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# Balanced Mix Design for Surface Mixtures: 2020 Field Trials

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**Final Report VTRC 23-R13**

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**Standard Title Page - Report on Federally Funded Project**

| 1. Report No.: FHWA/VTRC 23-R13 | 2. Government Accession No.: | 3. Recipient's Catalog No.: |
|---|---|---|
| 4. Title and Subtitle: Balanced Mix Design for Surface Mixtures: 2020 Field Trials | | 5. Report Date: March 2023<br>6. Performing Organization Code: |
| 7. Author(s): Stacey D. Diefenderfer, Ph.D., P.E., Jhony Habbouche, Ph.D., P.E., and Ilker Boz, Ph.D. | | 8. Performing Organization Report No.: VTRC 23-R13 |
| 9. Performing Organization and Address:<br>Virginia Transportation Research Council<br>530 Edgemont Road<br>Charlottesville, VA 22903 | | 10. Work Unit No. (TRAIS):<br>11. Contract or Grant No.: 119857 |
| 12. Sponsoring Agencies' Name and Address:<br>Virginia Department of Transportation<br>1401 E. Broad Street<br>Richmond, VA 23219 | Federal Highway Administration<br>400 North 8th Street, Room 750<br>Richmond, VA 23219-4825 | 13. Type of Report and Period Covered: Final<br>14. Sponsoring Agency Code: |

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


16. Abstract:

The Virginia Department of Transportation (VDOT) has been working toward the implementation of balanced mix design (BMD) for several years. During that time, special provisions have been developed to address dense-graded surface mixtures with reclaimed asphalt pavement (RAP) contents up to 30% and with RAP contents of 40% and above. In 2020, five field trials encompassing 12 mixtures were constructed to evaluate BMD mixtures designed and produced in accordance with VDOT's special provision for surface mixtures with high RAP contents. Typical dense-graded Superpave surface mixtures were used as controls. This study documented and assessed these trials to provide information to evaluate the impact of various RAP contents and additives, production variability, reheating, and binder properties on BMD performance test results.

Twelve mixtures were evaluated during the five field trials. The mixtures included combinations of different RAP contents, two binder grades, four recycling agents, and fiber. Volumetric and gradation analysis was performed on the mixtures. The Cantabro mass loss test (Cantabro test), the indirect tensile cracking test (IDT-CT), and the Asphalt Pavement Analyzer (APA) test were performed on laboratory-produced design specimens and non-reheated and reheated plant-produced, laboratory-compacted specimens. All findings and conclusions are limited to the mixtures evaluated.

Based on the test results, mixtures containing 35% or greater RAP contents, softer binders, recycling agents, and fiber may be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements. It was found that some mixtures that were volumetrically designed under current VDOT specifications met BMD requirements. In addition, the expected trends in mixture performance testing were not always observed, likely due to masking by variability due to specimen fabrication practices or by inherent test variability. Results showed that modest relationships between non-reheated and reheated specimen results for the Cantabro test and IDT-CT were present. In addition, changes due to the use of a softer binder and/or recycling agents were seen in the BMD mixture binders as compared with the control mixture binder. Finally, comparisons of extracted and recovered binders from control and BMD mixtures were found to depend on the binder test under consideration, with different tests indicating differences in expected performance.

Based on the outcomes of the study, a testing protocol capable of evaluating the performance of recycling agents used in BMD mixtures is needed. This protocol would provide a means for VDOT to evaluate and accept these materials such that their use in innovative mixtures can be allowed in a manner that preserves the goals of sustainable, longer-lasting, and cost-effective pavements. In addition, efforts should be made to determine the effect of asphalt binder properties on the overall performance of asphalt mixtures with a primary focus on cracking and durability to allow VDOT to specify better-performing binders for use in asphalt mixtures. This would allow for the further optimization of mixture properties that should result in improved mixture performance.


| 17 Key Words: | 18. Distribution Statement: |
|---|---|
| Balanced mix design, field trial, plant production, rutting, cracking, durability, performance testing, APA rut test, Cantabro test, indirect tensile cracking test, cracking index | No restrictions. This document is available to the public through NTIS, Springfield, VA 22161. |

| 19. Security Classif. (of this report): | 20. Security Classif. (of this page): | 21. No. of Pages: | 22. Price: |
|---|---|---|---|
| Unclassified | Unclassified | 82 | |

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# FINAL REPORT

# BALANCED MIX DESIGN FOR SURFACE MIXTURES: 2020 FIELD TRIALS

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In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

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

Charlottesville, Virginia

March 2023
VTRC 23-R13

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# ABSTRACT

The Virginia Department of Transportation (VDOT) has been working toward the implementation of balanced mix design (BMD) for several years. During that time, special provisions have been developed to address dense-graded surface mixtures with reclaimed asphalt pavement (RAP) contents up to 30% and with RAP contents of 40% and above. In 2020, five field trials encompassing 12 mixtures were constructed to evaluate BMD mixtures designed and produced in accordance with VDOT's special provision for surface mixtures with high RAP contents. Typical dense-graded Superpave surface mixtures were used as controls. This study documented and assessed these trials to provide information to evaluate the impact of various RAP contents and additives, production variability, reheating, and binder properties on BMD performance test results.

Twelve mixtures were evaluated during the five field trials. The mixtures included combinations of different RAP contents, two binder grades, four recycling agents, and fiber. Volumetric and gradation analysis was performed on the mixtures. The Cantabro mass loss test (Cantabro test), the indirect tensile cracking test (IDT-CT), and the Asphalt Pavement Analyzer (APA) test were performed on laboratory-produced design specimens and non-reheated and reheated plant-produced, laboratory-compacted specimens. All findings and conclusions are limited to the mixtures evaluated.

Based on the test results, mixtures containing 35% or greater RAP contents, softer binders, recycling agents, and fiber may be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements. It was found that some mixtures that were volumetrically designed under current VDOT specifications met BMD requirements. In addition, the expected trends in mixture performance testing were not always observed, likely due to masking by variability due to specimen fabrication practices or by inherent test variability. Results showed that modest relationships between non-reheated and reheated specimen results for the Cantabro test and IDT-CT were present. In addition, changes due to the use of a softer binder and/or recycling agents were seen in the BMD mixture binders as compared with the control mixture binder. Finally, comparisons of extracted and recovered binders from control and BMD mixtures were found to depend on the binder test under consideration, with different tests indicating differences in expected performance.

Based on the outcomes of the study, a testing protocol capable of evaluating the performance of recycling agents used in BMD mixtures is needed. This protocol would provide a means for VDOT to evaluate and accept these materials such that their use in innovative mixtures can be allowed in a manner that preserves the goals of sustainable, longer-lasting, and cost-effective pavements. In addition, efforts should be made to determine the effect of asphalt binder properties on the overall performance of asphalt mixtures with a primary focus on cracking and durability to allow VDOT to specify better-performing binders for use in asphalt mixtures. This would allow for the further optimization of mixture properties that should result in improved mixture performance.

# FINAL REPORT

# BALANCED MIX DESIGN FOR ASPHALT SURFACE MIXTURES: 2020 FIELD TRIALS

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## INTRODUCTION

According to the former Federal Highway Administration Expert Task Group on mixtures and construction (West et al., 2018; Yin and West, 2021), *balanced mix design* (BMD) is defined as an "asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration, mix aging, traffic, climate, and location within the pavement structure." Numerous state highway agencies are looking into designing and accepting asphalt mixtures using the BMD concept (National Center for Asphalt Technology, 2021). As one of these agencies, the Virginia Department of Transportation (VDOT) has been working toward the implementation of BMD for several years. VDOT's roads had been undergoing increased surface cracking over a number of years, and BMD was seen as providing a means to address cracking concerns. Another benefit of moving toward BMD that was attractive to VDOT was the opportunity to consider innovations in mix designs. The efforts began during a time of interest in the use of high reclaimed asphalt pavement (RAP) contents and stemmed from the concern about the potential performance of these mixtures and the knowledge that volumetric design could not account for the performance of mixtures with higher RAP contents and/or other additives.

VDOT has been a leader in supporting successful recycling of asphalt pavement for more than 40 years (Hajj et al., 2021). In 2013, field trial projects featuring the use of 40% to 45% RAP contents in surface mixtures were constructed (Nair et al., 2019). In January 2018, an initial effort was undertaken by researchers at the Virginia Transportation Research Council (VTRC) to provide benchmark indications of performance for a number of asphalt mixtures produced and sampled in 2015 (Bowers et al., 2022; Diefenderfer and Bowers, 2019) to support proposed pilot projects with mixtures containing higher RAP contents. Three fast, simple, and practical performance-indicative tests addressing different modes of distress were selected for use as part of the BMD method. The three tests were (1) the Cantabro mass loss test (Cantabro test) to assess the potential for durability; (2) the indirect tensile cracking test (IDT-CT) at intermediate temperatures to assess the potential for cracking; and (3) the Asphalt Pavement Analyzer (APA) rut test to assess the potential for rutting. Initial performance threshold criteria were then developed for the selected tests: a maximum of 7.5% mass loss for the Cantabro test; a minimum cracking tolerance (CT) index of 70 for the IDT-CT at 25°C; and a maximum 8.0 mm rut depth at 64°C for the APA rut test. Further, Diefenderfer et al. (2021) assessed and validated the developed performance-based specifications for surface asphalt mixtures produced using unmodified asphalt binders prior to full implementation in Virginia.

Two VDOT BMD special provisions were then drafted and revised for use in pilot projects: (1) *Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria*, and (2) *Special Provision for Dense Graded Surface Mixtures Designed Using Performance Criteria*. In 2019, two field trials were planned and executed to design, produce, and place BMD asphalt mixtures in Virginia. These field trials constituted the first applications of these BMD specifications. Nine mixtures were evaluated from the two field trials. The mixtures incorporated combinations of different RAP contents, two binder grades, two recycling agents (RAs), and two warm mix asphalt additives (Diefenderfer et al., 2021). Based on the test results, mixtures containing a softer binder, warm mix asphalt additives, 40% RAP, and RAs may be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements. However, the long-term field and laboratory performance of all of these mixtures needs to be evaluated to verify these early findings. In 2020, additional field trials featuring the use of higher RAP content, softer binder, RAs, and various other additives such as fibers and softening oils were planned and constructed.

## PURPOSE AND SCOPE

The purpose of this study was to document and assess field trials constructed in 2020 to evaluate the use of BMD specifications. BMD mixtures were designed and produced in accordance with VDOT's special provision for surface mixtures with high RAP contents. Typical dense-graded surface mixtures were used as controls. The study provided information to evaluate the impact of various RAP contents and additives, production variability, reheating, and binder properties on BMD performance test results.

The scope included the development of field trials, verification of mix design performance properties, mixture sampling during production, coring of as-placed material, testing and analysis of the volumetric and performance properties of mixtures, and documentation of observations and lessons learned. The data analysis addressed several topics:

- application of the BMD concept
- production variability
- comparisons of typical surface mixtures and BMD mixtures featuring the use of softer binder, RAs, fibers, softening oils, and/or other additives
- differences in test responses of specimens fabricated from reheated mixtures compared to specimens prepared from non-reheated mixtures

- comparisons of performance properties for asphalt binders extracted and recovered from the evaluated control and BMD mixtures.

The 2020 trials built on the experiences from 2019 (Diefenderfer et al., 2021). They provided an opportunity to continue evaluating the impact of the specifications on the design, production, quality control and assurance practices, and construction of surface mixtures. In addition, they served as a means to evaluate the long-term performance implications of using the BMD method. Further, the 2020 trials provided additional resources to evaluate the impact of performance specifications on the field performance of pavement surfaces.

## METHODS

Four tasks were performed to achieve the study objectives:

1. Document the project selection, mix design, production, and construction processes of each trial.

2. Obtain producer-supplied design specimens or test results and sample plant-produced mixtures and as-paved material during production.

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

4. Conduct laboratory testing on asphalt binders extracted and recovered from the 2020 control and BMD mixtures and perform analyses to evaluate the binder performance properties under various aging and temperature conditions.

### Field Trials

Field trials were developed in collaboration with VDOT districts and asphalt producers using no-cost change orders added to plant mix schedule contracts. As much as possible, trial locations were selected to have sufficient tonnage on a singular route having consistent underlying conditions. A goal of approximately 2,000 tons per mixture was used as guidance to allow for 2 days of paving for each mixture. These conditions were difficult to meet, and most trial locations deviated from them in some manner.

Trials included control non-BMD dense-graded surface mixtures designed in accordance with Section 211 of VDOT's *Road and Bridge Specifications* (VDOT, 2016) and trial BMD mixtures. The trial BMD mixtures were designed in accordance with VDOT's 2020 *Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria*, provided in Appendix A, except for the mixtures with 35% RAP content. The specification defines *BMD high RAP mixtures* as containing 40% or more RAP; however, to meet the performance criteria, some of the high RAP mixtures in this study were designed using only 35% RAP, as higher RAP content mixtures could not meet performance criteria. The special provision covers requirements for materials, the job-mix formula (JMF), production testing, acceptance, and initial production. The requirements for performance, recommended in Diefenderfer and Bowers (2019), are summarized in the JMF requirements, which also define the two types of BMD approaches that VDOT is evaluating.

In the BMD special provision, surface mixtures with an A or D designation (SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D) may be designed to meet either Performance + Volumetric (P+V) criteria or Performance Only (P) criteria. The JMF must meet the nominal maximum aggregate size (NMAS) of the designated mixture type. For both mixture types, performance test results must meet the criteria outlined in Table 1 and be reported in the design submission.

Once trial locations were determined, the proposed mix designs were evaluated by VTRC to determine their performance response, and the results were used by the VDOT district for mix design approval. During production, specimens were fabricated at the plant without reheating for performance testing by VTRC and the producer in accordance with the special provision. In addition, loose mixture samples were collected for additional testing at VTRC, including volumetric analysis and performance testing of specimens fabricated from reheated loose mixture. Cores were collected to evaluate the as-placed material but are not discussed herein, as testing is not complete.

During production and paving, standard equipment and practices were used. No operations-related issues were observed.

**Table 1. Performance Testing Criteria**

| Distress | Test | Test Method | No. of Specimens | Criterion |
|---|---|---|---|---|
| Durability | Cantabro test | AASHTO TP 108 | 3 replicates | Mass loss ≤ 7.5% |
| Rutting | APA test | AASHTO T 340 | 4 replicates | Rutting ≤ 8.0 mm |
| Cracking | IDT-CT test | ASTM D8225 | 5 replicates | $CT_{index} \geq 70$ |

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

## Materials

The field trials were constructed in three VDOT districts: Northern Virginia, Fredericksburg, and Richmond. Twelve total mixtures produced at five plants were evaluated. Three mixtures each were produced at the Northern Virginia and Fredericksburg plants. Each of three plants in the Richmond District produced one, two, or three mixtures. All sampled mixtures were surface mixtures having an NMAS of 9.5 mm or 12.5 mm. Mixtures were produced with either PG 64S-22 or PG 58-28 binders; RAs were used in three mixtures, and a combination of fiber and a softening oil was used in one mixture. Table 2 shows the descriptions and designations for all mixtures.

