPM mixtures performed similarly at higher frequencies and colder temperatures in terms of |E*|. SM-9.5D2 exhibited lower |E*| at lower frequencies and higher temperatures than the RPM mixtures (SM-9.5RPM P1 and SM-9.5RPM P3). The data presented in Figure 19b indicate that the control and RPM mixtures exhibited similar |E*| values across all frequencies and temperatures, with SM-9.5D3 being slightly softer than the RPM mixtures at higher temperatures and low frequencies. Based on the data in Figure 19c, SM-9.5HRAP RA2 and SM-12.5HRAP P3 exhibited similar |E*| values across all frequencies.



(a) (b) (c)

Figure 19. Dynamic Modulus (|E*|) Master Curves at 21.1°C: (a) Control and RPM Mixtures Produced by Contractor A; (b) Control and RPM Mixtures Produced by Contractors B and C; (c) HRAP RA Mixtures Produced by Contractors D and E. D = mixture designation; HRAP = high reclaimed asphalt pavement; RA = recycling agent; RPM = recycled plastic-modified; SM = surface mixture.

Based on the results in Figure 20a, SM-9.5D2 exhibited the highest δ values, indicating less elastic behavior. SM-9.5RPM P3 had the next highest δ values, likely because it is an RPM mixture with high RAP content. SM-9.5RPM P1 displayed the lowest δ among the mixtures produced by Contractor A. The data in Figure 20b indicate that SM-9.5D3 and SM-9.5RPM P4 had similar magnitudes of δ, but the peak for SM-9.5RPM P4 occurs at a higher reduced frequency than that of SM-9.5D3. SM-9.5RPM P5 exhibited the lowest δ among the mixtures produced by Contractor B. SM-9.5RPM P6 exhibited the lowest δ values among all evaluated RPM mixtures. The data in Figure 20c indicate that SM-9.5HRAP RA2 and SM-12.5HRAP RA3 exhibited similar δ values, with the master curve for SM-12.5HRAP RA3 slightly shifted to the right (higher frequencies).



(a) (b) (c)

Figure 20. Phase Angle Master Curves at 21.1°C: (a) Control and RPM Mixtures Produced by Contractor A; (b) Control and RPM Mixtures Produced by Contractors B and C; (c) HRAP RA Mixtures Produced by Contractors D and E. D = mixture designation; HRAP = high reclaimed asphalt pavement; RA = recycling agent; RPM = recycled plastic-modified; SM = surface mixture.

Cracking Assessment—Cyclic Fatigue Test Results and Analyses

RPM Mixtures. Figure 21 shows the S_{app} values for all control and RPM mixtures. Among the mixtures produced by Contractor A, the RPM mixtures exhibited similar S_{app} values to the control mixture. This result is likely due to either the use of BMD to design RPM mixtures with performance equal to or better than typical conventional control mixtures or the non-sensitivity of CF to capture the cracking performance of RPM mixtures. Mixtures produced by Contractor B had higher S_{app} values on average and therefore more elasticity than those produced by Contractor A. SM-9.5RPM P5 displayed the highest S_{app} value, followed by SM-9.5D3 and SM-9.5RPM P4. The difference between the observed S_{app} values for SM-9.5RPM P4 and SM-9.5RPM P5 is likely due to differences in the recycled plastic and polymer used for mixture modification. These results indicate that the addition of recycled plastic to asphalt can result in either a decrease or an increase in elasticity for RPM mixtures relative to conventional mixtures. SM-9.5RPM P6 produced by Contractor C had the highest S_{app} value among all evaluated RPM mixtures. The red dashed lines in Figure 21 represent recommended S_{app} value thresholds for four traffic categories (standard traffic, heavy traffic, very heavy traffic, and extremely heavy traffic). All evaluated mixtures exhibited S_{app} values above 8.0, the recommended threshold for the standard traffic category. These thresholds are provided only for reference purposes because the analyses used to develop these thresholds did not include mixtures from Virginia or RPM mixtures. Cracking occurs at a later stage in pavements, typically around 7 years of service life. Therefore, an assessment of these mixtures after long-term aging to simulate long-term performance is needed to assess the true performance of these mixtures.

