Balanced Mix Design for Surface Mixtures: 2021 and 2022 Plant Mix Schedule Pilots

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16. Abstract:

Many state highway agencies are currently exploring a new approach for designing and accepting asphalt mixtures, known as the balanced mix design (BMD) method (hereinafter "BMD"). The Virginia Department of Transportation (VDOT) has made a commitment to adopt BMD to enhance the performance of asphalt mixtures. Since 2018, VDOT has taken incremental steps to phase in the use of BMD in production while addressing concerns expressed by VDOT and the industry. The use of BMD line items in selected 2021 and 2022 contracts has been an important learning opportunity for VDOT and the industry along the path to implementation. This study documented and assessed the 2021 and 2022 maintenance plant mix schedule pilots. The objectives of the study were to provide information on quality control, acceptance testing, and independent assurance testing; analyze the performance properties of reheated mixtures and extracted and recovered binders; and document lessons learned from the process. The analysis addressed several topics, including variability in production and testing and binder characterization and implications for performance.

The pilot projects were developed by the VDOT districts using maintenance plant mix schedule contracts. In 2021, approximately 72,000 tons of BMD mixtures were paved on selected routes in 10 maintenance schedules across five districts. In 2022, approximately 222,000 tons of BMD mixtures were paved in 13 maintenance schedules distributed across all nine VDOT districts, with at least one BMD contract executed per district. The Cantabro mass loss test, the indirect tensile cracking test (IDT-CT), the Asphalt Pavement Analyzer rut test, and the indirect tensile test at high temperature (IDT-HT) were performed on laboratory-produced design specimens and non-reheated and reheated plant-produced, laboratory-compacted specimens. Basic and advanced binder testing and analysis were conducted on extracted and recovered binders from selected samples of the mixtures.

Based on the test results, the successful outcomes observed during the pilot projects in 2021 and 2022 clearly demonstrated the efficacy of applying BMD to surface mixtures (SMs) with A and D designations. Moreover, there was a decrease in variability in test results from 2021 to 2022, showcasing the benefits derived from training and experience in BMD testing performance. Notably, it was found that the source and formulation of the virgin binder used, along with the properties of the aged binder in reclaimed asphalt pavement (RAP) stockpiles, contributed to substantial variations in binder properties and affected the expected performance of the produced mixtures.

The study recommends that (1) efforts be pursued toward full implementation of BMD in Virginia for SMs with A and D designations, as supported by VDOT's 2024 BMD special provision; (2) a comprehensive ruggedness study focusing on the refinement of specimen preparation and test methods for the IDT-CT and IDT-HT be initiated to assess key factors that demand stricter control and additional guidance during specimen preparation for the IDT-CT and IDT-HT; and (3) a comprehensive study to assess the relationships between the properties of virgin and RAP asphalt binders and those of the corresponding asphalt mixtures be conducted.

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FINAL REPORT

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ABSTRACT

Many state highway agencies are currently exploring a new approach for designing and accepting asphalt mixtures, known as the balanced mix design (BMD) method (hereinafter "BMD"). The Virginia Department of Transportation (VDOT) has made a commitment to adopt BMD to enhance the performance of asphalt mixtures. Since 2018, VDOT has taken incremental steps to phase in the use of BMD in production while addressing concerns expressed by VDOT and the industry. The use of BMD line items in selected 2021 and 2022 contracts has been an important learning opportunity for VDOT and the industry along the path to implementation. This study documented and assessed the 2021 and 2022 maintenance plant mix schedule pilots. The objectives of the study were to provide information on quality control, acceptance testing, and independent assurance testing; analyze the performance properties of reheated mixtures and extracted and recovered binders; and document lessons learned from the process. The analysis addressed several topics, including variability in production and testing and binder characterization and implications for performance.

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Based on the test results, the successful outcomes observed during the pilot projects in 2021 and 2022 clearly demonstrated the efficacy of applying BMD to surface mixtures (SMs) with A and D designations. Moreover, there was a decrease in variability in test results from 2021 to 2022, showcasing the benefits derived from training and experience in BMD testing performance. Notably, it was found that the source and formulation of the virgin binder used, along with the properties of the aged binder in reclaimed asphalt pavement (RAP) stockpiles, contributed to substantial variations in binder properties and affected the expected performance of the produced mixtures.

The study recommends that (1) efforts be pursued toward full implementation of BMD in Virginia for SMs with A and D designations, as supported by VDOT's 2024 BMD special provision; (2) a comprehensive ruggedness study focusing on the refinement of specimen preparation and test methods for the IDT-CT and IDT-HT be initiated to assess key factors that demand stricter control and additional guidance during specimen preparation for the IDT-CT and IDT-HT; and (3) a comprehensive study to assess the relationships between the properties of virgin and RAP asphalt binders and those of the corresponding asphalt mixtures be conducted.

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INTRODUCTION

Many state highway agencies are currently exploring a new approach for designing and accepting asphalt mixtures, known as the balanced mix design (BMD) method (hereinafter "BMD" (National Center for Asphalt Technology, 2021). The goal of using BMD is to create asphalt mixtures that are safe, durable, and long-lasting in a more efficient and cost-effective manner than current mixtures. This is to be achieved by incorporating performance criteria into the mix design and acceptance process. The Virginia Department of Transportation (VDOT) has made a commitment to adopt BMD to enhance the performance of asphalt mixtures.

To ensure a successful implementation of BMD, the Federal Highway Administration identified eight tasks as guiding principles in this effort (Federal Highway Administration, 2022). VDOT has developed initiatives and achieved progress in each of these tasks.

1. *Identify motivations and benefits*. In this task, agencies identify motivations for implementing BMD such as improving the overall service life of asphalt pavements, assessing the impact of using recycled materials, and facilitating the use of truly innovative materials with good performance prospects. VDOT has a long-term goal of selecting the optimal mixture (such as subdivision mixtures, secondary mixtures, primary route mixtures, high traffic mixtures, and interstate mixtures) for each specific location, considering the required performance thresholds to achieve the desired performance outcomes.

2. *Conduct overall planning*. In this task, champions are identified and collaborations with stakeholders are established. This task also includes defining and setting clear goals, mapping the necessary tasks, and developing a roadmap with an implementation timeline. Within VDOT, two committees were created to coordinate efforts internally and with industry partners. The first committee, the BMD Advisory Group, operates at the executive level. Its primary responsibilities include addressing key issues, overseeing VDOT-wide communication, formulating final policies, and making crucial decisions. The committee consists of representatives from VDOT and

the industry. The second committee, the Technical Committee, focuses on addressing the technical aspects of BMD through collaborative efforts involving VDOT, the Virginia Transportation Research Council (VTRC), and industry representatives. Its objective is to address the technical challenges and considerations related to BMD implementation collectively.

3. *Select performance tests*. In this task, primary modes of distress that are of interest to the agency are identified and appropriate performance tests are selected and assessed. For BMD implementation in Virginia, three practical tests, the Cantabro mass loss test (hereinafter the "Cantabro test"), the indirect tensile cracking test (IDT-CT), and the Asphalt Pavement Analyzer (APA) rut test, were selected for assessing durability, cracking potential, and rutting potential, respectively (Bowers et al., 2022). Precision estimates for one of the three performance tests (the IDT-CT) have been determined and included in the specifications. The establishment of precision estimates and statements for the remaining two tests (the Cantabro and APA rut tests) is underway.

4. *Acquire performance testing equipment*. This task primarily covers acquiring equipment, managing resources, conducting initial training, evaluating performance, and conducting interlaboratory studies to assess variability in the selected performance tests. In 2021, equipment was acquired and provided to the VDOT districts for BMD testing.

5. *Establish baseline data*. In this task, historical data and pavement management system information/data are reviewed. Benchmarking studies are conducted, and corresponding threshold criteria for the selected performance tests are determined. This task also calls for conducting shadow projects, analyzing production data, and deciding how to adjust asphalt mixtures featuring the use of locally available materials. An initial benchmarking of the performance of asphalt surface mixtures (SMs) was completed using mixtures produced and sampled in 2015. Initial performance threshold criteria were developed for the selected BMD tests using reheated mixtures: a maximum mass loss of 7.5% for the Cantabro test, a minimum cracking tolerance (CT) index of 70 for the IDT-CT at 25°C, and a maximum rut depth at 64°C of 8 mm for the APA rut test (Bowers et al., 2022). In 2019, two field trials were planned and executed to design, produce, and place BMD asphalt mixtures in Virginia. These trials constituted the first applications of the BMD specifications in Virginia (Diefenderfer et al., 2021b). In 2020, additional field trials featuring the use of a higher reclaimed asphalt pavement (RAP) content, softer binder, recycling agents, and various other additives such as fibers and softening oils were planned and constructed (Diefenderfer et al., 2023). In 2021, approximately 72,000 tons of BMD mixtures were paved on selected routes in 10 maintenance schedules across five districts. In 2022, there were approximately 222,000 tons of BMD mixtures paved in 13 maintenance schedules distributed across all nine VDOT districts (at least one BMD contract was executed per district). In 2023, approximately 335,000 tons of BMD mixtures are planned for placement in 15 maintenance schedules in VDOT's nine districts (again with at least one BMD contract per district).

6. *Develop specifications and program*. This task includes establishing sampling and testing plans. If part of the agency's goals, pay adjustment factors are also determined in this task. Moreover, pilot specifications and policies are developed, and then pilot projects are conducted and executed. Continuous revisions of specifications, if needed, are also executed. The initial products of the Technical Committee were the 2019 versions of two special provisions for BMD SMs: (1) *Special Provision for Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria,* and (2) *Special Provision for High RAP Content Surface Mixtures Designed Using Performance Criteria.* The first special provision has been undergoing annual updates to incorporate lessons learned, best practices, and the latest findings from ongoing and completed research efforts.

7. *Develop training, certification, and accreditation programs*. Under this task, specified training and certification programs are developed and the existing programs are updated. VTRC and VDOT's Materials Division, with the help of the Virginia Asphalt Association and Germanna Community College through the Virginia Education Center for Asphalt Technology, organized and hosted multiple in-person BMD training classes in 2022 and 2023. The first half of the curriculum included course work and presentations (study guides) on topics related to BMD, VDOT's BMD approach, BMD tests and associated performance thresholds, and VDOT's BMD special provisions. The second half of the curriculum included hands-on training on how to perform BMD tests, including the IDT-CT, using various types of machines/devices.

8. *Consider and conduct the initial implementation*. As part of this task, initial implementation of BMD is considered and launched. This can occur through a phased strategy over the course of many years. VDOT's current implementation plan is to require BMD for 9.5 and 12.5 nominal maximum aggregate size (NMAS) SMs with A and D designations (i.e., VDOT SM-9.5 and SM-12.5 A/D mixtures) on all maintenance paving schedules in 2024. The A mixtures will be placed on routes with less than 2,000 average daily traffic, and the D mixtures will be placed on routes meeting or exceeding 2,000 average daily traffic. Both the A and D mixtures will be designed using BMD; only D mixtures will undergo BMD performance testing during production.

The efforts leading up to the planned 2024 use of BMD for SM-9.5 and SM-12.5 A/D mixtures on all maintenance paving schedules have incorporated incremental steps to phase the use of BMD into production while mitigating concerns expressed by VDOT and the industry. The use of BMD line items in selected 2021 and 2022 contracts has been an important learning opportunity for VDOT and the industry along the path to implementation.

PURPOSE AND SCOPE

The purpose of this study was to document and assess BMD mixtures paved under line items in VDOT's 2021 and 2022 maintenance plant mix schedules. BMD mixtures were designed and produced in accordance with VDOT's 2021 and 2022 BMD special provisions. Typical dense-graded SMs were used as controls for performance comparisons in 2021. No control mixtures were specified in the 2022 contracts.

The scope included the documentation of mix design performance properties, mixture sampling during production, quality control and acceptance testing and independent assurance testing, testing and analysis of the volumetric and performance properties of reheated mixtures, binder evaluation, and lessons learned. The analysis addressed several topics, including variability in production and testing and binder characterization and implications for performance.

The 2021 maintenance schedule pilots initiated VDOT's implementation of BMD under competitive bidding conditions. They and the 2022 pilots provided an opportunity to continue evaluating the impact of the specifications on design, production, and quality control and assurance practices and to consider the potential economic consequences of implementation. In addition, the trials will serve to evaluate the long-term performance implications of using the BMD method. The 2021 and 2022 schedule pilots provide additional resources to evaluate the effect of performance specifications on the field performance of pavement SMs.

METHODS

Five tasks were performed to achieve the study objectives:

1. Document the mix design, production, and construction processes of control (in 2021) and BMD mixtures.

2. Obtain producer-supplied design test results and sample plant-produced mixtures during production.

3. Obtain producer and VDOT laboratory test results for plant-produced mixtures.

4. Conduct volumetric and BMD laboratory testing on specimens fabricated from reheated plant-produced mixtures and perform analyses to evaluate the mixtures.

5. Conduct laboratory testing on asphalt binders extracted and recovered from control and BMD mixtures and perform analyses to evaluate the binder performance properties under various loading and temperature conditions.

Maintenance Schedule Pilots

The pilot projects were developed by the VDOT districts using maintenance plant mix schedule contracts. These contracts typically cover various maintenance activities, including mill and fill operations and overlays, on various interstate, primary, and/or secondary routes within a county or group of counties in the associated district. In 2021, approximately 72,000 tons of BMD mixtures were paved on selected routes in 10 maintenance schedules across five districts. In 2022, there were approximately 222,000 tons of BMD mixtures paved in 13 maintenance schedules distributed across all nine VDOT districts with at least one BMD contract executed per district.

The 2021 pilots included control non-BMD dense-graded SMs designed in accordance with Section 211 of VDOT's *Road and Bridge Specifications* (VDOT, 2020) and BMD mixtures designed in accordance with VDOT's 2021 *Special Provision for Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria* or *Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria*. The 2021 BMD special provisions defined SMs with an A or D designation (SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D) that were designed to meet either Performance + Volumetric (P+V) criteria or Performance Only (P) criteria. The high RAP content specification defines BMD high RAP mixtures as containing greater than 30% RAP. The 2021 BMD special provisions are provided in Appendix A.

The 2022 pilots did not include control non-BMD mixtures. The 2022 BMD mixtures were designed in accordance with VDOT's 2022 *Special Provision for Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria*. The 2022 BMD special provision addressed SMs with an A or D designation (SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D) that were designed to meet Performance + Volumetric Optimized (P+VO) criteria. No high RAP content mixtures were included. The 2022 special provision is provided in Appendix B.

For all BMD specifications, the job-mix formula (JMF) was required to meet the NMAS of the designated mixture type, and performance test results were required to meet the criteria outlined in Table 1 and be reported in the design submission.

Table 1. Performance Testing Criteria for Reheat Mixtures

Distress	Test	Test Method	Specimens	Criteria
Durability	Cantabro test	AASHTO TP 108	3 replicates	Mass loss ≤ 7.5%
Rutting	APA rut test	AASHTO T 340	4 replicates	Rutting ≤ 8.0 mm
Cracking	IDT-CT	ASTM D8225	5 replicates	$CT_{index} \geq 70$

APA = Asphalt Pavement Analyzer; IDT-CT = indirect tensile cracking test; CT = cracking tolerance.

Materials

The 2021 schedule pilots consisted of nine contracts let in five districts, as shown in Table 2. All nine VDOT districts let at least one contract incorporating BMD mixture tonnage in 2022, as shown in Table 3.

Table 2. 2021 BMD Schedule Pilots

District	Schedule	Producer, Plant	Job-Mix Formula	Mix ID	Mix Type	Route	Paving Dates	Samples
Salem	PM-2D-21	Adams Const., Blacksburg	2025-2021-143	21-A1	SM-9.5D	US 11	4/16-23/21	L1 S3, L1 S6
			2025-2021-143 BPV	21-A2			4/28/21-5/14/21	L1 S1, L1 S3, L1 S 6, L2 S1
	PM-2L-21	Boxley, Lynchburg	3020-2021-48	21-B1	SM-9.5D	SR 122	5/25/2021	L2 S 4
			3020-2021-48 BPV	21-B2			5/18-21/21	L1 S4, L1 S 6
Lynchburg	PM-3E-21	Adams Const., South Boston	3008-2021-33	21-C1	SM-12.5D	US 58	7/26/2021	L4 S 4
			3008-2021-33 BPV	21-C2			7/26-28/21	L1 S1, L1 S5
	PM-3F-21	APAC, Shelton	3007-2021-433	21-D1	SM-12.5D	US 29	7/7/2021	L 4 S7
			3007-2021-433 BPV	21-D2			7/9-16/21	L1 S1, L1 S4, L1 S5
Richmond	PM-4A-21	Allan Myers, Rockville	4053-2021-32	21-E1	SM-12.5D	SR 627	7/26/21	L2 S3
			4053-2021-32 BP	21-E2			7/7-13/21	L1 S1, L1 S6
	PM-4F-21	Colony, Powhatan	4052-21925	21-F1	SM-9.5D	SR 625	7/28/21	L3, S5
			4052-21925 P	21-F2			7/12-28/21	L1 S6, L2 S2
Hampton Roads	PM-5E-21	Branscome, Inc., Lee Hall	5011-2021-5	21-G1	SM-12.5D	SR 199W	8/2/21, 8/12/21	L1 S1, L1 S2
			5011-2021-30 BPV	21-G2			8/4-17/21	L1 S1, L1 S5
	PM-5D-21	Adams Const., Skippers	5001-2021-19	21-H1	SM-12.5D	US 58W	8/15-23/21	L7 S3, L7 S7
			5001-2021-16 BPV	21-H2			8/24/21-9/2/21	L1 S6, L1 S8
			5001-2021-16 BP	21-H3			8/25/21-9/3/21	L1 S1, L1 S5
Northern Virginia	PM-9S-21	Virginia Paving, Chantilly	9005-2021-180 WM	21-I1	SM-9.5D	SR 287	8/3-12/21	L5 S7
			9005-2021-180 HRPWM	21-I2			8/29/21-9/7/21	L1 S1, L1 S2, L1 S4
			9005-2021-180 HRPVWM	21-I3		US 7	8/23-26/21	L1 S 1, L1 S3, L1 S6

SM = surface mixture; BPV = balanced mix design performance + volumetrics; BP, P = balanced mix design performance; WM = warm mix; HRPWM = balanced mix design high RAP performance warm mix; HRPVWM = balanced mix design high RAP performance + volumetrics warm mix; A and D = mixture designations according to VDOT specifications; L = lot; S = sample.

Table 3. 2022 BMD Schedule Pilots

District	Schedule	Producer, Plant	Job-Mix Formula	Mix ID	Mix Type	Sample Date	Sample
Bristol	PM1W-22	W-L Construction, Wytheville	1073-2022-226	22-A	12.5A	-	-
Salem	PM2D-22	Adams Const., Sylvatus	2065-2022-443	22-B	9.5D	8/12/2022	L1S4
	PM2W-22	JC Joyce, Martinsville	2028-2022-443	22-C1	9.5D	12/1/2022	L8S6
			2028-2022-463 fiber	22-C2	9.5D fiber	12/11/2022	L1S3
	PM24-22	Adams Const., Rockydale	2012-2022-443 BPV	22-D1	9.5D	6/28/2022	L1S4
		Adams Const., Jack's Mountain	2016-2022-443 BPV	22-D2		5/26/2022	L2S4
	PM25-22	Boxley, Salem	2009-2022-443 BPV	22-E	9.5D	4/12/2022	L1S6
Lynchburg	PM3B-22	Boxley, Lynchburg	3020-2022-77	22-F	9.5D	7/12/2022	L3S1
Richmond	PM-4D-22	Colony Const., Burkeville	4052-22932 BMD	22-G1	9.5D	-	-
		Colony Const., Powhatan	4056-22232 BMD	22-G2	12.5D	-	-
	PM-4G-22	Branscome, Chesterfield	4043-2224 BMD	22-H1	9.5A	4/26/2022	L1S2
			4043-2225 BMD	22-H2	9.5D	7/21/2022	L2S2
Hampton Roads	PM-5F-22	Lee Hy, Mountcastle	4042-2232 BMD	22-I	12.5D	5/19/2022	L1S5
Fredericksburg	PM-6E-22	Superior Paving, Stafford	6041-2022-47 WM	22-J	12.5A	6/29/2022	L3S5
Culpeper	PM-7T-22	SL Williamson, Shadwell	7017-2022-33 BMD	22-K	12.5A	7/18/2022	L2S3
Staunton	PM-8E-22	SL Williamson, Shadwell	7017-2022-33 BMD	22-L	12.5D	-	-
Northern Virginia	PM-9S-22	Allan Myers, Leesburg	9035-2022-280WMPV	22-M1	9.5D	6/23/2022	L2S1
			9035-2022-86WMPV	22-M2	12.5D	6/23/2022	L3S4

SM = surface mixture; BPV = balanced mix design performance + volumetrics optimized; BMD = balanced mix design; WM = warm mix; WMPV = warm mix balanced mix design performance + volumetrics; A and D = mixture designations according to VDOT specifications; - = no sample; L = lot; S = sample.

After schedules were let, mix designs were submitted by the producer and evaluated by the VDOT district for mix design approval. During production, in addition to the determination of volumetric properties for quality control and acceptance, specimens were fabricated at the plant without reheating for performance testing by the producer and VDOT in accordance with the BMD special provision. In addition, loose mixture samples were collected for additional testing at VTRC and, in some cases, the district laboratories, including volumetric analysis and performance testing of specimens fabricated from reheated loose mixture. In 2021, the BMD special provisions directed the collection of loose mixture samples by the producer for VTRC testing. In 2022, except for four mixtures, one loose mixture sample of each BMD mixture under production was collected for VTRC testing by district or VTRC staff.

Mix Designs

Prior to paving, producers were required to submit mix designs to VDOT for approval. In 2021, the designs for the volumetrically designed control mixtures were required to meet current VDOT volumetric and gradation requirements. The 2021 specifications required that BMD P+V mixtures meet both current VDOT volumetric and gradation requirements and the special provision performance requirements; BMD P mixtures were required to meet the special provision performance requirements but the volumetric requirements were waived.

The 2022 specification required that BMD P+VO mixtures meet both current VDOT volumetric and gradation requirements and the special provision performance requirements.

Project Information

Project information was documented to support the monitoring of long-term performance in service. The basic information for the projects paved with these mixtures is summarized in Tables 2 and 3. More detailed information is available from the authors upon request.

In this report, mixtures are denoted based on the year of production. All mixtures produced in 2021 are denoted 21-*X*1, where 21 indicates the production year, *X* indicates the contract, and 1 indicates the first mixture (control non-BMD mixture) of the group of mixtures in each contract. Either one or two BMD mixtures were included in each 2021 contract, and these mixtures are denoted 2 or 3. In 2022, contracts did not include control non-BMD mixtures. The mixtures are denoted 22-*X* if only a single BMD mixture was used in the contract. If more than one mixture was used, the mixtures are denoted 22-*X*1 and 22-*X*2.

In addition to the data collected from VTRC testing, VDOT's Materials Inventory System (MITS) was used to collect producer and district production testing data. Districts and producers were also contacted, and performance test data were requested.

Sampling and Specimens

Sampling and testing were performed in accordance with the frequencies specified in the 2021 and 2022 BMD special provisions. Tables 4 and 5 present the production sampling and testing plans for the 2021 and 2022 pilots, respectively. In addition, in 2021, virgin binder and RAP samples were also collected for testing by VTRC.

Table 4. 2021 BMD Special Provision Sampling and Testing Plan per 4,000T Lot

Property/Test	Frequency (tons)	No. of Specimens (per lot)
CT_{index}[a,b] – QC	1,000	20
Cantabro[a,b] – QC	1,000	12
CT_{index}[b] – VDOT QA[c]	2,000	10
Cantabro[b] – VDOT QA[c]	2,000	6
Rutting[b] – VDOT QA[c]	2,000	8
Loose mix sample – Research[c]	2,000	12 boxes

BMD = balanced mix design; CT = cracking tolerance; QC = quality control; QA = quality assurance.
[a] With a minimum of 1 QC sample per day.
[b] Minimize any cooling of the plant-produced mixture and bring the specimens to the compaction temperature and compact immediately to the specimen size requirements in Table 1 of the 2021 BMD special provision, provided in Appendix B.
[c] QA pills must be fabricated and provided to VDOT by the contractor. Loose mix sampling must also be performed by the contractor and provided to VDOT. Boxes used for loose mix samples will be supplied by VDOT.

Table 5. 2022 BMD Special Provision Sampling and Testing Plan per Lot

Property/Test	Frequency (tons)	No. of Specimens (per lot)
CT_{index}[a]	2,000	10
Cantabro[a]	2,000	6
CT_{index}[a] – VDOT[b]	4,000	5
Cantabro[a] – VDOT[b]	4,000	3
Rutting[a] – VDOT[b]	1 per project	4 per project

BMD = balanced mix design; CT = cracking tolerance.
[a] Minimize any cooling of the plant-produced mix and bring the specimens to the compaction temperature and compact immediately to the specimen requirements in Table 1 of the 2022 BMD special provision, provided in Appendix B.
[b] VDOT pills must be fabricated in accordance with Table 1 of the 2022 BMD special provision , provided in Appendix B, and provided to VDOT by the contractor.

Loose Mixture Samples

Plant-produced loose material was collected from each mixture. In 2021, each VTRC sample of loose mixture was collected at the same time as a VDOT independent assurance sample. In 2022, the VTRC loose mixture samples were collected at the same time as a VDOT independent assurance sample when possible. Producer samples were taken into the producer laboratory and immediately tested. VDOT independent assurance and VTRC samples were placed into boxes or bags and taken to the respective laboratory for testing. VDOT samples were tested as soon as possible, being independent assurance samples, and VTRC samples were stored in a climate-controlled area until evaluation.

Non-Reheated Compacted Specimens

Loose plant-produced mixtures intended for specimens compacted without reheating at the plant were taken into the laboratory and immediately placed into ovens. The mixture maximum (Rice) specific gravity (G_{mm}) was determined and used to calculate the approximate mass required to fabricate IDT-CT and APA rut test specimens. While the G_{mm} was being determined, volumetric specimens were compacted. The volumetric specimens were also used for Cantabro testing.

Once the G_{mm} was determined, it was used to calculate the mass of loose mixture necessary to compact IDT-CT and APA rut test specimens meeting the test criteria requiring air-void contents of 7.0 ± 0.5% and the specimens were compacted. As they cooled, specimens were bulked to confirm that air-void contents were within the requirements for testing.

Non-reheated compacted specimens were provided to VDOT for testing in accordance with the sampling and testing plans outlined in Tables 4 and 5.

Reheated Compacted Specimens

Specimens were also fabricated from reheated loose mixture sampled during production. Reheated specimens were fabricated by reheating the loose mixture in boxes or bags until workable, splitting the material into specimen quantities, heating to the appropriate compaction temperature, and compacting.

The G_{mm} was determined as an average of two tests completed during volumetric analysis and was used to calculate the approximate mass required to fabricate IDT-CT and APA rut test specimens. Volumetric specimens were used for Cantabro testing.

Laboratory Testing and Evaluation

Testing was conducted on specimens fabricated from mixtures, as shown in Figure 1. In addition to the performance tests shown in Figure 1, mixture volumetric properties and gradation were determined for all mixtures.

Specimen Types

Laboratory mixture testing was conducted on three types of specimens:

1. *Design or JMF:* laboratory-produced, laboratory-compacted specimens fabricated and tested by producer staff.

2. *Non-Reheat or Plant*: plant-produced, laboratory-compacted specimens fabricated on-site at the plant by the producer without reheating. These specimens are further described by the entity that performed testing on the specimens, either the producer or VDOT.

3. *Reheat:* plant-produced, laboratory-compacted specimens compacted by VDOT or VTRC staff after reheating cooled loose mixture. These specimens are further described by the entity that performed testing on the specimens, either the producer or VDOT.