**Table 2. 2020 BMD Field Trial Projects**

| Mixture | Paving Dates | Location | Mix Type | Job-Mix Formula |
|---|---|---|---|---|
| A-1 | 7/19-20/20 | US 50 | SM-9.5D 30% RAP PG 64S-22 | 9002-2020-80 WM |
| A-2 | 7/29-30/20 | Loudoun County | SM-9.5D 40% RAP PG 64S-22 + RA1 | 9002-2020-V-REJD |
| A-3 | 7/26-27/20 | Northern Virginia | SM-9.5D 40% RAP PG 58-28 | 9002-2020-V-58-28D WM |
| B-1 | 8/19-20/20 | SR 628 | SM-9.5A 30% RAP PG 64S-22 | 6041-2020-31 |
| B-2 | 8/26-27/20 | Stafford County | SM-9.5A 40% RAP PG 64S-22 + RA2 | 6041-2020-7 |
| B-3 | 8/21,24/20 | Fredericksburg | SM-9.5A 40% RAP PG 58-28 | 6041-2020-46 |
| C-1 | 9/15-16/20 | SR 623 Goochland County Richmond | SM-12.5A 35% RAP PG 58-28 | 4009-2031P |
| D-1 | 8/19,25/20 | SR 903 | SM-12.5A 30% RAP PG 64S-22 | 4056-2031 |
| D-2 | 8/20-21/20 | Mecklenburg County | SM-12.5A 35% RAP PG 58-28 + RA3 | 4056-2031PC |
| D-3 | 8/26-27/20 | Richmond | SM-12.5A 35% RAP PG 58-28 + fiber + softening oil | 4056-2031PS |
| E-1 | 10/13-14/20 | US 360 | SM-12.5A 30% RAP PG 64S-22 | 4052-2031 |
| E-2 | 10/15,19/20 | Chesterfield County Richmond | SM-12.5A 40% RAP PG 58-28 | 4052-2031P |

BMD = balanced mix design; SM = surface mixture; RAP = reclaimed asphalt pavement; PG = performance grade; RA = recycling agent; A and D = mixture designations according to VDOT specifications; S = standard traffic.

### Mix Designs

Prior to paving, producers were required to submit mix designs to VDOT for approval for all mixtures paved on VDOT projects. The designs for the volumetrically designed control mixtures were required to meet current VDOT volumetric and gradation requirements. Most BMD mixtures used in this study met current VDOT volumetric and gradation requirements and, in addition, the performance requirements of the special provision for surface mixtures with high RAP contents.

### Project Location

Project locations were documented to support monitoring of long-term performance in service. The locations and basic information for the projects paved with these mixtures were summarized in Table 2. The locations of cores for each mixture are shown in Figures B1 through B5, Appendix B. The distance paved each day for each mixture was greater than that shown in the figures.

## Sampling

Loose mixture sampling was performed twice during each day of production unless production was shortened due to weather or other factors. Table 3 presents the production sampling plan for each mixture. For the most part, sampling proceeded as planned; however, there were occasions when strict adherence was not possible. Samples were designated 1 through 4, and specimen sets for each test were labelled in accordance with the sample from which they originated (e.g., Cantabro sample 1 was fabricated from the first mixture sample).

**Table 3. 2020 Sampling and Testing Plan**

| | **Producer-Made Pills (No Reheating)** | | **Loose Mixture Sampling** | |
|---|---|---|---|---|
| **Identification** | **Producer Testing** | **VTRC Testing** | **VTRC Reheat Testing** | **Cores** |
| Sample 1 | Volumetrics<br>3 Cantabro<br>5 IDT-CT | 3 Cantabro<br>5 IDT-CT<br>4 APA | Volumetrics<br>3 Cantabro<br>5 IDT-CT<br>4 APA | 10 cores per day:<br>IDT-CT<br>APA |
| Sample 2 | Volumetrics<br>3 Cantabro<br>5 IDT-CT | 4 APA | Volumetrics<br>3 Cantabro<br>5 IDT-CT<br>4 APA | |
| Sample 3 | Volumetrics<br>3 Cantabro<br>5 IDT-CT | 3 Cantabro<br>5 IDT-CT<br>4 APA | Volumetrics<br>3 Cantabro<br>5 IDT-CT<br>4 APA | |
| Sample 4 | Volumetrics<br>3 Cantabro<br>5 IDT-CT | 4 APA | Volumetrics<br>3 Cantabro<br>5 IDT-CT<br>4 APA | |

*Note:* Virgin binder was also collected for testing along with extracted and recovered binder from loose mixture samples.
VTRC = Virginia Transportation Research Council; IDT-CT = indirect tensile cracking test; APA = Asphalt Pavement Analyzer.

### *Loose Mixture Samples*

Plant-produced loose material was collected from each mixture. Each sample of loose mixture was collected from an approximately 3- to 5-ton quantity of mixture dumped on the ground at the plant and struck off with a loader. Loose mixture samples were either taken into the producer's laboratory and immediately compacted into specimens or placed into boxes, taken to the VTRC laboratory, and stored in a climate-controlled area for further evaluation.

### *Plant-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 test specimens. While the $G_{mm}$ was being determined, volumetric specimens were compacted. These 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 test specimens meeting the test criterion requiring air-void contents of 7.0 ± 0.5%. Using the calculated masses, trial IDT-CT and APA test specimens were compacted. The specimens were cooled as rapidly as possible so that the air-void contents could be measured. Cooling was facilitated by the use of fans, and in some cases, placement of the specimens on perforated racks for better airflow.

If the air-void content of the trial specimens met the test requirements, compaction proceeded using the calculated masses. If the air-void content was below or above the requirements, the mass of loose mixture was reduced or increased, respectively, and another trial specimen was compacted. As laboratory staff gained experience, the process became faster and fewer specimens were discarded for not meeting the air-void requirements. Once the correct mass was determined, all required specimens were compacted. As they cooled, specimens were bulked to ensure that air-void contents were within the requirements for testing.

This process led to a number of ways to accomplish pill compaction. In all cases, loose mixture was kept in an oven and held at compaction temperature until each specimen was compacted. In some laboratories, an approximate mass for each pill was split into a smaller pan such that material could be removed to reach the target mass before compacting. In some cases, these smaller pans were covered with foil while in the oven. In other laboratories, the loose mixture remained in uncovered pans in larger quantities until the required mass was determined and was then split into appropriate pill-size quantities. These differing practices were in addition to any differences in the time it took each laboratory to determine the required mass and compact the necessary pills for testing. There was potential for each of these steps and practices to influence the final test result significantly, and further work is needed to address variability due to specimen fabrication. However, determining the influence of each factor on the final test result was beyond the scope of this study.

Plant-compacted specimens were provided to VTRC for testing in accordance with the sampling plan outlined in Table 3.

*Reheated Compacted Specimens*

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

The $G_{mm}$ was determined as an average of two tests completed during volumetric analysis. The resulting volumetric specimens were used for Cantabro testing. The $G_{mm}$ was used to calculate the approximate mass required to fabricate IDT-CT and APA test specimens in the same manner as that used for the plant-compacted specimens. The same process of compacting trial IDT-CT and APA specimens to verify masses was followed, and once the appropriate masses were determined, all required specimens were compacted. Table 4 shows the plan for fabricating reheated specimens from the boxes of loose mixture sampled at the plant.

Table 4. Reheated Specimen Fabrication Plan

| Day | Sample | No. of Reheated Specimens | | |
|---|---|---|---|---|
| | | Cantabro | APA | IDT-CT |
| 1 | 1 | 3 | 4 | 5 |
| | 2 | 3 | 4 | 5 |
| 2 | 3 | 3 | 4 | 5 |
| | 4 | 3 | 4 | 5 |

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

## Laboratory Testing and Evaluation

Laboratory 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 plant-produced mixtures. The binder from all plant-produced mixtures was also extracted and recovered for performance grading and subjected to additional laboratory testing.

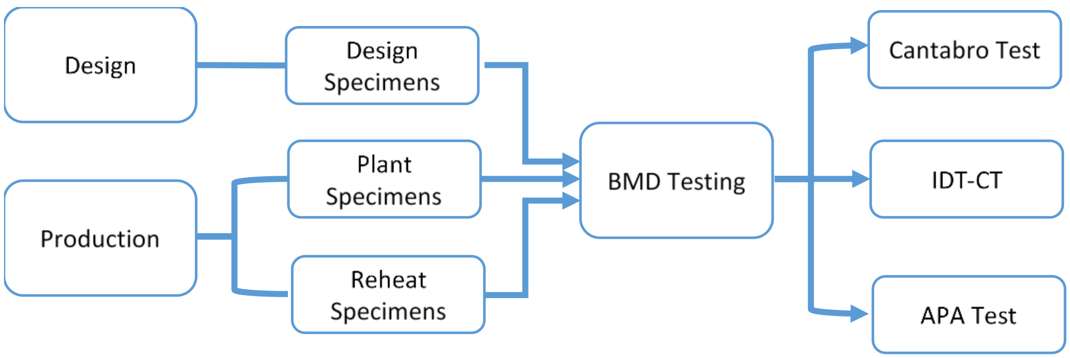


**Figure 1. Experimental Plan for Laboratory- and Plant-Produced Mixtures. BMD = balanced mix design; IDT-CT = indirect tensile cracking test; APA = Asphalt Pavement Analyzer.**

### Specimen Designations

All laboratory mixture testing was conducted in the VTRC laboratory on three types of specimens:

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

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

3. *Reheat:* plant-produced, laboratory-compacted specimens compacted by VTRC staff after reheating cooled loose mixture.

## Mixture Volumetric Properties and Gradations

Volumetric and gradation analyses were performed on production samples obtained by VTRC. The data collected included asphalt content and gradation; $G_{mm}$ and bulk specific gravity ($G_{mb}$); air voids (voids in total mixture [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 ($P_{be}$).

Producer data for volumetric properties and gradations corresponding to VTRC samples were obtained from VDOT's Materials Information Tracking System.

## Mixture Testing

### *Cantabro Test*

The Cantabro test was performed on mixtures to evaluate durability in accordance with AASHTO TP 108, *Standard Method of Test for Abrasion Loss of Asphalt Mixture Specimens*. Test specimens were compacted to $N_{design}$ and tested in triplicate at a temperature of 25 ± 1°C.

### *IDT-CT Test*

Testing was conducted at 25 ± 0.5°C 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*, and with the use of dry specimens. Five replicate specimens compacted to 7 ± 0.5% air voids were tested, although in cases of testing errors, results from only four or three replicates may have been considered.

### *APA Test*

Testing was performed 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. An APA Junior test machine was used such that two replicate tests consisting of two specimens each were conducted for each mixture. The test specimens were compacted to 7 ± 0.5% air voids.

## Binder Testing

### *Extraction and Recovery*

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

*Performance Grading*

Performance grading (PG) on extracted and recovered asphalt binders was performed 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*.

*Difference in Critical Low Temperature Performance Grade ($\Delta T_c$)*

The difference in critical low temperature PG limiting temperatures, commonly referred to as $\Delta T_c$, was calculated by subtracting the m-critical low temperature ($T_{c,m}$) from the S-critical low temperature ($T_{c,S}$), as shown in Equation 1:

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

Both temperatures were determined using the bending beam rheometer (BBR) in accordance with AASHTO T 313-2019, *Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binders Using the Bending Beam Rheometer (BBR)*. The m-critical low temperature ($T_{c,m}$) is the resulting low temperature at which the creep relaxation m-value at 60 seconds of loading is exactly equal to the specification value of 0.300. The S-critical low temperature ($T_{c,S}$) is the resulting low temperature at which the creep stiffness S-value at 60 seconds of loading is exactly equal to the specification value of 300 MPa (Federal Highway Administration, 2021).

*Frequency Sweep*

Frequency sweep tests were conducted to evaluate the extracted and recovered asphalt binders over multiple frequencies and temperatures in terms of dynamic shear modulus (G*) and phase angle (δ) master curves. The induced strains were monitored and kept within the linear viscoelastic region. Testing was performed on binder specimens 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 on binder specimens 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. The two results measured at 45°C were used for verification purposes as no differences are usually observed at this temperature regardless of the specimen geometry used (8-mm or 25-mm diameter). All specimens were evaluated at 16 frequencies ranging from 0.1 to 100 rad/s at each testing temperature.

No standard currently exists for the construction of a binder master curve. In this study, the rheological software package Rheology Analysis Software (RHEA) was used to perform the shifting of the G* master curves to a reference temperature of 45°C (Abatech, 2022). The software adopts the method of free shifting to fit the frequency sweep measured data into a smooth master curve. The term *free shifting* indicates that the measured data are shifted to a master curve without a predefined shape function (Habbouche et al., 2022). Figure 2 shows a RHEA output example for the binder extracted and recovered from mixture A-1 and aged for 20 hr using the pressure aging vessel (PAV), referred to herein as “20-hour PAV.”

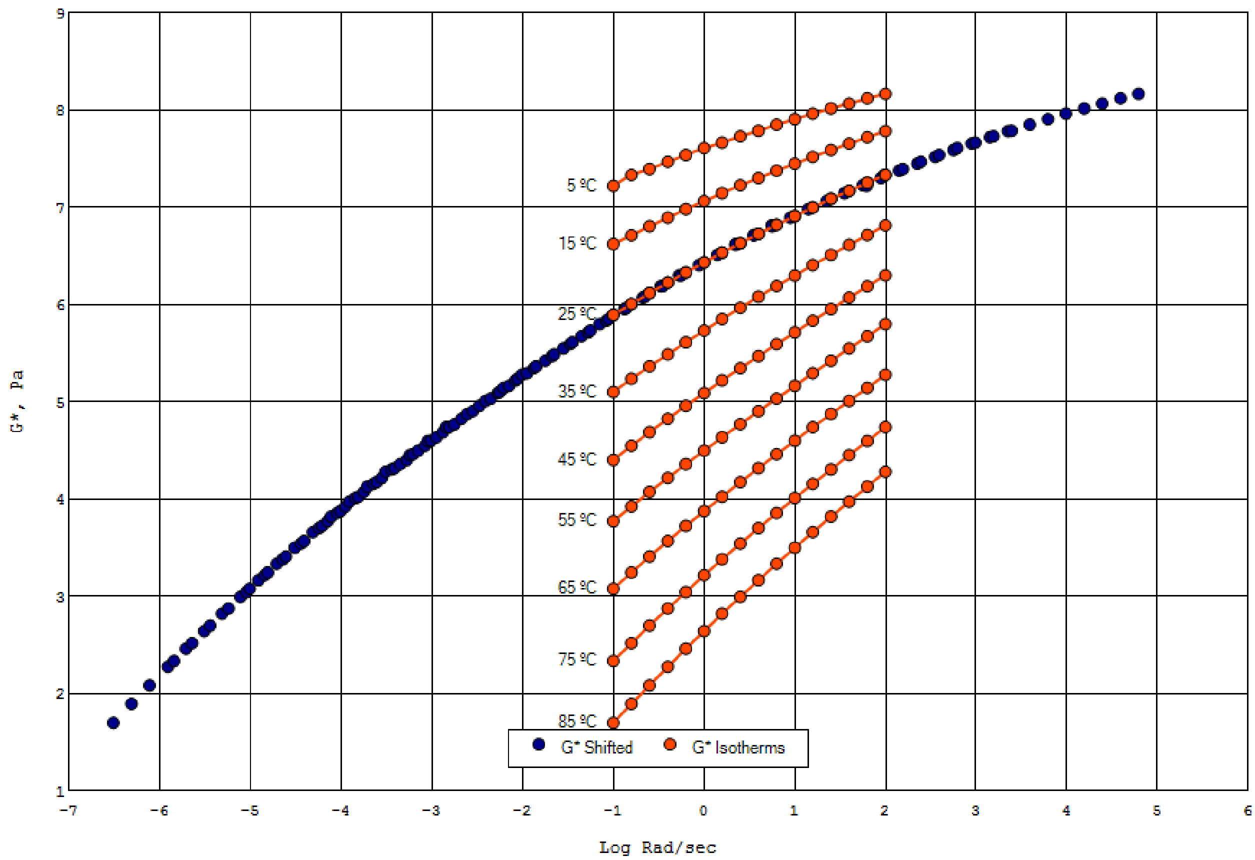


**Figure 2. Output Example of Binder Dynamic Shear Modulus (G*) Master Curve Using RHEA**

*Glover-Rowe Parameter*

The Glover-Rowe (G-R) parameter was originally defined by Glover et al. (2005) as the dynamic shear rheometer (DSR) function shown in Equation 2 and reformulated for greater practical use by Rowe et al. (2011) in a discussion (Anderson et al., 2011). The G-R parameter is expressed using Equation 3. The G-R parameter 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 $\delta$).

$$DSR\ Function = \frac{G'}{\frac{\eta'}{G'}} \quad \text{[Eq. 2]}$$

$$G - R = \frac{G*(cos\delta)^2}{sin\delta} \quad \text{[Eq. 3]}$$

where

$G^*$ = complex dynamic shear modulus, Pa
$G'$ = storage or elastic shear modulus, Pa
$\eta'$ = storage dynamic viscosity, Pa*s/rad
$\delta$ = phase angle, °.