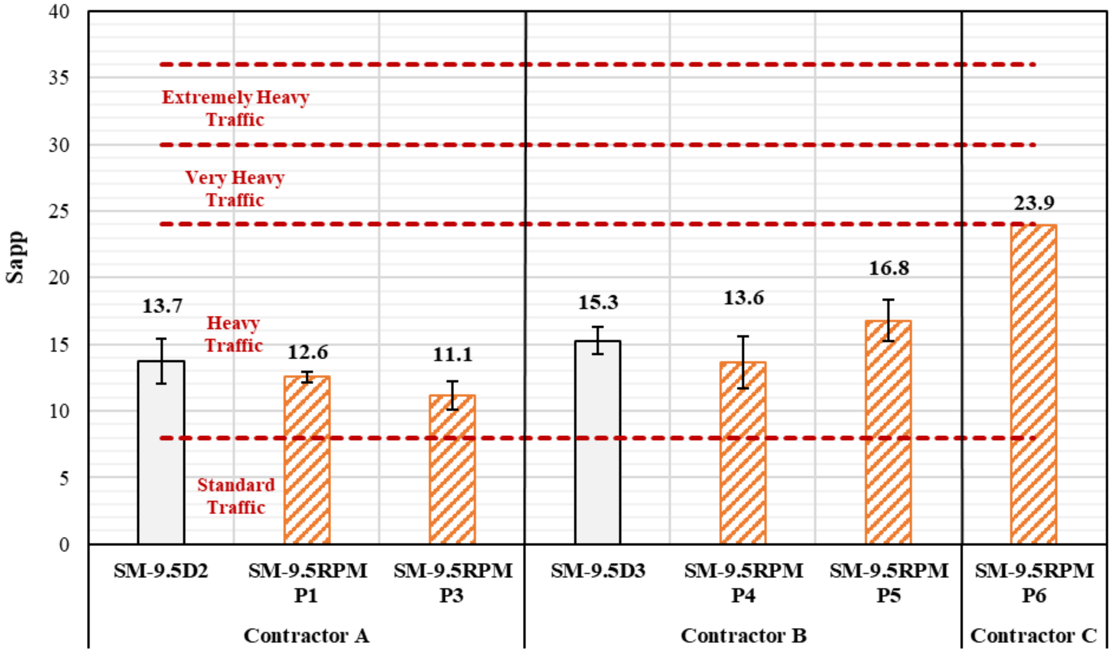


Figure 21. Cyclic Fatigue Performance Test Data for Mean S_{app} of Reheat Specimens for All Evaluated Control and RPM Mixtures. Error bars indicate ± 1 standard deviation. Dashed red line denotes recommended threshold values for S_{app} index parameter as a function of traffic tier. D = mixture designation; RPM = recycled plastic-modified; S_{app} = fatigue index parameter; SM = surface mixture.

Figure 22 displays the D^R parameter for the seven evaluated RPM and control comparator asphalt mixtures. The D^R parameter is used as an indicator of mixture toughness, which is defined as the material's ability to absorb energy without fracturing. All seven mixtures displayed very similar values for the D^R parameter, indicating that the addition of recycled plastic to asphalt has no significant effect on the toughness of asphalt mixtures relative to the control mixtures. The true performance of the durability of asphalt mixtures should be evaluated through an assessment of these mixtures after long-term aging to simulate long-term performance.

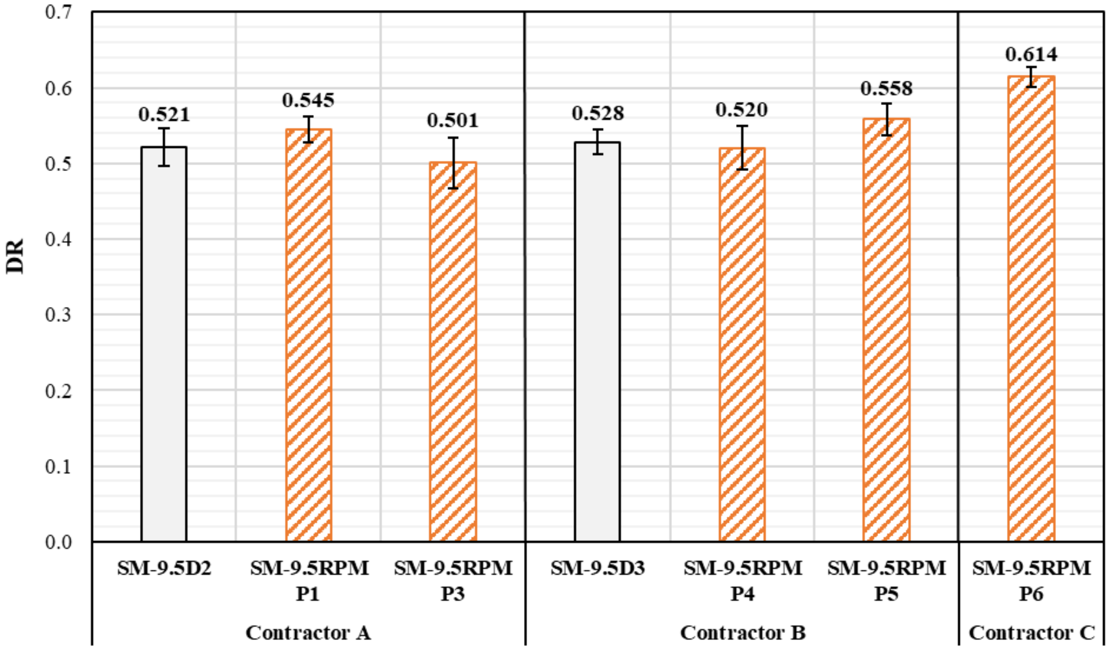


Figure 22. Cyclic Fatigue Performance Test Data for Mean D^R of Reheat Specimens for All Evaluated Control and RPM Mixtures. Error bars indicate ± 1 standard deviation. D = mixture designation; D^R = pseudo-energy-based failure criterion; RPM = recycled plastic-modified; SM = surface mixture.

HRAP RA Mixtures. Figure 23 shows the S_{app} values for all HRAP RA mixtures. Mixtures SM-9.5HRAP RA2 and SM-12.5HRAP RA3 exhibited similar S_{app} values above 24.0, exceeding the recommended threshold for the "very heavy" traffic category. Meanwhile, SM-9.5HRAP RA1 exhibited a lower S_{app} value compared with the other mixtures, placing it in the "heavy" traffic category. Figure 24 shows the D^R values for all HRAP RA mixtures. SM-12.5HRAP RA3 exhibited the highest D^R value, followed by SM-9.5HRAP RA2, which had a higher D^R value than SM-9.5HRAP RA1. This result could be attributed to the RA product used.