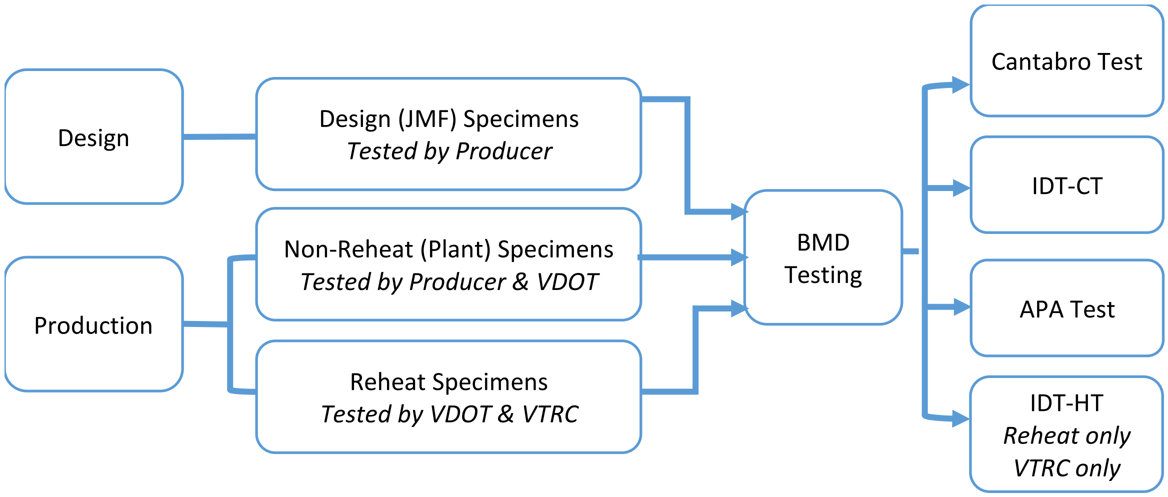


Figure 1. Testing Performed on Laboratory- and Plant-Produced Mixtures. JMF = job-mix formula; VDOT = Virginia Department of Transportation; BMD = balanced mix design; IDT-CT = indirect tensile cracking test; APA = Asphalt Pavement Analyzer; IDT-HT = indirect tensile test at high temperature; VTRC = Virginia Transportation Research Council.

Mixture Volumetric Properties and Gradations

Volumetric and gradation analyses were performed on production samples. Producer and VDOT data for volumetric properties and gradations were obtained from VDOT's MITS.

Producer data were generated from non-reheated samples; VDOT and VTRC data were obtained from reheated samples. The data collected included asphalt content and gradation; G_{mm} and bulk specific gravity (G_{mb}); air voids (voids in total mix [VTM]); voids in mineral aggregate (VMA); voids filled with asphalt (VFA); bulk and effective aggregate specific gravities (G_{sb} and G_{se}); fines/asphalt (F/A) ratio; percent binder absorbed (P_{ba}); and effective binder content (P_{be}).

Mixture Testing

BMD test results generated by the producers and districts were requested from VDOT's Materials Division or the VDOT districts and obtained to the extent possible.

Cantabro Test

The Cantabro test is intended to provide an indication of mixture durability and was performed in accordance with AASHTO TP 108, Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens. The test is performed on volumetric test specimens compacted to N_{design} and tested in triplicate at a temperature of 25 ± 1°C.

IDT-CT

Testing to determine the CT_{index} was conducted in accordance with ASTM D8225, Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature. Five replicate specimens compacted to 7 ± 0.5% air voids were tested in the dry condition at 25 ± 0.5°C, although in cases of testing errors, results from only four or three replicates may be presented.

APA Rut Test

Rutting susceptibility was assessed using the APA in accordance with AASHTO T 340, Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA), at a test temperature of 64 ± 0.5°C and test specimen voids of 7 ± 0.5%. Two replicate tests consisting of two specimens each were conducted for each mixture using an APA Junior test machine.

IDT-HT

The IDT-HT was also performed to evaluate the rutting susceptibility of the mixtures. The testing was performed in accordance with the procedure described in a previous study (Boz et al., 2023). Three replicate specimens compacted to 7 ± 0.5% air voids were tested in the dry condition at 54.4 ± 1°C.

Asphalt Binder Testing and Characterization

Performance Grading

The evaluation of asphalt binder performance grading (PG) was conducted in accordance with AASHTO M 320, Standard Specification for Performance-Graded Asphalt Binder, and AASHTO M 332, Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test. The asphalt binder was extracted from the collected mixtures in accordance with AASHTO T 164, Quantitative Extraction of Asphalt Binder From Hot Mix Asphalt (HMA), Method A, using n-propyl bromide as the solvent. Subsequently, the asphalt binder was recovered from the solvent using the Rotavap recovery procedure in accordance with AASHTO T 319, Quantitative Extraction and Recovery of Asphalt Binder From Asphalt Mixtures.

Difference in Critical Low Temperature Performance Grade (ΔT_c)

The calculation of the difference in critical low temperature PG limiting temperatures, ΔT_c, involved subtracting the m-critical low temperature ($T_{c,m}$) from the S-critical low temperature ($T_{c,S}$), as demonstrated in Equation 1 (Federal Highway Administration, 2021).

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

The temperatures were determined using the bending beam rheometer (BBR) in accordance with AASHTO T 313, Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binders Using the Bending Beam Rheometer (BBR). The m-critical low temperature ($T_{c,m}$) represents the specific 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 ($T_{c,S}$) represents the specific low temperature at which the creep stiffness S-value at 60 seconds of loading is exactly equal to the specification value of 300 MPa.

Frequency Sweep

Frequency sweep tests were conducted on the asphalt binders extracted and recovered from the collected mixtures at the plant during production. The tests were conducted to assess the dynamic shear modulus (G*) and the phase angle (δ) master curves of the binders at various frequencies and temperatures while maintaining strains within the linear viscoelastic range. Binder specimens were tested at temperatures of 45°C, 55°C, 65°C, 75°C, and 85°C using a 25-mm-diameter plate with a 1-mm gap. In addition, testing was performed at temperatures of 5°C, 15°C, 25°C, 35°C, and 45°C using an 8-mm-diameter plate with a 2-mm gap. Each specimen was evaluated at 16 frequencies ranging from 0.1 to 100 rad/s at each testing temperature. As there is currently no standard for constructing a binder master curve, the Rheology Analysis Software package (Abatech, 2022), specifically the shifting function, was used to align the G* master curves with a reference temperature of 45°C (Habbouche et al., 2022). The Glover-Rowe parameter and R-Value can be derived from these tests and were used to evaluate the performance of asphalt binders.

Glover-Rowe Parameter

The Glover-Rowe (G-R) parameter, determined using Equation 2, captures both rheological parameters needed to characterize binder viscoelastic behavior: stiffness (represented by the complex shear dynamic modulus G*) and relaxation (represented by the phase angle δ) (Anderson et al., 2011; Glover et al., 2005; Rowe et al., 2011).

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

where

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

In this study, two versions of the G-R parameter, referred to herein as G-R1 and G-R2, were considered. G-R1, determined at a temperature of 15°C and a frequency of 0.005 rad/s, has a strong correlation with ductility, cracking resistance, and binder oxidation levels (Ruan et al., 2003). The G-R1 parameter, with universal limits set at 180 kPa and 600 kPa, can serve as a common benchmark to monitor the effect of aging and/or rejuvenation on asphalt binders. The G-R2 parameter was determined at a frequency of 10 rad/s and at the corresponding binder fatigue test temperature. The specific test temperature was determined based on the low PG of the binder, as indicated by Christensen and Tran (2022). For this study, the proposed binder fatigue test temperatures were 25°C and 27°C for binders with low PG temperatures of -22°C and -16°C, respectively.

R-Value

The R-value is an indicator of binder rheology type. A higher R-value signifies increased ductility in the binder's behavior under intermediate loading conditions and temperatures. Christensen and Tran (2022) introduced a novel approach to compute the R-value. This method uses the creep stiffness (S) and coefficient of relaxation (m-value) at the low PG temperature as expressed in Equation 3.

$$\text{R-Value} = \log(2) * \frac{\log(\frac{S}{3{,}000})}{\log(1-m)} \quad \text{[Eq. 3]}$$

where

S = creep stiffness measured at 60-second loading using a BBR, MPa
m = coefficient of relaxation measured at 60-second loading using a BBR.

Linear Amplitude Sweep (LAS) Test

The LAS test was conducted in accordance with AASHTO TP 101, Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep. This test was performed to analyze the fatigue damage characteristics of the binders at an intermediate temperature. The test consisted of a frequency sweep at 0.1% strain across frequencies ranging from 0.2 to 30 Hz, followed by an amplitude sweep oscillatory shear in strain-control mode test at a frequency of 10 Hz with induced strains ranging from 0.1% to 30%. The test was performed at 23°C, which was determined as the average of the high and low PG temperatures minus 4°C. This temperature selection was to ensure that the linear complex shear modulus G* remained within the range of 12 to 60 MPa at 10 Hz, thereby mitigating potential edge flow and/or adhesion loss concerns (Safaei and Castorena, 2016). The binder fatigue performance parameter, N_f, is calculated using Equation 4.

$$N_f = A * (\Upsilon_{max})^{-B} \quad \text{[Eq. 4]}$$

where

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

RESULTS AND DISCUSSION

Volumetric Properties and Gradation

Mix designs for all evaluated mixtures are shown in Tables 6 and 7 for 2021 mixtures and in Tables 8 and 9 for 2022 mixtures: 9.5 mm NMAS mixtures and 12.5 mm NMAS mixtures were evaluated. Design binder contents ranged from 5.2% to 6.5%. All 2021 control mixtures contained 30% or less RAP and were produced with PG 64S-22 binder. BMD mixtures contained varying RAP contents and were produced with either PG 64S-22 or PG 58S-28 binder. Production data were obtained from VDOT's MITS for comparison with VTRC results.

Mixture Testing and Evaluation

BMD testing, consisting of Cantabro, APA rut, and IDT-CT testing, was performed on three types of specimens, as mentioned previously. Design specimens, denoted JMF, were laboratory-batched specimens fabricated and tested by the producer as part of the JMF submission. Plant specimens were fabricated from production samples of loose mixture immediately after sampling by the producer and were tested by the producer or VDOT and are designated as such. Reheat specimens were fabricated from production samples of loose mixture after cooling and being reheated; these were produced and tested by VDOT or VTRC. In addition, IDT-HT testing was performed on reheat specimens by VTRC.

BMD test results were compiled from information provided by the districts and/or producers. One challenge encountered was the lack of standardization in data reporting. Although this improved over time, the lack of a fully unified and enforced reporting format and central repository for data collection resulted in an incomplete dataset. There are plans to incorporate the collection of BMD test data into VDOT's MITS; however, the cost and complexity have delayed this effort.

Unless mentioned otherwise, no data were discarded from any tests. All replicates tested in accordance with the respective test standards were included in the analysis of results; no outliers were removed. In addition, all statistical analyses were conducted at a 95% confidence interval and included checking the assumptions of normality and equal variances.

2021 Schedules

Graphic examples of the production BMD test results are presented and discussed herein; the full set of results available for the 2021 schedules is presented in Appendix C.

Figure 2 shows an example of the mass loss testing performed for Mixtures 21-A1 (control mixture) and 21-A2 (BMD mixture) for schedule PM-2D. The results from the producer and VDOT plant specimens generally compared well, a trend seen across most of the 2021 mixture samples. The VTRC reheat sample mass losses were notably different from those of the other samples, including the VDOT reheat samples. It is unclear why this trend is seen, as the only other reheat mass loss testing available was for the VDOT reheat samples shown in this figure. Although it is expected that reheat mass loss values will be higher than non-reheat values, a trend that is seen in the results from other schedules, the difference between the VDOT reheat and VTRC reheat values indicates a need to examine reheat practices further.

Table 6. 2021 Mix Design Information for Salem, Lynchburg, and Richmond Schedules

District		Salem		Lynchburg						Richmond	
Schedule		PM-2D		PM-2L		PM-3E		PM-3F		PM-4A	
Producer		Adams Const.		Boxley Materials Co.		Piedmont Asphalt		Piedmont Asphalt		Allan Myers	
Plant		Blacksburg		Lynchburg		South Boston		Shelton		Rockville	
Mix ID		21-A1	21-A2	21-B1	21-B2	21-C1	21-C2	21-D1	21-D2	21-E1	21-E2
JMF		2025-2021-143	2025-2021-443 BPV	3020-2021-48	3020-2021-48 BPV	3008-2021-33	3008-2021-33 BPV	3007-2021-33	3007-2021-433 BPV	4053-2132	4053-2132 BP
RAP, %		30	30	26	26	30	30	30	27	30	30
Binder Grade		64S-22	64S-22	64S-22	64S-22	64S-22	64S-22	64S-22	64S-22	64S-22	58S-28
Asphalt Content, %		5.8	5.9	5.7	5.9	6.3	6.5	5.8	6.5	5.5	5.8
VTM, %		3.6	4.0	4.0	3.5	4.0	4.0	4.0	4.2	4.0	3.9
Rice SG, G_{mm}		2.468	2.474	2.586	2.577	2.492	2.492	2.442	2.437	2.458	2.472
Sieve Size		Percent Passing, %									
3/4 in (19 mm)		100	100	100	100	100	100	100	100	100	100
1/2 in (12.5 mm)		100	100	100	100	99	99	99	99	97	98
3/8 in (9.5 mm)		94	93	97	97	90	90	89	89	89	88
No. 4 (4.75 mm)		59	58	65	65	64	64	65	65	59	60
No. 8 (2.36 mm)		41	40	44	44	43	43	43	43	45	42
No. 30 (0.6 mm)		23	23	21	21	22	22	21	21	23	22
No. 200 (0.075 mm)		6.2	6.2	7	7	4.3	4.3	6.4	5.0	6.3	6.5
Mass Loss	Average, %	-	4.3	-	6.1	6.9	5.4	5.2	5.5	6.4	3.0
	STDEV	-	0.8	-	0.9	0.5	0.5	0.2	0.1	0.2	0.5
	COV, %	-	0.19	-	0.14	0.07	0.09	0.04	0.01	0.03	0.15
Rut Depth	Average, mm	-	3.3	-	-	3.6	3.3	3.8	3.5	3.2	3.4
	STDEV	-	0.3	-	-	0.5	0.7	0.0	0.0	0.2	0.3
	COV, %	-	0.09	-	-	0.15	0.20	0.01	0.01	0.07	0.09
CT index	Average	-	137.1	-	88	14.8	78.0	-	155	40	147
	STDEV	-	26.8	-	16.1	2.1	21.7	-	30.0	24.8	36.3
	COV, %	-	0.20	-	0.18	0.14	0.28	-	0.19	0.62	0.25

RAP = reclaimed asphalt pavement; PG = performance grade; VTM = voids in total mix; SG = specific gravity; STDEV = standard deviation; COV = coefficient of variation; - = data not available.

Table 7. 2021 Mix Design Information for Richmond, Hampton Roads, and Northern Virginia Schedules

District		Richmond		Hampton Roads					Northern Virginia		
Schedule		PM-4F		PM-5E		PM-5D			PM-9S		
Producer		Colony Const.		Branscome, Inc.		Adams Const.			Virginia Paving		
Plant		Powhatan		Lee Hall		Skippers			Chantilly		
Mix ID		21-F1	21-F2	21-G1	21-G2	21-H1	21-H2	21-H3	21-I1	21-I2	21-I3
Job Mix		4052-21925	4052-21925 P	5011-2021-05	5011-2021-30 BPV	5001-2021-19	5001-2021-17 BPV	5001-2021-16 BP	9005-2021-180 WM	9005-2021-180HRPVWM	9005-2021-180HRPWM
RAP, %		30	30	30	30	30	26	26	30	40	41
Binder Grade		64S-22	64S-22	64S-22	58S-28	64S-22	64S-22	64S-22	64S-22	58S-22	58S-22
Asphalt Content, %		5.9	6.2	5.2	5.5	5.7	5.8	5.8	5.8	5.8	5.8
VTM, %		3.9	3.1	4.0	3.6	4.0	3.4	3.4	3.5	4.0	4.0
Rice SG, G_{mm}		2.492	2.478	2.493	2.491	2.440	2.470	2.470	2.584	2.624	2.624
Sieve Size		Percent Passing, %									
3/4 in (19 mm)		100	100	100	100	100	100	100	100	100	100
1/2 in (12.5 mm)		100	100	98	96	100	97	97	100	100	100
3/8 in (9.5 mm)		94	94	89	88	95	90	90	90	91	91
No. 4 (4.75 mm)		58	58	62	61	88	61	61	59	61	61
No. 8 (2.36 mm)		38	38	47	42	67	44	44	38	39	39
No. 30 (0.6 mm)		19	20	23	19	23	23	23	18	20	20
No. 200 (0.075 mm)		5.7	6.0	5.7	4.9	5.1	4.6	4.6	6.2	6.5	6.5
Mass Loss	Average, %	-	4.5	9.9	2.8	4.8	4.3	4.3	-	4.4	4.4
	STDEV	-	0.4	0.3	0.2	0.4	0.5	0.5	-	0.4	0.4
	COV, %	-	0.09	0.03	0.07	0.08	0.11	0.11	-	0.10	0.10
Rut Depth	Average, mm	-	3.6	6.1	6.9	5.4	5.3	5.3	-	4.9	4.9
	STDEV	-	0.5	0.1	0.4	0.1	0.1	0.1	-	0.7	0.7
	COV, %	-	0.15	0.01	0.05	0.02	0.02	0.02	-	0.14	0.14
CT index	Average	-	82.9	59.6	102.8	64.7	102.1	102.1	122	148	148
	STDEV	-	14.5	13.2	14.2	2.0	14.2	14.2	20	52	52
	COV, %	-	0.18	0.22	0.14	0.03	0.14	0.14	0.17	0.35	0.35

RAP = reclaimed asphalt pavement; PG = performance grade; VTM = voids in total mix; SG = specific gravity; STDEV = standard deviation; COV = coefficient of variation; - = data not available.

Table 8. 2022 Mix Design Information for Bristol, Salem, and Lynchburg Schedules

District		Bristol	Salem						Lynchburg
Schedule		PM-1W	PM-2D	PM-2W		PM-24		PM-25	PM-3B
Producer		W-L Constr.	Adams Constr.	JC Joyce		Adams Constr.		Boxley Materials	Boxley Materials
Plant		Wytheville	Sylvatus	Martinsville		Rockydale	Jack's Mountain	Salem	Lynchburg
Mix ID		22-A	22-B	22-C1	22-C2	22-D1	22-D2	22-E	22-F
Job Mix		1073-2022-226	2065-2022-443	2028-2022-443	2028-2022-463 fiber	2012-2022-443 BPV	2016-2022-443 BPV	2009-2022-443 BPV	3020-2022-77
RAP, %		25	30	26	26	30	30	26	26
Binder Grade		64S-22	64S-22	64S-22	64S-22	64S-22	64S-22	64S-22	64S-22
Asphalt Content, %		5.6	6.0	6.1	6.0	5.9	5.9	5.8	5.9
VTM, %		3.7	3.4	3.4	3.1	3.5	3.5	3.7	3.5
Rice SG, G_{mm}		2.462	2.472	2.58	2.584	2.612	2.612	2.548	2.577
Sieve Size		Percent Passing, %							
3/4 in (19 mm)		100	100	100	100	100	100	100	100
1/2 in (12.5 mm)		97	100	100	100	100	100	100	100
3/8 in (9.5 mm)		86	92	95	95	96	96	94	94
No. 4 (4.75 mm)		-	53	67	67	59	59	66	63
No. 8 (2.36 mm)		30	39	41	41	41	41	48	45
No. 30 (0.6 mm)		-	-	-	-	-	-	-	-
No. 200 (0.075 mm)		6.3	6.4	4.9	4.9	6	6	6.5	6.5
Mass Loss	Average, %	-	5.8	6.3	-	-	-	3.9	6.0
	STDEV	-	-	-	-	-	-	-	0.3
	COV, %	-	-	-	-	-	-	-	0.06
Rut Depth	Average, mm	-	2.9	2.2	-	-	-	2.6	3.0
	STDEV	-	-	-	-	-	-	-	0.1
	COV, %	-	-	-	-	-	-	-	0.02
CT index	Average	119	102	103	-	-	-	78	92
	STDEV	-	-	-	-	-	-	-	12
	COV, %	-	-	-	-	-	-	-	0.13

RAP = reclaimed asphalt pavement; PG = performance grade; VTM = voids in total mix; SG = specific gravity; - = data not available; STDEV = standard deviation; COV = coefficient of variation.

Table 9. 2022 Mix Design Information for Richmond, Hampton Roads, Fredericksburg, Culpeper, Staunton, and Northern Virginia Schedules

District		Richmond				HR	Fredericksburg	Culpeper	Staunton	NOVA	
Schedule		PM-4D		PM-4G		PM-5F	PM-6E	PM-7T	PM-8E	PM-9S	
Producer		Colony Const.		Branscome, Inc.		Lee Hy	Superior Paving	SL Williamson	SL Williamson	Allan Myers	
Plant		Powhatan	Burkeville	Chesterfield		Mountcastle	Stafford	Shadwell	Shadwell	Leesburg	
Mix ID		22-G1	22-G2	22-H1	22-H2	22-I	22-J	22-K	22-L	22-M1	22-M2
Job Mix		4052-22925 BMD	4056-22932 BMD	4043-2224 BMD	4043-2225 BMD	4042-2232 BMD	6041-2022-47 WM	7017-2022-33 BMD	7017-2022-33 BMD	9035-2022-280WMPV 95D	9035-2022-86WMPV 125D
RAP, %		30	30	30	30	30	30	30	30	30	30
Binder Grade		64S-22	64S-22	58S-28	58S-28	58S-28	64S-22	64S-22	64S-22	64S-22	64S-22
Asphalt Content, %		6.1	6.0	5.7	5.7	5.8	5.3	5.7	5.7	5.6	5.4
VTM, %		3.1	3.9	4	4	4	3.6	4.2	4.2	4	4
Rice SG, G_{mm}		2.478	2.482	2.507	2.507	2.459	2.671	2.600	2.600	2.668	2.671
Sieve Size		Percent Passing, %									
3/4 in (19 mm)		100	100	100	100	100	100	100	100	100	100
1/2 in (12.5 mm)		100	96	100	100	95	97	97	97	100	94
3/8 in (9.5 mm)		94	88	94	94	85	88	85	85	93	82
No. 4 (4.75 mm)		57	-	64	64	-	-	-	-	54	-
No. 8 (2.36 mm)		36	40	45	46	36	42	39	39	39	35
No. 30 (0.6 mm)		-	-	23	23	-	-	-	-	-	-
No. 200 (0.075 mm)		6.4	6.0	5.5	5.5	5.2	5.5	5.9	5.9	5.5	5.9
Mass Loss	Average, %	4.6	6.8	5.9	-	7.1	5.3	-	-	-	-
	STDEV	0.2	0.5	0.5	-	0.2	0.3	-	-	-	-
	COV, %	0.05	0.07	0.09	-	0.03	0.06	-	-	-	-
Rut Depth	Average, mm	3.8	2.9	4.1	-	4.0	2.1	-	-	-	7.4
	STDEV	0.2	0.5	0.2	-	0.2	0.0	-	-	-	0.2
	COV	0.07	0.17	0.05	-	0.05	0.02	-	-	-	0.0
CT index	Average	153	101	140	-	139	109	-	-	-	177
	STDEV	22	12	21	-	35	12	-	-	-	24
	COV	0.14	0.11	0.15	-	0.25	0.11	-	-	-	0.10

RAP = reclaimed asphalt pavement; PG = performance grade; VTM = voids in total mix; SG = specific gravity; - = data not available; STDEV = standard deviation; COV = coefficient of variation.

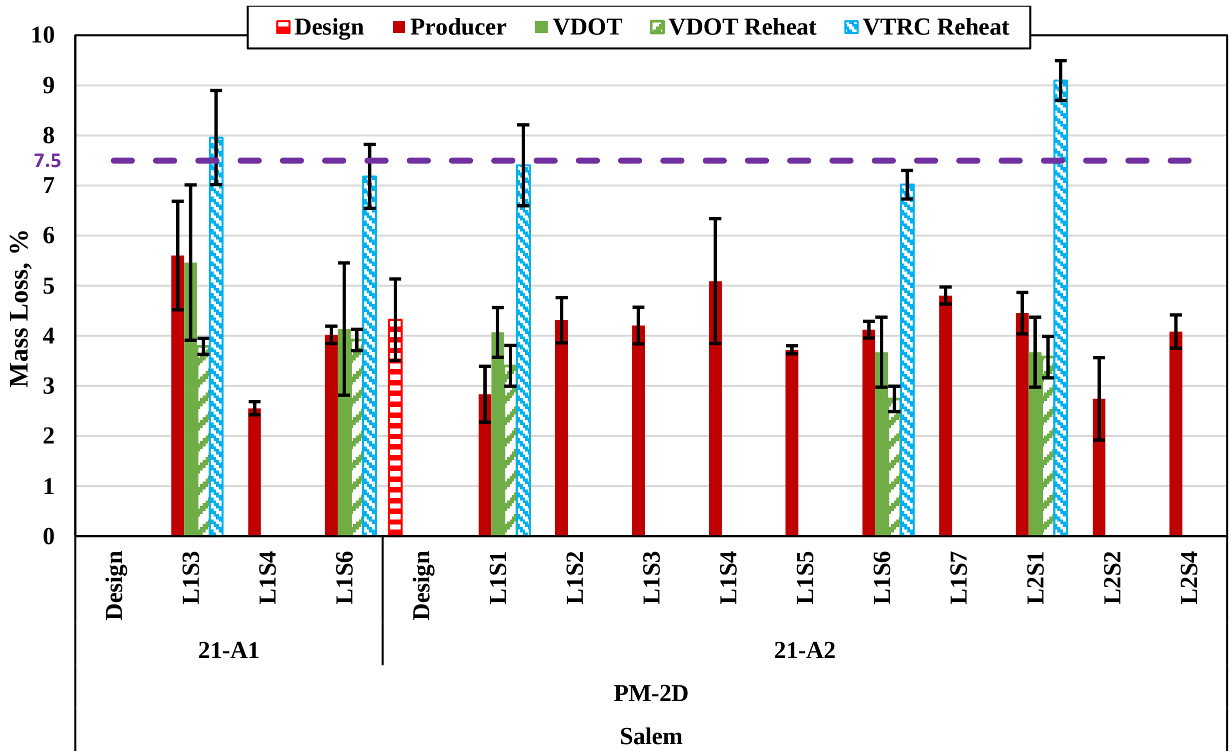


Figure 2. Mass Loss Values for Samples Collected From Mixtures 21-A1 and 21-A2 Paved on Schedule PM-2D. I-bars indicate one standard deviation. Purple dashed line indicates maximum allowable mass loss. L = lot number; S = sample number.

Figure 3 shows rut testing results for Mixtures 21-A1 and 21-A2 from schedule PM-2D. Due to the time required to complete APA rut tests, they are not considered practical for production testing; work is in progress to adopt the IDT-HT. In addition, the APA rut test, AASHTO T 340, does not provide precision estimates; this means that test repeatability and reproducibility cannot be assessed. As shown in Figure 3, some of the rut test results showed larger standard deviations; there is a need to develop precision estimates to assess these results.

Results of the IDT-CT for schedule PM-2D are shown in Figure 4. The producer results were generally consistent, although having large within-specimen variations (standard deviations or coefficient of variances). For some samples, the producer and VDOT plant samples were comparable; however, for two of the samples, one from the control mixture and one from the BMD mixture, the results were notably different. Since the producer compacted the non-reheated test specimens for VDOT to test, there could be variability from sampling, specimen fabrication, or testing procedures. Similar observations were made across the 2021 dataset. This demonstrates the need to evaluate further the effects of sampling and specimen preparation practices on IDT-CT testing.