The initial version of the G-R parameter, referred to herein as G-R1, is determined at a temperature of 15°C and a frequency of 0.005 rad/s. G-R parameter values at this temperature and frequency have been shown to correlate well with ductility, thus indicating cracking resistance as well as binder oxidation levels (Ruan et al., 2003). G-R1 refers to non-load cracking at intermediate temperature, and its limits relate to specific environmental conditions. However, the universal limits of G-R1, 180 kPa and 600 kPa, are usually used as a reference to track the effect of aging and/or rejuvenation.

Christensen and Tram (2022) evaluated the relationships between the fatigue properties of asphalt binders and the fatigue performance of asphalt mixtures as part of NCHRP Project 09-59. Based on the research conducted, it was recommended that the G-R parameter, referred to herein as G-R2, be determined at a frequency of 10 rad/s and at the corresponding binder fatigue test temperature. This testing temperature is a function of the low PG grade. For this study, the proposed binder fatigue test temperatures were 22°C and 25°C for binders with low PG temperatures of -28°C and -22°C, respectively.

*R-Value and Crossover Frequency ($w_c$)*

The R-Value, referred to herein as R-Value1, is an indicator of binder rheological type. It is defined as the difference between the log of the glassy modulus and the log of the dynamic modulus at the crossover frequency ($w_c$). As the value of R-Value increases, the behavior of the binder at intermediate loading times and temperatures becomes more ductile. R-Value1 of all extracted and recovered binders was determined using RHEA at a reference temperature of 45°C using the Christensen-Anderson model. The crossover frequency, $w_c$, is a measure of the overall hardness of the binder: $w_c$ is determined when the storage/elastic (G') and loss/viscous (G") moduli are equal at the reference temperature (i.e., at a phase angle of 45°). As $w_c$ decreases, the hardness of the evaluated binder increases.

Christensen and Tram (2022) provided a new way to calculate the R-Value, referred to herein as R-Value2, using the creep stiffness, S, and coefficient of relaxation, m-value, at the low PG temperature as expressed in Equation 4:

$$R - Value2 = \log(2) * \frac{log(\frac{S}{3,000})}{log(1-m)} \quad \text{[Eq. 4]}$$

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.

*Crossover Temperature ($T_{\delta=45^\circ}$)*

The crossover temperature ($T_{\delta=45^\circ}$) is defined as the temperature at which the storage/elastic modulus (G') is equal to the loss/viscous modulus (G") at a frequency of 10 rad/s. $T_{\delta=45^\circ}$ is another parameter that was found to characterize successfully the viscoelastic properties of binders at the intermediate service temperature range for asphalt pavements.

*Linear Amplitude Sweep (LAS) Test*

The linear amplitude sweep (LAS) test was performed in accordance with AASHTO TP 101, *Estimating Fatigue Resistance of Asphalt Binders Using the Linear Amplitude Sweep*, to investigate the fatigue damage characterization of the evaluated binders at an intermediate temperature of interest. The test included a frequency sweep test at 0.1% strain over a range of frequencies from 0.2 to 30 Hz followed by an amplitude sweep oscillatory shear in strain-control mode test at a frequency of 10 Hz over a range of induced strains from 0.1% to 30%. The test was conducted at 23°C, the average of the high and low PG temperatures minus 4°C for the majority of the evaluated binders. This temperature was also selected such that the linear complex shear modulus G* fell within the range of 12 to 60 MPa at 10 Hz to mitigate any potential edge flow and/or adhesion loss (Safaei and Castorena, 2016). The binder fatigue performance parameter $N_f$ is calculated using Equation 5:

$$N_f = A * (\Upsilon_{max})^{-B} \quad \text{[Eq. 5]}$$

where

$N_f$ = fatigue performance parameter, number of cycles to fatigue failure
$\Upsilon_{max}$ = 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 Table 5. Three 9.5 mm NMAS mixtures were evaluated; the remaining nine were 12.5 mm NMAS mixtures. Design binder contents ranged from 5.3% to 6.4%. All control mixtures contained 30% RAP and were produced with PG 64S-22 binder. All BMD mixtures contained either 35% or 40% RAP and were produced with either PG 64S-22 or PG 58-28 binder. Three RAs and one combination of fibers and a softening oil were used in the mixtures.

Production data were obtained from VDOT’s Materials Information Tracking System for comparison with VTRC results. Each pair of samples, consisting of material tested by the producer and VTRC, was evaluated. Overall, samples were comparable and production was consistent from sample to sample for control and BMD mixtures. Details of all volumetric and gradation results for each mixture are presented in Appendix B. Results were compared to the process tolerance for four tests from Table II-15 in the VDOT specifications (VDOT, 2016). Although the mixtures exceeded the process tolerance for various properties, the occurrences and differences were not excessive or recurring, indicating that production variability was reasonably controlled.

**Table 5. Mix Design Properties**

| Mix | A-1 | A-2 | A-3 | B-1 | B-2 | B-3 | C-1 | D-1 | D-2 | D-3 | E-1 | E-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mix Type | SM-9.5D | | | SM-12.5A | | | SM-12.5A | SM-12.5A | | | SM-12.5A | |
| Binder PG | 64S-22 | 58-28 | 64S-22 | 64S-22 | 58-28 | 64S-22 | 58-28 | 64S-22 | 58-28 | 58-28 | 64S-22 | 58-28 |
| RAP Content, % | 30 | 40 | 40 | 30 | 40 | 40 | 35 | 30 | 35 | 35 | 30 | 40 |
| Asphalt Content, % | 5.5 | 5.6 | 5.6 | 5.3 | 5.6 | 5.6 | 6.2 | 5.8 | 6.2 | 6.2 | 5.9 | 5.8 |
| Rice SG, $G_{mm}$ | 2.693 | 2.648 | 2.648 | 2.641 | 2.680 | 2.680 | 2.458 | 2.470 | 2.471 | 2.469 | 2.485 | 2.479 |
| Additive | - | - | RA1 | - | - | RA2 | - | - | RA3 | RA4 | - | - |
| **Gradation, percent passing** | | | | | | | | | | | | |
| 3/4 in (19.0 mm) | - | - | - | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 100 | 100 | 100 | 97 | 98 | 98 | 97 | 97 | 98 | 98 | 95 | 96 |
| 3/8 in (9.5 mm) | 92 | 94 | 94 | 90 | 90 | 90 | 85 | 88 | 90 | 90 | 85 | 89 |
| No. 4 (4.75 mm) | 58 | 64 | 64 | 59 | 58 | 58 | 49 | 61 | 61 | 61 | 58 | 53 |
| No. 8 (2.36 mm) | 38 | 45 | 45 | 40 | 38 | 38 | 32 | 41 | 42 | 42 | 37 | 35 |
| No. 30 (0.6 mm) | 19 | 22 | 22 | 22 | 19 | 19 | 16 | 23 | 25 | 25 | 18 | 17 |
| No. 200 (0.075 mm) | 5.8 | 5.9 | 5.9 | 5.5 | 5.8 | 5.8 | 4.8 | 4.8 | 5.7 | 5.7 | 6.0 | 5.2 |
| Avg. Mass Loss, % | 7.4 | 6.2 | 6.7 | 9.6 | 6.5 | 6.1 | 4.1 | - | 2.1 | 2.9 | - | 5.0 |
| Avg. Rut Depth, mm | 6.2 | 6.3 | 7.4 | 4.9 | 5.0 | 3.6 | 3.0 | - | 3.9 | 3.2 | - | 2.5 |
| Avg. CT index | 92 | 75 | 73 | 61 | 146 | 130 | 163 | - | 94 | 103 | - | 86 |

SM = surface mix; PG = performance grade; RAP = reclaimed asphalt pavement; SG = specific gravity; RA = recycling agent; A and D = mixture designation in accordance with VDOT specifications; Avg. = average; CT = cracking tolerance; - = not applicable.

## Mixture Testing

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 to indicate that they match the 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 VTRC, as designated. Reheat specimens were fabricated from production samples of loose mixture after cooling and reheating in the VTRC laboratory.

Unless mentioned otherwise, no data were discarded from any tests. All replicates properly 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 of the assumptions of normality and equal variances.

### Producer A

Three mixtures were evaluated from Producer A, designated A-1, A-2, and A-3. The volumetric and gradation properties of the mixtures are shown in Tables C1 through C3, Appendix C. Mixture A-1 was a dense-graded 9.5 mm NMAS surface mixture designed to meet current VDOT requirements (VDOT, 2016) and served as the control mixture for comparisons. Mixture A-1 contained 30% RAP and a PG 64S-22 binder. Mixture A-2 was a 9.5 mm NMAS mixture designed to meet the requirements of VDOT's BMD special provision and contained 40% RAP and a PG 58-28 binder. Mixture A-3 was a 9.5 mm NMAS mixture designed to meet the requirements of VDOT's BMD special provision and contained 40% RAP, PG 64S-22 binder, and RA1.

Figure 3 presents the results of the Cantabro testing. All sample sets met the mass loss criteria except for the mixture A-1 sample 4 reheat set. The mixture A-1 JMF results barely passed the criteria. As mixture A-1 was not designed to meet BMD requirements, being the control, the failing or nearly failing results were not surprising. Several trends regarding the three mixtures are shown. Producer-tested and VTRC-tested plant samples had less mass loss than the JMF samples. The reheat mass loss values were generally similar to or less than the JMF values except for one occurrence where the mixture A-1 sample 4 reheat results exceeded the JMF results. The results for the VTRC-tested plant samples were slightly higher than or similar to those of the producer-tested plant samples for all mixtures. Reheat results were assessed to determine if the results for the four samples were statistically similar using the Tukey pairwise comparison procedure. The results are shown in Table D1, Appendix D. The results for samples having the same letter were not statistically different. Only the results for mixture A-1 were significantly different between samples.

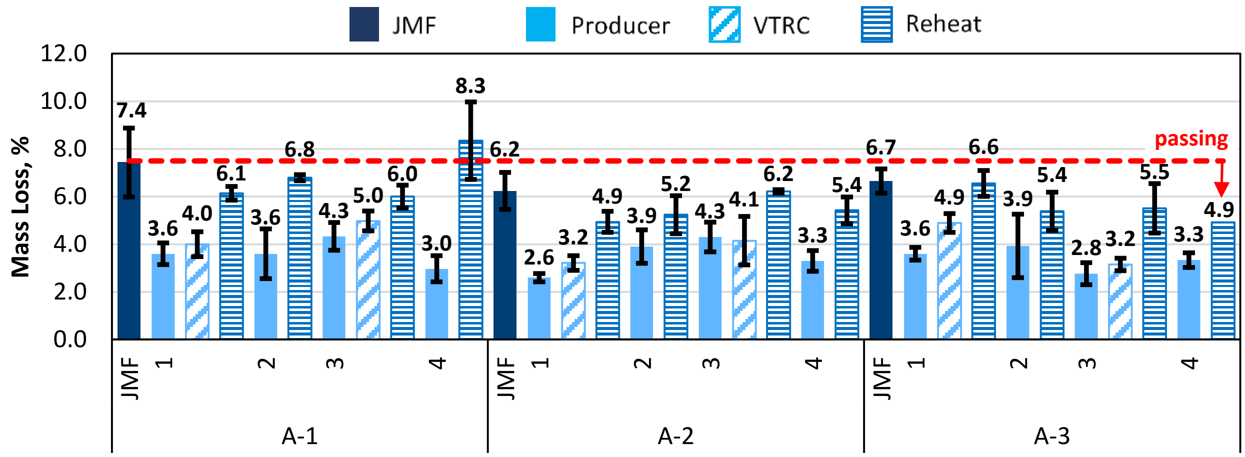


**Figure 3. Producer A Test Results for Mass Loss. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

Figure 4 shows the average results for the four samples collected for each mixture. All results met the 7.5% maximum mass loss criterion. The JMF samples had the greatest mass loss for each mixture, and the plant samples had the least. Mixtures A-2 and A-3 showed similar or improved performance over that of mixture A-1 for the JMF and reheat results.

Statistical analysis was conducted to compare the JMF, plant, and reheat mass loss values. The results indicated that there were no statistical differences between the JMF and reheat values for mixtures A-1, A-2, and A-3. All plant values were significantly different from the JMF and reheat values. Results are shown in Table D2, Appendix D. In addition, statistical comparison of the reheat mass loss values was performed using the Tukey procedure and is presented in Table D3, Appendix D. The results indicated that there were no significant differences between the reheat mass losses for mixtures A-1 and A-2 or A-1 and A-3.