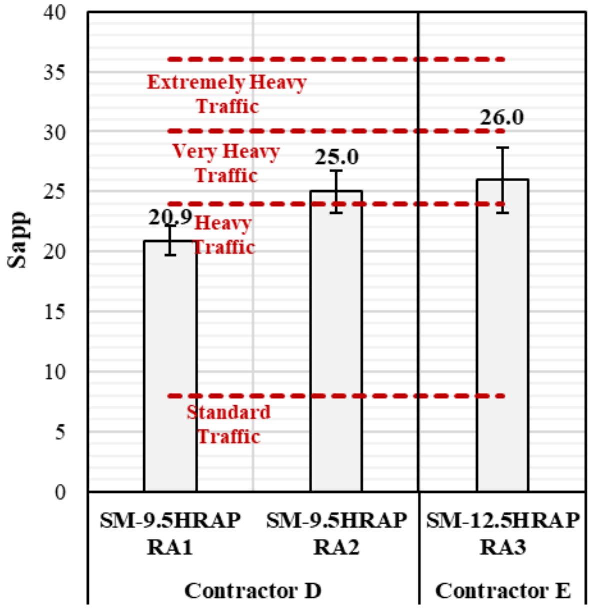


Figure 23. Cyclic Fatigue Performance Test Data for Mean S_{app} of Reheat Specimens for All Evaluated HRAP RA Mixtures. Error bars indicate ± 1 standard deviation. Dashed red line denotes recommended threshold values for S_{app} index parameter as a function of traffic tier. HRAP = high reclaimed asphalt pavement; RA = recycling agent; S_{app} = fatigue index parameter; SM = surface mixture.

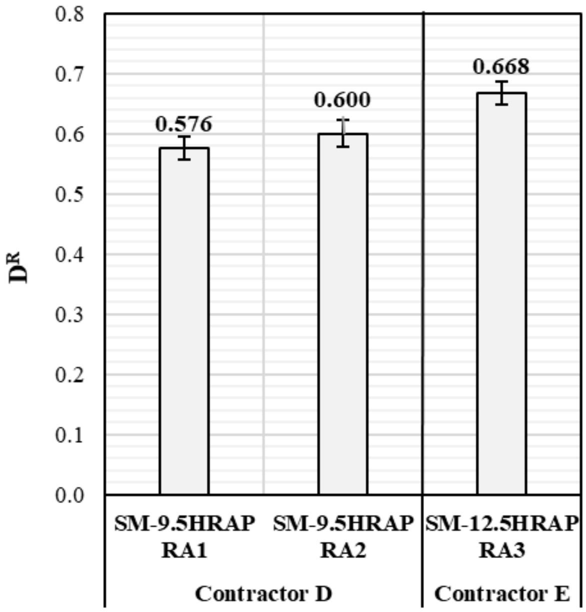


Figure 24. Cyclic Fatigue Performance Test Data for Mean D^R of Reheat Specimens for All Evaluated HRAP RA Mixtures. Error bars indicate ± 1 standard deviation. D^R = pseudo-energy-based failure criterion; HRAP = high reclaimed asphalt pavement; RA = recycling agent; SM = surface mixture.

Rutting Assessment—Rutting Strain Index

RPM Mixtures. Figure 25 shows the RSI values for the seven evaluated control and RPM mixtures. For mixtures produced by Contractor A, the two RPM mixtures exhibited higher resistance to rutting than the control mixture. SM-9.5RPM P1 had the lowest RSI, followed by SM-9.5RPM P3 and SM-9.5D2. For mixtures produced by Contractor B, the use of recycled plastic had inconsistent effects on the resistance to rutting relative to the control mixture. SM-9.5RPM P5 displayed a higher RSI value than SM-9.5D3, and SM-9.5RPM P4 displayed the lowest RSI value among the evaluated mixtures. These results indicate that the addition of recycled plastic has the potential to improve or reduce the rutting resistance of asphalt mixtures, depending on the type and amount of plastic used. SM-9.5RPM P6 produced by Contractor C had the lowest RSI value among all evaluated RPM mixtures. The red dashed lines in Figure 25 represent recommended RSI value thresholds for four traffic categories—standard traffic, heavy traffic, very heavy traffic, and extremely heavy traffic. These thresholds are provided only for reference purposes because the analyses used to develop these thresholds did not include mixtures from Virginia or RPM mixtures.