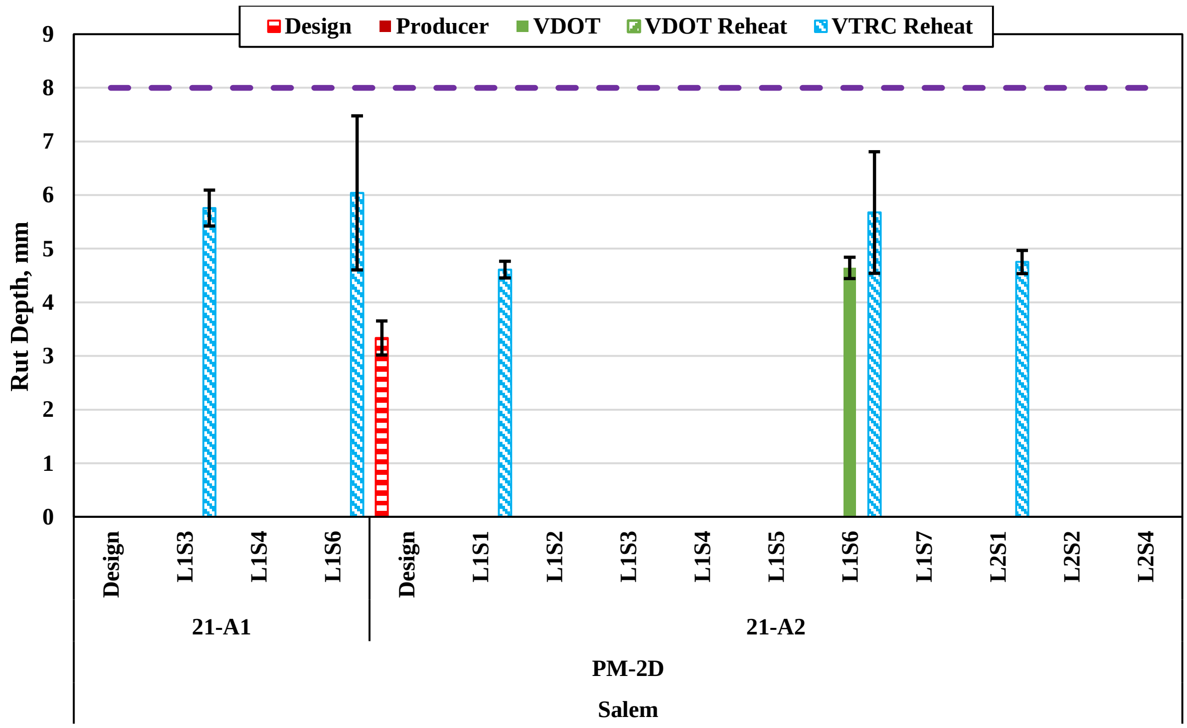


Figure 3. Rut Depth Values for Samples Collected From Mixtures 21-A1 and 21-A2 Paved on Schedule PM-2D. I-bars indicate one standard deviation. Purple dashed line indicates maximum allowable rut depth. L = lot number; S = sample number.

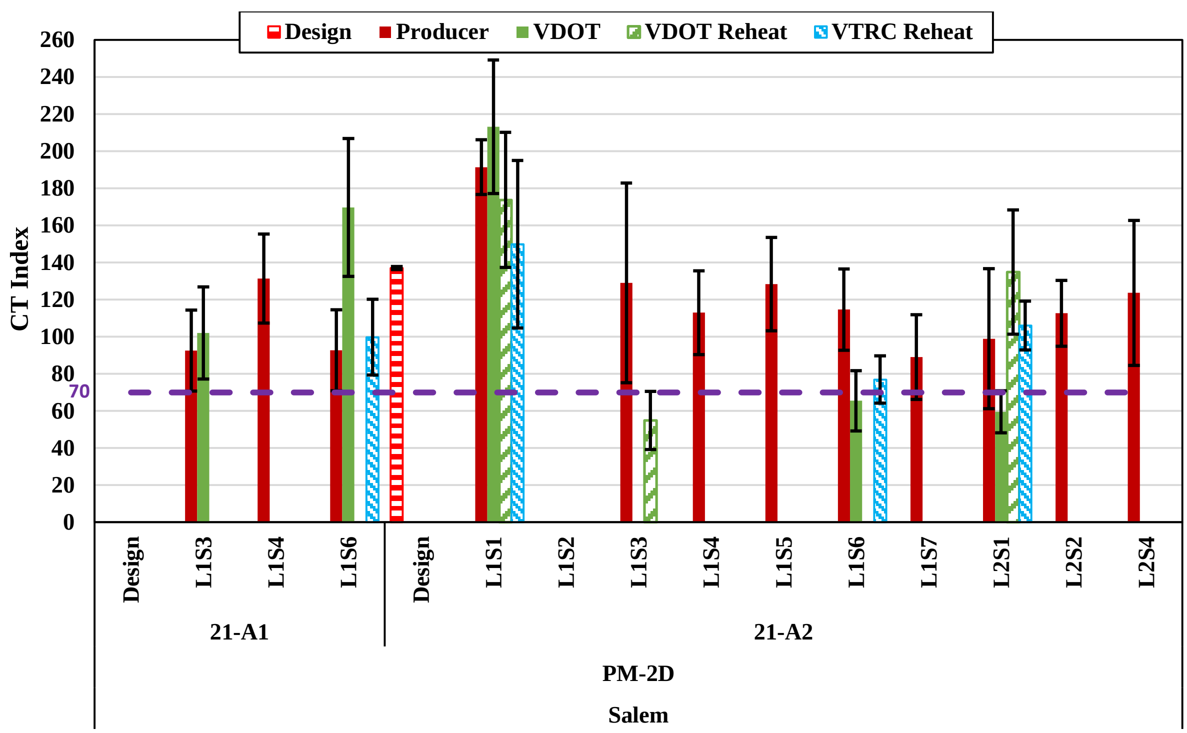


Figure 4. CT Index Values for Samples Collected From Mixtures 21-A1 and 21-A2 Paved on Schedule PM-2D. I-bars indicate one standard deviation. Purple dashed line indicates minimum allowable CT index. CT = cracking tolerance; L = lot number; S = sample number.

2022 Schedules

One sample was collected for each of the BMD mixtures used in most schedules in 2022. The sample was collected at the same time as a split sample such that comparisons could be made among the producer, VDOT, and VTRC test results. Due to scheduling conflicts, samples were not obtained for Mixtures 22-A, 22-G1, and 22-G2. Mixture 22-L was the same mixture as Mixture 22-K, although it was used on a different schedule, so sampling was not duplicated. Mixture 22-C2, although part of the BMD schedule mixtures, is not discussed herein, as it contains fibers and will be evaluated as part of another VDOT study.

Figure 5 presents the mass loss results for the 2022 mixtures. As seen with the 2021 data, some of the VTRC reheat results were notably higher than the VDOT reheat results. There were still occurrences of significant differences between the producer and VDOT test results on non-reheated plant specimens, which were all fabricated by the producer. Overall, the testing variability had decreased, compared to the 2021 test results, indicating that all parties were gaining experience with the testing procedures and appeared to be aware of the importance of consistency in BMD testing.

APA rut test results are presented in Figure 6. Results for VTRC reheated samples ranged from approximately 2.7 mm to 5.7 mm, well below the maximum rut depth BMD criterion of 8 mm. These results were from mixtures collected across Virginia, indicating that BMD mixtures do not seem to be approaching the rutting limit due to the need to meet the minimum CT index at this time. The variability of the rut test results was more consistent as compared to the results for the 2021 mixtures.

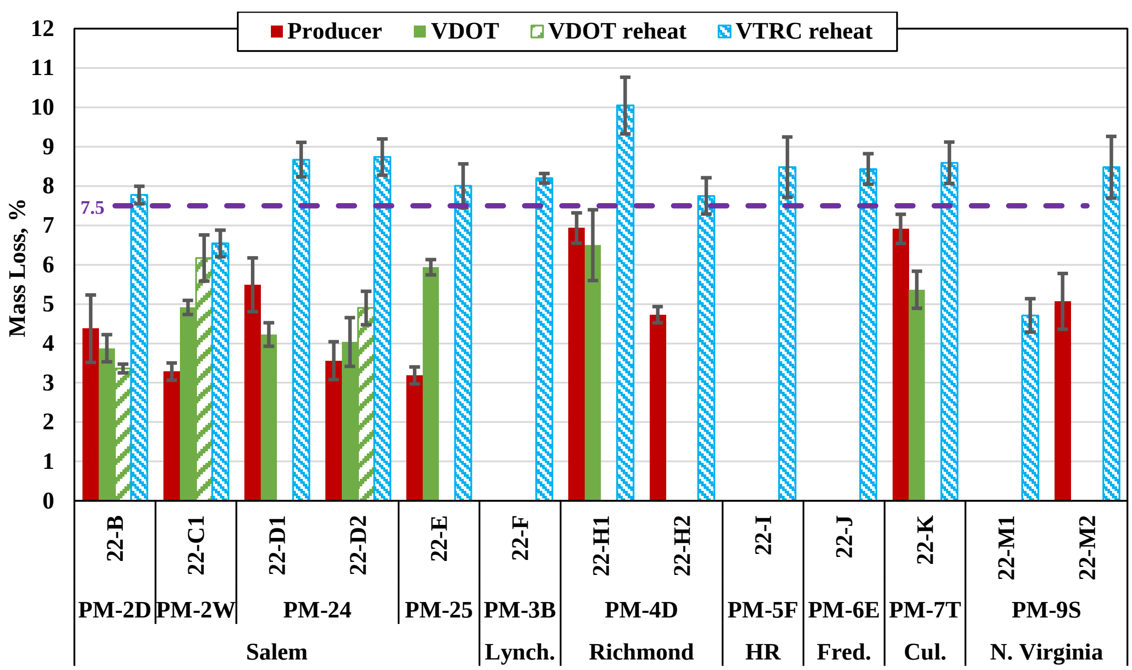


Figure 5. Mass Loss Values for 2022 Sampled Mixtures. I-bars indicate one standard deviation. Purple dashed line indicates maximum allowable mass loss. Lynch. = Lynchburg District; HR = Hampton Roads District; Fred. = Fredericksburg District; Cul. = Culpeper District; N. Virginia = Northern Virginia District.

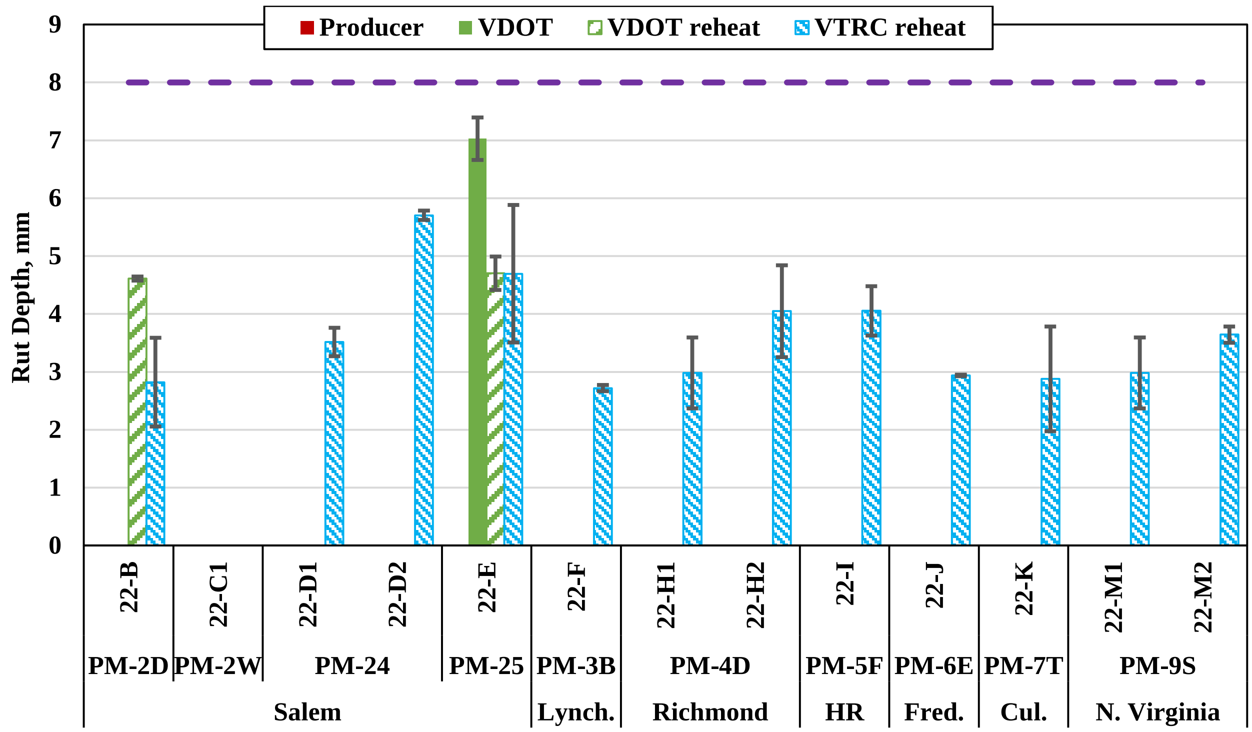


Figure 6. Rut Depth Values for 2022 Sampled Mixtures. I-bars indicate one standard deviation. Purple dashed line indicates maximum allowable rut depth. Lynch. = Lynchburg District; HR = Hampton Roads District; Fred. = Fredericksburg District; Cul. = Culpeper District; N. Virginia = Northern Virginia District.

Cracking test results are shown in Figure 7. Of the samples shown, only three failed to meet the minimum CT index requirement of 70.

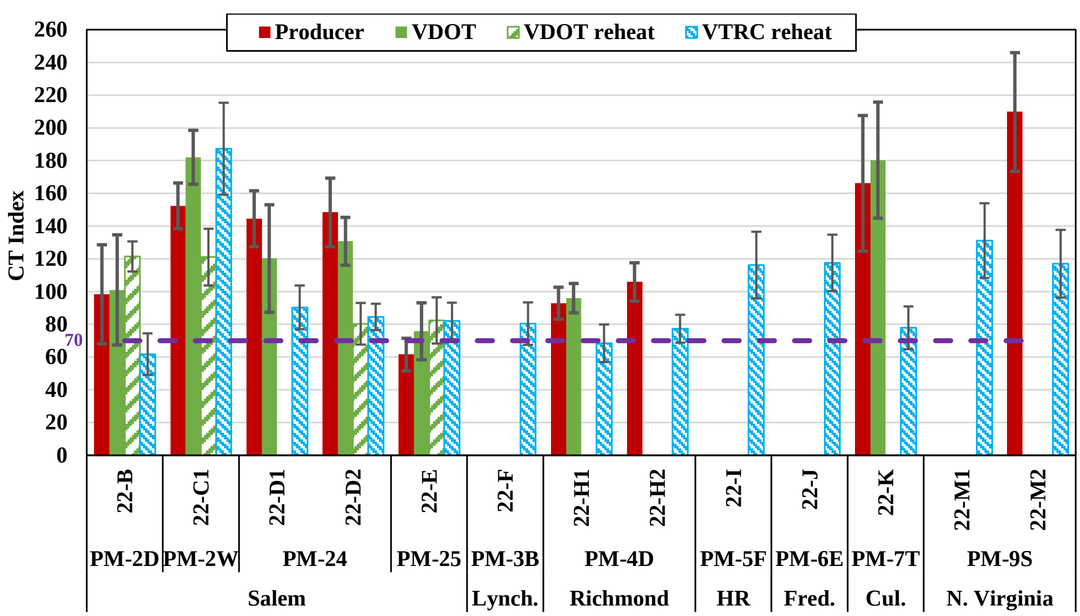


Figure 7. CT Index Values for 2022 Sampled Mixtures. I-bars indicate one standard deviation. Purple dashed line indicates minimum allowable CT index. CT = cracking tolerance; Lynch. = Lynchburg District; HR = Hampton Roads District; Fred. = Fredericksburg District; Cul. = Culpeper District; N. Virginia = Northern Virginia District.

One of the samples was the producer plant sample from Mixture 22-E; however, the companion sample tested by VDOT passed the criterion, indicating that variability in sampling, specimen fabrication, or testing could have affected the results.

Variability Assessment

Due to the difficulties encountered in fully compiling producer and VDOT results, the assessment of variability was performed on the VTRC reheat test results. Tables 10 and 11 summarize the 2021 and 2022 VTRC BMD test results, respectively.

Table 10. VTRC Reheat BMD Test Results for 2021 Mixtures

District	Schedule	Mix	Mass Loss, % Avg.	Mass Loss, % COV, %	Rut Depth, mm Avg.	Rut Depth, mm COV, %	CT Index Avg.	CT Index COV, %	IDT-HT Strength, kPa Avg.	IDT-HT Strength, kPa COV, %
Salem	PM-2D	21-A1	**8.0**	11.8	5.8	5.8	-	-	389.5	35.7
			7.2	8.9	6.0	23.8	100	**20.5**	157.5	9.3
		21-A2	7.4	10.9	4.6	3.4	150	**30.1**	130.6	5.0
			7.0	4.0	5.7	20.0	77	16.6	219.5	23.5
			9.1	4.4	4.8	4.6	106	12.5	134.7	8.8
Lynchburg	PM-2L	21-B1	**9.7**	10.8	3.5	0.3	72	**21.9**	209.5	12.4
		21-B2	**8.2**	3.6	4.1	9.8	97	**18.5**	190.9	11.0
			8.2	11.3	3.4	15.0	**68**	9.5	237.5	23.8
	PM-3E	21-C1	7.5	5.3	4.5	6.5	**65**	11.7	337.4	27.4
		21-C2	7.0	6.4	5.3	4.8	80	**26.5**	192.5	5.7
			7.2	4.2	5.3	10.7	72	5.4	222.9	17.6
	PM-3F	21-D1	**8.4**	4.6	7.6	19.5	**45**	5.1	217.1	7.2
		21-D2	**8.7**	6.6	3.4	5.6	79	**19.5**	182.2	18.0
			8.3	4.5	5.6	5.7	80	7.9	167.6	5.0
			9.2	5.7	4.3	29.2	79	**24.8**	232.8	22.2
Richmond	PM-4A	21-E1	**8.1**	10.2	2.9	3.0	92	16.1	170.2	8.9
		21-E2	6.4	8.6	4.7	34.2	111	12.9	146.5	3.2
			5.7	10.4	6.8	17.9	101	**19.5**	149.4	15.3
	PM-4F	21-F1	**9.0**	4.5	5.5	18.5	138	**20.9**	242.3	18.2
			7.3	4.5	4.1	0.2	140	16.1	159.0	7.1
		21-F2	6.3	1.1	3.7	7.4	128	12.9	257.9	20.0
			6.7	6.2	5.2	29.6	207	**20.4**	140.8	1.6
			7.3	8.4	4.8	4.6	119	8.5	302.7	26.9
Hampton Roads	PM-5E	21-G1	**9.9**	6.4	4.6	12.8	**33**	16.7	556.8	28.1
		21-G2	7.1	2.0	5.9	3.7	81	5.1	142.0	7.9
			7.2	9.7	7.7	22.3	92	4.7	-	-
	PM-5D	21-H1	**7.6**	6.8	6.3	12.2	60	18.3	204.9	20.2
			8.3	3.5	7.5	38.6	57	**19.6**	188.5	23.2
		21-H2	7.3	5.5	6.1	38.5	96	17.6	172.1	17.5
			7.7	11.2	6.0	3.6	73	11.8	135.4	7.0
		21-H3	6.3	17.9	6.7	27.5	119	2.7	**130.3**	14.4
			7.3	7.3	4.7	3.6	79	9.5	150.9	6.3
Northern Virginia	PM-9S	21-I1	4.1	21.5	7.5	8.1	167	10.6	**127.1**	16.7
		21-I2	6.9	8.8	5.3	28.4	156	8.0	153.7	12.5
		21-I3	5.6	15.2	6.7	43.1	131	18.8	**109.9**	4.2
			5.8	13.7	6.7	7.9	168	10.8	**117.4**	28.2

CT = cracking tolerance; IDT-HT = indirect tensile test at high temperature; Avg. = average; COV = coefficient of variation; - = data not available.
Values in red indicate that the results did not meet test criteria from Table 1, the IDT-HT minimum strength of 133 kPa, or the CT index maximum COV criterion of 18.3%. Mixtures designated “1” were control mixtures and were not designed to meet BMD criteria.

Table 11. VTRC Reheat BMD Test Results for 2022 Mixtures

District	Schedule	Mix	Mass Loss, %		Rut Depth, mm		CT Index	
			Avg.	COV, %	Avg.	COV, %	Avg.	COV, %
Salem	PM-2D	22-B	**7.8**	2.9%	2.8	27.1%	**62**	**20.7%**
	PM-2W	22-C1	6.5	5.2%	-	-	187	15.0%
	PM-24	22-D1	**8.7**	5.1%	3.5	7.0%	90	14.8%
		22-D2	**8.7**	5.3%	5.7	1.4%	85	9.6%
	PM-25	22-E	**8.0**	7.0%	4.7	25.3%	82	13.7%
Lynchburg	PM-3B	22-F	**8.2**	1.5%	2.7	1.9%	80	16.2%
Richmond	PM-4D	22-H1	**10.0**	7.2%	3.0	20.6%	**68**	16.8%
		22-H2	**7.7**	5.9%	4.0	19.6%	77	11.1%
Hampton Roads	PM-5F	22-I	**8.5**	9.1%	4.1	10.5%	116	17.5%
Fredericksburg	PM-6E	22-J	**8.4**	4.6%	2.9	0.5%	118	14.7%
Culpeper	PM-7T	22-K	**8.6**	6.1%	2.9	31.4%	78	16.8%
Northern Virginia	PM-9S	22-M1	4.7	9.0%	3.0	20.6%	131	17.4%
		22-M2	**8.5**	9.3%	3.6	3.8%	117	17.6%

CT = cracking tolerance; Avg. = average; COV = coefficient of variation; - = data not available.
Values in red indicate that the results did not meet test criteria from Table 1 or the CT index maximum COV criterion of 18.3%.

Within-Specimen Variability

Analysis of the within-specimen variability was performed on the VTRC reheat data from 2021 and 2022 to provide a robust dataset. Figure 8 shows the boxplots of the coefficient of variation (COV) of the results for each test. The COV was calculated from the specimen replicates of a given sample for each mixture. The average COV for the Cantabro test was 7.6%, with a COV ranging from 1.1% to 21.5%. The COV was higher than 20% for only 2 of the 49 observations, corresponding to 4.1% of the data. Although the precision estimates for the Cantabro test are not yet available, the results presented herein generally indicate good repeatability characteristics for this test.

The average COV for the IDT-CT was 14.8%, with a COV ranging from 2.7% to 30.1%. For 12 of the 49 observations (24.5% of the data), the COV was higher than 18.3%, which is VDOT's single-operator variability limit (one-sigma limit in percent [1s%]) for the test (Boz et al., 2021; Habbouche et al., 2021). This indicates that there is a high probability that some departure from the test procedure, including the specimen sampling and preparation process, occurred and/or changes in component materials characteristics (e.g., RAP binder stiffness and gradation) resulted in such an outcome (i.e., high variability). However, the latter is less likely for the within-specimen variability conditions.

The average COV for the APA rut test was 14.6%, with a COV ranging from 0.2% to 43.1%. The precision estimates for the test are not yet available for VDOT, but the single-operator precision estimate of 18.3% in terms of the COV was recently reported for the APA rut test, determined from an inter-laboratory study using a single mixture that had similar volumetric characteristics to VDOT's BMD mixtures (Taylor et al., 2022). Referencing that estimate, 19 of the 48 observations (39.6%) indicated high variability or low repeatability characteristics.
The average COV for the IDT-HT was 14.3%, with a COV ranging from 1.6% to 28.2%. The precision estimates for the IDT-HT are not yet available, but the range of the COV data indicates potential issues with the repeatability of the test results.

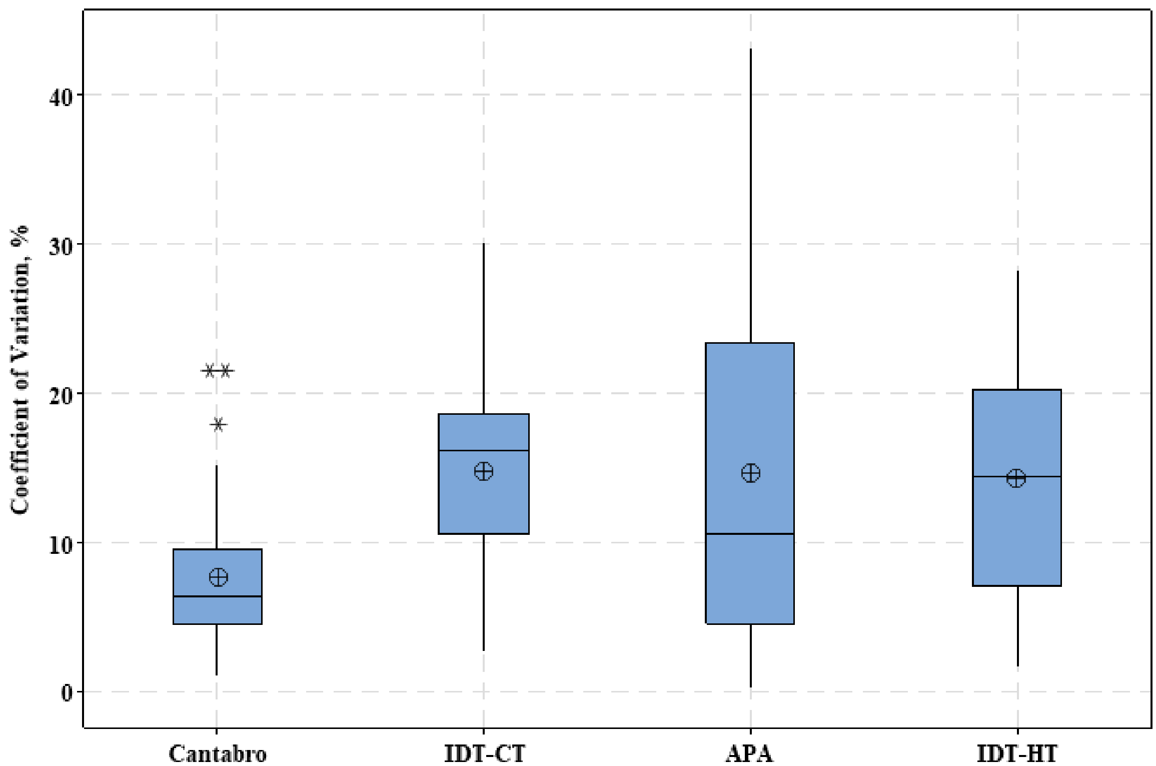


Figure 8. Boxplots of the Coefficient of Variation for Each Test. IDT-CT = indirect tensile cracking test; APA = asphalt pavement analyzer; IDT-HT = indirect tensile test at high temperature. The circle and line in the boxes symbolize the mean and median values of the data, respectively, and the interquartile range represents the middle 50% of the data. The whisker bars spreading out from either side of the box indicate the ranges for the bottom 25% and the top 25% of the data, not including outliers, which are represented by asterisks (*).

For example, 28.6% of the observations had a COV higher than 20%, which can be considered a potential "reference" point to indicate high variability in the test results. As can be seen from Figure 8, the IDT-HT variability was lower and narrower than that of the APA rut test. The better repeatability characteristics of the IDT-HT compared to the APA rut test were also found in a previous study (Boz et al., 2023).

The results in Figure 8 indicate that the average variability for all tests except for the Cantabro test was similar. In addition, the spread of distribution of the within-specimen variability, as can be quantified using the data range (all data points) or the interquartile range, varied for each test, indicating different levels of sensitivity to the test procedures, including the specimen preparation process, and/or changes in material composition.

Within-Lot Sample-to-Sample Variability

Analysis of the within-lot sample-to-sample variability was performed only on the VTRC reheat data from 2021, as replicate samples were not collected within lots in 2022 for VTRC evaluation. For each test considered, two samples were collected for testing from a given lot for the 13 mixtures in this study. This provided an opportunity to perform a within-lot sample-to-sample variability analysis. For the tests that do not currently have precision estimates, the variability is provided in this report for documentation purposes only. For the IDT-CT, the absolute difference of the test results from the two samples was calculated and compared to the single-operator precision estimate (d2s%) limit.

Figure 9 shows the within-lot sample-to-sample comparison for the Cantabro test. The absolute difference between the two samples ranged from 0% to 1%, with an average of 0.5%. When each individual difference was normalized by the corresponding average value of the two-sample results, the absolute percent difference between the two samples ranged from 0.1% to 15.4%, with an average value of 6.4%. Five (4 BMD and 1 non-BMD) of the 13 mixtures had failing mass losses for both the Sample 1 and Sample 2 test results. This indicates that production variability and/or test variability did not have any practical effect on the overall outcome for these mixtures. However, 1 BMD mixture that had a passing mass loss (7.3%) for Sample 1 testing had a failing mass loss (7.7%) for Sample 2 testing. The within-specimen COVs for Sample 1 and Sample 2 testing were 5.5% and 11.2%, respectively. The difference between the two samples (0.4%) for this mixture was less than the average difference (0.5%) between the samples of all 13 mixtures. This mixture failed to meet the performance criterion for the Cantabro test for one of the samples despite its relatively low variability characteristics (i.e., single operator 1s% and d2s%) during production. Of interest, although this mixture passed the CT index performance criterion, with a CT index of 96 for Sample 1, it had a CT index of 72 for Sample 2, barely meeting the performance criterion of a CT index of 70.

Figure 10 shows the within-lot sample-to-sample comparison for the IDT-CT. The figure also shows the single-operator difference limits (d2s%) with respect to the equity line. The absolute difference between the two samples ranged from 0.4 CT index units to 79.3 CT index units, with an average of 24.3 CT index units. The absolute percent difference between the two samples ranged from 0.5% to 64.3%, with an average value of 21.6%.