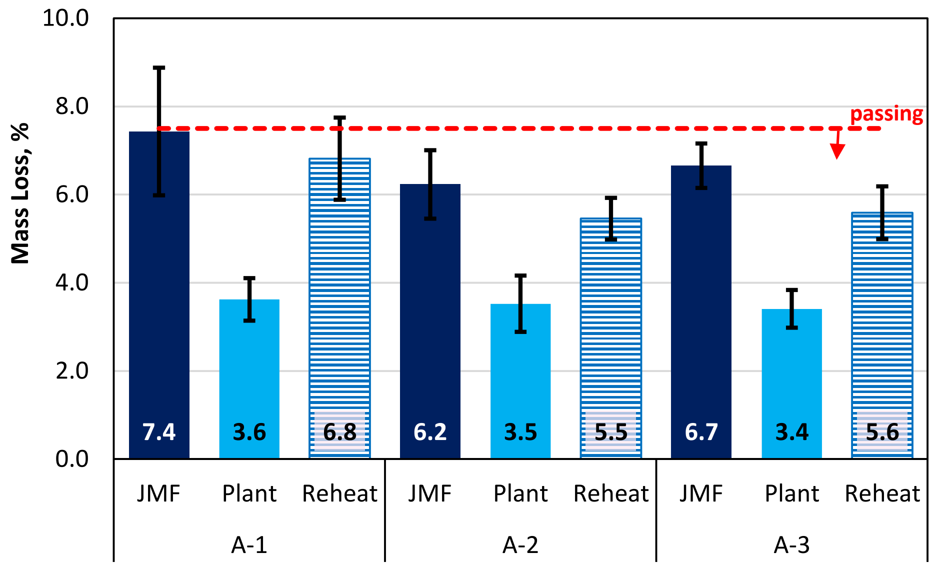


**Figure 4. Average Mass Loss Values for Mixtures A-1 Through A-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

Figure 5 presents the APA rut depth results for all samples collected for each mixture. Rut testing was performed by VTRC for all samples. All samples passed the 8.0 mm maximum rut depth test criterion. With the exception of two plant samples (A-1 sample 1 and A-2 sample 4), the JMF samples for each mixture showed the highest rut depths. It was expected that reheating the mixtures would result in the lowest rut depths; however, this was not seen consistently for any mixture. Mixtures A-1 and A-2 had mixed results when the rut depths for the plant and reheat samples were compared, and reheat rut depths for mixture A-3 were higher than the plant rut depths. These effects may be attributed to variability due to specimen preparation or the variability of the test itself masking the reheating effect.

The Tukey procedure was used to compare the reheat rut depths. No significant differences were found between the results for samples 1 through 4 for mixtures A-1 and A-2, indicating consistent results across production. The results for mixture A-3 showed two groupings: (1) the results for samples 1, 2, and 4 were not statistically different and neither were the results for samples 1, 3, and 4; and (2) the results for samples 2 and 3, the highest and lowest, were significantly different.

Figure 6 shows the average JMF, plant, and reheat results for each mixture. These results were compared statistically using the Tukey procedure; the data are provided in Table D5, Appendix D. The JMF samples had the highest rut depth for each mixture. The averaged results followed the expected trend for mixtures A-1 and A-2 wherein the reheat rut depth was less than the plant rut depth; this trend was reversed for mixture A-3. The JMF and plant values were statistically the same for mixtures A-1 and A-2, indicating that the combination of 40% RAP and PG 58-28 binder provided a response similar to that of the control mixture of 30% RAP and PG 64S-22; however, mixture A-1 appeared more sensitive to reheating, as the reheat value decreased more than that of mixture A-2. This indicated that, despite the higher RAP content, mixture A-2 did not stiffen as much with reheating as mixture A-1, likely due to the use of the softer PG 58-22 binder. The JMF, plant, and reheat values for mixture A-3 were statistically different.

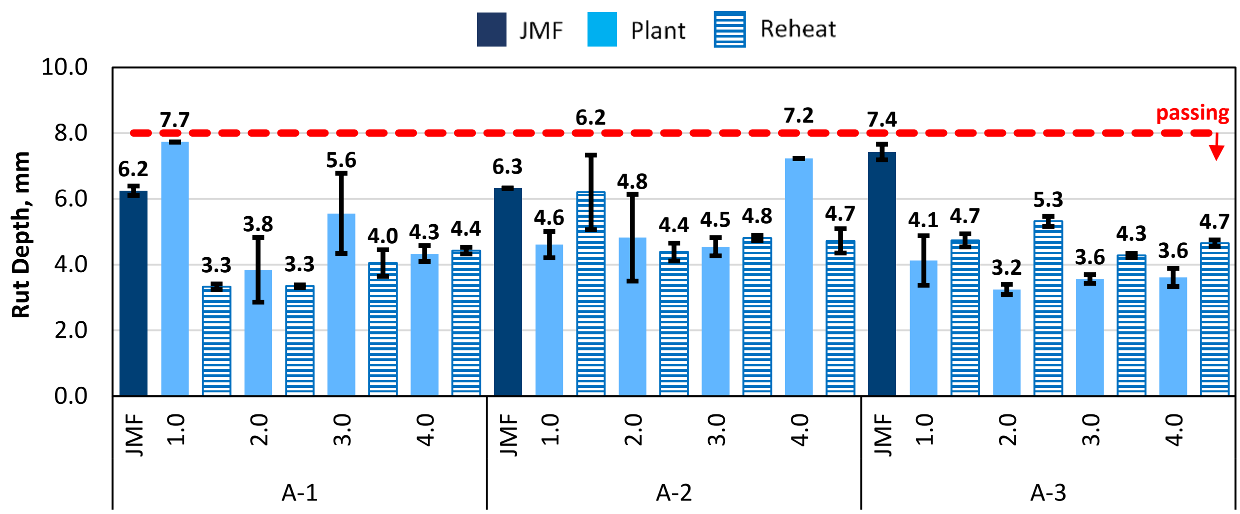


**Figure 5. Producer A Test Results for Rut Depth. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

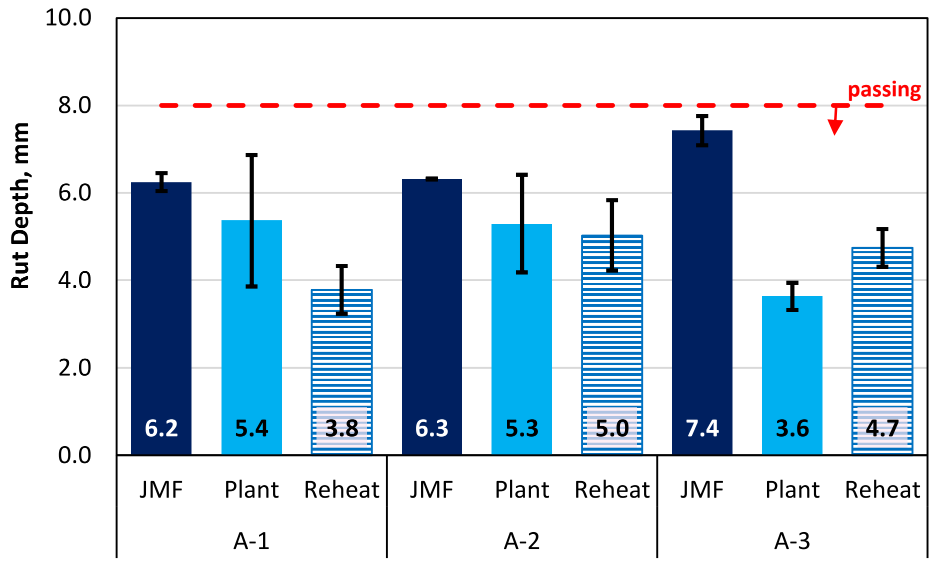


**Figure 6. Average Rut Depths for Mixtures A-1 Through A-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

The mixture A-3 JMF was softer, having a higher rut depth, than that of mixture A-1; however, during production, mixture A-3 became stiffer than mixture A-1, showing lower plant rut depths. The reheat result for mixture A-3 was higher than its plant value and that of mixture A-1. This may be due to the use of RA1; the RA efficacy in activating or softening the RAP binder may have increased with the additional time and temperature exposure provided during the cooling and reheating process. This demonstrates the need for additional work to address how RAs should be evaluated and accepted. The Tukey method was used to compare the reheat APA rut depths, as shown in Table D6, Appendix D. The results indicated that there was a significant difference between the results for mixtures A-1 and A-2. There was no significant difference between those for mixtures A-1 and A-3.

Figure 7 displays the CT index results for the samples from all mixtures. As shown, all samples met the minimum CT index requirement of 70. In general, the JMF values were lower than or similar to the reheat values. The producer and VTRC plant values were higher than the reheat values in nearly every case, as expected, since the reheating process ages and stiffens mixtures, thus decreasing the CT index. For mixture A-1, the VTRC values were lower than the paired producer values, and for mixture A-2, the results were mixed. The producer and VTRC values were similar for mixture A-3.

Evaluation of the reheat sample variability, shown in Table D7, Appendix D, indicated that there were significant differences between the results for samples for all three mixtures. The results for sample 3 were significantly different from those for samples 1, 2, and 4 for mixture A-1. The results for samples 1, 2, and 3 were significantly different from those for sample 4 for mixture A-2. Mixture A-3 showed two groupings of samples, with the results for samples 1 and 2 being significantly different from those for samples 3 and 4.

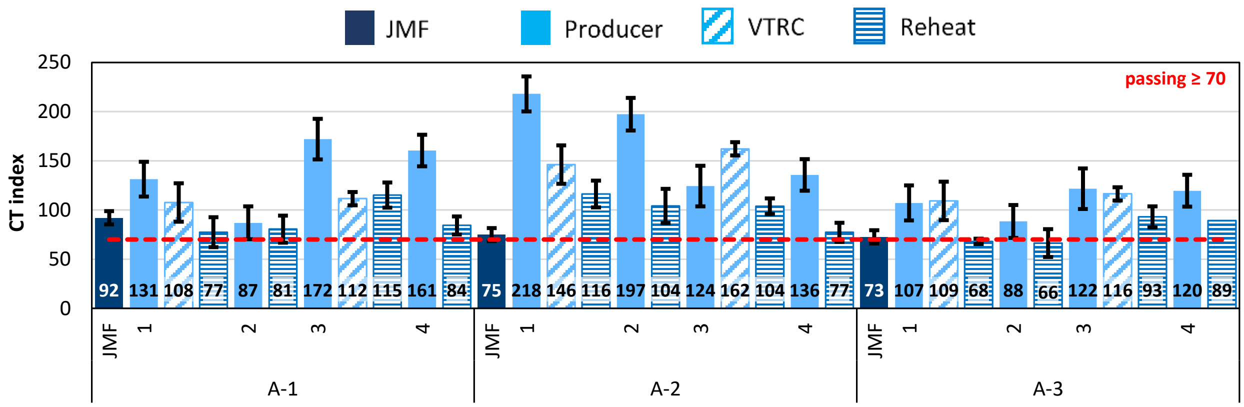


**Figure 7. Producer A Test Results for CT Index. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

The average CT index values are shown in Figure 8 for each mixture and sample type. The results of the Tukey analysis comparing the average values are shown in Table D8, Appendix D. The JMF and average reheat values were not significantly different for all three mixtures. The plant values were significantly different from the reheat values for all mixtures and from the JMF values for mixtures A-2 and A-3. Although the JMF value for mixture A-2 was lower than that for the control mixture A-1, the plant and reheat values were greater, indicating a benefit of the use of the PG 58-28 binder. The values of the JMF, plant, and reheat samples for mixture A-3 were lower than those for mixture A-1, indicating that RA1 may not have had the desired impact on the mixture performance. Statistical evaluation of the average reheat CT index results, shown in Table D9, Appendix D, showed no significant differences between the reheat results from the three mixtures.

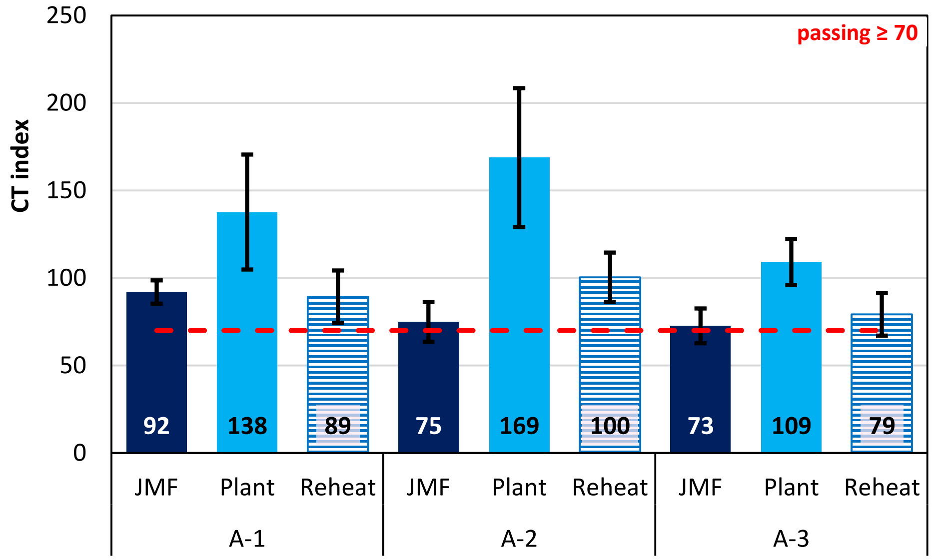


**Figure 8. Average CT Index Values for Mixtures A-1 Through A-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula.**

## Producer B

Three mixtures were evaluated from Producer B, designated B-1, B-2, and B-3. The volumetric and gradation properties of the mixtures are shown in Tables C4 through C6, Appendix C. Mixture B-1 was a 12.5 mm NMAS mixture designed to meet current VDOT requirements (VDOT, 2016) and served as the control mixture for comparisons. Mixture B-1 contained 30% RAP and a PG 64S-22 binder. Mixtures B-2 and B-3 were 12.5 mm NMAS surface mixtures designed to meet the requirements of VDOT's BMD special provision. Mixture B-2 contained 40% RAP and PG 58-28 binder, and mixture B-3 contained 40% RAP, PG 64S-22 binder, and RA2.

Mass loss results for all Producer B mixtures are shown in Figure 9. The control mixture B-1 was not designed in accordance with BMD criteria, so it was not surprising that the JMF values did not meet the minimum 7.5% mass loss criterion. The only other sample failing the criterion was the reheat sample 2 from mixture B-1. For all three mixtures, the values for the plant samples, whether tested by the producer or VTRC, were less than those for both the JMF and the associated reheat samples. The producer-tested and VTRC-tested plant sample results were similar. Reheat results were less than or similar to the JMF results except for sample 1 from mixture B-3, which had a higher mass loss than the JMF samples.

The Tukey analysis indicated that the reheat values for Mixtures B-1 and B-2 were significantly different, as shown in Table D1, Appendix D. For mixture B-1, the reheat results for samples 1 and 2 were significantly different. The results for reheat sample 3 from mixture B-2 were significantly different from those for all other mixture B-2 samples. The results for the reheat samples from Mixture B-3 were not significantly different.

The average mass loss values for each type of specimen are shown in Figure 10. The trends were the generally same for the three mixtures: the JMF and reheat mass loss values were higher than those for the plant mixtures.