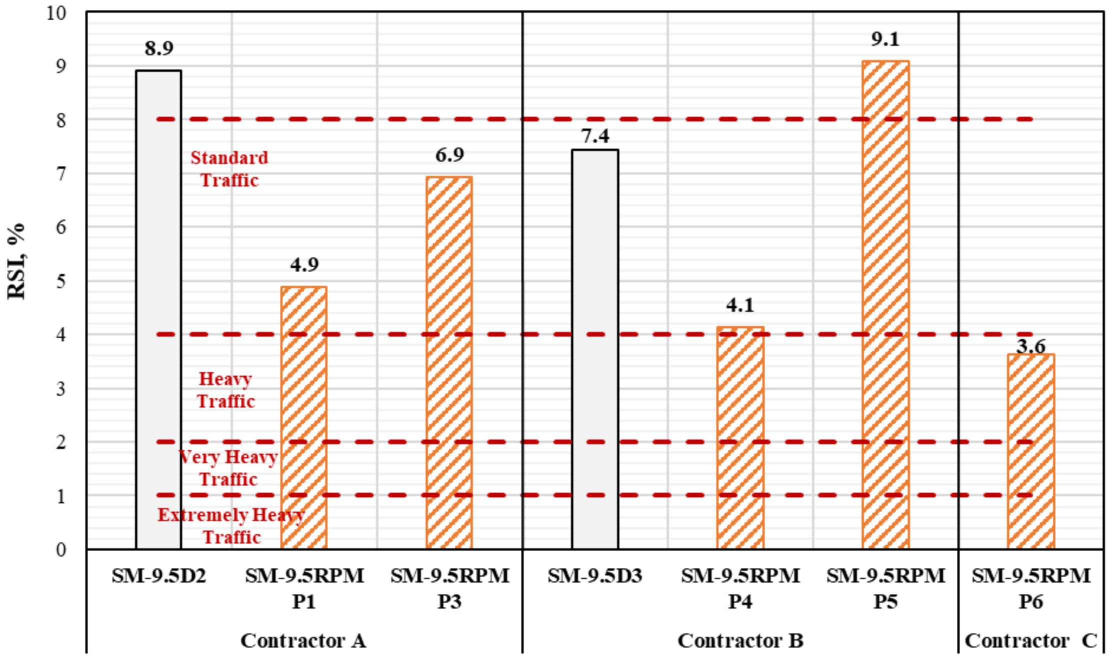


Figure 25. Stress Sweep Rutting Performance Test Data for Mean RSI of Reheat Specimens for All Control and RPM Evaluated Mixtures. Error bars indicate ± 1 standard deviation. Dashed red line denotes recommended threshold values for RSI parameter as a function of traffic tier. D = mixture designation; RPM = recycled plastic-modified; RSI = rutting strain index.

HRAP RA Mixtures. Figure 26 shows the RSI values for all HRAP RA mixtures. Mixtures SM-9.5HRAP RA2 and SM-12.5HRAP RA3 exhibited similar RSI values, between 4 and 8, which is within the recommended threshold for the “standard” traffic category, indicating no potential rutting issues. Meanwhile, mixture SM-9.5HRAP RA1 exhibited a lower RSI value compared with the other two mixtures, placing it in the “heavy” traffic category and also indicating no potential rutting issues.

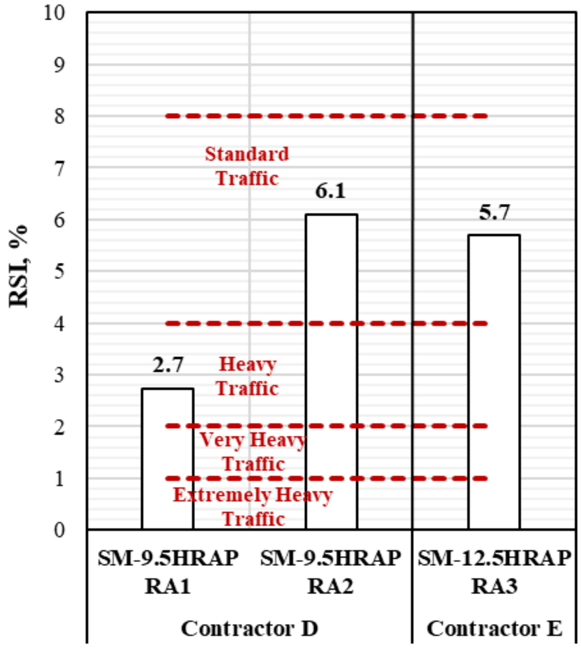


Figure 26. Stress Sweep Rutting Performance Test Data for Mean RSI of Reheat Specimens for All HRAP RA Mixtures. Error bars indicate ± 1 standard deviation. Dashed red line denotes recommended threshold values for RSI parameter as a function of traffic tier. HRAP = high reclaimed asphalt pavement; RA = recycling agent; RSI = rutting strain index; SM = surface mixture.

Testing and Characterization of Extracted and Recovered Asphalt Binders

Performance Grading

Table 13 presents the PG of extracted and recovered asphalt binders for all evaluated mixtures. For mixtures produced by Contractor A, SM-9.5D2 and SM-9.5RPM P3 exhibited similar high, intermediate, and low PG temperatures, and SM-9.5RPM P1 exhibited lower temperature values, which could be attributed to the RAP content and recycled plastic type used. It is important to note that it is uncertain whether the plastic added during production by means of the dry process was completely extracted and recovered and, thus, evaluated by means of plastic-modified binder testing. For mixtures produced by Contractor B, SM-9.5D3 and SM-9.5RPM P4 exhibited similar high, intermediate, and low PG temperatures, whereas SM-9.5RPM P5 exhibited higher high and low temperature values. Mixtures SM-9.5HRAP RA1 and SM-12.5HRAP RA3 were found to be PG 70-16 and 64-22, respectively, which could be attributed to the RAP properties and RA product used.