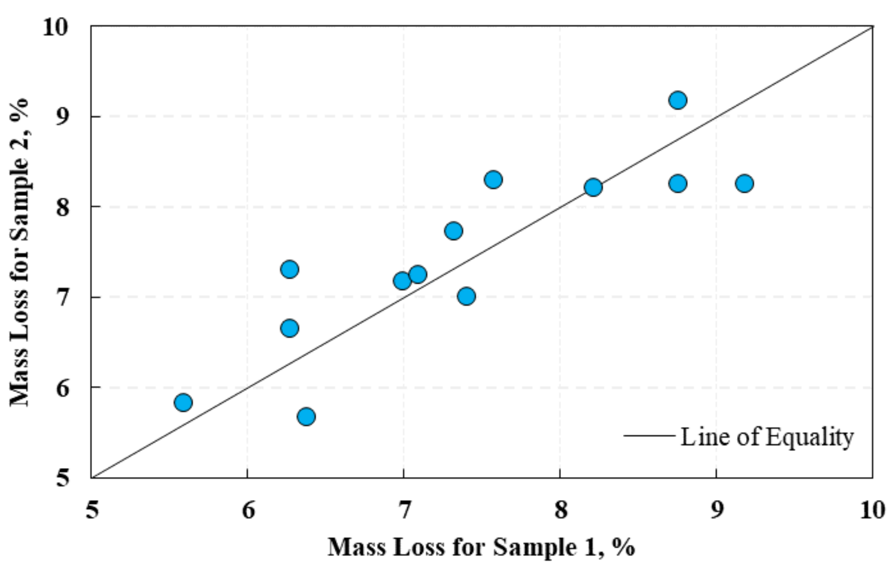


Figure 9. Within-Lot Sample-to-Sample Comparison for Cantabro Test

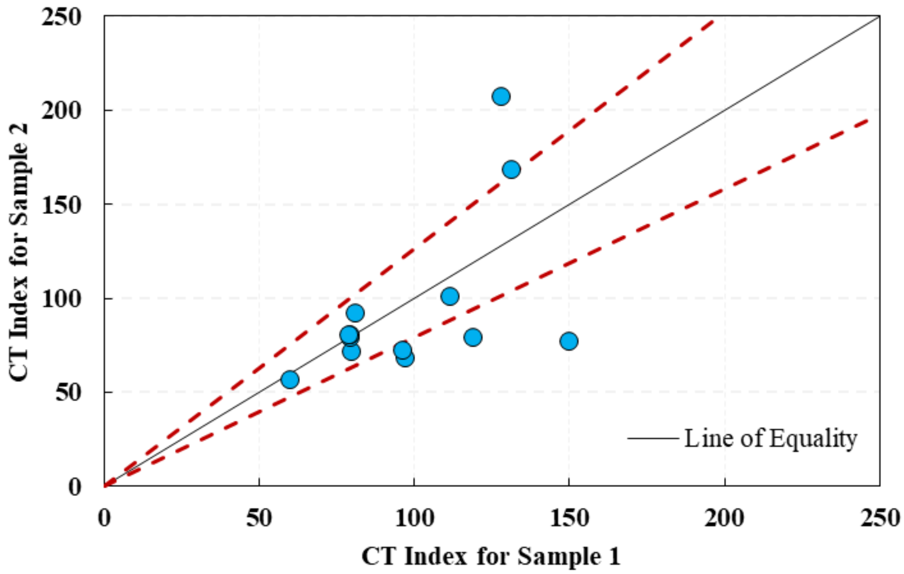


Figure 10. Within-Lot Sample-to-Sample Comparison for the Indirect Tensile Cracking Test. Red dashed lines indicate VDOT's single-operator difference limits (d2s%). CT = cracking tolerance.

Among the 13 mixtures, only 1 non-BMD mixture had a failing CT index of 60 and 57 for Sample 1 and Sample 2, respectively. The sample-to-sample variability for this mixture was acceptable as it fell within the single-operator difference limits. In other words, the production variability and/or test variability did not have any effect on the outcome, despite the mixture being a failing mixture to start with.

It is evident from Figure 10 that six mixtures fell outside the acceptable difference limits of the sample-to-sample variability and that all these mixtures belonged to the BMD category. The details for these BMD mixtures were as follows:

- *Mixture I:* This mixture had CT indexes of 150 and 77 for Sample 1 and Sample 2, respectively. Inspection of the volumetric properties of the samples indicated a 0.5% drop in asphalt content from Sample 1 to Sample 2. The average asphalt content for this mixture was 6.3%. In addition, Sample 1 failed to meet the single-operator within-specimen variability limit (1s%) despite meeting the CT index criterion.

- *Mixture II:* This mixture had a passing CT index of 97 for Sample 1 and a failing CT index of 68 for Sample 2. The volumetric properties of the samples did not indicate any significant differences, but Sample 1 failed to meet the single-operator within-specimen variability limit (1s%) despite meeting the CT index criterion.

- *Mixture III:* This mixture had CT indexes of 128 and 207 for Sample 1 and Sample 2, respectively. Inspection of the volumetric properties of the samples indicated a 0.24% increase in asphalt content from Sample 1 to Sample 2. The average asphalt content for this mixture was 6.1%. In addition, significant variation in aggregate gradation between the samples was evident. Further, Sample 2 failed to meet the single-operator within-specimen variability limit (1s%) despite meeting the CT index criterion.

- *Mixture IV:* This mixture had CT indexes of 96 and 73 for Sample 1 and Sample 2, respectively. Inspection of the volumetric properties of the samples indicated a 0.52% drop in asphalt content from Sample 1 to Sample 2. The average asphalt content for this mixture was 5.1%. In addition, significant variation in aggregate gradation between the samples was evident. Both samples met the single-operator within-specimen variability limit (1s%).

- *Mixture V:* This mixture had CT indexes of 119 and 79 for Sample 1 and Sample 2, respectively. Inspection of the volumetric properties of the samples indicated a 0.34% drop in asphalt content from Sample 1 to Sample 2. The average asphalt content for this mixture was 5.1%. No other significant variations in volumetric properties were observed. Both samples met the single-operator within-specimen variability limit (1s%).

- *Mixture VI:* This mixture had CT indexes of 131 and 168 for Sample 1 and Sample 2, respectively. Inspection of the volumetric properties of the samples indicated no significant variations in volumetric properties. Both samples met the single-operator within-specimen variability limit (1s%).

Figure 11 shows the within-lot sample-to-sample comparison for the APA rut test. The absolute difference between the two samples ranged from 0.1 mm to 2.2 mm, with an average of 1.1 mm. The absolute percent difference between the two samples ranged from 1.4% to 47.5%, with an average value of 22.2%. None of the mixtures had samples failing the APA rut test requirement. This indicates that production variability and/or test variability did not have any practical effect on the overall outcome for these mixtures.

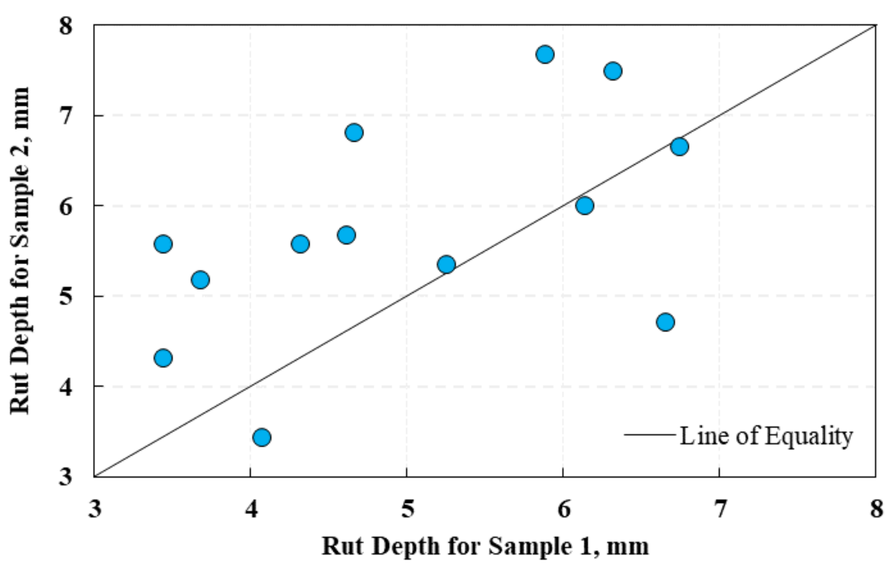


Figure 11. Within-Lot Sample-to-Sample Comparison for Asphalt Pavement Analyzer Rut Test

Figure 12 shows the within-lot sample-to-sample comparison for the IDT-HT. The absolute difference between the two samples ranged from 2.8 kPa to 117.1 kPa, with an average of 41.5 kPa. The absolute percent difference between the two samples ranged from 1.9% to 58.8%, with an average value of 22.2%. Among the 12 mixtures (the test results for 1 mixture were discarded due to data quality issues), 3 BMD mixtures failed to meet the IDT-HT performance criterion of 133 kPa for Sample 1, but 2 of these 3 mixtures met the criterion for Sample 2, likely resulting from an average decrease of 0.4% in asphalt content.

The results indicate that each test has a different response to the inherent production variability. The number of mixtures with statistically different sample-to-sample test results varied for each test; the same mixtures did not, in general, have statistically different sample-to-sample test results for all tests. For some tests, statistically significant variations in sample-to-sample test results also led to practical differences (passing vs. failing performance). These observed variations within sample-to-sample testing might be attributable to any departure from the standard test procedure, including specimen sampling and preparation processes. In addition, the inherent test variability coupled with changes in component materials characteristics (e.g., changes in virgin asphalt binder content, gradation, and RAP binder stiffness from one sample to another one) could have led to the observations in this study. For example, IDT tests at intermediate or high temperatures are more sensitive to changes in material composition and have better repeatability characteristics and performance discrimination potential compared to other alternative index-based and fundamental tests such as semicircular bending, cyclic fatigue, APA rut, and flow number tests (Boz et al., 2023; Seitllari et al., 2019, 2022). This might, for example, explain the differences in the APA rut and IDT-HT results for rutting evaluation.

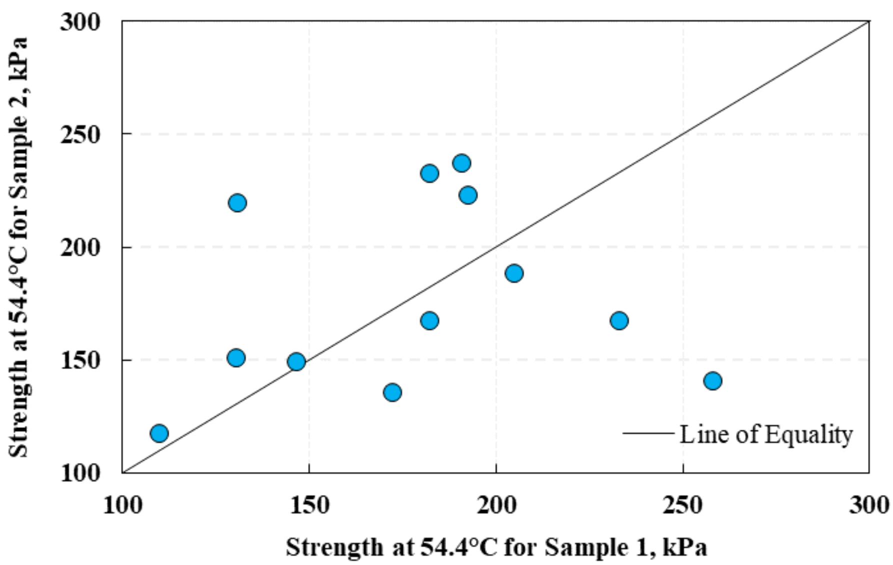


Figure 12. Within-Lot Sample-to-Sample Comparison for Indirect Tensile Test at High Temperature

Finally, even though the tests may have been performed normally and correctly, there is a probability of 5% that the differences between two samples can exceed the difference limits of a test method. Thus, a better understanding of the sensitivity and variability characteristics of test methods is crucial for establishing/refining tolerance limits and successfully implementing the BMD acceptance practice. Fine-tuning the test procedures, determining the material properties that statistically influence the test results, and establishing precision estimates of the test methods are important key components to that end.

Another important observation from the variability assessment is that designing asphalt mixtures with performance metrics (results) within a proximity of performance thresholds may carry a risk of having failures during the production due to the inherent material and test variability, even if the process is "well-controlled." "A proximity" is defined as an average test result being within single-operator acceptable limits (e.g., 1s% and/or d2s%) of a test method with respect to an established performance threshold.

Laboratory Evaluation of Asphalt Binder

Performance Grading

Tables 12 and 13 present the PG and rheological properties of the extracted and recovered binders for the mixtures placed during the 2021 construction season. All binders showed PG high temperatures ranging between 70°C and 76°C, PG intermediate temperatures ranging between 21.7°C and 29.2°C, and PG low temperatures ranging between -16°C and -22°C (in accordance with AASHTO M 320), regardless of the RAP content and the virgin binder used. The 2021 mixtures had RAP contents ranging between 26% and 30% except for Mixtures I2 and I3, which had a 40% RAP content, making them compliant with the requirements for high RAP mixtures. Overall, all BMD mixtures had similar continuous PG high, intermediate, and low temperatures when compared to the control mixtures. However, in some cases, certain BMD mixtures showed a full grade difference for the high and low temperatures compared to the control mixtures. This occurred because some of these temperatures were close to the cutoff for the grade itself. For example, Mixtures F1 and F2 had PG high temperatures of 76.4°C and 74.2°C, respectively. Although these temperatures are considered close, their proximity to 76°C resulted in the resultant binders having a PG with one grade difference. Similarly, Mixtures B1 and B2 had PG low temperatures of −20.1°C and −22.2°C, respectively, which were close to the −22°C cutoff, resulting in the resultant binders having a low PG with one grade difference. Specific examples are Mixtures I2 and I3, which had PG high and low temperatures one grade softer than the control Mixture I1. This difference was due to the use of a softer binder (PG 58-28) with 40% RAP for Mixtures I2 and I3, compared to the use of PG 64S-22 with 30% RAP for Mixture I1. This clearly indicates a potential softening effect when softer binders are used.

Table 12. Performance Grading Results of Extracted and Recovered Asphalt Binders for Mixtures Collected in 2021 Construction Season from Salem, Lynchburg, and Richmond Districts

Property		District and Mixture ID											
		Salem				Lynchburg				Richmond			
		21-A1	21-A2	21-B1	21-B2	21-C1	21-C2	21-D1	21-D2	21-E1	21-E2	21-F1	21-F2
Dynamic Shear, 10 rad/sec, specification: |G*|/sinδ > 2.20 kPa													
RTFO |G*|/sin δ, kPa	70°C	3.99	4.44	--	--	--	--	--	--	4.19	3.37	--	3.76
	76°C	1.85	2.07	3.12	2.27	3.57	2.98	3.17	2.36	1.96	1.58	2.31	1.75
	82°C	--	--	1.49	1.10	1.72	1.43	1.52	1.14	--	--	1.13	--
RTFO Failure Temperature, °C		74.6	75.5	78.8	76.3	80.0	78.5	79.0	76.6	75.1	73.4	76.4	74.2
Dynamic Shear, 10 rad/sec, specification: |G*|.sinδ < 5,000 kPa													
PAV |G*|.sin δ, kPa	19°C	--	--	--	--	--	--	--	--	--	6,590	--	--
	22°C	--	--	--	--	--	--	--	--	--	4,870	--	--
	25°C	5,520	5,810	5,960	5,570	--	--	6,410	5,630	5,490	--	8,790	5,440
	28°C	2,870	4,100	4,410	4,020	5,720	5,250	4,670	4,150	3,830	--	5,880	3,810
	31°C	--	--	--	--	4,040	3,680	--	--	--	--	--	--
PAV Failure Temperature, °C		25.5	26.3	26.7	26.0	29.2	28.4	27.4	26.2	25.8	21.7	26.5	25.7
Creep Stiffness, 60 sec, specification: Stiffness (S) < 300 MPa and m-value > 0.300													
Stiffness (S), MPa	-6°C	--	--	113	--	145	146	120	114	--	--	--	--
	-12°C	233	226	218	220	288	289	227	223	246	143	240	239
	-18°C	461	459	428	430	514	525	428	410	483	273	471	438
m-value	-6°C	--	--	0.330	--	0.330	0.332	0.332	0.333	--	--	--	--
	-12°C	0.310	0.307	0.287	0.302	0.278	0.279	0.287	0.294	0.306	0.314	0.307	0.303
	-18°C	0.258	0.254	0.243	0.252	0.235	0.240	0.245	0.248	0.252	0.267	0.253	0.263
Stiffness Failure Temperature (Ts), °C		-14.2	-14.4	-14.8	-14.8	-12.4	-12.3	-14.4	-14.9	-13.8	-18.9	-14.0	-14.3
m-value Failure Temperature (Tm), °C		-13.1	-12.7	-10.1	-12.2	-9.3	-9.5	-9.3	-11.0	-12.6	-13.7	-12.7	-12.4
PAV Low Failure Temperature, °C		-23.1	-22.7	-20.1	-22.2	-19.3	-19.5	-19.3	-21.0	-22.6	-23.7	-22.7	-22.4
$\Delta T_c = T_{c,S} - T_{c,m}$, °C		-1.1	-1.7	-4.7	-2.6	-3.1	-2.8	-5.1	-3.9	-1.2	-5.2	-1.3	-1.9
PG (AASHTO M 320)		70-22	70-22	76-16	76-22	76-16	76-16	76-16	76-16	70-22	70-22	76-22	70-22
Multiple Stress and Creep Recovery (MSCR) Test at 64°C													
J_{nr} kPa-1	0.1 kPa	0.8624	0.8374	0.4478	0.7226	0.3745	0.4561	0.4579	0.6206	0.8055	0.6337	0.7336	0.9364
	3.2 kPa	0.9415	0.9141	0.4840	0.7815	0.4007	0.4828	0.4949	0.6800	0.8868	0.5972	0.8047	1.0170
Avg. % Recovery, %	0.1 kPa	9.4912	9.8559	17.5496	11.0971	18.4533	14.6851	16.6023	14.5493	12.2130	12.4411	11.0888	9.4310
	3.2 kPa	5.0625	5.3564	12.8955	6.8538	14.2466	0.0993	11.9964	8.9722	6.4185	7.9290	6.5001	4.7104
PG (AASHTO M 322)		64V-22	64V-22	64E-16	64V-22	64E-16	64E-16	64E-16	64V-16	64V-22	64V-22	64V-22	64H-22

RTFO = rolling thin film oven; PAV = pressure aging vessel; PG = performance grade; $T_{c,S}$ = S-critical low temperature; $T_{c,m}$ = m-critical low temperature; Jnr = non-recoverable creep compliance; Avg. = average; % = percent; - = no data collected.

Table 13. Performance Grading Results of Extracted and Recovered Asphalt Binders for Mixtures Collected in 2021 Construction Season from Hampton Roads and Northern Virginia Districts

Property		District and Mixture ID							
		Hampton Roads					Northern Virginia		
		21-G1	21-G2	21-H1	21-H2	21-H3	21-I1	21-I2	21-I3
Dynamic Shear, 10 rad/sec, specification: |G*|/sinδ > 2.20 kPa									
RTFO |G*|/sin δ, kPa	70°C	--	--	--	4.07	--	4.58	4.22	4.22
	76°C	3.17	2.74	2.42	1.89	2.23	2.11	1.95	1.95
	82°C	1.54	1.36	1.16	--	1.09	--	--	--
RTFO Failure Temperature, °C		74.6	79.0	77.9	76.8	75.8	76.1	75.7	75.7
Dynamic Shear, 10 rad/sec, specification: |G*|.sinδ < 5,000 kPa									
PAV |G*|.sin δ, kPa	19°C	--	--	--	--	--	--	--	--
	22°C	--	6410	--	--	--	6490	6160	6160
	25°C	6660	4790	6070	5550	6110	4780	4520	4520
	28°C	4790	--	4290	4010	4340	--	--	--
	31°C	--	--	--	--	--	--	--	--
PAV Failure Temperature, °C		25.5	27.6	24.6	26.7	26.0	26.8	24.6	24.6
Creep Stiffness, 60 sec, specification: Stiffness (S) < 300 MPa and m-value > 0.300									
Stiffness (S), MPa	-6°C	134	96	111	128	120	--	--	--
	-12°C	256	182	275	249	239	181	174	174
	-18°C	487	343	504	471	444	336	342	342
m-value	-6°C	0.337	0.331	0.348	0.347	0.339	--	--	--
	-12°C	0.287	0.294	0.281	0.297	0.295	0.304	0.306	0.306
	-18°C	0.240	0.256	0.246	0.251	0.257	0.264	0.261	0.261
$T_{c,S}$, °C		-14.2	-13.5	-16.7	-12.6	-13.8	-14.2	-16.9	-16.9
$T_{c,m}$, °C		-13.1	-10.3	-11.0	-10.2	-11.6	-11.3	-12.6	-12.6
PAV Low Failure Temperature, °C		-23.1	-20.3	-21.0	-20.2	-21.6	-21.3	-22.6	-22.6
$\Delta Tc = T_{c,S} - T_{c,m}$, °C		-1.1	-3.2	-5.7	-2.4	-2.2	-2.9	-4.3	-4.3
PG (AASHTO M 320)		70-22	76-16	76-16	76-16	70-16	76-16	70-22	70-22
Multiple Stress and Creep Recovery (MSCR) Test at 64°C									
J_{nr}, kPa-1	0.1 kPa	0.4041	0.4162	1.0826	0.8177	0.6553	0.6600	0.7411	0.7411
	3.2 kPa	0.4479	0.4909	1.2427	0.9098	0.7026	0.7525	0.8396	0.8396
Avg. % Recovery, %	0.1 kPa	21.8387	30.5129	11.3860	12.3003	11.3245	17.3272	15.2338	15.2338
	3.2 kPa	14.9451	19.0521	4.7547	6.1359	7.2720	9.3275	7.7676	7.7676
PG (AASHTO M 322)		64V-22	64E-16	64E-16	64H-16	64V-16	64V-16	64V-22	64V-22

RTFO = rolling thin film oven; PAV = pressure aging vessel; PG = performance grade; $T_{c,S}$ = S-critical low temperature; $T_{c,m}$ = m-critical low temperature; J_{nr} = non-recoverable creep compliance; Avg. = average; % = percent; - = no data collected.

Tables 12 and 13 present the ΔTc values for all evaluated binders collected from the 2021 mixtures. The ΔTc values for all binders ranged from −5.7°C to −1.1°C. It is worth noting that all evaluated binders had negative ΔTc values, indicating an m-controlled behavior. Only three binders (Binders 21-D1, 21-E2, and 21-H1) slightly exceeded the traditional cracking zone of −5.0°C (Yang et al., 2022). Nine binders (Binders 21-B1, 21-B2, 21-C1, 21-C2, 21-D2, 21-G2, 21-I1, 21-I2, and 21-I3) fell within the cracking warning zones, with ΔTc values ranging between −5.0°C and −2.5°C. The remaining eight binders (Binders 21-A1, 21-A2, 21-E1, 21-F1, 21-F2, 21-G1, 21-H2, and 21-H3) had ΔTc values surpassing the cracking warning limit of −2.5°C. These results indicate a promising resistance to non–load-related cracking (Yang et al., 2022).

Binder grading was conducted in accordance with AASHTO M 322, which incorporates the non-recoverable creep compliance at 3.2 kPa (J_{nr}, 3.2 kPa) and percent recovery at 3.2 kPa (%R3.2 kPa) determined using the MSCR test. The MSCR test was performed at 64°C, which represents the average 7-day maximum pavement design temperature for Virginia. AASHTO M 332 specifies maximum J_{nr}, 3.2 kPa requirements for standard (S), heavy (H), very heavy (V), and extremely heavy (E) traffic conditions as 4.5 kPa^{-1}, 2.0 kPa^{-1}, 1.0 kPa^{-1}, and 0.5 kPa^{-1}, respectively. VDOT specifications require a minimum of PG 64S-16 and PG 64H-16 "virgin" asphalt binders for SMs with A and D designations, respectively (VDOT, 2020). The data presented in Tables 10 and 11 indicate that of the 20 evaluated binders, 12 fell into Category V (Binders 21-A1, 21-A2, 21-B2, 21-D2, 21-E1, 21-E2, 21-F1, 21-G1, 21-H3, 21-I1, 21-I2, and 21-I3). Six binders met the requirements for extremely heavy traffic (E) (Binders 21-B1, 21-C1, 21-C2, 21-D1, 21-G2, and 21-H1). This could be attributed to the presence of elastomeric polymers in the corresponding RAP stockpiles, as indicated by the low percent recovery values compared to typical polymer-modified asphalt binders. Only two binders fell into the heavy (H) category (Binders 21-F2 and 21-H2). Overall, all recorded percent recovery values were very low, which is commonly observed for typical unmodified binders.

Table 14 presents the PG and a few rheological properties of the extracted and recovered binders for the mixtures placed during the 2022 construction season. Two major observations can be made regarding the 2022 binders. First, slightly softer behavior and lower PG high temperatures were observed for the evaluated binders compared to the previous year (2021). Second, significantly higher ΔTc values (more negative values) were observed for these binders in comparison to the values for the 2021 binders, indicating a potential for cracking in these mixtures. This can be primarily attributed to the source and formulation of the base binder used, which still met the current VDOT binder specifications, although the RAP binder characteristics likely also contributed. It is noteworthy that none of the binders fell into the extremely heavy traffic (E) category; instead, they all fell into either the heavy (H) or very heavy (V) categories in accordance with AASHTO M 322.

Table 14. Performance Grading Results of Extracted and Recovered Asphalt Binders for Mixtures Collected in 2022 Construction Season

Property		District and Mixture ID																
		Bristol	Salem					Lynch-burg	Richmond				Hampton Roads	Fredericks-burg	Cul-peper	Staunton	Northern Virginia	
		22-A	22-B	22-C1	22-D1	22-D2	22-E	22-F	22-G1	22-G2	22-H1	22-H2	22-I	22-J	22-K	22-L	22-M1	22-M2
Dynamic Shear, 10 rad/sec, specification: |G*|/sinδ > 2.20 kPa																		
RTFO |G*|/sin δ, kPa	64°C	--	4.80	11.49	10.34	5.32	8.43	9.31	--	--	5.70	21.19	9.08	3.62	4.60	--	12.39	3.51
	70°C	--	2.19	5.13	4.67	2.43	3.82	4.19	--	--	2.57	9.45	4.16	1.73	2.15	--	5.60	1.64
	76°C	--	--	2.37	2.14	1.15	1.80	1.96	--	--	1.21	4.26	1.95	--	--	--	2.62	--
	82°C	--	--	1.14	--	--	--	--	--	--	--	1.97	--	--	--	--	1.28	--
RTFO Failure Temperature, °C		--	69.98	76.72	75.75	70.86	74.38	75.06	--	--	71.33	81.06	75.02	68.04	69.82	--	77.55	67.68
Dynamic Shear, 10 rad/sec, specification: |G*|.sinδ < 5,000 kPa																		
PAV |G*|.sin δ, kPa	19°C	--	--	--	--	--	--	--	--	--	--	5979	--	--	--	--	--	--
	22°C	--	5656	6639	--	6630	--	6118	--	--	--	4228	6213	6213	6430	--	--	--
	25°C	--	4032	4883	5900	4694	5105	4388	--	--	5123	2945	4402	4409	4542	--	5573	6411
	28°C	--	--	--	4314	3249	3745	--	--	--	3708	--	2945	--	--	--	4121	4464
PAV Failure Temperature, °C		--	23.09	24.77	26.59	24.41	25.20	23.82	--	--	25.23	20.54	23.90	23.90	24.17	--	26.08	27.06
Creep Stiffness, 60 sec, specification: Stiffness (S) < 300 MPa and m-value > 0.300																		
Stiffness (S), MPa	-6°C	--	78	94	89	--	--	91	--	--	89	--	--	--	--	--	94	85
	-12°C	--	110	160	147	140	141	157	--	--	167	121	160	176	160	--	170	160
	-18°C	--	--	--	--	311	208	--	--	--	--	225	335	274	335	--	--	--
m-value	-6°C	--	0.350	0.334	0.332	--	--	0.331	--	--	0.308	--	--	--	--	--	0.311	0.341
	-12°C	--	0.230	0.262	0.254	0.315	0.302	0.267	--	--	0.290	0.317	0.308	0.371	0.305	--	0.283	0.278
	-18°C	--	--	--	--	0.251	0.171	--	--	--	--	0.287	0.228	0.256	0.216	--	--	--
$T_{c,S}$, °C		--	-29.4	-19.2	-20.5	-17.7	-23.6	-19.1	--	--	-17.6	-20.8	-23.9	-19.2	-17.1	--	-17.8	-18.0
$T_{c,m}$, °C		--	-8.5	-8.8	-8.5	-13.4	-12.1	-8.9	--	--	-8.7	-15.4	-12.6	-15.7	-12.3	--	-8.4	-9.9
PAV Low Failure Temperature, °C		--	-18.5	-18.8	-18.5	-23.4	-22.1	-18.9	--	--	-18.7	-25.4	-22.6	-25.7	-22.3	--	-18.4	-19.9
ΔTc = Tc,S-Tc,m, °C		--	-20.9	-10.3	-12.1	-4.3	-11.5	-10.2	--	--	-8.9	-5.4	-11.3	-3.5	-4.8	--	-9.4	-8.1
PG (AASHTO M 320)		--	70-16	76-16	70-16	70-22	70-22	70-16	--	--	70-16	76-22	70-22	64-22	70-22	--	76-16	64-16
Multiple Stress and Creep Recovery (MSCR) Test at 64°C																		
J_{nr}, **kPa-1**	0.1 kPa	--	1.3780	0.5873	0.6781	1.4570	0.9061	0.7916	--	--	1.4260	1.7580	0.3135	2.3220	1.8650	--	0.4666	0.9643
	3.2 kPa	--	1.5740	0.6430	0.7319	1.5970	0.9911	0.8611	--	--	1.5740	1.9730	0.3327	2.7900	2.0830	--	0.5172	1.0330
Avg. % Recovery, %	0.1 kPa	--	10.5100	17.7700	13.9800	7.4790	11.8600	13.2800	--	--	8.3840	7.9200	18.7900	9.4790	7.2780	--	23.4000	8.6550
	3.2 kPa	--	4.0110	11.6400	9.1570	3.4640	6.6670	8.0710	--	--	3.4610	2.7590	15.6400	2.3540	2.3350	--	16.9400	4.6460
PG (AASHTO M 322)		--	64H-16	64V-16	64V-16	64H-16	64V-22	64V-16	--	--	64H-16	64H-22	64E-22	64S-22	64H-22	--	64E-16	64H-16

RTFO = rolling thin film oven; PAV = pressure aging vessel; PG = performance grade; $T_{c,S}$ = S-critical low temperature; $T_{c,m}$ = m-critical low temperature; J_{nr} = non-recoverable creep compliance; Avg. = average; % = percent; - = no data collected.