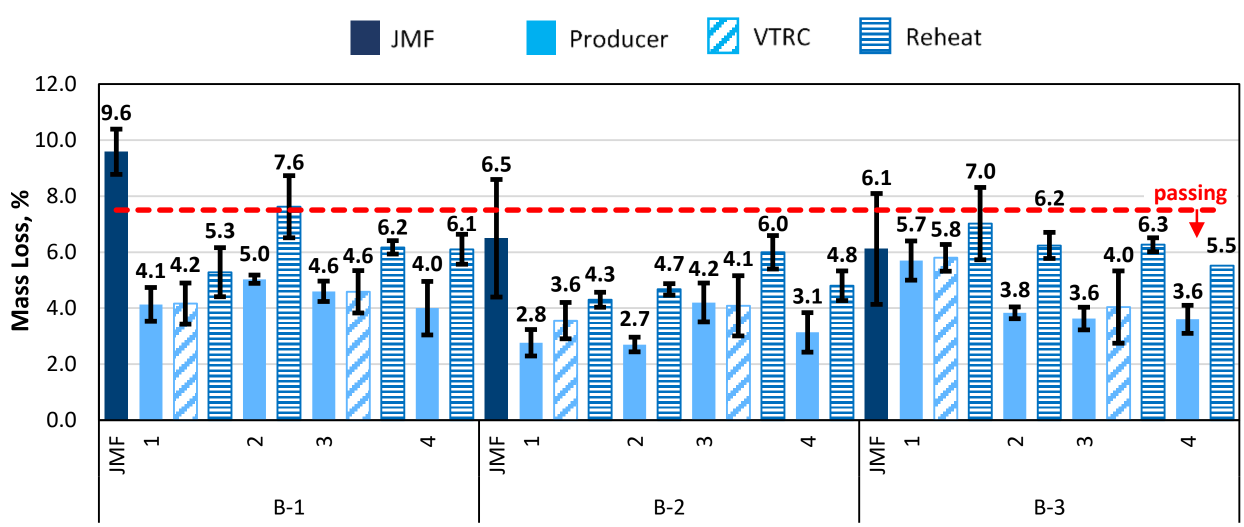


**Figure 9. Producer B Test Results for Mass Loss. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

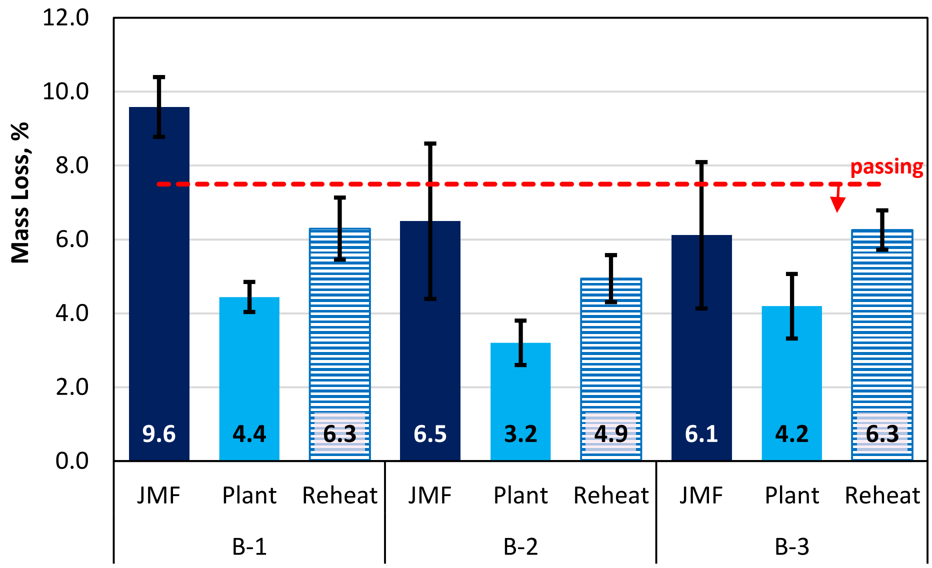


**Figure 10. Average Mass Loss Values for Mixtures B-1 Through B-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

For mixture B-1, statistical analysis indicated that the differences between the JMF, plant, and reheat values were significant, as shown in Table D2, Appendix D. The analysis also found that the JMF, plant, and reheat results for mixture B-3 were not significantly different. The JMF and reheat mass losses were similar for mixture B-2; the plant and reheat values were also statistically similar. Mixtures B-2 and B-3 showed reductions in JMF mass loss compared to that of the control mixture B-1. The improvement in performance was also shown in the plant and reheat mass loss values for mixture B-2, likely due to the use of the softer binder (PG 58-28). However, mixture B-3, containing PG 64-22 binder and an RA, showed plant and reheat values similar to those of mixture B-1. Analysis of the average reheat mass loss values (shown in Table D3, Appendix D) indicated that statistically, the reheat results for all mixtures were similar.

Figure 11 shows the rut depth results for each sample collected for mixtures B-1 through B-3. No result failed the maximum 8.0 mm rut depth criterion. Overall, the results for the reheat samples were higher than for the plant samples with the exception of four pairs of samples (mixture B-1 samples 1 and 4, mixture B-2 sample 3, and mixture B-3 sample 3). For these mixtures, there were no consistent trends in the results compared to those for the JMF rut depths. Statistical analysis of the reheat rut depth results, shown in Table D4, Appendix D, indicated that there was no statistical difference among the results of the reheat samples evaluated for each mixture.

The average rut depth values for each sample type and mixture are shown in Figure 12. The averaged values indicated that the JMF sample had the lowest rut depth for each mixture, with the averaged plant and reheat values being higher. Statistical analysis, shown in Table D5, Appendix D, indicated no significant differences between the JMF, plant, or reheat values for any of the three mixtures. The Tukey analysis of the average reheat values in Table D6, Appendix D, showed that there were no significant differences between the mixture reheat values.

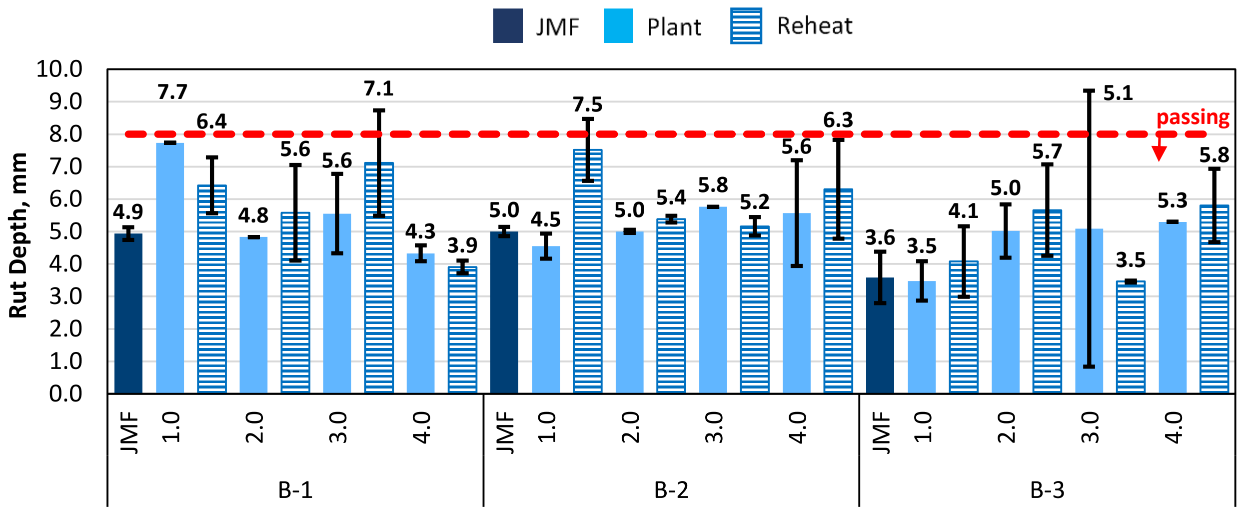


**Figure 11. Producer B Test Results for Rut Depth. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

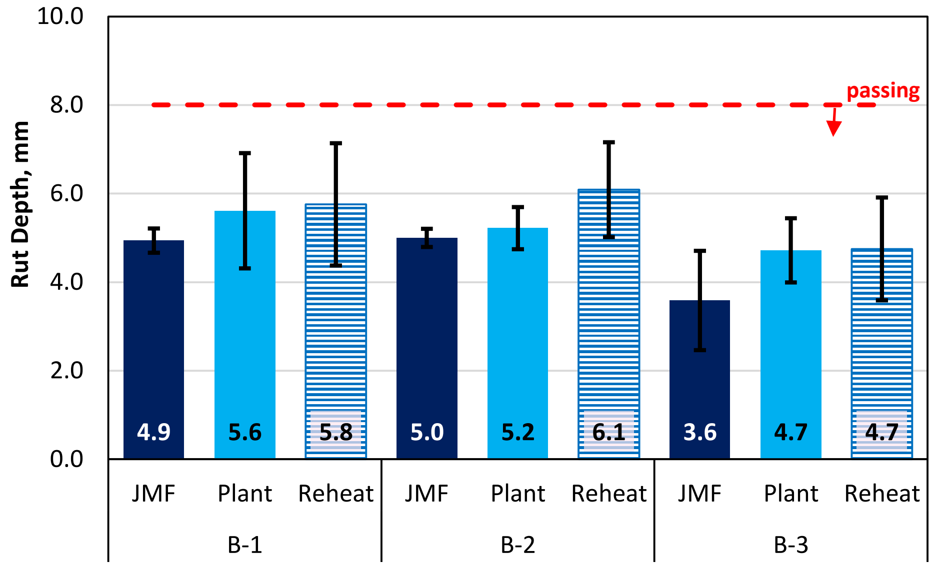


**Figure 12. Average Rut Depths for Mixtures B-1 Through B-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

Cracking test results for each sample of each of the three mixtures are shown in Figure 13. All samples met the minimum CT index criterion of 70 except for the mixture B-1 JMF and the mixture B-3 reheat sample 1. For all three mixtures, the VTRC-tested plant results were lower than the producer-tested plant results. Reheat results were generally lower than the corresponding plant sample results. For the control mixture B-1, the reheat results were higher than the JMF results, whereas the opposite was seen for mixture B-3. The reheat results were either similar to or less than the JMF results for mixture B-2.

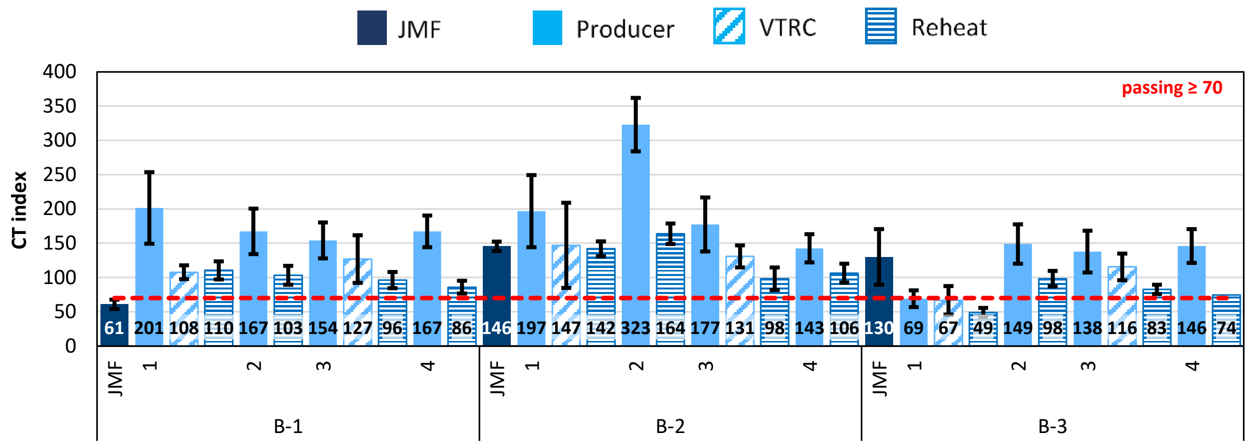


**Figure 13. Producer B Test Results for CT Index. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; VTRC = Virginia Transportation Research Council.**

The Tukey analysis of the reheat results for each mixture is shown in Table D7, Appendix D. For all three mixtures, there was variability between sample results. Two groupings were seen for mixture B-1, indicating that the results for samples 1 and 4 were significantly different. Mixture B-2 had two statistically distinct groupings, samples 1 and 2 and samples 3 and 4. Mixture B-3 had three groupings, indicating that the results for samples 1 and 2 were significantly different from each other and significantly different from those for samples 3 and 4.

The average values of the CT index for each mixture are shown in Figure 14. The Tukey analysis of the values is shown in Table D8, Appendix D. Mixtures B-1 and B-2 had average plant CT indices that were higher than the JMF and reheat CT index values.

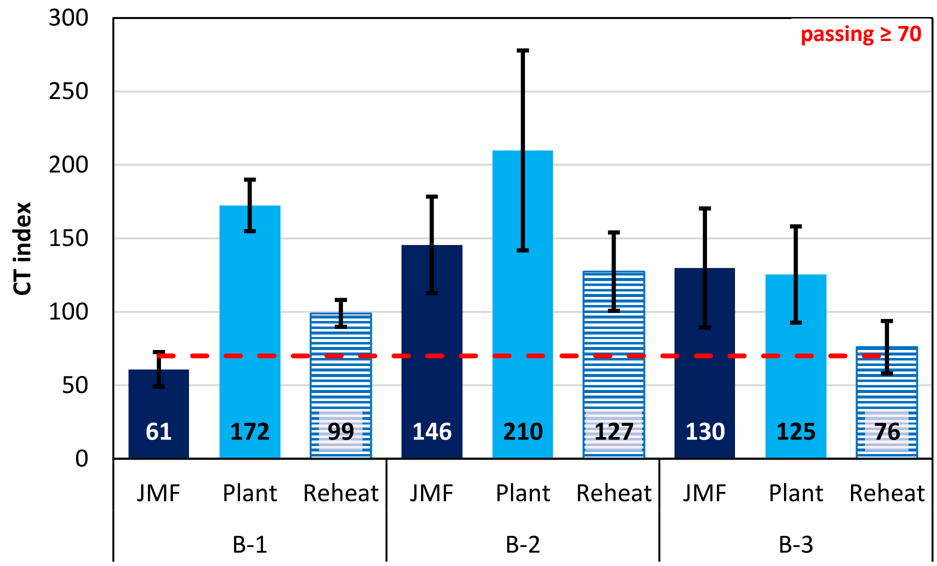


**Figure 14. Average CT Index Values for Mixtures B-1 Through B-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula.**

However, only mixture B-1 had significant differences between the JMF, plant, and reheat values; the values for mixture B-2 were not significantly different. Mixture B-2 had higher CT index values for the JMF, plant, and reheat samples than mixture B-1. The higher values for mixture B-2 should indicate improved cracking performance compared to mixture B-1. The values for the mixture B-3 JMF, plant, and reheat samples were also not significantly different. Mixture B-3 had a higher JMF CT index than mixture B-1, but the plant and reheat values were lower. Statistical analysis of the reheat results for the three mixtures using the Tukey procedure, shown in Table D9, Appendix D, indicated that there was no significant difference between the mixture B-2 or mixture B-3 results and the control mixture B-1 results, although the results for mixtures B-2 and B-3 were significantly different.

## Producer C

Only one mixture from Producer C was evaluated, due to overlap in projects and limited personnel. The volumetric and gradation properties of the mixture are shown in Table C7, Appendix C. Mixture C-1 was a 12.5 mm NMAS mixture designed to meet the requirements of VDOT's BMD special provision and contained 35% RAP and a PG 58-28 binder.