Table 13. Properties of Extracted and Recovered Asphalt Binders for All Evaluated Mixtures

Mix ID	**Continuous Grade**				**MSCR Results**			**Other Parameter**
	High[a], °C	**Int.[b], °C**	**Low, °C**	**PG**	**$J_{nr\,3.2}$, kPa^{-1}**	**%R, %**	**Traffic**	**ΔT$_c$, °C**
SM-9.5D2	72.8	22.4	– 23.2	70-22	1.6190	3.6420	H	– 2.6
SM-9.5RPM P1	68.5	19.1	– 25.1	64-22	2.3930	1.9890	S	– 3.6
SM-9.5RPM P3	72.4	21.7	– 23.8	70-22	1.3180	4.7540	H	– 4.1
SM-9.5D3	67.5	25.6	– 22.7	64-22	3.2680	1.6910	S	– 4.9
SM-9.5RPM P4	67.0	22.9	– 24.7	64-22	3.6090	1.2670	S	– 3.9

Mix ID	Continuous Grade				MSCR Results			Other Parameter
	High[a], °C	Int.[b], °C	Low, °C	PG	$J_{nr\ 3.2}$, kPa^{-1}	%R, %	Traffic	ΔT_c, °C
SM-9.5RPM P5	73.6	22.6	– 21.8	70-16	0.9640	7.8410	V	– 9.2
SM-9.5RPM P6	N/A							
SM-9.5HRAP RA1	70.8	24.1	– 20.7	70-16	1.7150	3.6820	H	– 9.5
SM-9.5HRAP RA2	N/A							
SM-12.5HRAP RA3	66.8	22.3	– 23.4	64-22	3.3400	1.1520	S	– 5.0

%R = percent recovery; ΔT_c = difference in critical low temperature performance grade limiting temperatures; D = mixture designation; H = heavy; HRAP = high reclaimed asphalt pavement; Int. = intermediate; $J_{nr\ 3.2}$ = non-recoverable creep compliance; MSCR = Multiple Stress Creep Recovery; N/A = not available; PG = performance grade; RA = recycling agent; RPM = recycled plastic-modified; S = standard; SM = surface mixture; V = very heavy.

[a] Temperature corresponds to $G^*/\sin\delta = 2.2$ kPa; [b] Temperature corresponds to $G^*\sin\delta = 5{,}000$ kPa.

Multiple Stress Creep Recovery Test Results

Binder grading was also performed in accordance with AASHTO M 322 (AASHTO, 2019), which incorporates the non-recoverable creep compliance at 3.2 kPa ($J_{nr,\ 3.2\ kPa}$) and percent recovery at 3.2 kPa (%R) determined using the Multiple Stress Creep Recovery (MSCR) test. The MSCR test was conducted at 64°C, the average 7-day maximum pavement design temperature for Virginia. AASHTO M 332 specifies maximum Jnr, 3.2 kPa requirements for standard, heavy, very heavy, and extremely heavy traffic of 4.5 kPa^-1, 2.0 kPa^-1, 1.0 kPa^-1, and 0.5 kPa^-1, respectively (AASHTO, 2019). Table 13 shows the MSCR testing data for all evaluated extracted and recovered binders. VDOT specifications require a minimum PG of 64S-16 and 64H-16 for asphalt binders for SMs with A and D designations, respectively (VDOT, 2020). The data in Table 13 indicate that all extracted and recovered binders from the mixtures evaluated in this study met or exceeded the VDOT specification criteria in terms of asphalt binder properties. For instance, binders SM-9.5RPM P1, SM-9.5D3, SM-9.5RPM P4, and SM-12.5HRAP RA3 were in the standard category. Binders SM-9.5D2, SM-9.5RPM P3, and SM-9.5HRAP RA1 were in the heavy category. Finally, binder SM-9.5RPM P5 was in the very heavy category.

Difference in Critical Low Temperature Performance Grade—ΔT_c Results

Table 13 presents the ΔTc values for all evaluated extracted and recovered binders. All binders had ΔTc values ranging from -9.5 to -2.6°C, with some exceeding the traditional cracking zone of -5.0°C, such as SM-9.5RPM P5 and SM-9.5HRAP RA1.

Evaluation of Field Cores

Table 14 summarizes the in-place layer thicknesses, air void levels, and permeability values for all sampled cores. The average layer thickness for SM-9.5RPM P1, SM-9.5RPM P3, and SM-9.5RPM P6 was less than the target of 38.1 mm. In contrast, the remaining mixtures (SM-9.5RPM P4, SM-9.5RPM P5, and SM-9.5HRAP RA1) had layer thicknesses exceeding the target. Similar density ranges were observed for all evaluated cores/mixtures, with no alarming values reported. The average permeability results for all evaluated mixtures were below the VDOT threshold value of 150*10-5 cm/s at 7.5% air voids (VDOT, 2005).

Table 14. Summary of In-Place Layer Thickness, Air Void Level, and Permeability for Core Samples

Mixture Type /	Layer Thickness (mm)			In-Place Air Voids (%)			Permeability (*10^{-5} cm/s)		
Measured Property	Avg.	CI	Target	Avg.	CI	Range	Avg.	CI	Target
SM-9.5D2	No core samples were collected.								150
SM-9.5RPM P1	29.8	1.3	38.1	9.4	1.7	7.7 to 11.1	123	76	
SM-9.5RPM P3	30.4	3.1	38.1	9.4	1.8	7.6 to 11.2	112	98	
SM-9.5D3	No core samples were collected.								
SM-9.5RPM P4	39.5	3.6	38.1	8.4	1.0	7.4 to 9.4	136	106	
SM-9.5RPM P5	42.7	6.5	38.1	7.0	0.8	6.1 to 7.8	50	56	
SM-9.5RPM P6	34.7	2.7	38.1	8.9	1.9	7.0 to 10.8	92	72	
SM-9.5HRAP RA1	43.3	5.6	38.1	8.5	1.5	7.1 to 10.0	118	78	
SM-9.5HRAP RA2	No core samples were collected.								
SM-12.5HRAP RA3	No core samples were collected.								