G-R Parameter

Figure 13 illustrates the G-R1 values of all evaluated binders after 20-hour PAV aging conditions. These binders were extracted and recovered from the 2021 mixtures. It is important to note that frequency sweep tests were not conducted on the binders from the 2022 mixtures. The G-R1 values provide insight into the potential for cracking due to brittle rheological behavior. A damage zone or range, where cracking is likely to initiate, is defined by G-R1 values between 180 kPa (onset of cracking) and 600 kPa (significant cracking). These values correlate with low ductility values of 5 cm to 3 cm, respectively. Among the evaluated binders, only one binder (21-C1) had a G-R1 value exceeding 600 kPa, indicating a higher susceptibility to significant cracking. All the other binders fell within the damage cracking zone after undergoing 20-hour PAV aging.

Figure 14 displays the black space diagram illustrating the behavior of all evaluated binders from 2021. The green dashed dotted and orange dashed lines represent the current PG boundaries for G* and δ, respectively, under the as-recovered and 20-hour PAV aging conditions. It is evident that all binders fell comfortably within these criteria, although aging resulted in an increase in binder G* and a decrease in δ. In Figure 13, the dashed and solid black lines indicate the limits of the G-R parameter at 180 kPa and 600 kPa, respectively. These lines, also visible in Figure 14, correspond to the thresholds where the onset of cracking and significant cracking are expected to occur. The collected data indicated a cluster within the damage zone and fell within a phase angle range of 48° to 58°.

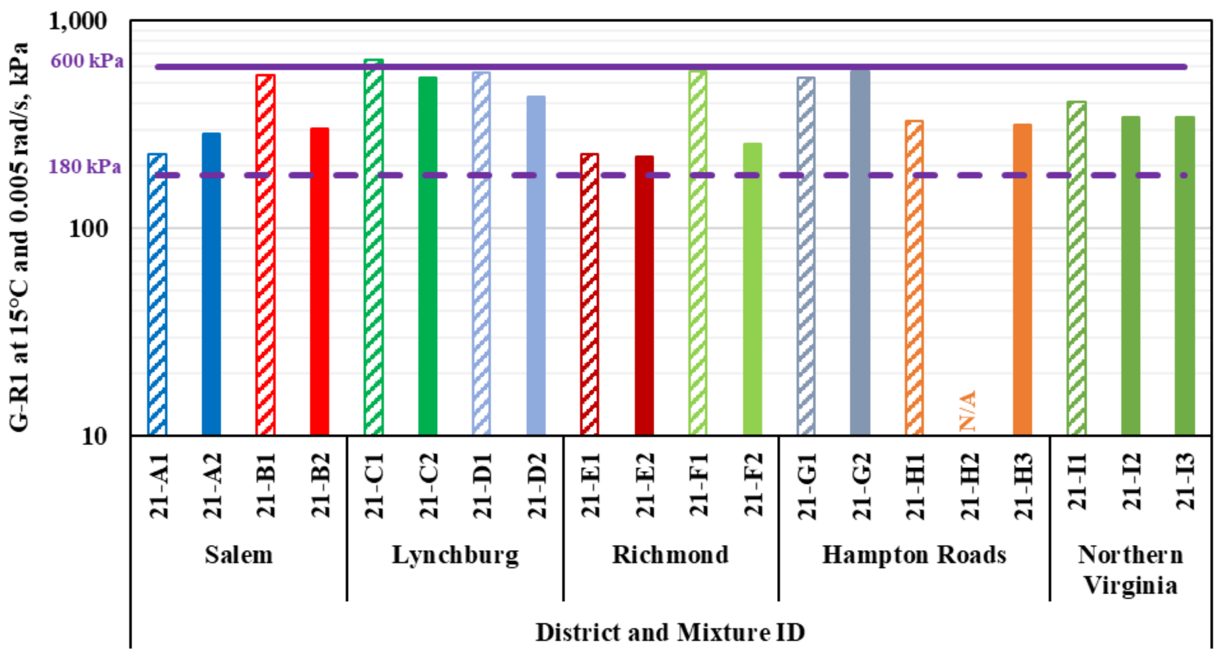


Figure 13. Glover-Rowe (G-R1) Values at 15°C and 0.005 rad/s of the Evaluated Binders at 20-Hour PAV Aging Conditions. Purple dashed and solid lines indicate onset and significant cracking limits, respectively. PAV = pressure aging vessel; N/A = not available.

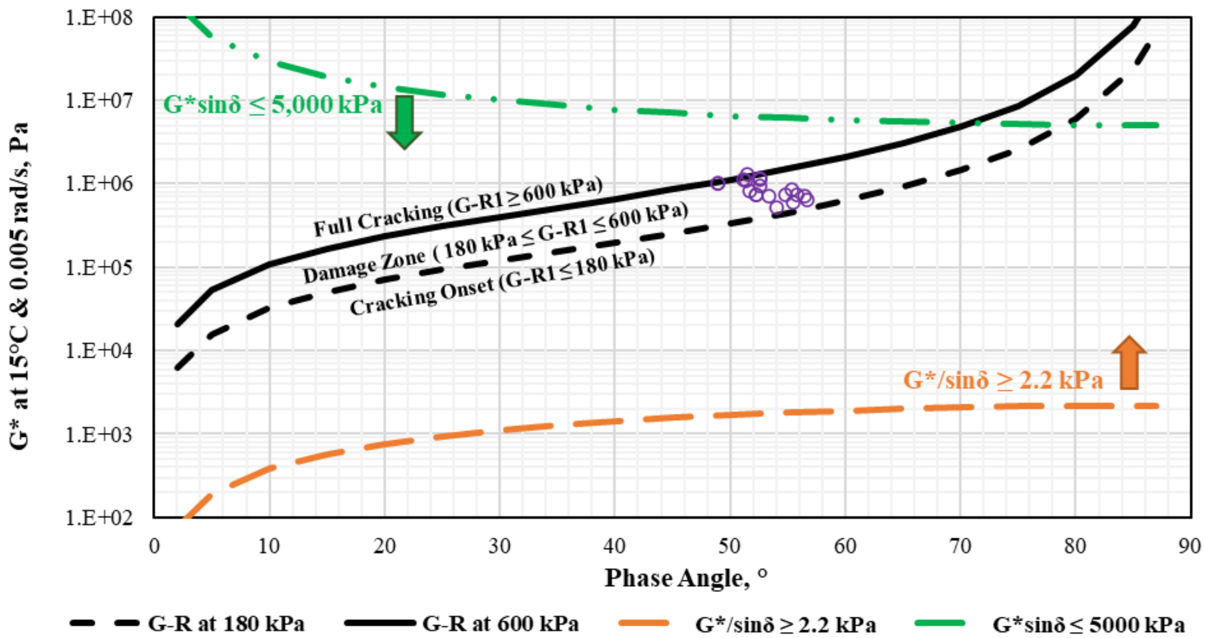


Figure 14. Black Space Diagram in Terms of Glover-Rowe (G-R1) Values at 15°C and 0.005 rad/s for 2021 Binders at 20-Hour PAV Aging Conditions. PAV = pressure aging vessel; G* = complex shear modulus; δ = phase angle.

Figure 15 displays the G-R2 values for all evaluated binders under 20-hour PAV aging conditions. As determined by Christensen and Tran (2022), a maximum allowable value of 5,000 kPa was established for G-R2 after the 20-hour PAV aging. Figure 16 presents the black space diagram, comparing the properties of the binders to the G-R2 limit of 5,000 kPa and the G*sinδ limit of 5,000 kPa. The G*sinδ limit of 5,000 kPa is currently employed as part of the binder Superpave specifications for intermediate temperatures. Most of the binders met the G*sinδ limit of 5,000 kPa at the corresponding fatigue temperature. Except for 21-H3, all evaluated binders had G-R2 values exceeding 5,000 kPa, indicating a potential susceptibility to cracking. It is crucial to note that the proposed maximum threshold for G-R2 is still considered tentative. Any revisions to this threshold should be based on extensive laboratory evaluations of materials commonly used in Virginia, along with corresponding field validations.

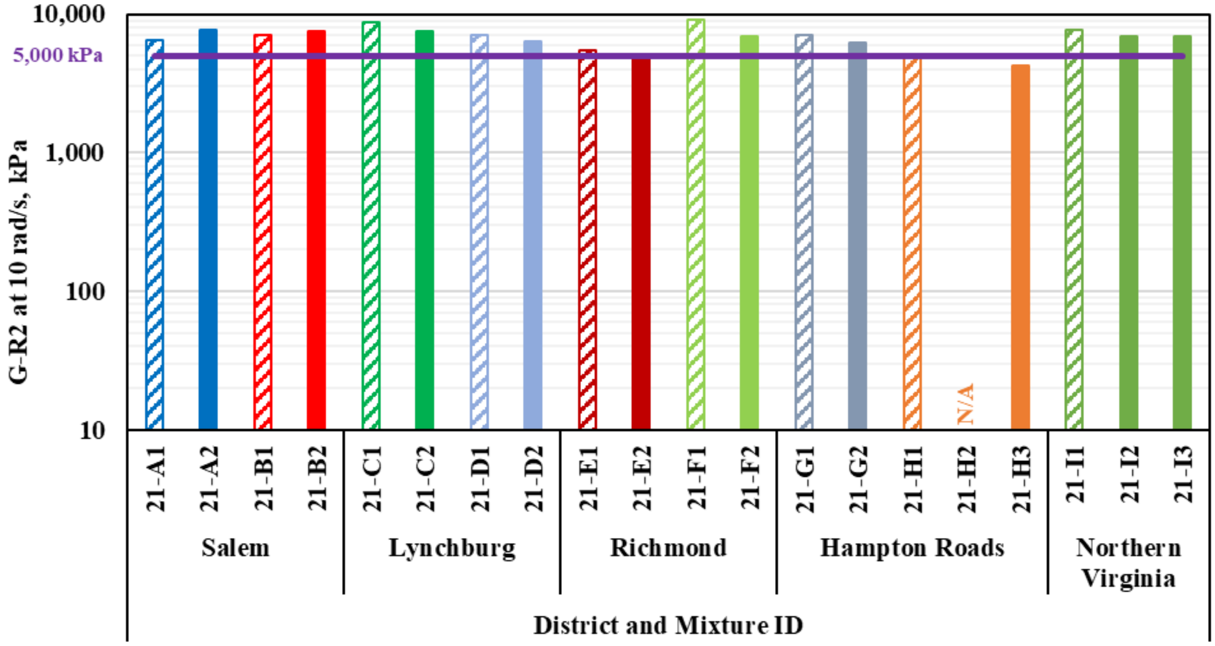


Figure 15. Glover-Rowe (G-R2) Values at the Corresponding Binder Fatigue Test Temperature and 10 rad/s of the Evaluated Binders at 20-Hour PAV Aging Conditions. Purple line indicates the recommended specification limit. PAV = pressure aging vessel.

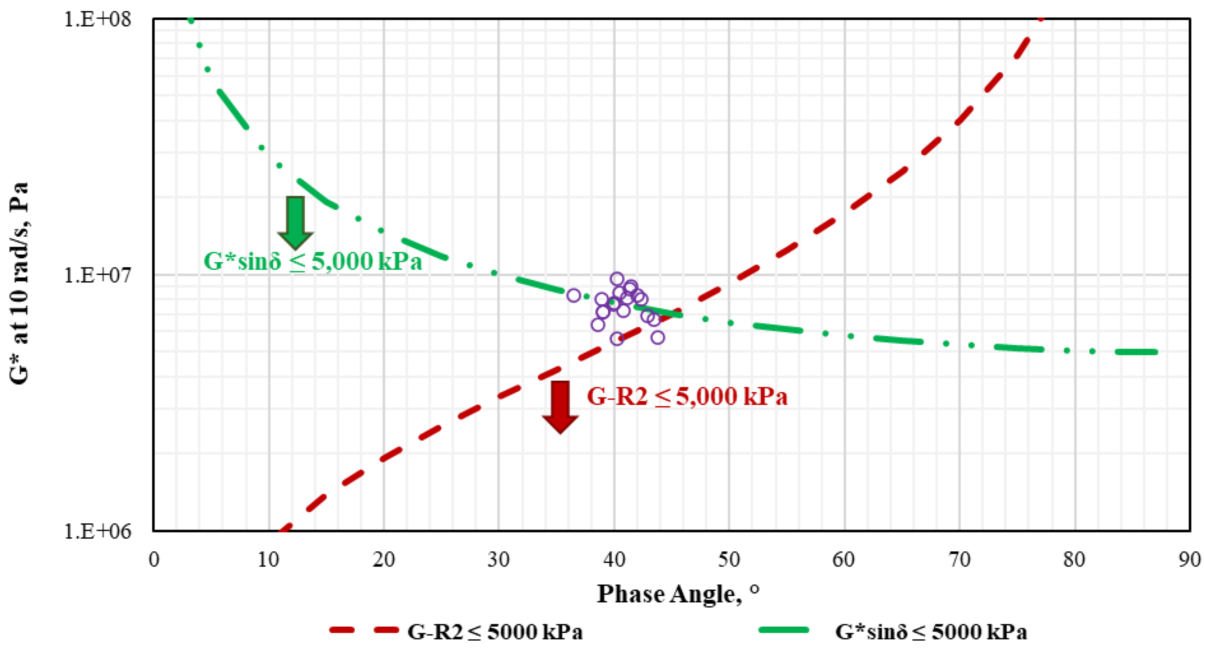


Figure 16. Black Space Diagram in Terms of Glover-Rowe (G-R2) Values at the Corresponding Binder Fatigue Test Temperature and 10 rad/s of the Evaluated Binders at the 20-Hour PAV Aging Conditions. PAV = pressure aging vessel; G* = complex shear modulus; δ = phase angle.

R-Value

Figure 17 shows the R-values for all evaluated 2021 binders. It is generally observed that high R-values can lead to poor fatigue performance at lower temperatures in thin pavements, and low R-values can result in poor fatigue performance in thick pavements (Christensen and Tran, 2022). According to Christensen and Tran (2022), an allowable range of R-value between 1.5 and 2.5 was defined for binders under the 20-hour PAV aging condition. All evaluated binders had R-values within the specified range of 1.5 to 2.5, except for 21-G2, which had an R-value greater than 2.5.

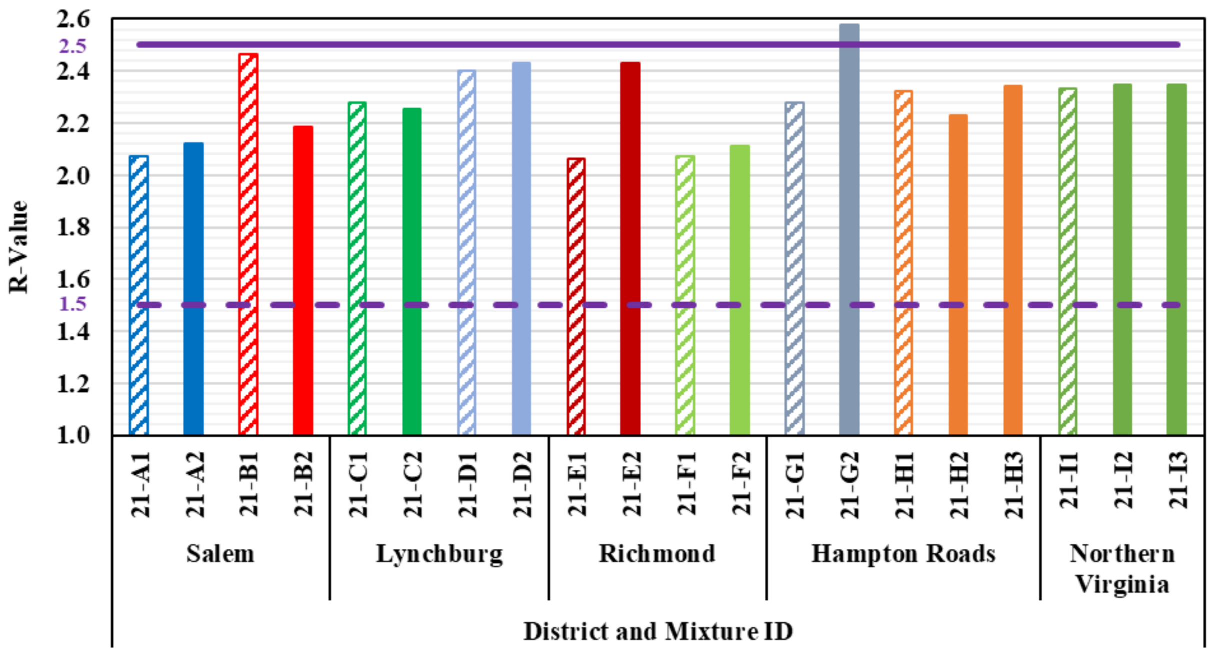


Figure 17. R-Value for All Evaluated 2021 Binders at the 20-Hour PAV Aging Condition. PAV = pressure aging vessel.

Assessment of Cracking Performance for Evaluated Asphalt Binders

The fatigue life of an asphalt binder can be predicted using the LAS test results in conjunction with the viscoelastic continuum damage model. Equation 4 represents a power function that establishes a relationship between the fatigue performance, N_f, of the binder and the maximum strain amplitude. The parameters A and B directly influence the fatigue resistance of the evaluated binder. The model parameter A reflects the inherent fatigue resistance of the asphalt binder, and the parameter B" represents the rate of damage evolution (Yang et al., 2022). Figure 18 displays the LAS binder fatigue parameter for all tested binders at strain levels of 5% and 10%. As anticipated, the fatigue life (N_f) decreased as the induced strain increased. Upon analyzing the data, no clear trends emerged regarding the relationship between N_f and the RAP content or the type of virgin binder used. However, it is noteworthy that the N_f values for all BMD mixtures were either comparable to or higher than those of the corresponding control mixtures, irrespective of the applied strain (5% and 10%). In addition, Mixtures I2 and I3 had the highest N_f values at both 5% and 10% strain. This observation can be attributed to the use of a softer binder to account for the relatively higher RAP content.

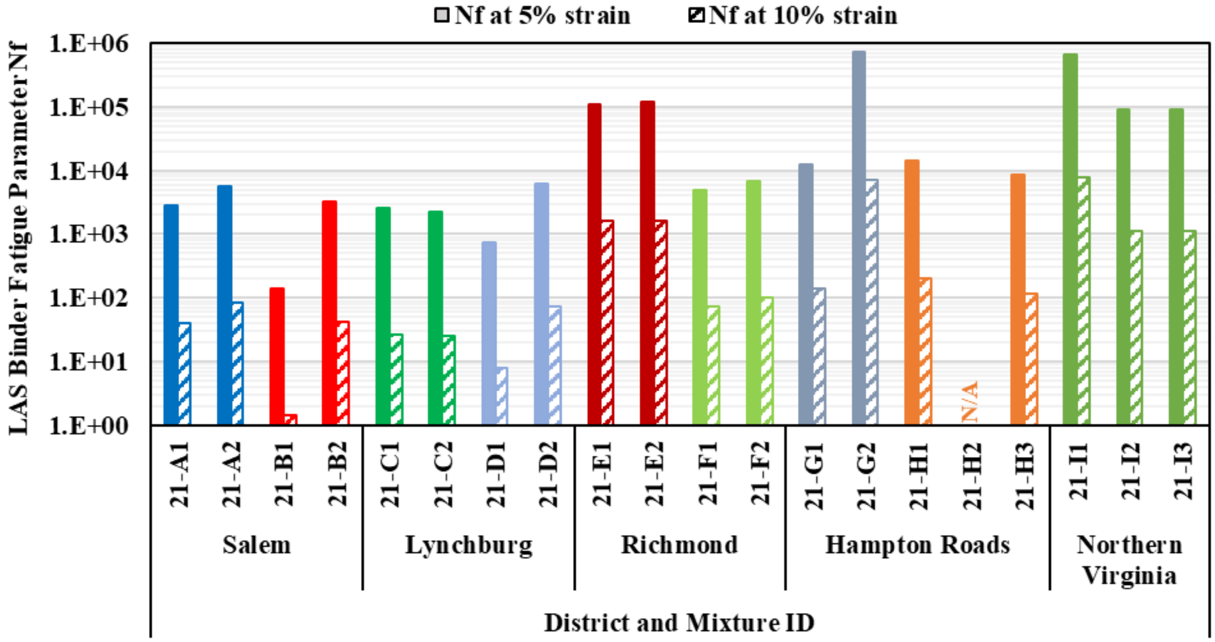


Figure 18. LAS Binder Fatigue Parameter (N_f) for All Evaluated Binders at the 20-Hour PAV Aging Condition at 5% and 10% Induced Strain. LAS = linear amplitude sweep; PAV = pressure aging vessel.

Preliminary Correlation Between Mixture and Binder Properties

Preliminary correlation and an understanding of the relationships between the properties of asphalt mixtures and asphalt binders are essential for optimizing mixture performance and durability. The properties of asphalt mixtures, such as durability and resistance to rutting and cracking, are influenced by the characteristics of the virgin and RAP asphalt binders used in their composition. By establishing correlations and relationships between these properties, engineers and researchers can optimize the selection of virgin binders, assess RAP binder characteristics, and tailor mix designs to meet specific project requirements. The correlation work presented herein is preliminary and is provided for observation purposes only. Further data processing and analysis are needed.

In this investigation, the aim was to investigate any meaningful trends among various parameters, which were grouped into three categories. The first category focused on rutting and aimed to identify trends between the BMD parameter, such as the APA rut depth at 64°C and the IDT-HT strength at 54.4°C, and binder parameters, including G*/sinδ and $J_{nr,\,3.2\,kPa}$. Figure 19 illustrates the relationship between the $J_{nr,\,3.2\,kPa}$ values of the extracted and recovered binders and the APA rut depth and IDT-HT strength of the reheated mixtures. Overall, the data were scattered widely and revealed weak relationships. This outcome may be attributed to the limited quantity and narrow range of data that were evaluated in this study along with the presence of other influencing factors such as binder content and volumetric composition. Although the correlations were weak, it was noted that an APA rut depth BMD threshold of 8 mm corresponded to an equivalent $J_{nr,\,3.2\,kPa}$ value of 0.85, falling within Category H. This indicates that no issues related to rutting were observed. In addition, an IDT-HT strength of 133 kPa resulted in a $J_{nr,\,3.2\,kPa}$ value of 0.77, which also fell within Category H.

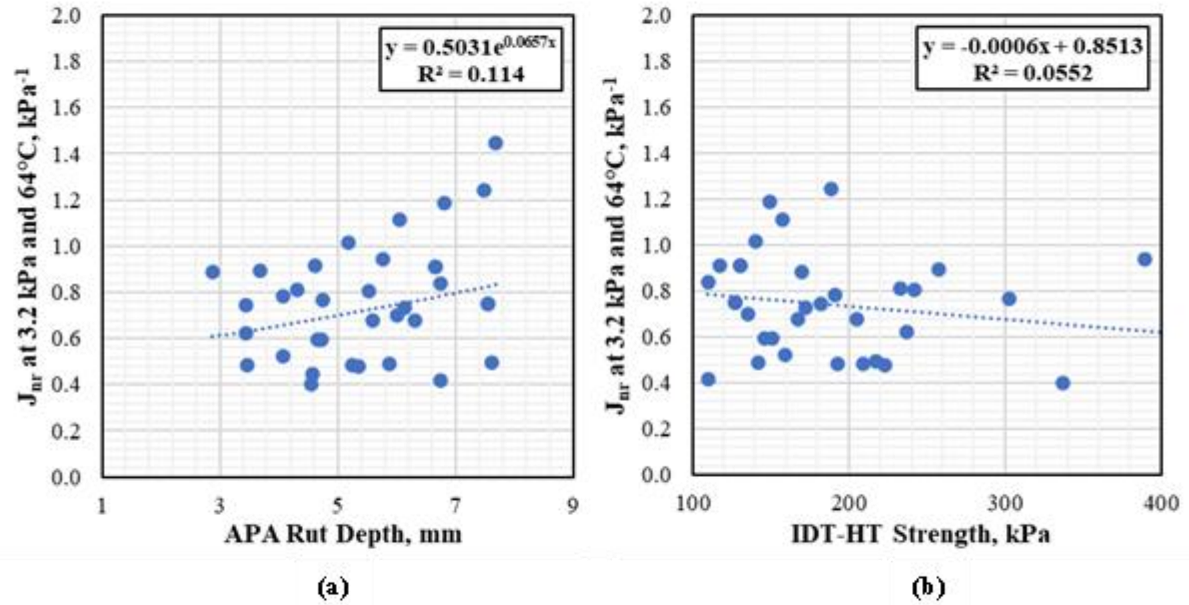
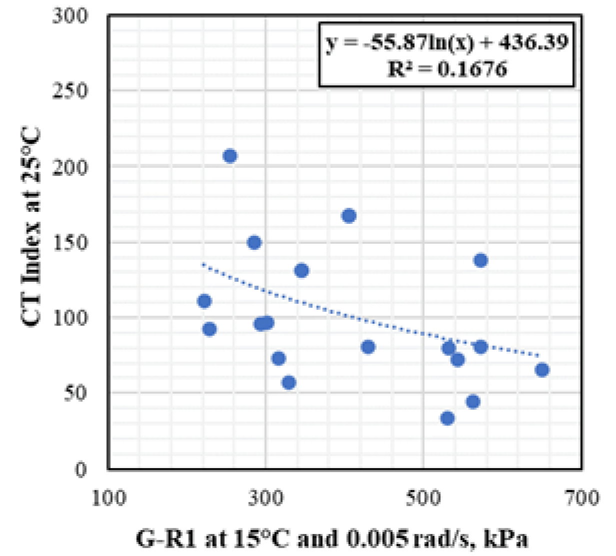


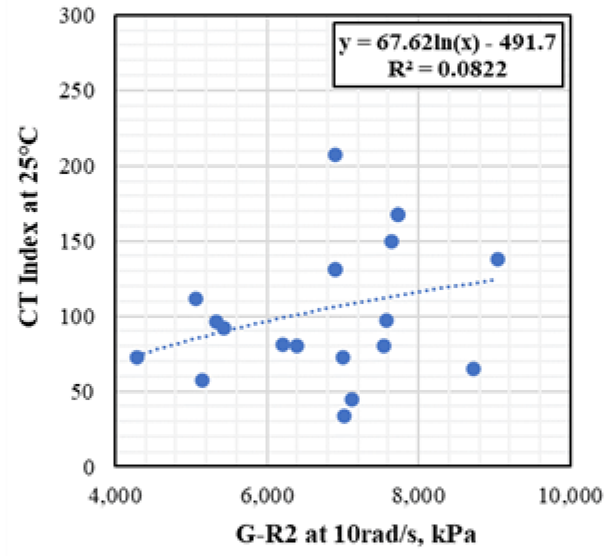
Figure 19. Correlation Between $J_{nr,\ 3.2\ kPa}$ and (a) APA Rut Depth and (b) IDT-HT Strength. $J_{nr,\ 3.2\ kPa}$ = non-recoverable creep compliance at 3.2 kPa; APA = asphalt pavement analyzer; IDT-HT = indirect tensile test at high temperature.