The mass loss results for all mixture C-1 samples are shown in Figure 15. Three samples failed the maximum mass loss criterion of 7.5%: reheat samples 1 and 4 and the VTRC-tested plant sample 3. The JMF mass loss was less than for any other sample. The values for the VTRC-tested plant samples were higher than for the producer-tested plant samples. If loose mixture remains in the oven awaiting compaction and the resulting pills are not assigned in a way that equalizes the impact, this sort of difference can be seen. The results for the reheat samples were higher than for the corresponding plant samples. Statistical analysis of the reheat results, shown in Table D1, Appendix D, indicated no significant difference between reheat samples.

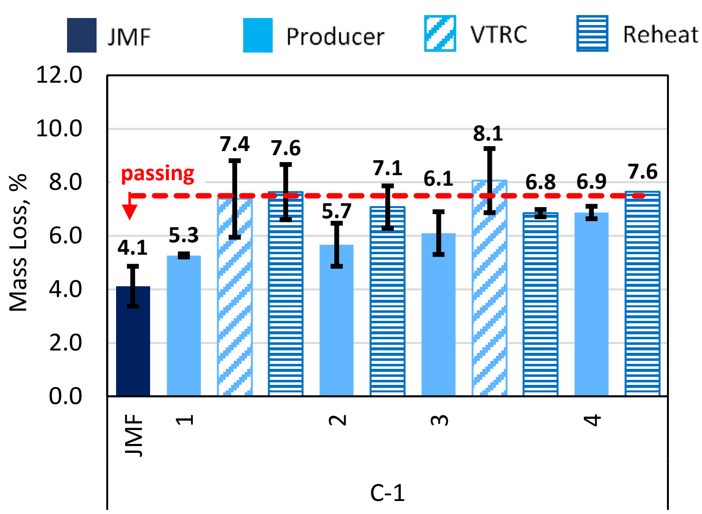


**Figure 15. Producer C Test Results for Mass Loss. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

The average mass loss values shown in Figure 16 indicate that the mixture passed the mass loss criterion. A clear trend of increasing mass loss from JMF to plant to reheat samples is also shown. The Tukey analysis, shown in Table D3, Appendix D, showed that each result was statistically different.

Rut depth values for mixture C-1 are presented in Figure 17. The JMF had the lowest rut depth, with plant samples having higher rut depths. Reheat samples 1 and 3 showed a reduction in rut depth after reheating, as expected; however, sample 4 had an increased rut depth after reheating. Analysis of the reheat values (Table D4, Appendix D) indicated no statistical difference between the reheat results.

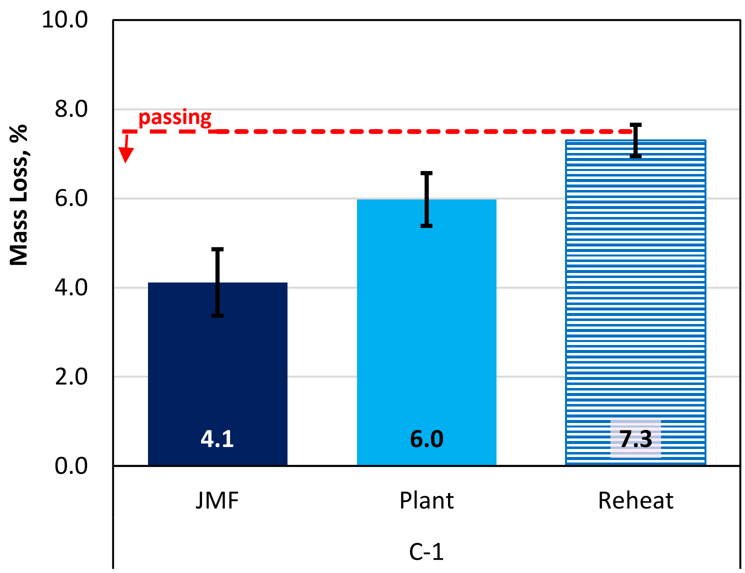


**Figure 16. Average Mass Loss Values for Mixture C-1. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

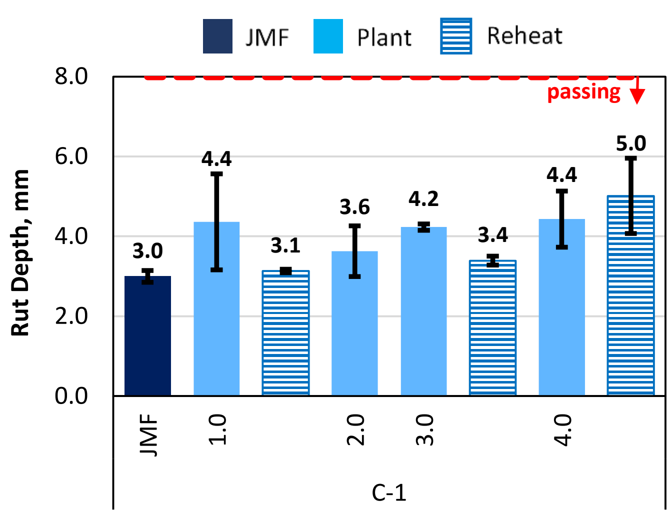


**Figure 17. Producer C Test Results for Rut Depth. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

Average rut depths for the JMF, plant, and reheat samples are shown in Figure 18. The JMF rut depth was less than the average plant and reheat values; however, all values were statistically similar, as shown in Table D5, Appendix D.

Figure 19 presents the CT index results for each sample. All samples passed the minimum CT index criterion of 70. The plant and reheat results were less than or similar to the JMF results. The producer-tested and VTRC-tested plant results were moderately comparable. Reheat results were less than the comparable plant results. Statistical comparison of the reheat results, shown in Table D7, Appendix D, found two groupings, indicating a significant difference between reheat samples 3 and 4.

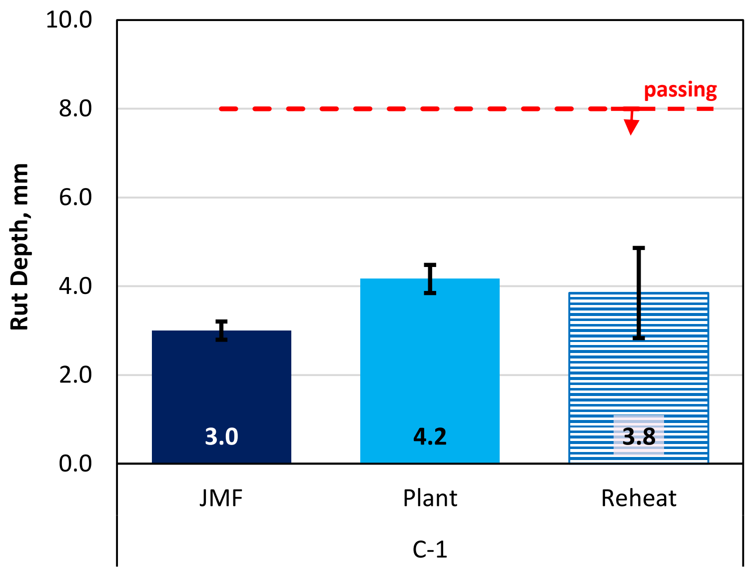


**Figure 18. Average Rut Depths for Mixture C-1. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

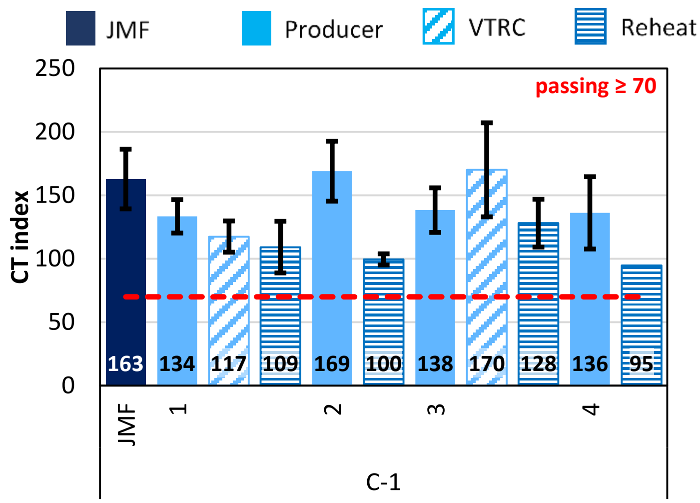


**Figure 19. Producer C Test Results for CT Index. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

Figure 20 shows the average results for the JMF, plant, and reheat samples. For this mixture, the JMF sample had the highest value, followed by the plant sample and then the reheat sample. Statistical comparison of the CT index values in Table D8, Appendix D, showed that the JMF and reheat values were statistically different.

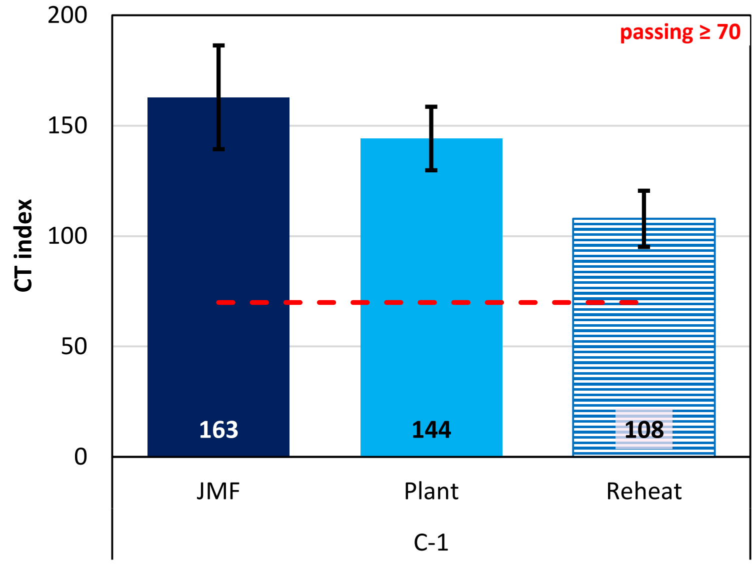


**Figure 20. Average CT Index Values for Mixture C-1. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula.**

## Producer D

Three mixtures were evaluated from Producer D, designated D-1, D-2, and D-3. The volumetric and gradation properties of the mixtures are shown in Tables C8 through C10, Appendix C. Mixture D-1 was a 12.5 mm NMAS mixture designed to meet current VDOT requirements (VDOT, 2016) and served as the control mixture for comparisons. Mixture D-1 contained 30% RAP and a PG 64S-22 binder. Mixtures D-2 and D-3 were 12.5 mm NMAS mixtures designed to meet the requirements of VDOT's BMD special provision. Mixture D-2 contained 35% RAP, PG 58-28 binder, and RA3. Mixture D-3 contained 35% RAP, PG 58-28 binder, fibers, and RA4.

Mass loss results for all samples of mixtures D-1 through D-3 are shown in Figure 21. A JMF mass loss value for mixture D-1 was not available. In addition, the results for mixture D-1 reheat samples 3 and 4 and VTRC-tested plant sample 4 were not available. Mixture D-1 VTRC-tested plant sample 3 failed the maximum mass loss criterion of 7.5%, despite the mixture not being designed in accordance with the BMD specification, although both reheat samples and the producer-tested plant sample 3 nearly failed the criterion. The producer-tested and VTRC-tested plant sample results had mixed trends for mixtures D-1 and D-2, whereas the results matched very well for mixture D-3. Reheat values were higher than the corresponding producer-tested plant values in all cases. Overall, mass losses for mixtures D-2 and D-3 were less than those for mixture D-1, indicating an improvement in the BMD-designed mixtures. The Tukey analysis of the reheat samples indicated that the reheat samples for each mixture were not statistically different, as shown in Table D1, Appendix D.

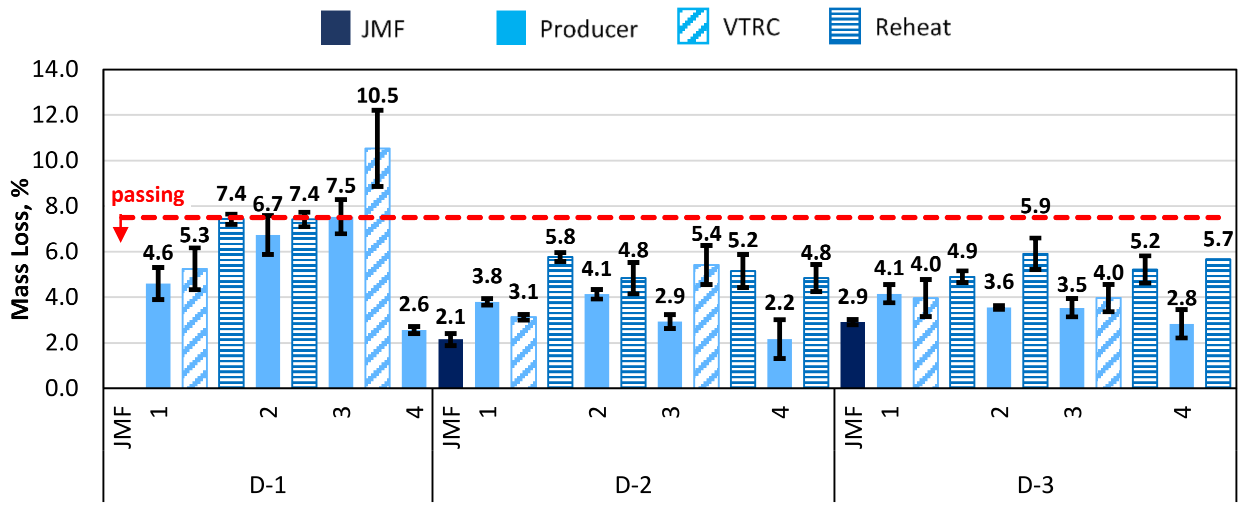


**Figure 21. Producer D Test Results for Mass Loss. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

The average mass loss values for each mixture followed the trend, as seen in Figure 22, where the mass loss increased from the JMF to the average plant and average reheat results. The BMD mixtures had improved performance over the control mixture for both the plant and reheat conditions. However, the plant and reheat values for mixture D-1, and the JMF, plant, and reheat values for mixture D-3, were not significantly different according to the Tukey analysis, shown in Table D2, Appendix D. This analysis also showed a significant difference between the JMF and reheat values for mixture D-2. Statistical analysis for each mixture, seen in Table D3, Appendix D, showed that the average reheat values for mixtures D-1 and D-3 and mixtures D-2 and D-3 were statistically similar.