Avg. = average; CI = 95% confidence interval; D = mixture designation; HRAP = high reclaimed asphalt pavement; RA = recycling agent; RPM = recycled plastic-modified; SM = surface mixture.

Figure 27 shows the CT index values of all cores by mixture type. All mixtures exhibited similar values overall. Regarding the mean or average values, RPM mixtures from Contractor A had the highest CT index values, followed by RPM mixtures from Contractor B and then Contractor C. The HRAP RA mixture from Contractor D exhibited the lowest CT index value among all evaluated cores.

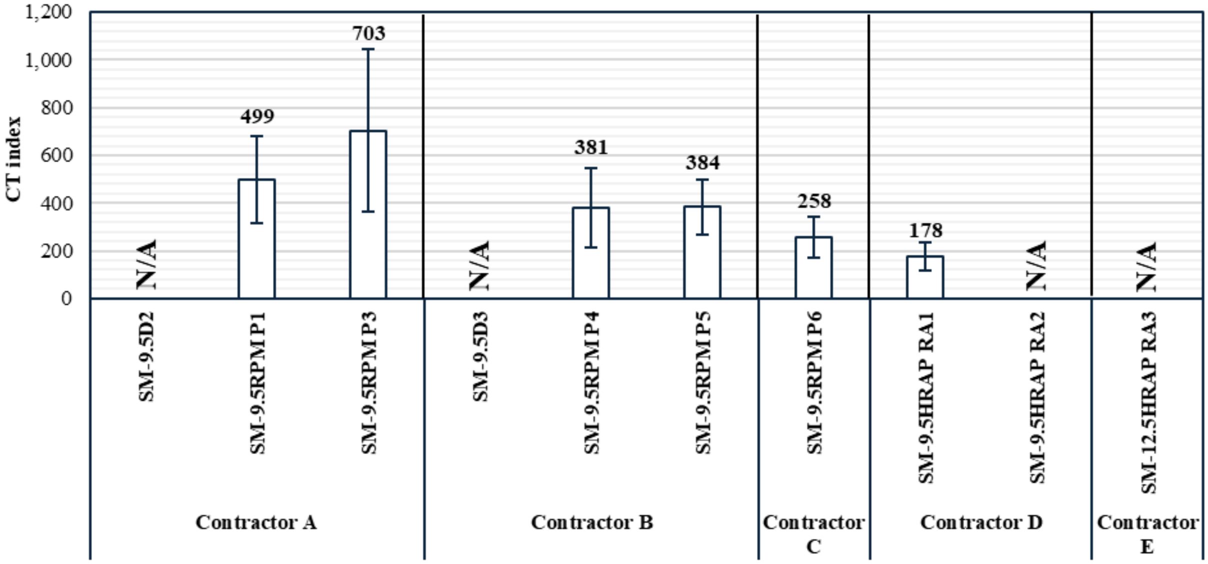


Figure 27. Indirect Tensile- Cracking Test Performance Data of Collected Field Cores. Error bars indicate ± 1 standard deviation. CT = cracking tolerance; HRAP = high reclaimed asphalt pavement; N/A = not available; RA = recycling agent; RPM = recycled plastic-modified; SM = surface mixture.

Initial In-Service Performance of Evaluated Pavement Structures

The RPM and HRAP RA sections are in very good condition after 1 to 2 years post-construction, demonstrated in Figures 28 through 30 by photos of some of the RPM and HRAP RA sections. Because the evaluated sections were placed during the 2022 and 2023 construction seasons, the observations of their 1- to 2-year performance are still considered preliminary. The performance of the RPM and HRAP RA sections evaluated in this study will continue to be monitored.

Figure 28. Photographs Taken 22 Months Post-Paving for Sections with Mixtures: (a) SM-9.5RPM P1 (State Route 645); (b) SM-9.5RPM P3 (State Route 630). RPM = recycled plastic-modified; SM = surface mixture.

Figure 29. Photograph Taken 8 Months Post-Paving for Section with Mixture SM-9.5RPM P6 (State Route 1220). RPM = recycled plastic-modified; SM = surface mixture.

(a) (b)

Figure 30. Photographs Taken Post-Paving after: (a) 23 Months for SM-9.5HRAP RA1 (State Route 2401); (b) 11 Months for SM-9.5HRAP RA2 (State Route 659). HRAP = high reclaimed asphalt pavement; RPM = recycled plastic-modified; SM = surface mixture.

Evaluation of Emissions

Polycyclic Aromatic Hydrocarbon Analysis

Table 15 provides the results of the PAH analysis. Total PAH concentration (∑PAH) equaled 0.0934 mg/m^3, which is below the 0.2 mg/m^3 limit set by OSHA (n.d.). In addition, it should be noted that of the 18 PAH constituents evaluated, only 7 produced results above the reporting limits of the laboratory.