It is crucial to recognize the limitations of these relationships due to the restricted dataset examined in this study. Further investigations with a larger and more diverse dataset are needed to strengthen and understand the correlations and provide more comprehensive insights into the rutting performance of asphalt mixtures in relation to binder properties.

The second category focused on cracking and aimed to establish relationships between the BMD parameter of the mixtures, such as the CT index, and binder parameters including G-R1, G-R2, R-Value, N_f at 5% and 10% strain, and ΔTc. Figure 20 depicts the relationship between the CT index of the reheated mixtures and the G-R1 and G-R2 values of the extracted and recovered binders. As with the first category, the data were widely dispersed, and weak relationships were observed. In addition, an unexpected trend was observed for G-R2, as higher CT index values should typically correspond to lower G-R2 values, which was not the case in this study. It is important to acknowledge the limitations of these relationships due to the weak correlations observed. However, disregarding the weaknesses, it is worth noting that a CT index BMD threshold of 70 resulted in a G-R1 value of 705 kPa, exceeding the cutoff limit of 600 kPa. A CT index of 70 resulted in a G-R2 value of 4,051 kPa, below the threshold of 5,000 kPa, suggesting the potential absence of cracking issues. Figure 21 illustrates the relationship between the CT index of the reheated mixtures and the R-value and N_f at 10% strain of the extracted and recovered binders. The BMD CT index threshold of 70 yielded an R-value of 2.570, surpassing the upper limit of 2.5 recommended by Christensen and Tran (2022). Further, there was a positive relationship between the CT index and N_f at 10% strain, indicating that higher CT index values corresponded to greater N_f values. It is important to consider the limitations of these correlations given the weak relationships observed and the need for further research with a broader dataset to enhance the understanding of the cracking performance of asphalt mixtures in relation to binder properties.

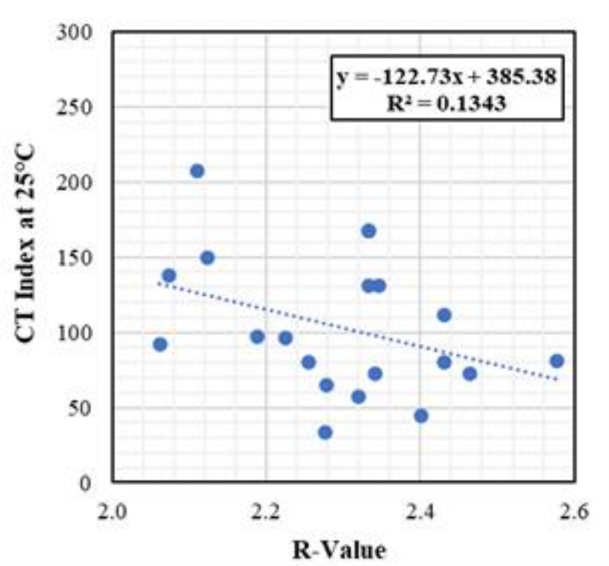


(a)

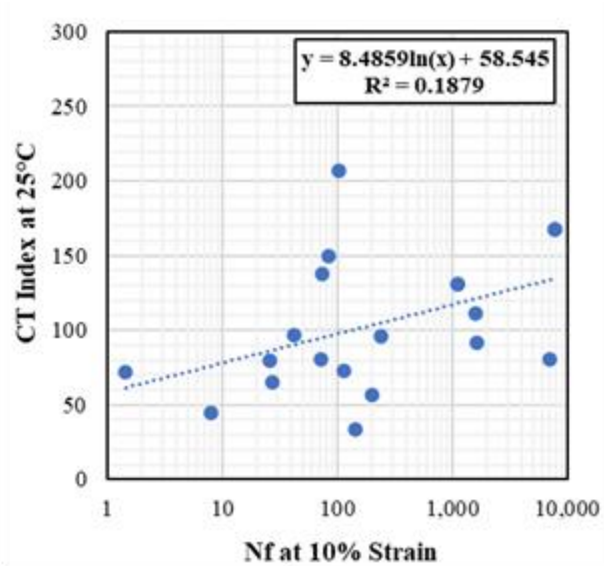


(b)

Figure 20. Correlation Between CT Index and (a) G-R1 at 15°C and 0.005 rad/s and (b) G-R2 at 10 rad/s. CT = cracking tolerance; G-R = Glover Rowe parameter.



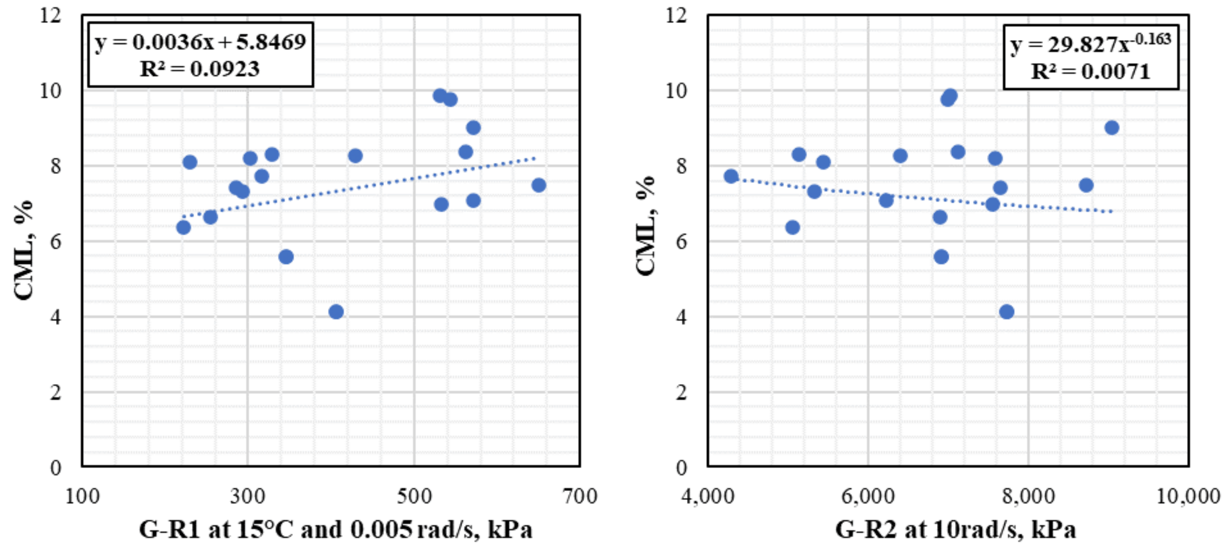
(a)



(b)

Figure 21. Correlation Between CT Index and (a) R-Value and (b) LAS Binder Fatigue Parameter, N_f, at 10% strain. CT = cracking tolerance; LAS = linear amplitude sweep.

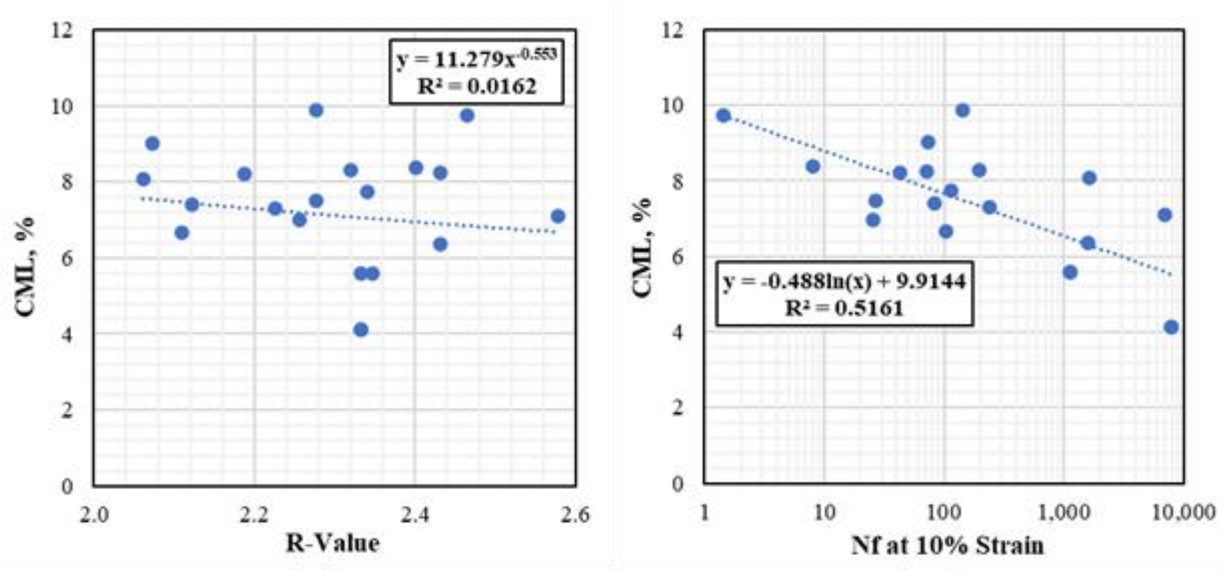
The third category focused on durability and aimed to establish relationships between the BMD parameters of the mixtures, specifically the Cantabro mass loss (CML), and the same binder properties and parameters used to evaluate cracking in the previous section. Figure 22 presents the relationship between the CML of the reheated mixtures and the G-R1 and G-R2 values of the extracted and recovered binders. As with the first two categories, the data were widely dispersed, and weak relationships were observed.



(a) **(b)**

Figure 22. Correlation Between CML and (a) G-R1 at 15°C and 0.005 rad/s and (b) G-R2 at 10 rad/s. CML = Cantabro mass loss; G-R = Glover Rowe parameter.

In addition, an unexpected trend was observed for G-R2, as higher CML values would typically result in higher G-R2 values, which was not the case in this study. It is important to acknowledge the limitations of these relationships due to the weak correlations observed. However, disregarding the weaknesses, it is worth noting that a CML BMD threshold of 7.5% resulted in a G-R1 value of 459 kPa, falling below the significant cracking limit of 600 kPa. Further, a CML of 7.5% resulted in a G-R2 value of 4,767 kPa, below the cutoff limit of 5,000 kPa, suggesting the potential absence of durability issues. Figure 23 illustrates the relationship between the CML of the reheated mixtures and the R-value and N_f at 10% strain of the extracted and recovered binders. The BMD CML threshold of 7.5% yielded an R-value of 2.091, which falls within the range of 1.5 to 2.5 recommended by Christensen and Tran (2022). Further, a logical relationship was observed between CML and N_f at 10% strain, indicating that lower CML values corresponded to greater N_f values. It is crucial to consider the limitations of these correlations given the weak relationships observed and the need for further research with a broader dataset to enhance the understanding of the durability performance of asphalt mixtures in relation to binder properties.



(a) (b)

Figure 23. Correlation Between CML and (a) R-Value and (b) LAS Binder Fatigue Parameter, N_f, at 10% strain. CML = Cantabro mass loss; LAS = linear amplitude sweep.

CONCLUSIONS

- *The 2021 and 2022 BMD schedule pilot projects demonstrated conclusively that BMD can be applied to contracts by VDOT.* Although there are still many lessons to be learned and improvements to be made, the implementation of BMD is promising.

- *Precision statements for the Cantabro and APA rut tests are necessary to evaluate test results for acceptable variability.* The variability in test results within single laboratory datasets and the need to be able to compare results between laboratories in this study support this need.

- *Defined practices for reheating mixture samples and fabricating test specimens are needed based on the differences between VDOT and VTRC reheat test results.*

- *There is a need to evaluate further the effects of sampling and specimen preparation practices on BMD testing.* This was illustrated by differences in the results of tests performed on specimens fabricated in a single laboratory.

- *Overall, variability in test results decreased from 2021 to 2022, demonstrating the benefits of training and experience in the performance of BMD testing.*

- *A better understanding of the sensitivity and variability characteristics of each BMD test method is crucial for the establishment and refining of test tolerance limits and the successful implementation of BMD acceptance practices.* Each BMD test was shown to have a different response to inherent production variability through analysis of the within-lot sample-to-sample variability.

- *Designing and producing asphalt mixtures having performance properties in near proximity to required performance thresholds carry a risk of failure during production due to inherent material and test variability, even for well-controlled processes*. "Near proximity" is defined as an average test result being within the single-operator acceptable limits of the performance threshold.

- *The source and formulation of the base binder used, along with the properties of the aged binder in RAP stockpiles, lead to substantial variations in binder properties and the anticipated performance of produced mixtures*. The evaluation of extracted and recovered binders used in the 2021 and 2022 construction season revealed consistent PG temperatures among binders used within the same year, irrespective of the RAP content and virgin binder. However, notable differences were observed between the extracted and recovered binders employed in 2021 and 2022.

- *Establishing correlations between asphalt mixture properties and virgin and RAP asphalt binder properties is crucial for optimizing mixture performance and durability. However, to conduct sound analyses and observations, a large and diverse dataset with a wide range of data is still needed.* It is important to acknowledge the limitations of the relationships evaluated in this study and emphasize the need for further research that involves larger and more diverse datasets. This will help strengthen the correlations and provide a comprehensive understanding of the performance of asphalt mixtures in relation to binder properties.

RECOMMENDATIONS

1. *VDOT's Materials Division should continue to pursue efforts toward full implementation of BMD in Virginia for SMs with A and D designations.* The successful outcomes observed during the 2019 and 2020 field trials, and the 2021 and 2022 maintenance plant mix schedule pilots, clearly demonstrate the efficacy of applying BMD to SMs with A and D designations. These successes encompass various aspects, including design, production, laboratory-based performance assessment, bidding on contract schedules for pilots, and mix data collection and processing carried out collaboratively by the three parties involved: the industry, VDOT, and VTRC.

2. *VTRC with support from VDOT's Materials Division should conduct a comprehensive ruggedness study focused on the refinement of specimen preparation and test methods for the IDT-CT and IDT-HT.* This effort is necessary to assess key factors that demand stricter control and additional guidance during the specimen preparation of plant mixtures for IDT-CT and IDT-HT testing. The outcome of this effort should involve recommending enhanced and unified best practices, with a specific emphasis on specimen preparation, to reduce single-operator and multi-laboratory test variability, especially during production. These recommendations will support VDOT's implementation efforts moving forward. This recommendation aims to improve variability during production without affecting the 2024 implementation plan and outcomes. This effort is crucial as more states are transitioning toward or progressing with the adoption of BMD.

3. *VTRC should conduct a comprehensive study to assess the relationships between the properties of virgin and RAP asphalt binders and those of the corresponding asphalt mixtures.* To optimize pavement performance and enhance durability, it is crucial to consider the properties of asphalt mixtures, including resistance to rutting and cracking and overall mixture durability. These properties are significantly influenced by the characteristics of both the virgin and RAP asphalt binders used in the mixture. By establishing correlations and relationships between these properties, engineers and researchers can effectively select appropriate virgin binders, assess RAP binder characteristics, and customize mix designs to meet the specific requirements of each project, resulting in improved pavement performance and longevity.

The 2021 and 2022 plant mix schedule pilots reported in this study built upon the experiences from the initial roadmap development and specification verification presented in detail in *Balanced Mix Design for Surface Asphalt Mixtures: Phase I: Initial Roadmap Development and Specification Verification* (Diefenderfer et al., 2021a) and from the 2019 and 2020 field trials presented in detail in *Balanced Mix Design for Asphalt Surface Mixtures: 2019 Field Trials* (Diefenderfer et al., 2021b) and *Balanced Mix Design for Asphalt Surface Mixtures: 2020 Field Trials* (Diefenderfer et al., 2023). The recommendations from the 2019 and 2020 field trial studies remain applicable to this study. To avoid redundancy, only recommendations resulting from the data collected and corresponding analyses in this study are presented here.

IMPLEMENTATION AND BENEFITS

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

Implementation

Regarding Recommendation 1, VDOT's Materials Division, with the support of VTRC and the industry, has developed the 2024 BMD special provision that is planned for inclusion in 2024 maintenance plant mix contracts. The special provision will support the implementation of BMD for all SM-9.5 and SM-12.5 mixtures having A and D binders.

Regarding Recommendation 2, VTRC drafted and submitted a research needs statement to the VTRC Pavement Research Advisory Committee, Subcommittee B, for ranking with the intent of initiating the effort in Fiscal Year 2024.

Regarding Recommendation 3, VTRC will draft and submit a research needs statement to the appropriate VTRC Pavement Research Advisory Committee Subcommittee by no later than Fiscal Year 2025.

Benefits

Regarding Recommendation 1, continued forward movement in BMD implementation is expected to result in longer lasting SMs as mixture performance properties are prioritized. This will allow for the further optimization of mixture properties and development of innovative mixtures that support the goals of longer lasting, cost-effective, and sustainable pavements.

Regarding Recommendation 2, understanding the key factors that demand stricter control and additional guidance during the specimen preparation of plant mixtures for the IDT-CT and IDT-HT will provide for the development of enhanced and unified best practices, with a specific emphasis on specimen preparation. The application of best practices, whether through training and/or refinement of the test method, will reduce variability in performance testing, providing more confidence in test results and the ability to consider the use of performance-based specifications for acceptance.

Regarding Recommendation 3, improved understanding of the interactions of virgin and RAP asphalt binder characteristics and mixture performance properties will allow mix designers to optimize the use of materials to meet performance expectations and produce more consistent mixtures. Both of these outcomes will contribute to longer lasting pavements.

ACKNOWLEDGEMENTS

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APPENDIX A

2021 BMD SPECIAL PROVISIONS

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

October 28, 2020

I. Description

These Specifications cover the requirements and materials used to produce Surface Mixtures designed using Performance Criteria. Balanced Mix Design (BMD) Surface Mixtures shall be designed, produced, and placed as required by this Special Provision and Sections 211 and 315 of the Specifications.

II. Materials

All materials shall conform to Section 211.02 of the Specifications with the exception that Recycled Asphalt Shingles (RAS) will not be allowed in these mixes.

III. Job-Mix Formula (JMF)

Mix Types SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D may be designed to meet either the Performance + Volumetric (BMD P+V) criteria or the Performance Only (BMD P) criteria included in this section. Each mix type used shall conform to Section 211 of the Specifications and any related Special Provisions included in the Contract. Approval from the Engineer is required if the Contractor uses a PG binder grade not currently approved or an asphalt rejuvenator to meet the performance criteria.

Control mixture in this specification refers to the surface mixture designated as such in the Contract. The control mix shall conform to Section 211 of the Specifications.

Type Performance + Volumetric (BMD P+V) asphalt mixtures shall be designed to conform to Section 211.03 of the Specifications as well as Table 1. Mix design number for BMD P+V mix shall have BPV at the end of the control mix design number (i.e. 1234-5678-90 BPV).

Type Performance Only (BMD P) asphalt mixtures shall be designed to conform to Section 211.03 of the Specifications except that the requirements in Tables II-13 and II-14 shall be waived. However, the grading and Superpave volumetric properties shall be reported in the mix design submittal in accordance with AASHTO R 35, and shall include the varying AC analysis. Mix design number for BMD P mix shall have BP at the end of the control mix design number (i.e. 1234-5678-90 BP).

In addition, these mix types shall conform to Table 1 at the design binder content. Testing shall be reported as follows:

- APA rut testing (AASHTO T 340): at design and 0.5% above the design binder content
- Cantabro testing (AASHTO TP 108): at design and 0.5% below the design binder content
- CT_{Index} testing (ASTM D8225): at design, at 0.5% above, and 0.5% below the design binder content

For any three mix types including the control mixture, a set of 5 CT_{index} pills with the final design JMF (only at the design binder content) shall be fabricated from long-term aged loose mix and tested in accordance with ASTM D8225. Test results shall be submitted with the JMF for the mix design review. Long-term aging shall be performed by aging loose laboratory produced mix for 8 hours at 135ºC, after short term oven aging is performed as required by Table 1. During long-term aging, the mix shall be uniformly placed in a pan such that the height of the loose mix shall not exceed the mixture NMAS. Opening of the oven door shall be minimized during long-term aging. Specimens shall be heated to compaction temperature following aging and then compacted. The heating to compaction temperature shall not exceed 75 minutes.

The JMFs for three mix types (Control, BMD P+V, and BMD P) shall meet the nominal max aggregate size (NMAS) of the designated mix type.

The JMF for (BMD P) type mixes shall establish a single percentage of aggregate passing each required sieve, a single percentage of liquid asphalt material to be added to the mix, the ranges for which the SUPERPAVE volumetric properties defined by AASHTO R 35 will be held to during production, and a temperature at which the mixture is to be produced.

The performance qualities (as defined in Table 1) for the type (BMD P or BMD P+V) JMF shall exhibit improvement over the original JMF (Control), specifically: higher CT_{index}, lower rutting depth, and less mass loss on Cantabro.

Table 1
Performance Testing Requirements

Test	Requirements	Criteria
AASHTO T 340 METHOD OF TEST FOR DETERMINING RUTTING SUSCEPTIBILITY OF HMA USING THE ASPHALT PAVEMENT ANALYZER (APA)	• Testing shall be performed at 64ºC. • 4 gyratory pills: 150 mm dia., 75 ± 2 mm ht. • Compact to 7±0.5% air voids. • Lab-produced mix: Condition loose mix for 2 hours at the design compaction temperature before compacting. • Plant-produced mix: Minimize any cooling, bring mix to the compaction temperature, and compact immediately.	Rutting ≤ 8.0mm
AASHTO TP 108 Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens (Cantabro)	• 3 gyratory pills: 150 mm dia., 115 ± 5 mm ht. • Compact to N_{design}, report air voids. • Lab-produced mix: Condition loose mix for 2 hours at the design compaction temperature before compacting.	Mass loss ≤ 7.5%
ASTM D8225 Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature	• 5 gyratory pills: 150mm dia., 62 ± 1 mm ht. • Compact to 7±0.5% air voids. • Lab-produced mix: Condition loose mix for 4 hours at the design compaction temperature before compacting. • Before testing, condition pills at 25 ± 1°C for 2 hours ± 10 min. Pills must remain dry; if conditioning in a water bath, pills must be sealed in plastic bags.	CT_{index} ≥ 70

IV. Production Testing

The Contractor and the Department will conduct testing as required by Sections 211.05 and 211.06 of the Specifications for control and P+V mixes.

Performance testing shall be conducted in accordance with Table 1 and at the frequency shown in Table 2. Should any performance tests fail to meet the criteria as specified in Table 1, the Department may require that production be stopped until corrective actions are taken by the Contractor. Nothing in Table 2 is intended to change the lot sizes defined by Sections 211 and 315 of the Specifications. For the Control mix, Table 2 testing requirements may be applied to 2,000 tons. The Contractor shall report Quality Control (QC) test results within 2 weeks of sampling to the Department. Six boxes of loose mix shall be collected during the sampling for each set of VDOT Quality Assurance (QA) test pills, at the frequency noted in Table 2. Boxes will hold approximately 70 lbs. of loose mix and will be provided by the Department. Loose mix sampled should completely fill each box.

Table 2
Testing Frequency[1] (4,000T lot)

Property/Test	Frequency (tons)	Number of Specimens (per lot)
CT_{index}[2] – QC	1,000	20
Cantabro[2] – QC	1,000	12
CT_{index}[2] – VDOT QA[3]	2,000	10
Cantabro[2] – VDOT QA[3]	2,000	6
Rutting[2] – VDOT QA[3]	2,000	8
Loose Mix sample – Research[3]	2,000	12 boxes

[1]With a minimum of 1 QC sample per day.
[2]Minimize any cooling of the plant produced mix and bring the specimens to the compaction temperature and compact immediately to the specimen size requirements in TABLE 1.
[3]QA pills shall be fabricated and provided to the Department by the Contractor. Loose mix sampling shall be also performed by the Contractor and provided to the Department. Boxes used for loose mix samples will be supplied by the Department

V. Acceptance

Acceptance for mix types (BP+V) and (BP) shall be as required by the Special Provision for Section 211.

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

VI. Initial Production

Mix types (BMD P+V) and (BMD P) shall be subject to Section 211.15 of the Specifications at the Engineer’s discretion.

VII. Measurement and Payment

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

Payment will be made under:

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

BALANCED MIX DESIGN (BMD) - The Special Provision for **Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria** dated October 28, 2020 is amended as follows:

Section IV. Production Testing is amended by replacing the first paragraph with the following:

> The Contractor and the Department will conduct testing as required by Section 211.05 and 211.06 of the Specifications for Control, P+V, and P mixes.

11-24-20 (SPCN)

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
HIGH RECLAIMED ASPHALT PAVEMENT (RAP) CONTENT SURFACE MIXTURES DESIGNED USING PERFORMANCE CRITERIA

October 30, 2020

I. Description

These Specifications cover the requirements and materials used to produce High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures, containing higher than 30% RAP, designed using Performance Criteria. High RAP Content Surface Mixtures shall be designed, produced, and placed as required by this Special Provision and Sections 211 and 315 of the Specifications. High RAP Content Surface Mixtures consist of a combination of coarse aggregate, fine aggregate, RAP, and liquid asphalt binder mechanically mixed in a plant to produce a stable asphalt concrete paving mixture.

II. Materials

All materials shall conform to Section 211.02 of the Specifications with the exception that Recycled Asphalt Shingles (RAS) will not be allowed in these mixes.

III. Job-Mix Formula (JMF)

Mix Types SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D may be designed to meet either the Performance + Volumetric (HR P+V) criteria or the Performance Only (HR P) criteria included in this section. Each mix type used shall conform to Section 211 of the Specifications and any related Special Provisions included in the Contract, except the maximum RAP percentages as indicated in Table II-14A will be waived. Approval from the Engineer is required if the Contractor uses a PG binder grade not currently approved or an asphalt recycling agent to meet the performance criteria.

Control mixture in this specification refers to the surface mixture designated as such in the Contract. The control mix shall conform to Section 211 of the Specification.

Although the laboratory mixing and compaction temperatures for the control mixes shall conform to Section 211.03(d)6 of the Specifications, for all pilot mix types (HR P+V) and (HR P) the temperatures shall be as required for mix designation D.

Type Performance + Volumetric (HR P+V) asphalt mixtures shall be designed to conform to Section 211.03 of the Specifications as well as Table 1. Mix design number for HR P+V mix shall have PV at the end of the control mix design number (i.e. 1234-5678-90 PV).

Type Performance Only (HR P) asphalt mixtures shall be designed to meet the requirements of Section 211.03 of the Specifications except that the requirements in Tables II-13 and II-14 shall be waived. However, the grading and Superpave volumetric properties shall be reported in the mix design submittal in accordance with AASHTO R 35, and shall include the varying AC analysis. Mix design number for HR P mix shall have P at the end of the control mix design number (i.e. 1234-5678-90 P).

In addition, these mix types shall meet the criteria of Table 1 herein at the design binder content. Testing shall be reported as follows:

- APA rut testing (AASHTO T 340): at design and 0.5% above the design binder content
- Cantabro testing (AASHTO TP 108): at design and 0.5% below design binder content
- CT_{Index} testing (ASTM D8225): at design, at 0.5% above, and 0.5% below the design binder content

For any three mix types including the control mixture, a set of 5 CT_{index} pills with the final design JMF (only at the design binder content) shall be fabricated from long-term aged loose mix and tested in accordance with ASTM D8225. Test results shall be submitted with the JMF for the mix design review. Long-term aging shall be performed by aging loose laboratory produced mix for 8 hours at 135ºC, after short term oven aging is performed as required by Table 1. During long-term aging, the mix shall be uniformly placed in a pan such that the height of the loose mix shall not exceed the mixture NMAS. Opening of the oven door shall be minimized during long-term aging. Specimens shall be heated to compaction temperature following aging and then compacted. The heating to compaction temperature shall not exceed 75 minutes.