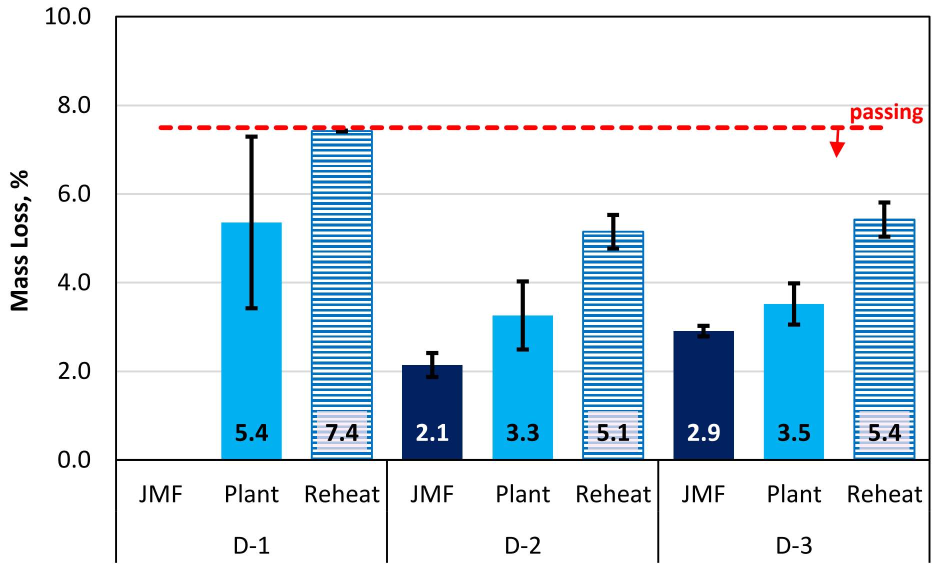


**Figure 22. Average Mass Loss Values for Mixtures D-1 Through D-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

Rut testing results for each mixture and sample are presented in Figure 23. No sample failed the maximum rut depth criterion of 8.0 mm. For mixture D-1, samples 1 and 3 had similar results for the plant and reheat samples, whereas sample 2 had very different results. Three of the four samples for mixture D-2 showed an increase in rut depth after reheating. The results for mixture D-3 indicated that the plant and reheat rut depths were greater than the JMF rut depths; in addition, the reheat results were greater than the plant results for all mixture D-3 samples. The Tukey procedure was performed to determine if the results for the reheat samples for each mixture were statistically similar. The results, shown in Table D4, Appendix D, indicated that there were no statistical differences in the four reheat sample results for each mixture.

The evaluation of the average rut depth results for each sample type, shown in Figure 24, indicated that mixtures D-2 and D-3 had higher plant and reheat rut depth values compared to mixture D-1. This indicated that the softer binder used in both mixtures, along with the RA used in mixture D-2 and the RA and fibers used in mixture D-3, was effective in reducing the stiffness of the BMD mixtures as compared to the control mixture. Comparison of the JMF, plant, and reheat values, shown in Table D5, Appendix D, indicated no significant differences between the plant and reheat values for mixture D-1 or between the JMF, plant, and reheat values for mixture D-2. The mixture D-3 reheat value was significantly different from the JMF and plant values. Analysis of the reheat values for each mixture, shown in Table D6, Appendix D, found no significant differences between the reheat rut depths of the three mixtures.

The CT index was also evaluated for each sample collected for each mixture, as seen in Figure 25. For mixtures D-1 and D-2, the VTRC-tested plant samples had higher CT index values than the producer-tested plant samples; the trend was different for mixture D-3, where the value for one VTRC-tested plant sample was lower and the other was similar to those of the comparable producer-tested plant samples.

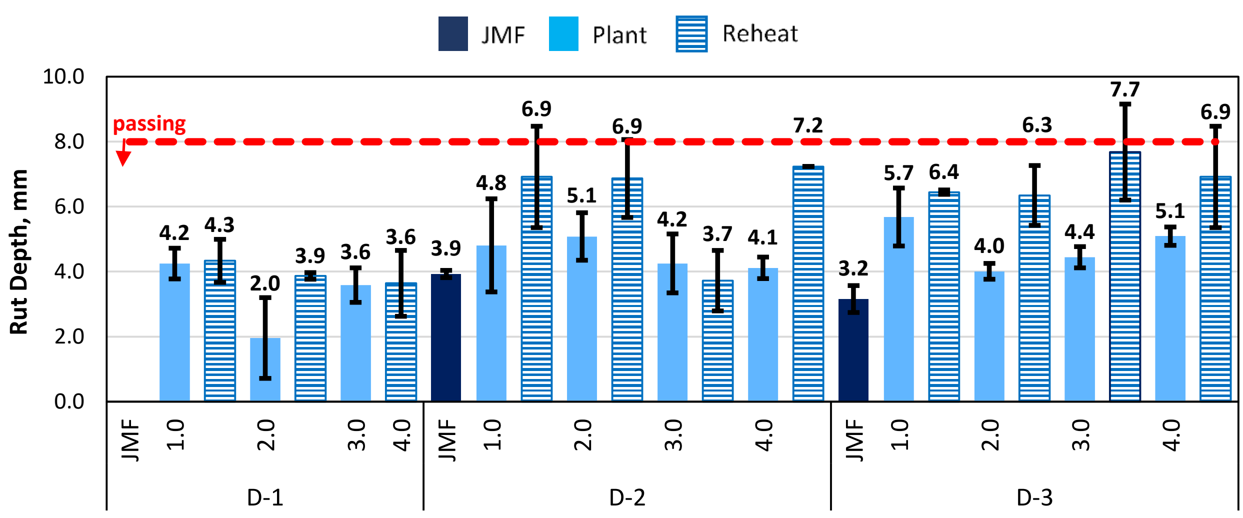


**Figure 23. Producer D Test Results for Rut Depth. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

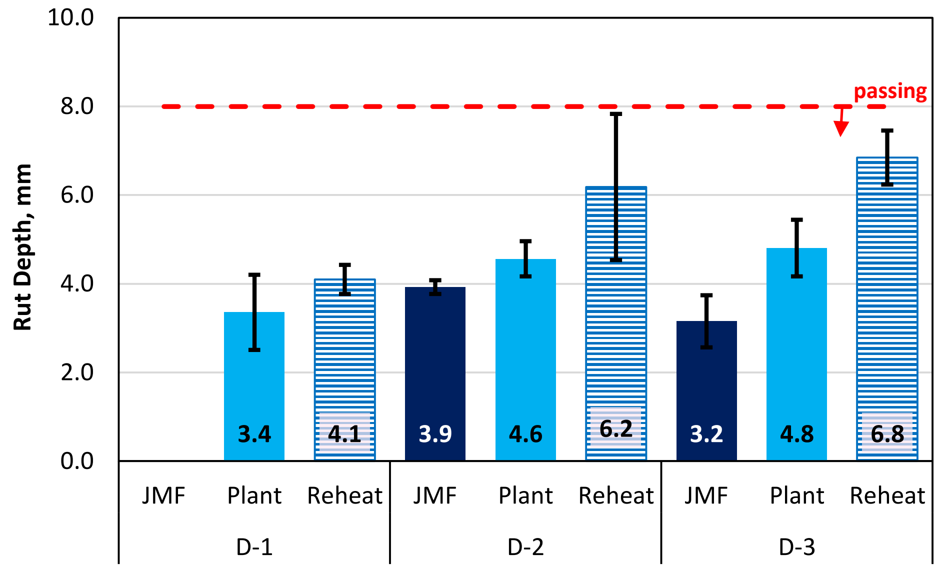


**Figure 24. Average Rut Depths for Mixtures D-1 Through D-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

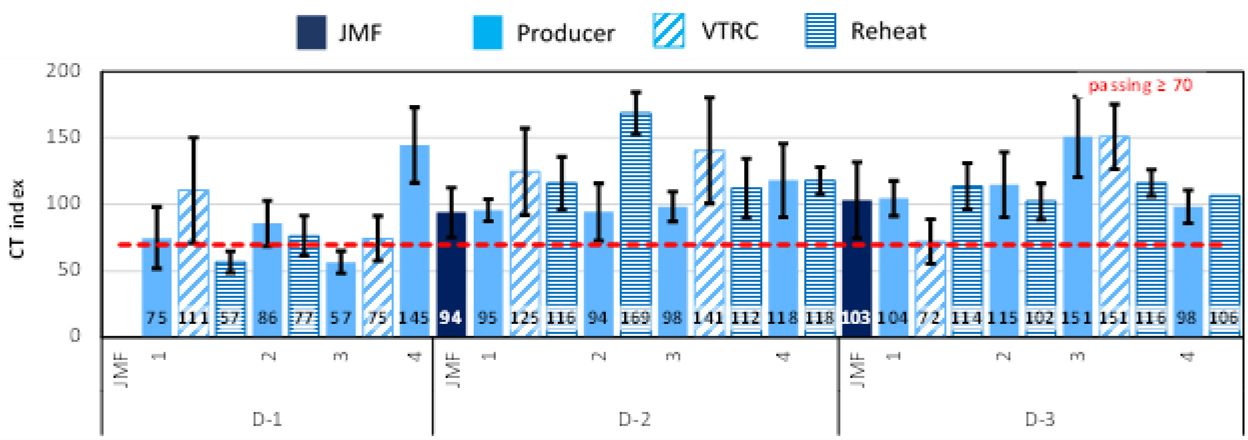


**Figure 25. Producer D Test Results for CT Index. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

The results for the producer-tested plant samples were variable for mixture D-1, with one sample failing the minimum CT index criterion of 70. The producer-tested plant sample results were more consistent for mixtures D-2 and D-3. Reheat results showed no trend with respect to producer-tested plant samples across all three mixtures; in some cases the reheat values were higher and in others the reheat values were similar to or less than those for the producer-tested plant samples. The Tukey analysis for the reheat samples is shown in Table D7, Appendix D. The results for the reheat samples for mixture D-1 were significantly different from each other. The results for reheat sample 2 of mixture D-2 were significantly different from those for the other three reheat samples, whereas the results for all reheat samples of mixture D-3 were statistically similar.

Figure 26 shows the averaged results for the JMF, plant, and reheat samples for each mixture. Both BMD mixtures showed improved cracking resistance in the form of higher CT index values when compared to the control mixture D-1. Statistical comparisons of the JMF, plant, and reheat values, summarized in Table D8, Appendix D, showed no significant differences between the values for mixtures D-1 and D-3, whereas the JMF and reheat values for mixture D-2 were significantly different. Statistical evaluation of the reheat values, shown in Table D9, Appendix D, indicated that the average reheat CT index values for mixtures D-1 and D-3 were statistically similar and that the average reheat CT index value for mixture D-2 was significantly different than that for mixture D-1.

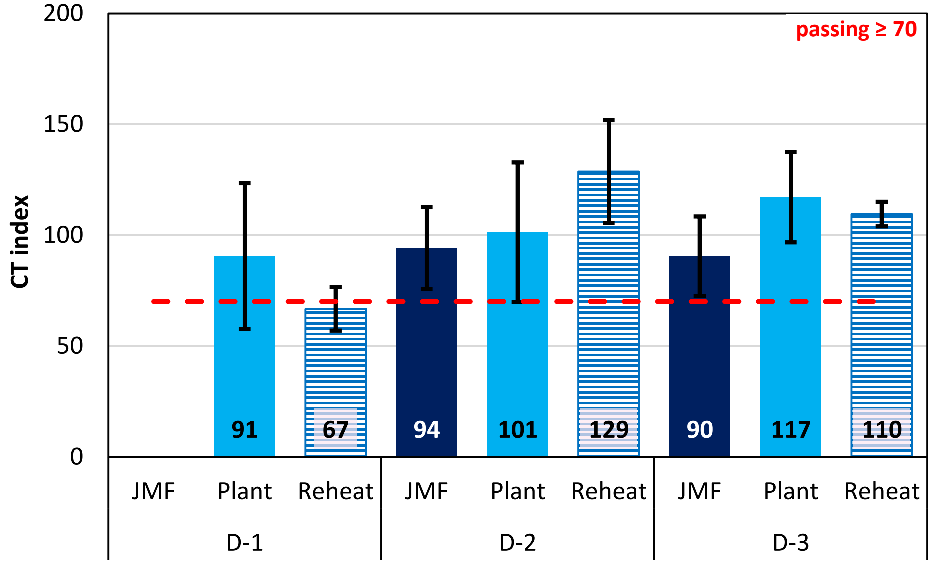


**Figure 26. Average CT Index Values for Mixtures D-1 Through D-3. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula.**

### Producer E

Two mixtures were evaluated from Producer E, designated E-1 and E-2. The volumetric and gradation properties of the mixtures are shown in Tables C11 and C12, Appendix C. Mixture E-1 was a 12.5 mm NMAS mixture designed to meet current VDOT requirements (VDOT, 2016) and served as the control mixture for comparisons. JMF values were not available for mixture E-1. Mixture E-2 was a 12.5 mm NMAS mixture designed to meet the requirements of VDOT's BMD special provision and contained 35% RAP and PG 58-28 binder. Only three samples were collected from each mixture due to logistical constraints.

Mass loss results for each sample from mixtures E-1 and E-2 are shown in Figure 27. For both mixtures, VTRC-tested plant samples and reheat samples had higher mass losses than producer-tested plant samples. The VTRC-tested plant samples and reheat samples were similar for the control mixture E-1; of the samples tested for mixture E-2, one pair was similar and the other showed a difference between the sample types. The Tukey analysis for the reheat samples for mixtures E-1 and E-2 is shown in Table D1, Appendix D. For mixture E-1, the results for samples 1 and 3 were significantly different. The results for sample 2 were significantly different from those for samples 1 and 3 for mixture E-2.

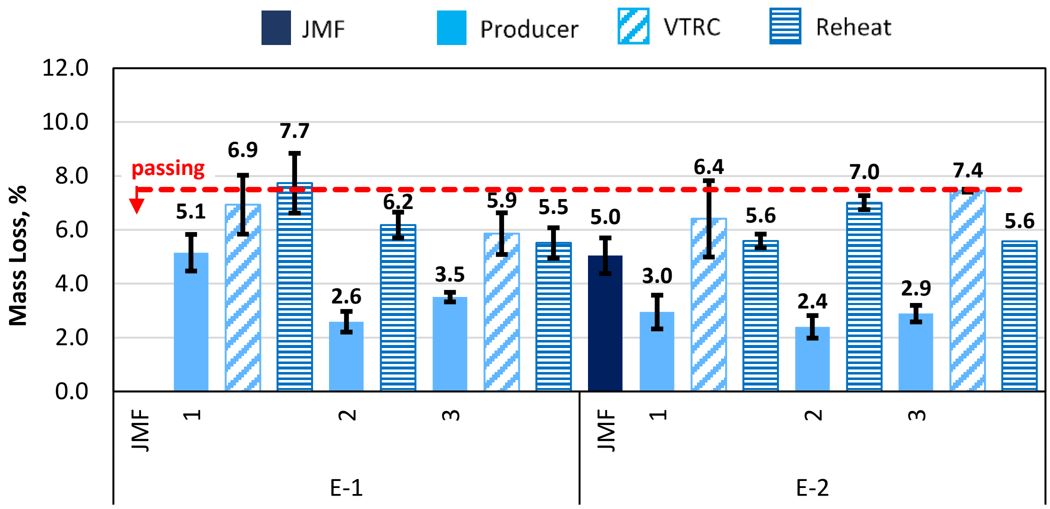


**Figure 27. Producer E Test Results for Mass Loss. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

The average values for the JMF, plant, and reheat samples are shown in Figure 28. The mass losses for the mixture E-2 plant and reheat samples were less than those for the control mixture E-1, indicating that the softer PG 58-28 binder used in mixture E-2 was effective in improving the mass loss compared to the control mixture E-1. Evaluation of the JMF, plant, and reheat values using the Tukey procedure, shown in Table D2, Appendix D, indicated no significant differences between the plant and reheat values for mixture E-1. The plant value was significantly different from the JMF and reheat values for mixture E-2. A comparison of the reheat values, presented in Table D3, Appendix D, showed no significant difference between the mixture E-1 and E-2 values.