Table 15. PAH Concentrations Taken from the Back of the Paver during Operation

Constituent	Concentration (mg/m^3)
1-Methylnaphthalene	0.010 [a]
2-Methylnaphthalene	0.014 [a]
Acenaphthene	0.0031
Acenaphthylene	< 0.0015[b]
Anthracene	< 0.0017
Benzo (a) antheracene	< 0.0019
Benzo (a) pyrene	< 0.0022
Benzo (b) fluoranthene	< 0.0020
Benzo (g, h, i) perylene	< 0.0025
Benzo (k) fluoranthene	< 0.0020
Chrysene	< 0.0019
Dibenz (a, h) anthracene	< 0.0020
Fluoranthene	< 0.0018
Fluorene	0.006
Indeno (1, 2, 3 - cd) pyrene	< 0.0020
Naphthalene	0.016[a]

Constituent	Concentration (mg/m^3)
Phenanthrene	0.021
Pyrene	< 0.0018
∑PAH (mg/m3)	0.0934

PAH = polycyclic aromatic hydrocarbon.
[a] Indicates possible breakthrough or migration.
[b] < indicates measured concentration below the reporting limits.

The Boom et al. (2022) study also evaluated PAH emissions generated from RPM asphalts. Like the results of the VOC emissions, the authors found that increasing the amount of recycled plastic added to the mixture led to a decrease in ∑PAH emissions for all plastic types and at all temperatures (Boom et al., 2022). As with the reductions in ∑VOC emissions, the authors attributed these results to increased thermal stability of the binder provided by the recycled plastics (Boom et al., 2022).

Another study conducted over a period of 10 years in France monitored PAH and AF emissions generated from 63 different worksites, including asphalt production sites, mechanical and manually rolled asphalt paving projects, and coal-tar asphalt milling projects (Germin-Aizac et al., 2023). Note that this study did not include asphalt mixtures incorporating recycled plastics. Average ∑PAH concentrations taken from 198 personnel samples on mechanical rolled asphalt paving projects equaled 0.001012 mg/m^3 (Germin-Aizac et al., 2023). Considering this result and the fact that several of the PAH constituents measured in this study were below reporting limits, it is likely that the ∑PAH concentration in the emissions from the SM-9.5RPM P6 mixture was less than the 0.0934 mg/m^3 concentration shown in Table 16. However, a more sensitive analytical method or larger sample volumes would be needed to verify this hypothesis.

Table 16. VOC Concentrations Measured at the Back Left and Right of the Paver

Constituent	VOC1	VOC2	OSHA PEL
Benzene (mg/m^3)	< 2.1[a]	< 2.1	15.97
Chlorobenzene (mg/m^3)	< 5.8	< 5.8	350
Cumene (mg/m^3)	< 6.1	< 6.1	245
Ethylbenzene (mg/m^3)	< 5.7	< 5.7	435
m-Dichlorobenzene (mg/m^3)	< 6.8	< 6.8	N/A
o-Dichlorobenzene (mg/m^3)	< 6.9	< 6.9	300
p-Dichlorobenzene (mg/m^3)	< 6.9	< 6.9	450
Toluene (mg/m^3)	< 5.4	< 5.4	750
Vinyl Toluene (mg/m^3)	< 12	< 12	480
Xylene (mg/m^3)	< 21	< 21	435
∑VOC (mg/m^3)	78.7	78.7	N/A

N/A = not available; OSHA = Occupational Safety and Health Administration; PEL = permissible exposure limits; VOC = volatile organic compound.
[a] < indicates measured concentration below reporting limits.

Volatile Organic Compound Analysis

Table 16 provides the results of the VOC analysis. Similar to the results of the PAH analysis, all the VOC constituents measured at both locations were below the laboratory reporting limits. This outcome could be a result of the limited sampling time, 100 minutes total, reducing the amount of constituents ultimately collected on the sample media. Regardless, assuming VOC emissions remain constant during the course of paving, none of the VOCs measured would have exceeded Occupational Safety and Health Administration (OSHA) permissible exposure levels (OSHA, n.d.).

A similar study, conducted by Boom et al. (2022), evaluated the VOCs emitted from a number of RPM asphalt mixes (including recycled low-density polyethylene, linear low-density polyethylene, high-density polyethylene, and polypropylene plastics) and traditional asphalt mixtures in a controlled laboratory environment. In that study, asphalt mixtures were created using 1%, 2%, 4%, and 6% of each type of plastic by weight of binder, and VOC samples were collected at 160˚C, 180˚C, and 200˚C. Results showed a maximum concentration of ∑VOCs emitted at 200˚C, which equaled about 7 mg/m^3 (Boom et al., 2022). Along with an active sampling methodology, this study used a much more sensitive analytical method, EPA Method 0031, capable of measuring VOCs at lower concentrations (EPA, 1996). Unfortunately, the research team was unable to find a suitable laboratory to conduct this analytical method at the time of this study. These factors, along with the limited passive sampling duration in the current study, likely explain the discrepancy between these sets of results.

The Boom et al. (2022) study also found that increasing the percentage of recycled plastics incorporated into the mixture reduced the ∑VOC emitted by up to 78% compared with the control mixture, depending on the plastic type. This result was achieved in an RPM mixture using recycled high-density polyethylene added at 6% by weight of binder at 160˚C (Boom et al., 2022). Although this temperature was the lowest evaluated, similar results were also recorded at the higher temperatures and all polymer types with recycled polypropylene plastics reducing ∑VOC emissions by 75 % when added at 6 % by weight of binder at 200˚C (Boom et al., 2022). The authors attribute these results to the recycled plastics improving the thermal stability of the binder (Boom et al., 2022).