The JMFs for three mix types (Control, HR P+V, and HR P) shall meet the nominal max aggregate size (NMAS) of the designated mix type.

The JMF for (HR P) type mixes shall establish a single percentage of aggregate passing each required sieve, a single percentage of liquid asphalt material to be added to the mix, the ranges for which the SUPERPAVE volumetric properties defined by AASHTO R 35 will be held to during production, and a temperature at which the mixture is to be produced.

The performance qualities (as defined in Table 1) for the type (HR P) JMF shall exhibit improvement over the type (HR P+V) JMF, specifically: higher CT_{index}, lower rutting depth, and less mass loss on Cantabro.

Table 1
Performance Testing Requirements

Test	Requirements	Criteria
AASHTO T 340 METHOD OF TEST FOR DETERMINING RUTTING SUSCEPTIBILITY OF HMA USING THE ASPHALT PAVEMENT ANALYZER (APA)	• Testing shall be performed at 64ºC. • 4 gyratory pills: 150 mm dia., 75 ± 2 mm ht. • Compact to 7±0.5% air voids. • <u>Lab-produced mix:</u> Condition loose mix for 2 hours at the design compaction temperature before compacting. • <u>Plant-produced mix</u>: Minimize any cooling, bring mix to the compaction temperature, and compact immediately.	Rutting ≤ 8.0mm
AASHTO TP 108 Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens (Cantabro)	• 3 gyratory pills: 150 mm dia., 115 ± 5 mm ht. • Compact to N_{design}, report air voids. • <u>Lab-produced mix:</u> Condition loose mix for 2 hours at the design compaction temperature before compacting.	Mass loss ≤ 7.5%
ASTM D8225 Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature	• 5 gyratory pills: 150mm dia., 62 ± 1 mm ht. • Compact to 7±0.5% air voids. • <u>Lab-produced mix:</u> Condition loose mix for 4 hours at the design compaction temperature before compacting. • Before testing, condition pills at 25 ± 1°C for 2 hours ± 10 min. Pills must remain dry; if conditioning in a water bath, pills must be sealed in plastic bags.	$CT_{index} \geq 70$

IV. Production Testing

The Contractor and the Department will conduct testing as required by Sections 211.05 and 211.06 of the Specifications for control and P+V mixes.

Performance testing shall be conducted in accordance with Table 1 and at the frequency shown in Table 2. Should any performance tests fail to meet the criteria as specified in Table 1, the Department may require that production be stopped until corrective actions are taken by the Contractor. Nothing in Table 2 is intended to change the lot sizes defined by Sections 211 and 315 of the Specifications. For the Control mix, Table 2 testing requirements may be applied to 2,000 ton. The Contractor shall report Quality Control (QC) test results within 2 weeks of sampling to the Department. Six boxes of loose mix shall be collected during the sampling for each set of VDOT Quality Assurance (QA) test pills, at the frequency noted in Table 2. Boxes will hold approximately 70 lbs. of loose mix and will be provided by the Department. Loose mix sampled should completely fill each box.

Table 2
Testing Frequency[1] (4,000T lot)

Property/Test	Frequency (tons)	Number of Specimens (per lot)
CT_{index}[2] – QC	1,000	20
Cantabro[2] – QC	1,000	12
CT_{index}[2] – VDOT QA[3]	2,000	10
Cantabro[2] – VDOT QA[3]	2,000	6
Rutting[2] – VDOT QA[3]	2,000	8
Loose Mix sample – Research[3]	2,000	12 boxes

[1]With a minimum of 1 QC sample per day.
[2]Minimize any cooling of the plant produced mix and bring the specimens to the compaction temperature and compact immediately to the specimen size requirements in TABLE 1.
[3]QA pills shall be fabricated and provided to the Department by the Contractor. Loose mix sampling shall be also performed by the Contractor and provided to the Department. Boxes used for loose mix samples will be supplied by the Department

V. Acceptance

Acceptance for mix types (HR P+V) and (HR P) shall be as required by the Special Provision for Section 211 of the Specifications.

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

VI. Initial Production

Mix types (HR P+V) and (HR P) shall be subject to Section 211.15 of the Specifications at the Engineer's discretion.

VII. Measurement and Payment

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

Payment will be made under:

Pay Item	Pay Unit
Asphalt Concrete HR P+V (mix type)	Ton
Asphalt Concrete HR P (mix type)	Ton

HIGH RECLAIMED ASPHALT PAVEMENT (RAP) - The Special Provision for **High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria** dated October 30, 2020 is amended as follows:

Section IV. Production Testing is amended by replacing the first paragraph with the following:

The Contractor and the Department will conduct testing as required by Section 211.05 and 211.06 of the Specifications for Control, HR P+V, and HR P mixes."

11-24-20 (SPCN)

APPENDIX B

2022 BMD SPECIAL PROVISION

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

October 26, 2021

I. Description

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

II. Materials

All materials shall conform to Section 211.02 of the Specifications with the exception that Recycled Asphalt Shingles (RAS) will not be allowed in these mixes.

III. Job-Mix Formula (JMF)

Mix Types SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D shall be designed to meet the Performance + Volumetric Optimized (BMD P+VO) criteria included in this section. Each mix type used shall conform to Section 211 of the Specifications. The Contractor shall submit the mix design at least 30 days before the mix is produced. Approval from the Engineer is required if the Contractor uses a PG binder grade not recommended by Table II-14A of Section 211 of the Specifications.

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

Asphalt Concrete Mixtures: Design Range

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

The design binder content should be selected at 3.0% - 4.5% air voids. Design type shall be 'BMD P+VO' when submitting the mix design.

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

- APA rut testing (AASHTO T 340): at design binder content and at 0.5% above the design binder content
- Cantabro testing (AASHTO TP 108): at design binder content and at 0.5% below the design binder content
- CT_{Index} testing (ASTM D8225): at design binder content, at 0.5% above, and at 0.5% below the design binder content

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

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

For the BMD P+VO mixtures, a set of 5 CT_{index} pills with the final design JMF (only at the design binder content) shall be fabricated from long-term aged loose mix and tested in accordance with ASTM D8225. Test results shall be submitted with the JMF for the mix design review. Long-term aging shall be performed by aging loose laboratory produced mix for 8 hours at 135ºC, after short term oven aging is performed as required by Table 1. During long-term aging, the mix shall be uniformly placed in a pan such that the height of the loose mix shall not exceed the mixture nominal max aggregate size. Opening of the oven door shall be minimized during long-term aging. Specimens shall be heated to compaction temperature following aging and then compacted. The heating to compaction temperature shall not exceed 75 minutes.

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

Table 1
Performance Testing Requirements

Test	Requirements	Criteria
AASHTO T 340 METHOD OF TEST FOR DETERMINING RUTTING SUSCEPTIBILITY OF HMA USING THE ASPHALT PAVEMENT ANALYZER (APA)	• Testing shall be performed at 64ºC. • 4 gyratory pills: 150 mm dia., 75 ± 2 mm ht. • Compact to 7±0.5% air voids. • Lab-produced mix: Condition loose mix for 2 hours at the design compaction temperature before compacting. • Plant-produced mix: Minimize any cooling, bring mix to the compaction temperature, and compact immediately.	Rutting ≤ 8.0mm
AASHTO TP 108 Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens (Cantabro)	• 3 gyratory pills: 150 mm dia., 115 ± 5 mm ht. • Compact to N_{design}, report air voids. • Lab-produced mix: Condition loose mix for 2 hours at the design compaction temperature before compacting. • Plant-produced mix: Minimize any cooling, bring mix to the compaction temperature, and compact immediately.	Mass loss ≤ 7.5%
ASTM D8225 Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature	• 5 gyratory pills: 150mm dia., 62 ± 1 mm ht. • Compact to 7±0.5% air voids. • Lab-produced mix: Condition loose mix for 4 hours at the design compaction temperature before compacting. • Plant-produced mix: Minimize any cooling, bring mix to the compaction temperature, and compact immediately. • Before testing, condition pills at 25 ± 1°C for 2 hours ± 10 min. Pills must remain dry; if conditioning in a water bath, pills must be sealed in plastic bags.	CT_{index} ≥ 70

IV. Production Testing

The Contractor and the Department will conduct testing as required by Sections 211.05 and 211.06 of the Specifications. In addition to all of the testing requirements for SUPERPAVE mixes, performance testing shall also be conducted by the Contractor**,** in accordance with Table 1 and at the frequency shown in Table 2. Nothing in Table 2 is intended to change the lot sizes defined by Sections 211 and 315 of the Specifications. The Contractor shall report Quality Control (QC) performance test results within 1 week of sampling to the Department. Submitting QC performance test results within 48 hrs by the Contractor is strongly recommended. If less than 300 tons of asphalt mixture is produced under a single JMF in a day, SUPERPAVE testing and performance testing will not be required on that day. That day's tonnage shall be added to subsequent production. When the accumulated tonnage exceeds 300 tons, minimum testing frequency for SUPERPAVE and performance testing shall apply and results shall be reported. The Contractor shall fabricate and provide the specimens meeting requirements in Table 1 including dimensions and air voids, to the Department.

Table 2
Performance Testing Frequency (per lot)

Property/Test	Frequency (tons)	Number of Specimens (per lot)
CT_{index}[1]	2,000	10
Cantabro[1]	2,000	6
CT_{index}[1] – VDOT[2]	4,000	5
Cantabro[1] – VDOT[2]	4,000	3
Rutting[1] – VDOT[2]	1 per project	4 per project

[1] Minimize any cooling of the plant produced mix and bring the specimens to the compaction temperature and compact immediately to the specimen requirements in TABLE 1.
[2] VDOT pills shall be fabricated in accordance with Table 1 and provided to the Department by the Contractor.

V. Acceptance

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

Although acceptance will be based on Section 211, should any performance test results (based on the average of required number of specimens tested) fail to meet the criteria as specified in Table 1, the Department may require that production be stopped until corrective actions are taken by the Contractor.

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

VI. Adjustment System

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

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

VII. Initial Production

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

VIII. Measurement and Payment

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

Payment will be made under:

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

APPENDIX C

2021 MAINTENANCE SCHEDULE BMD TEST RESULTS

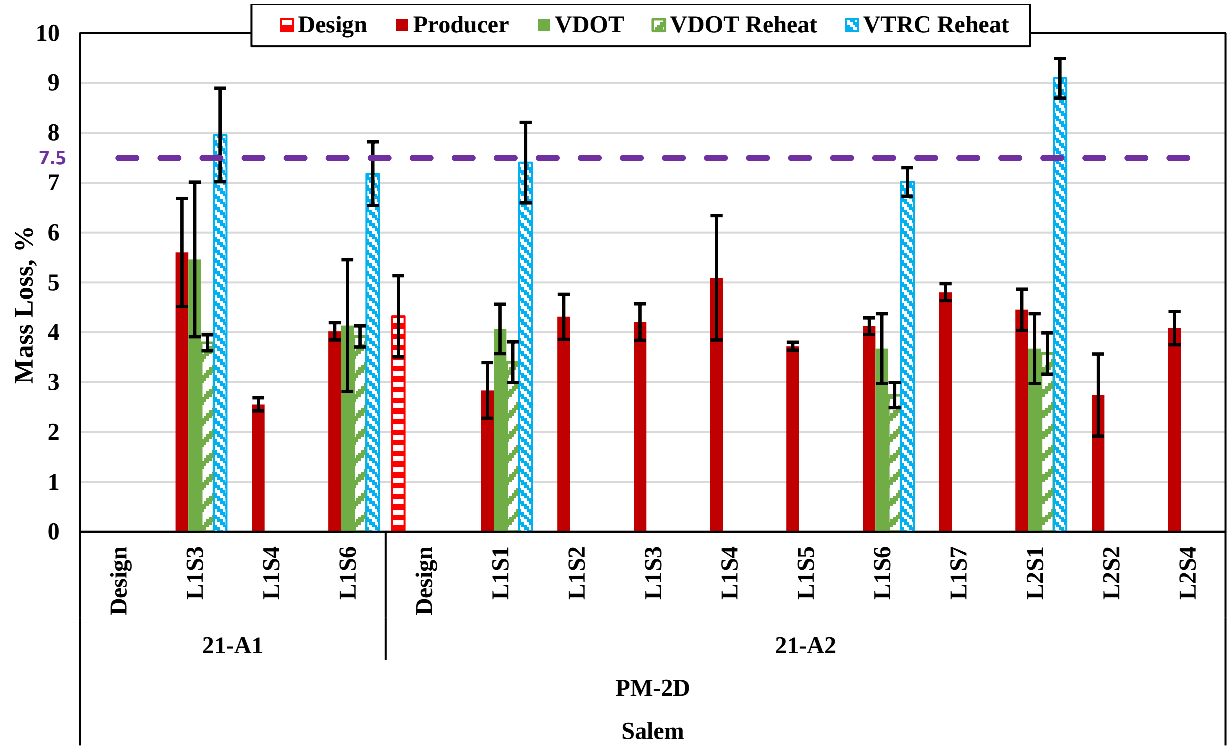

Figure C1. Mass Loss Values for Samples Collected From Mixtures Paved on Schedule PM-2D. Purple line indicates maximum allowable mass loss. L = lot number; S = sample number.

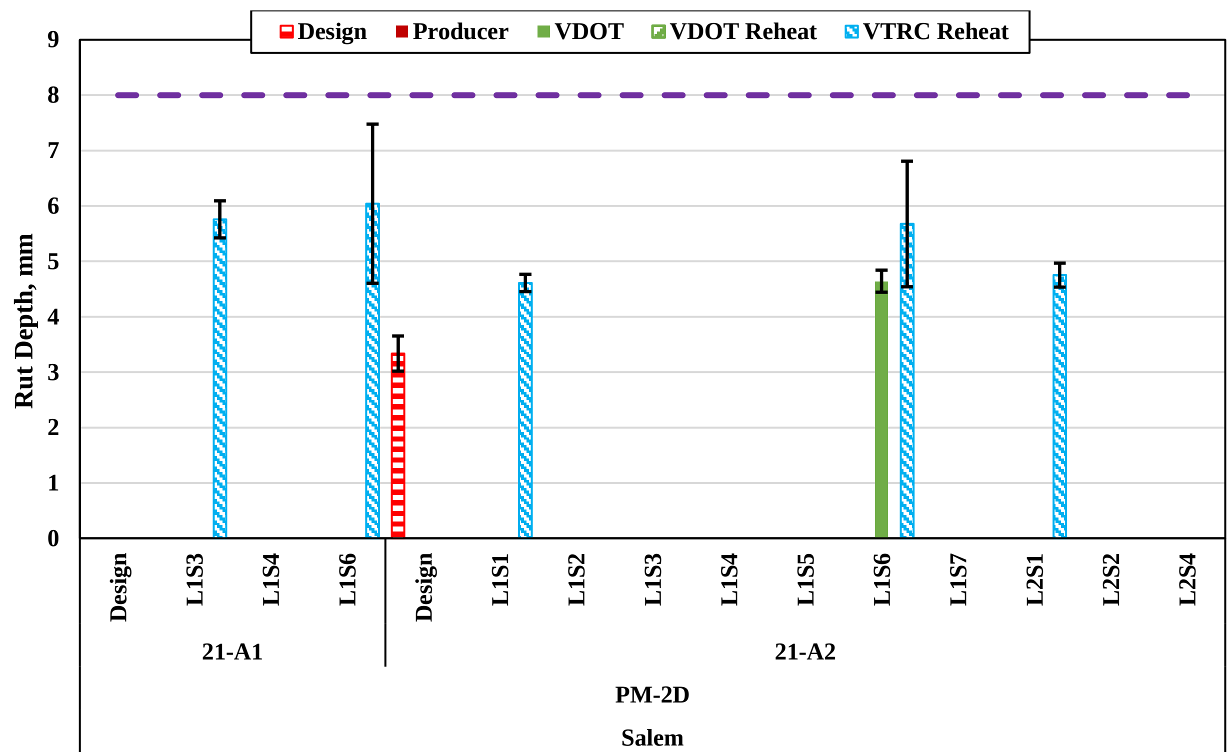

Figure C2. Rut Depth Values for Samples Collected From Mixtures Paved on Schedule PM-2D. Purple line indicates maximum allowable rut depth. L = lot number; S = sample number.

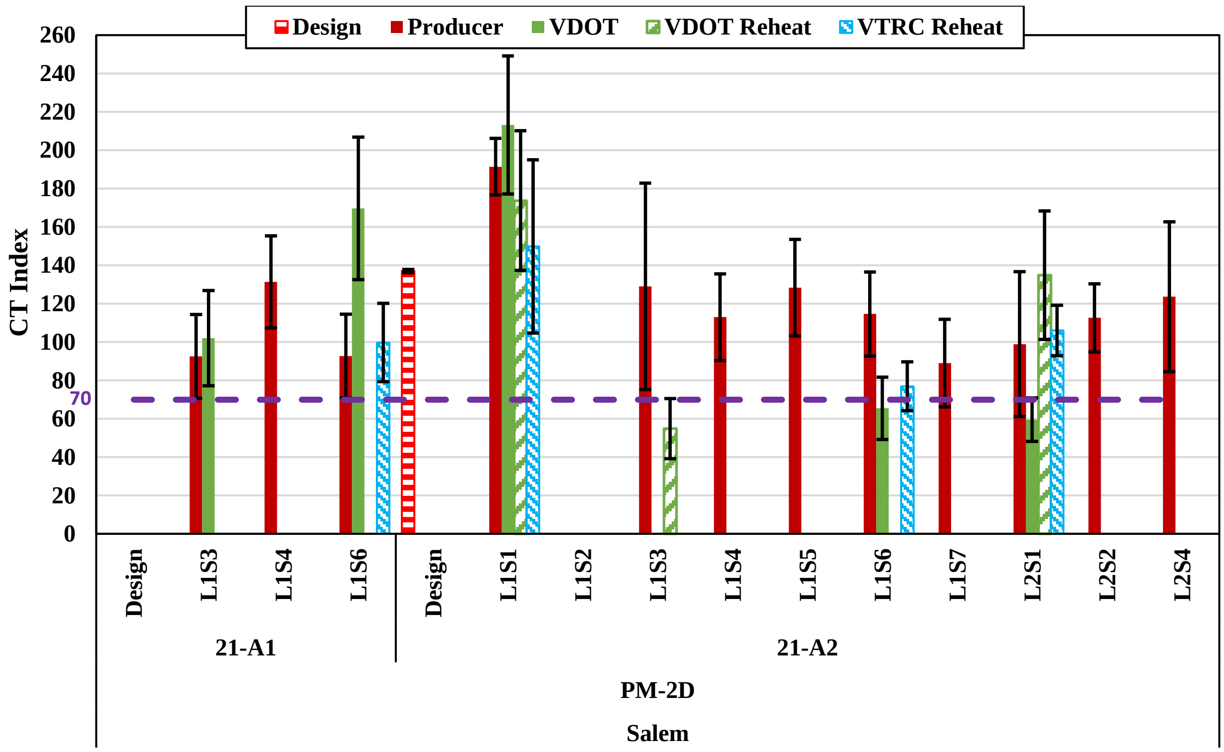

Figure C3. CT Index Values for Samples Collected From Mixtures Paved on Schedule PM-2D. Purple line indicates minimum allowable CT index. CT = cracking tolerance; L = lot number; S = sample number.

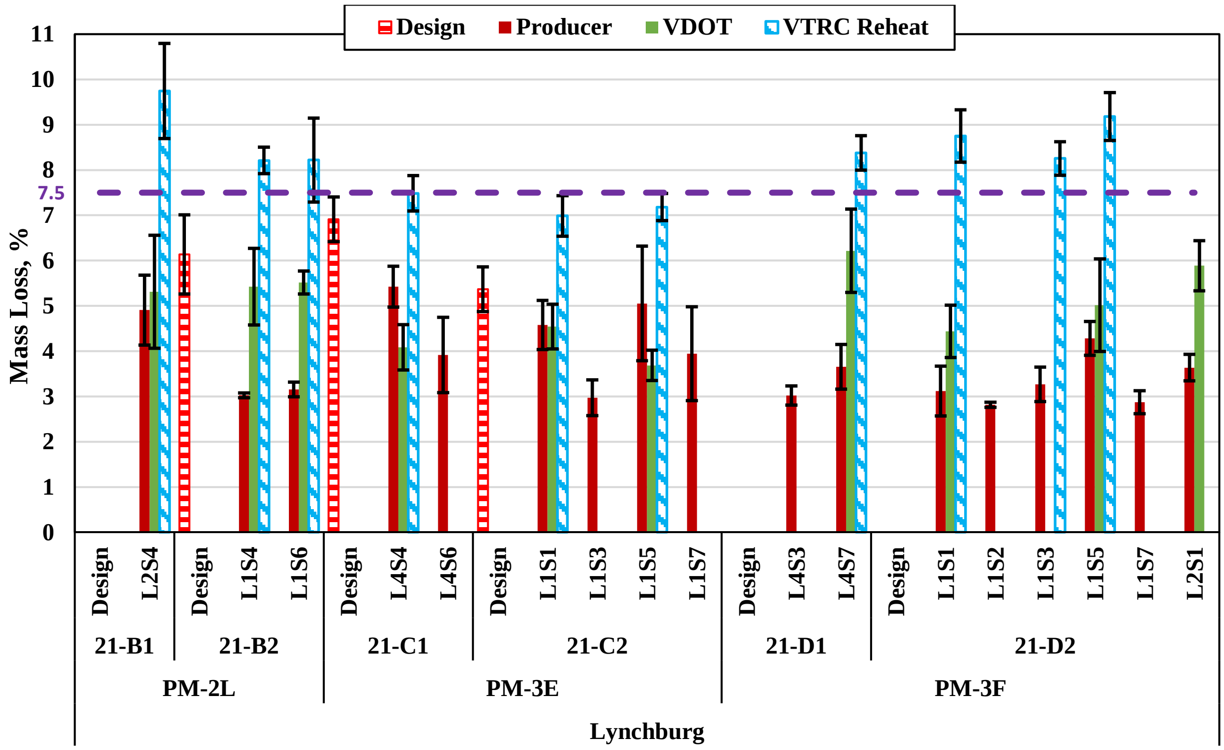

Figure C4. Mass Loss Values for Samples Collected From Mixtures Paved on Schedules PM-2L, PM-3E, and PM-3F. Schedule PM-2L was issued by the Salem District; the plant producing the mixture for the project was located in the Lynchburg District, and all plant sampling and testing were performed by the Lynchburg District. Purple line indicates maximum allowable mass loss. L = lot number; S = sample number.

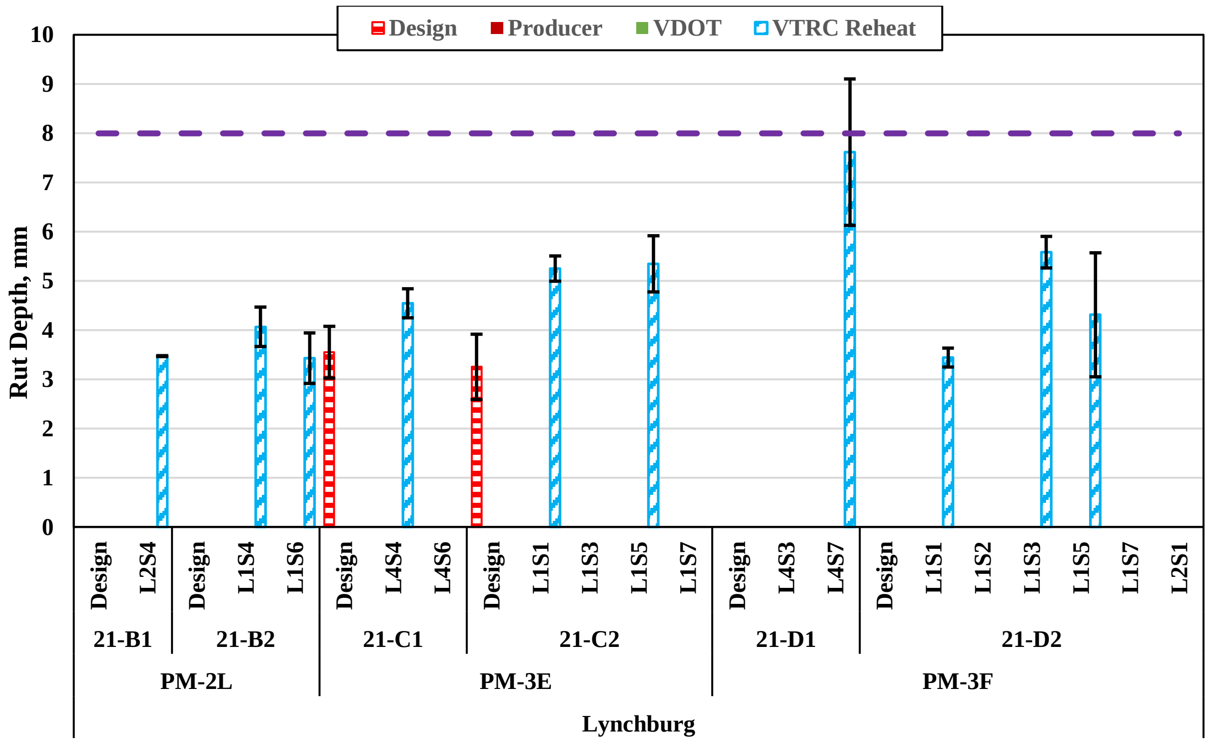

Figure C5. Rut Depth Values for Samples Collected From Mixtures Paved on Schedules PM-2L, PM-3E, and PM-3F. Schedule PM-2L was issued by the Salem District; the plant producing the mixture for the project was located in the Lynchburg District, and all plant sampling and testing were performed by the Lynchburg District. Purple line indicates maximum allowable rut depth. L = lot number; S = sample number.

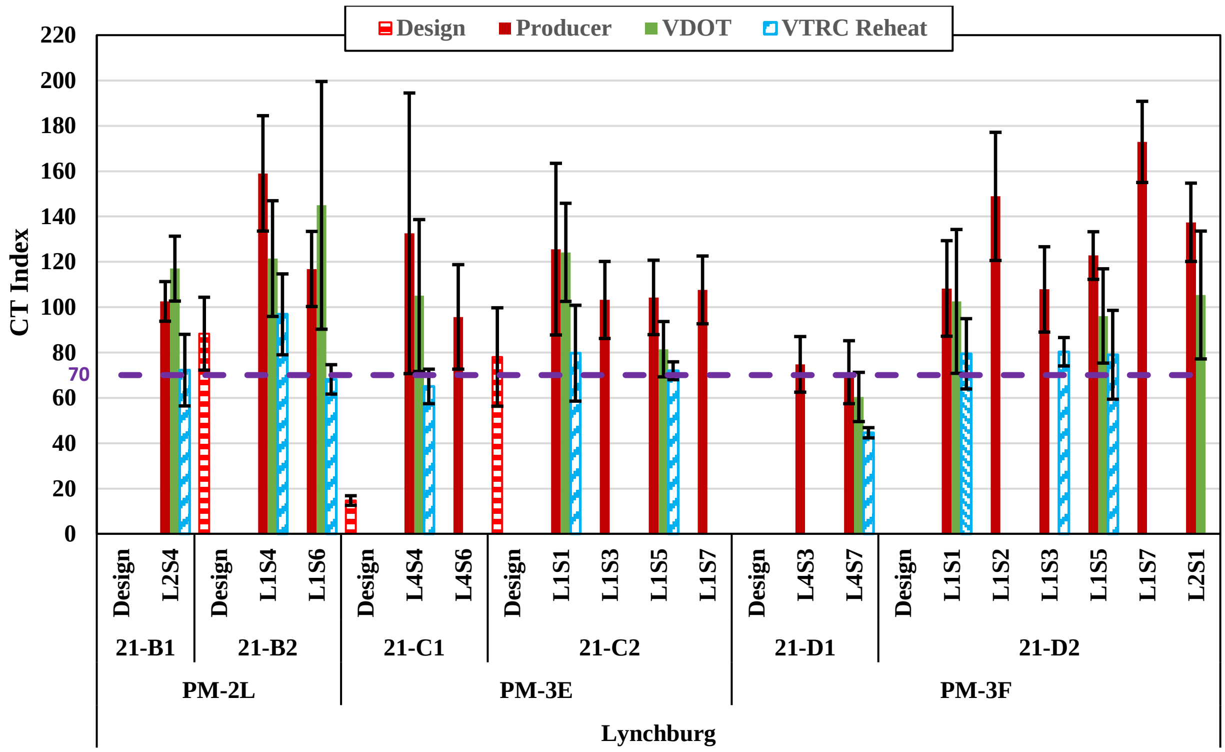

Figure C6. CT Index Values for Samples Collected From Mixtures Paved on Schedules PM-2L, PM-3E, and PM-3F. Schedule PM-2L was issued by the Salem District; the plant producing the mixture for the project was located in the Lynchburg District, and all plant sampling and testing were performed by the Lynchburg District. Purple line indicates minimum allowable CT index. L = lot number; S = sample number.