Asphalt Fume Analysis

Table 17 provides the results from the AF analysis, showing that concentrations collected at both locations were below the laboratory's reporting limits. These results could be due to the sampling time (100 minutes) or the limitations of the analytical methods used, particularly given that the NIOSH recommended exposure level for AF is 5 mg/m^3 during a 15-minute period.

Table 17. Results of the Asphalt Fume Sampling

Sample	Concentration (mg/m^3)
AF1	< 0.38[a]
AF2	< 0.38[a]

AF = asphalt fume.

[a] < indicates measured concentration below the reporting limits.

Results from the French study found similarly low AF emissions generated from mechanically rolled asphalt paving projects, averaging 0.27 mg/m^3 over 74 individuals (Germin-Aizac et al., 2023). In that same study, AF emissions measured at 15 asphalt production sites averaged slightly higher at 0.32 mg/m^3 (Germin-Aizac et al., 2023). It should be noted that the standard deviation for both averages was significant, equaling 3.4 mg/m^3 and 3.9 mg/m^3, respectively (Germin-Aizac et al., 2023). This result is an indication of the variability inherent in emissions sampling in the field. Changes in wind patterns, ambient temperatures, frequency, and duration of work breaks during the sampling period can all contribute to variations in emissions results.

Summary of Findings

- *Based on the results for the mixtures tested in this study, modification with engineered recycled plastics could provide similar or enhanced cracking performance properties and characteristics of the resulting mixtures compared with unmodified control mixtures, if designed properly.* Long-term cracking performance, as assessed in the laboratory, remains an unknown element because criteria for evaluating results were not available at the time of this study.

- *All RPM sections are in very good condition after 24 to 36 months of service. Continued monitoring of the sections is necessary to evaluate long-term performance and accurately quantify any potential cost savings compared with other reference mixtures, such as typical unmodified SMs.*

- *Emissions of PAHs, VOCs, and AF generated from SM-9.5RPM P6 during paving operations were consistently low and below the reporting limits provided by the laboratory in many cases.* This outcome could be due to sampling constraints, inherent variability associated with field emissions sampling, or an accurate reflection of the emissions generated by the material. Although these results align with those available in the relevant literature, additional field sampling would provide a better understanding of the effect the addition of recycled plastics could have on emissions.

- *Mixtures containing 40% RAP with a softer binder or RA and with or without warm mix asphalt additives may be designed and produced to meet current BMD performance thresholds, as well as volumetric properties, gradation, and asphalt content requirements.* Long-term cracking performance, as assessed in the laboratory, remains an unknown element because criteria for evaluating results were not available at the time of this study.

- *All HRAP sections are in very good condition after 24 to 36 months of service. Continued monitoring of the sections is necessary to determine long-term performance and accurately quantify any potential cost savings compared with other reference mixtures, such as SMs with typical RAP contents.*

CONCLUSIONS

- *The addition of recycled plastics into asphalt mixtures does not necessitate any changes from routine established practices in relation to paving operations, except for some cautions related to mixture temperature, weather, and air temperature.*
- *Higher RAP content SMs can be produced through the plant with no significant differences in aggregate gradations and asphalt binder content compared with the design.*

RECOMMENDATIONS

1. *VDOT districts and VTRC should continue to monitor the performance of the RPM and HRAP RA sections evaluated in this study*. This assessment will provide more accurate predictions of the service life of the RPM and HRAP RA overlays as the existing sections continue to age.
2. *VDOT should conduct additional field trials using RPM and HRAP RA mixtures to assess long-term field performance.* These evaluations will allow for the laboratory assessment of long-term cracking potential because methods for evaluation have been further developed since this study. They will also allow for the assessment of a wider variety of RPM and RA materials than could be incorporated in this study.

IMPLEMENTATION AND BENEFITS

The researchers 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 Recommendation 1, VTRC submitted a research needs statement to PaveRAC Subcommittee B on October 1, 2025, which proposes monitoring the performance of RPM and HRAP RA sections in Virginia for the next 3 to 5 years. This project will capture a more representative documentation of field performance for these types of paving materials. VTRC will coordinate and collect performance data for the sections evaluated in this study annually from VDOT's pavement management system and share the data with the Materials Divisions in VDOT's Northern Virginia, Richmond, Salem, and Hampton Roads Districts and VDOT's Central Office Materials Division.

Regarding Recommendation 2, VTRC will submit a research needs statement to the appropriate PaveRAC subcommittee for a research project to support this effort no later than the fall of 2026. If approved, VTRC will work with the Materials Division and VDOT districts to identify additional field projects for using RPM, high RAP contents, and RAs in the 2027 construction season.

Benefits

The benefit of implementing Recommendation 1 will be to assess if the initial performance indicators for RPM and HRAP with RA mixtures are consistent with in-service performance. This implementation will provide the Materials Division and districts confirmation of the feasibility of using RPM and RA materials considered in this study as sustainable options for improving the performance of asphalt pavements and conserving material resources, as well as informing the development of performance specifications for using these materials. The information will also provide quality assurance and acceptance programs with validated performance-based parameters and threshold criteria to accept or reject using a given RA.

The benefit of implementing Recommendation 2 will be to evaluate additional alternatives to modify asphalt binders and mixtures that may serve as a sustainable solutions for improving the performance of asphalt pavements and conserving material resources. This implementation will provide the opportunity to continue gaining knowledge about the potential performance of these materials. In addition, continuing to assess RPM modification alternatives will allow a better understanding of the potential environmental and human health impacts associated with using recycled plastics in asphalt mixtures.

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