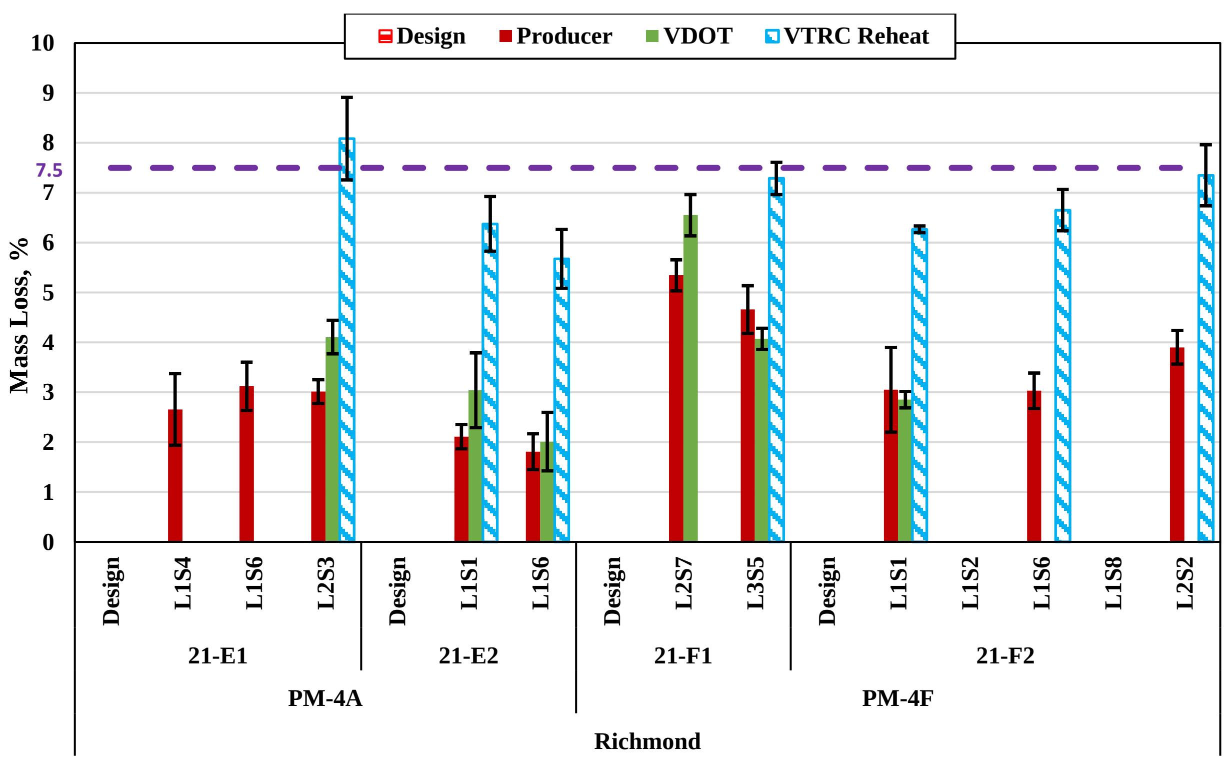

Figure C7. Mass Loss Values for Samples Collected From Mixtures Paved on Schedules PM-4A and PM-4F. Purple line indicates maximum allowable mass loss. L = lot number; S = sample number.

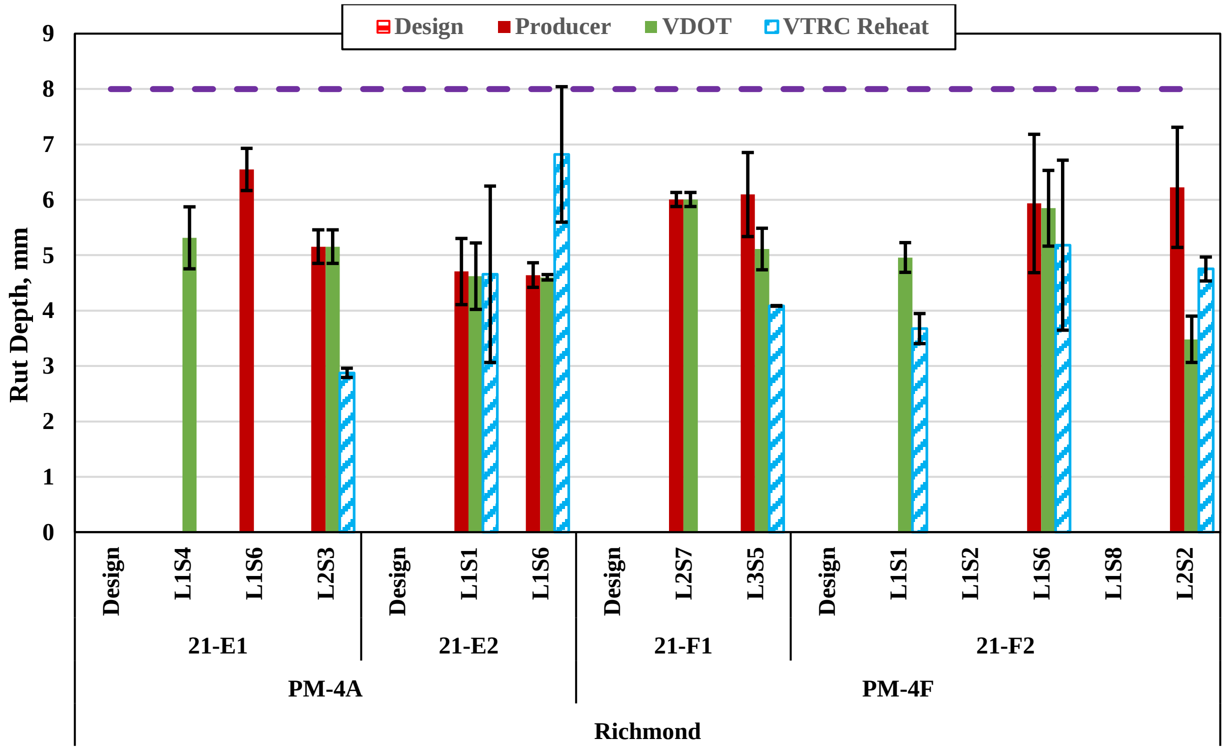

Figure C8. Rut Depth Values for Samples Collected From Mixtures Paved on Schedules PM-4A and PM-4F. Purple line indicates maximum allowable rut depth. L = lot number; S = sample number.

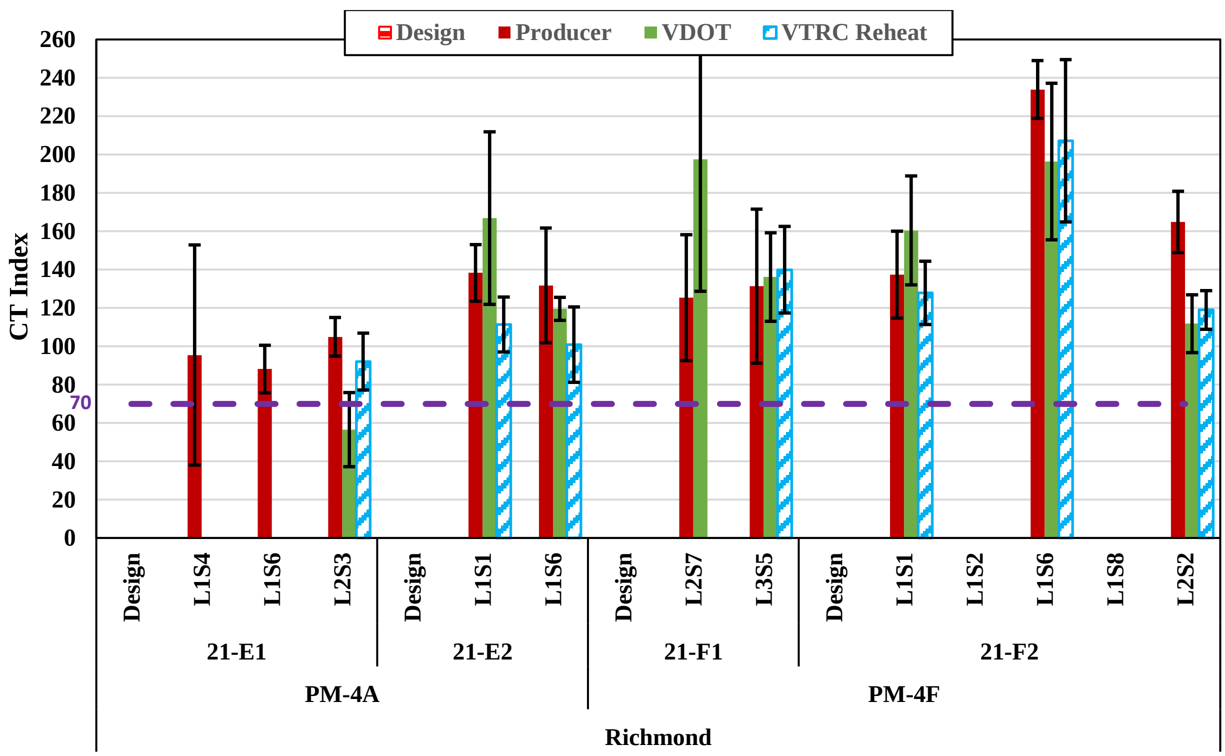

Figure C9. CT Index Values for Samples Collected From Mixtures Paved on Schedules PM-4A and PM-4F. Purple line indicates minimum allowable CT index. L = lot number; S = sample number.

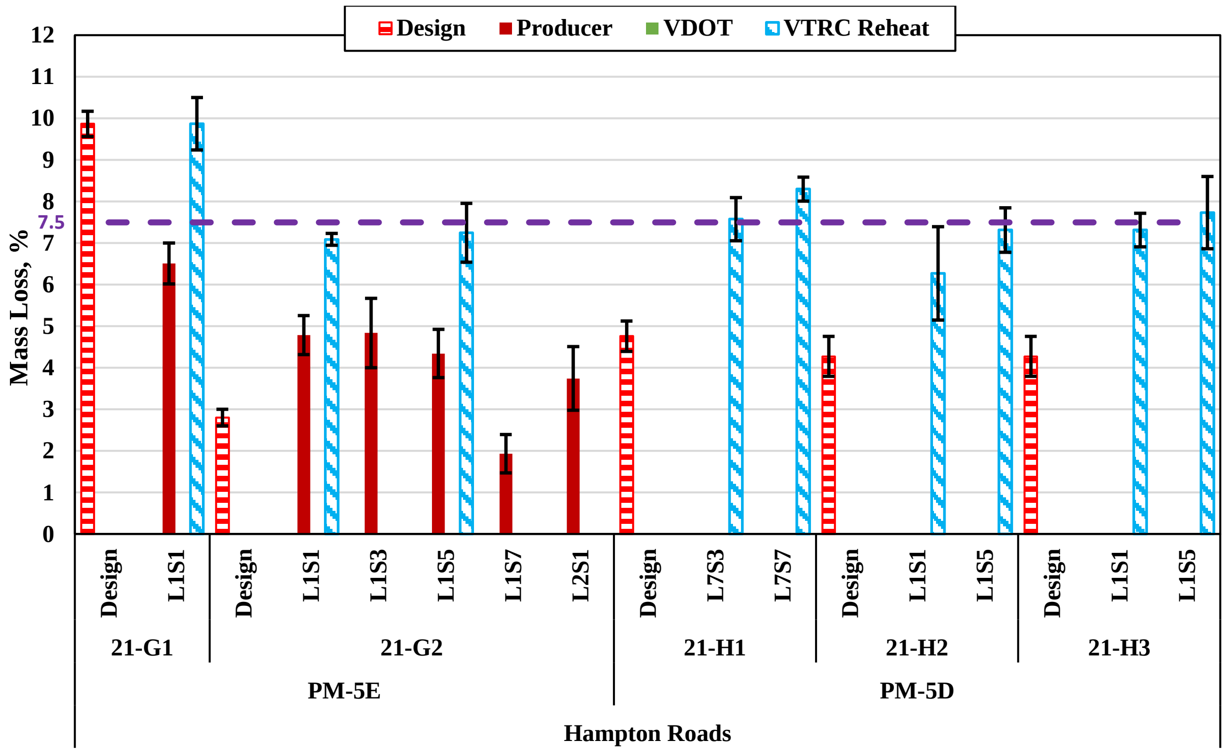

Figure C10. Mass Loss Values for Samples Collected From Mixtures Paved on Schedules PM-5E and PM-5D. Purple line indicates maximum allowable mass loss. L = lot number; S = sample number.

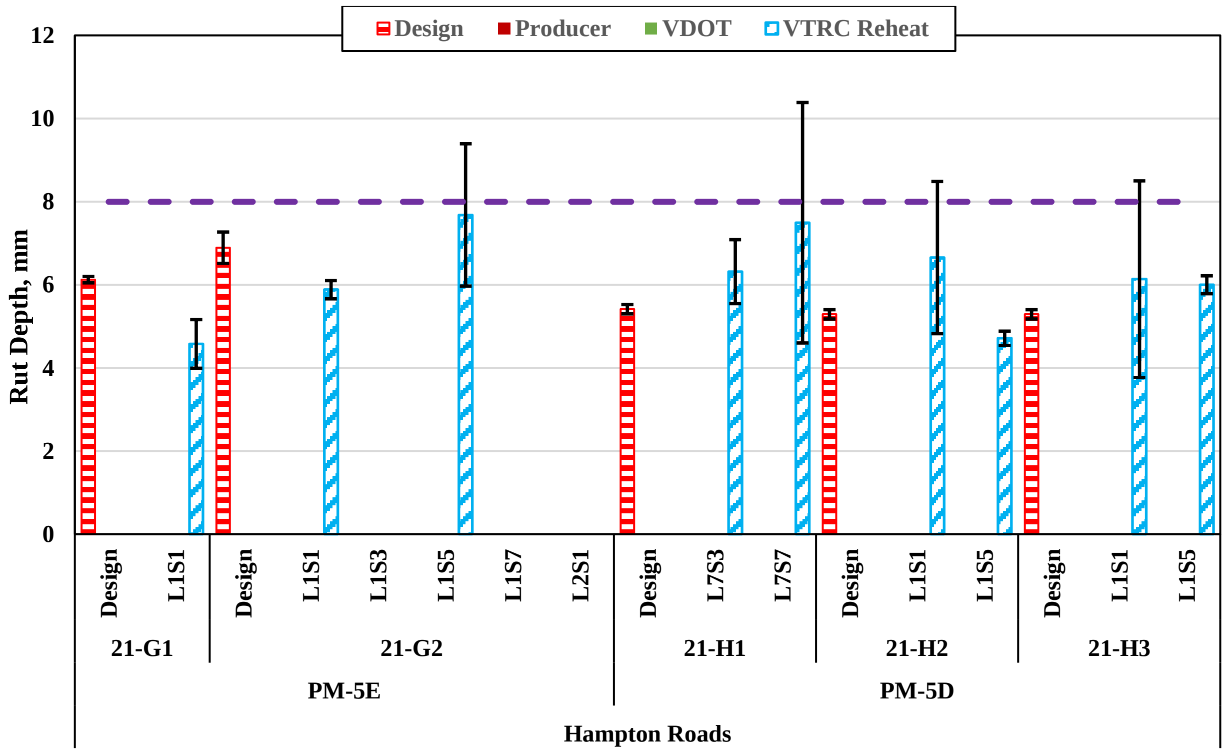

Figure C11. Rut Depth Values for Samples Collected From Mixtures Paved on Schedules PM-5E and PM-5D. Purple line indicates maximum allowable rut depth. L = lot number; S = sample number.

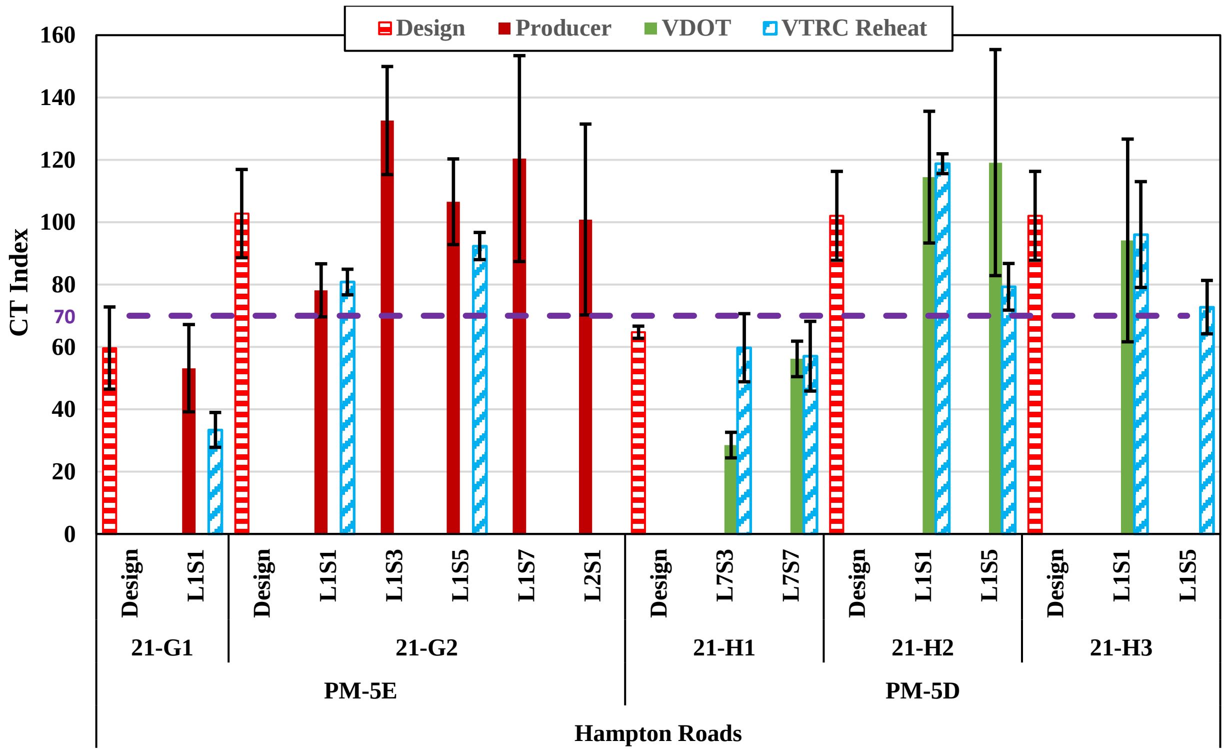

Figure C12. CT Index Values for Samples Collected From Mixtures Paved on Schedules PM-5EA and PM-5D. Purple line indicates minimum allowable CT index. L = lot number; S = sample number.

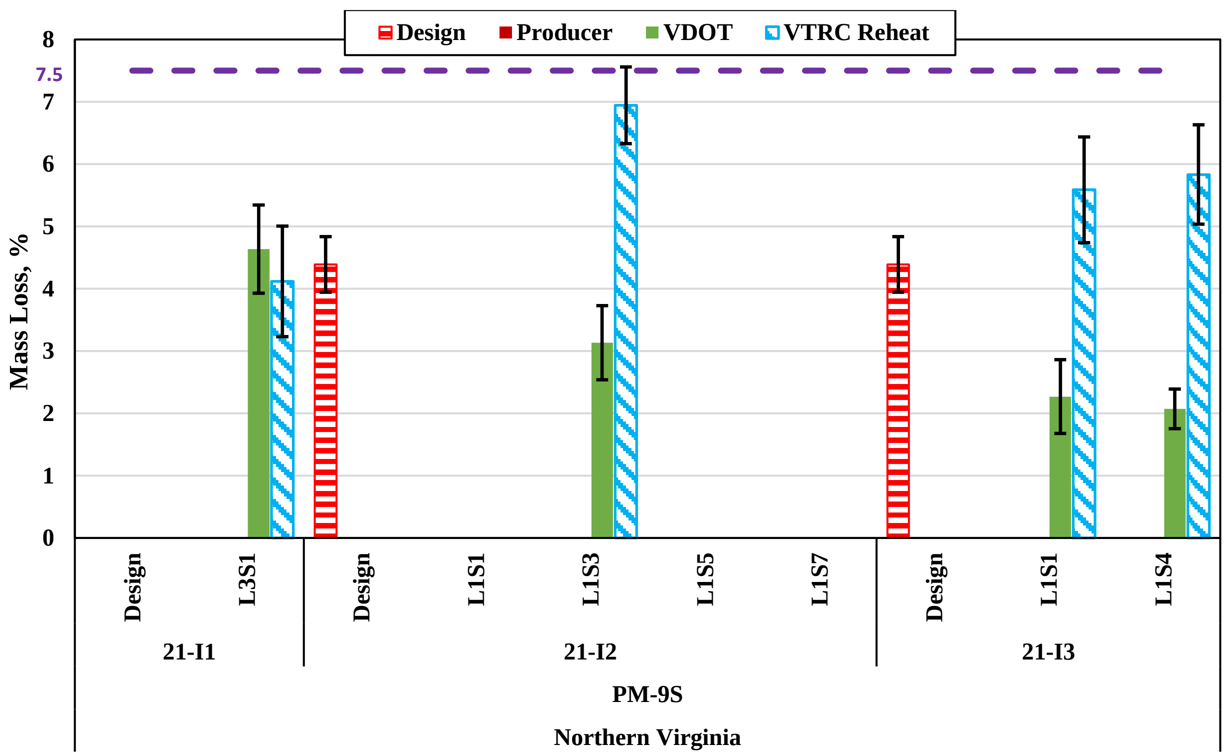

Figure C13. Mass Loss Values for Samples Collected From Mixtures Paved on Schedule PM-9S. Purple line indicates maximum allowable mass loss. L = lot number; S = sample number.

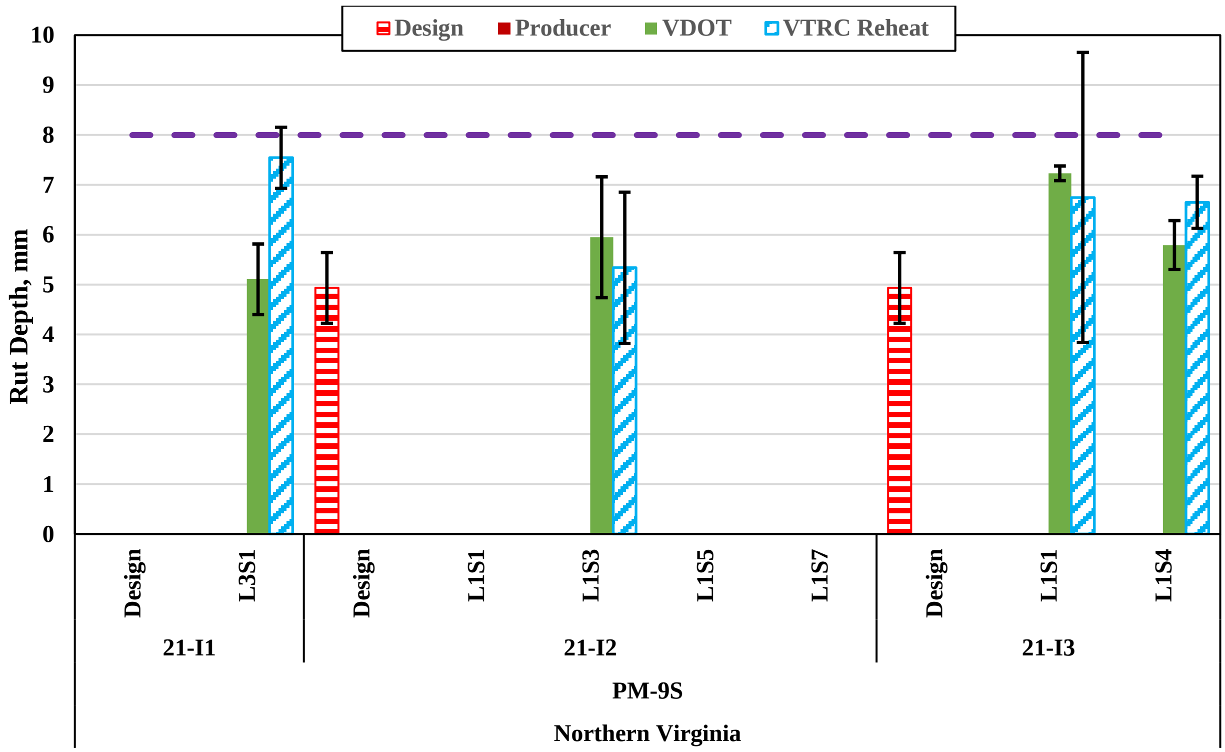

Figure C14. Rut Depth Values for Samples Collected From Mixtures Paved on Schedule PM-9S. Purple line indicates maximum allowable rut depth. L = lot number; S = sample number.

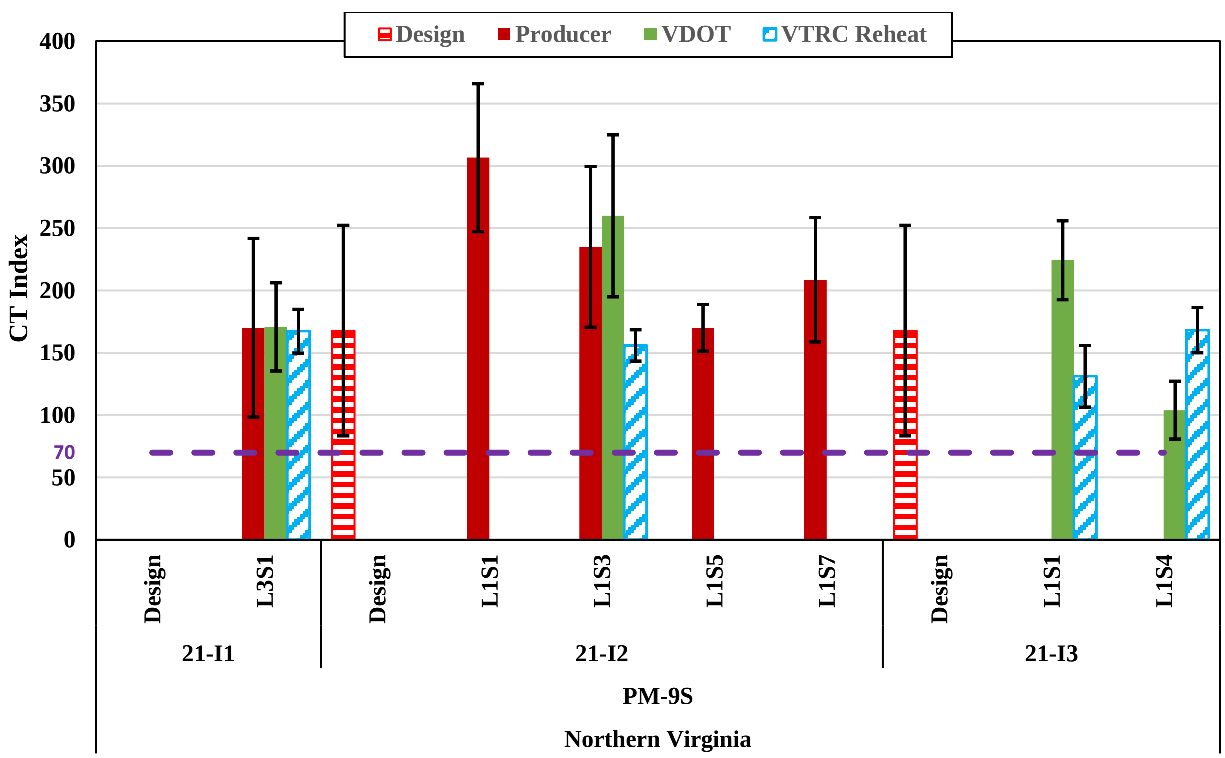

Figure C15. CT Index Values for Samples Collected From Mixtures Paved on Schedule PM-9S. Purple line indicates minimum allowable CT index. L = lot number; S = sample number.