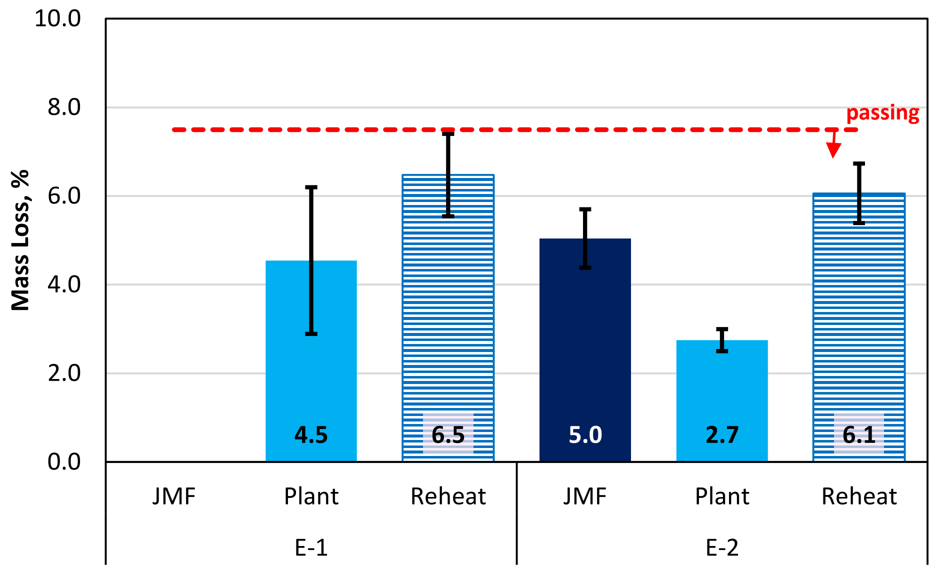


**Figure 28. Average Mass Loss Values for Mixtures E-1 and E-2. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

Figure 29 presents the rut depth results for each sample from mixtures E-1 and E-2. All samples passed the maximum rut depth criterion of 8.0 mm. The plant rut depths for mixture E-1 were less than or similar to the reheat values. Plant and reheat rut depths for mixture E-2 were greater than the JMF rut depth. Statistical analysis of the reheat samples showed no significant sample-to-sample differences, as shown in Table D4, Appendix D.

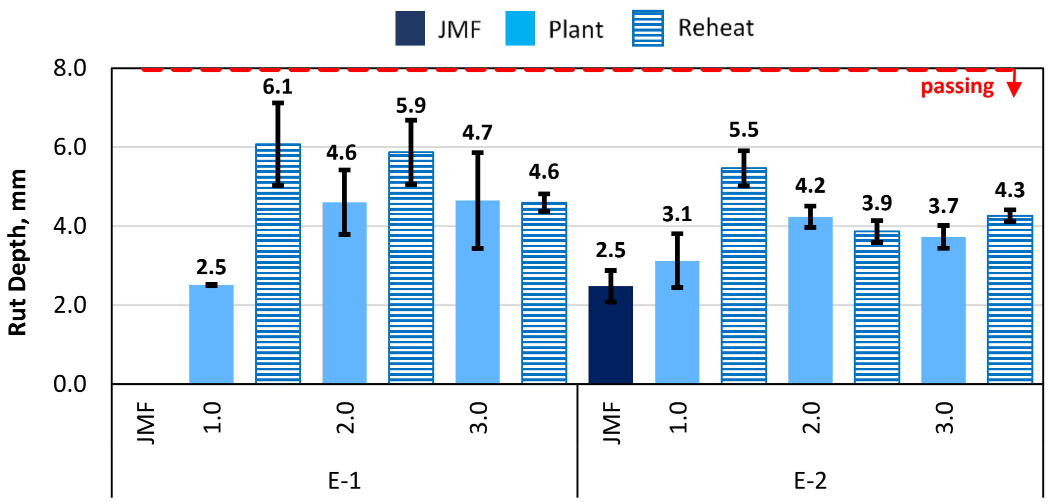


**Figure 29. Producer E Test Results for Rut Depth. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

The average rut depths for the JMF, plant, and reheat samples are shown in Figure 30. The average reheat results were greater than the average plant results for both mixtures. The JMF value for mixture E-2 was less than the average plant and average reheat values for the mixture.

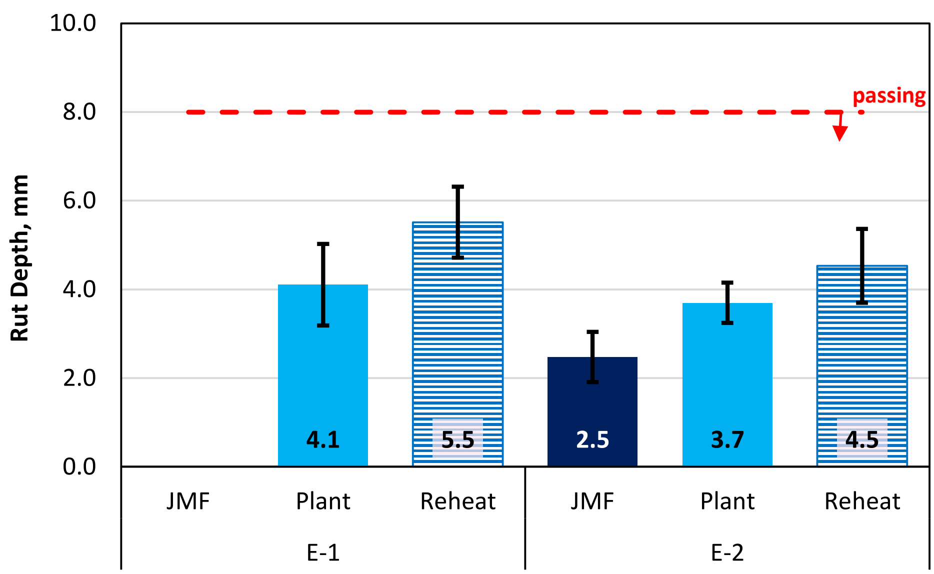


**Figure 30. Average Rut Depths for Mixtures E-1 and E-2. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. JMF = job-mix formula.**

A comparison of the values for mixtures E-1 and E-2 using the Tukey procedure, as presented in Table D5, Appendix D, indicated that the plant and reheat values for mixture E-1 were not significantly different and that the JMF and reheat values for mixture E-2 were significantly different. Similar evaluation of the reheat values for the two mixtures showed that the reheat values were statistically similar, as shown in Table D6, Appendix D.

Figure 31 shows the CT index values for mixtures E-1 and E-2. All samples passed the minimum CT index requirement of 70. The producer-tested and VTRC-tested plant values were comparable except for sample 1 from mixture E-2. Reheat samples had lower or similar CT index values compared to the producer-tested plant samples. A summary of the results of the Tukey procedure performed on the reheat CT index results is shown in Table D7, Appendix D. There were no significant differences among the results for the reheat samples for mixture E-1, whereas the result for the mixture E-2 reheat sample 2 was significantly lower than those for the other two reheat samples.

The average CT index values for mixtures E-1 and E-2 are shown in Figure 32. The average plant values for both mixtures were higher than the average reheat values. Comparison of the JMF, plant, and reheat values (shown in Table D8, Appendix D) indicated that the plant and reheat CT index values for each mixture were not significantly different. Comparison of the reheat values for the two mixtures, as seen in Table D9, Appendix D, showed that the two values were not significantly different.

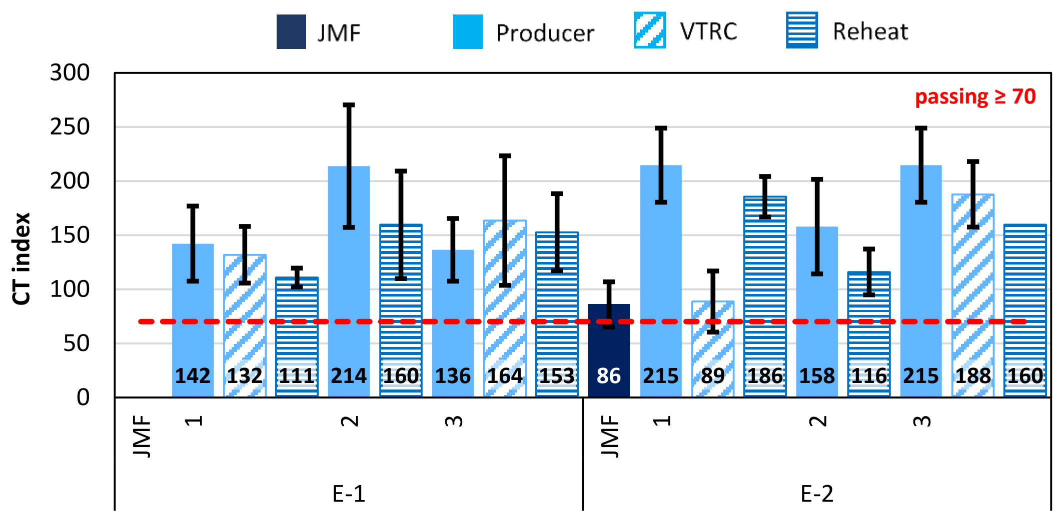


**Figure 31. Producer E Test Results for CT Index. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula; VTRC = Virginia Transportation Research Council.**

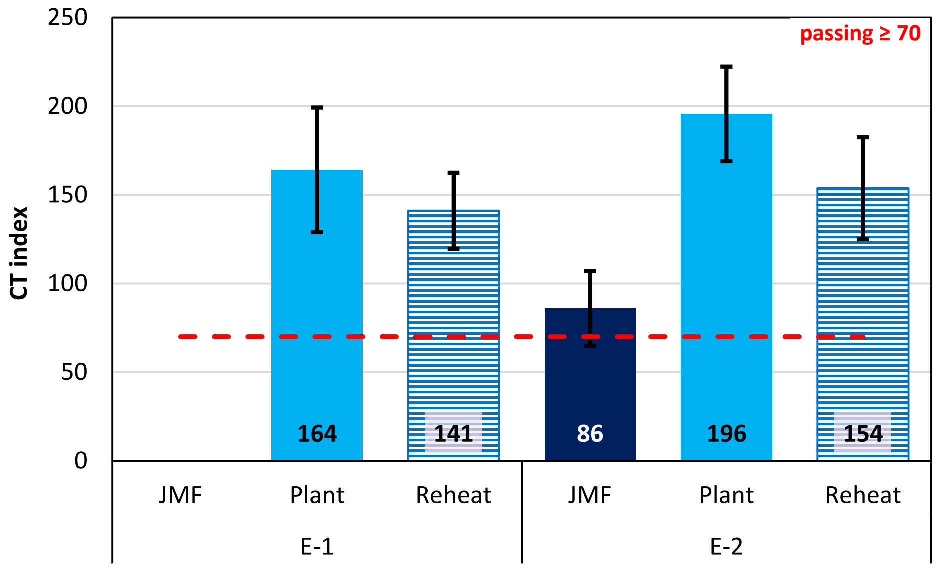


**Figure 32. Average CT Index Values for Mixtures E-1 and E-2. I-bars indicate ±1 standard deviation. Red dashed line indicates specification limit. CT = cracking tolerance; JMF = job-mix formula.**

## Plant Samples vs. Reheat Samples

One of the continuing questions related to BMD testing is the impact of reheating on mixture testing. Although the impact on volumetrics from reheating mixtures is negligible, the additional aging induced by reheating a mixture can have a significant impact on performance properties. As an example, this issue is addressed for the APA rut test in AASHTO T 340, as section 4.3.1 recommends that reheating of loose plant mixture be avoided when test specimens are fabricated. Addressing the issue is critical for quality control and acceptance purposes.

An initial investigation to determine the relationship between plant and reheat specimens was conducted for the mixtures in this study. Figure 33 shows a linear fit between the plant and reheat values in terms of mass loss. Although the correlation between the two was not strong ($R^2$ of 0.36), one of the factors known to influence the mass loss—specimen air-void content—was not accounted for.

Figure 34 shows a linear fit between the plant and reheat values for the CT index. With an $R^2$ of 0.26, it is clear that other factors also affect the CT index. Neither of these relationships accounts for volumetric properties or multi-laboratory variability conditions. Clearly, further work with a more robust data set that addresses the many factors influencing test results is necessary to evaluate and develop relationships between plant and reheat specimens; however, the data in this study indicate that these relationships can be developed.

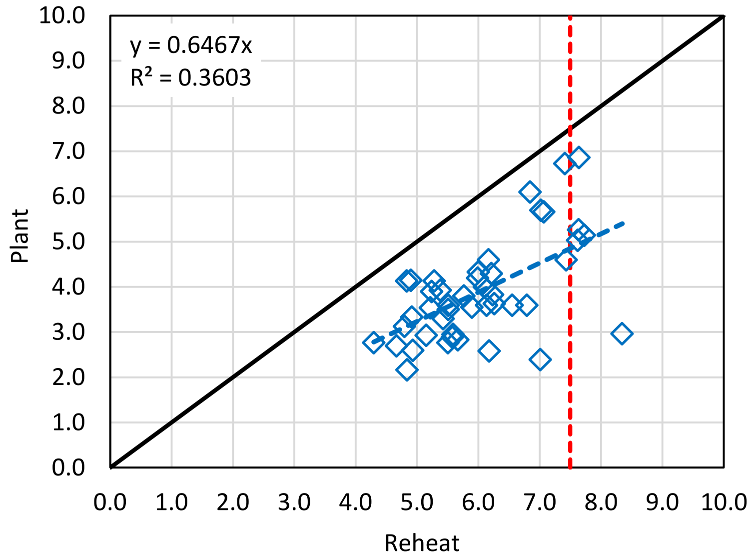


**Figure 33. Reheat vs. Plant Mass Loss Values**

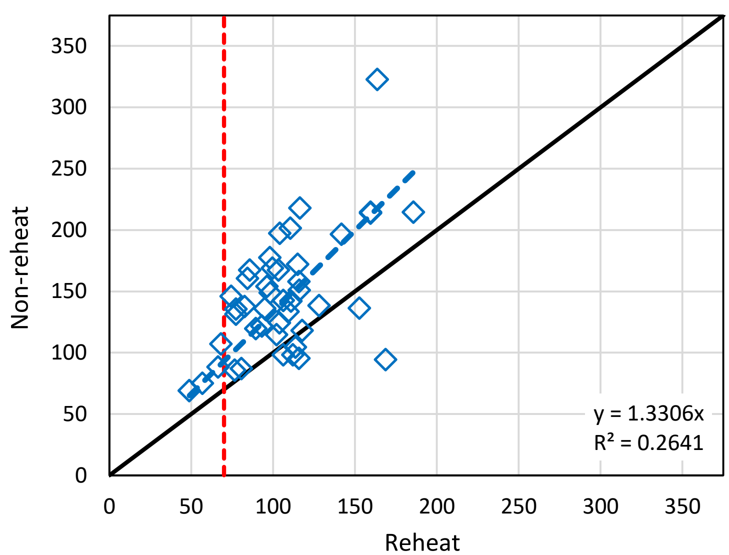


**Figure 34. Reheat vs. Plant CT Index Values. CT = cracking tolerance.**

## Binder Testing

### Performance Grading

The PG and a few rheological properties of the extracted and recovered binders from the evaluated mixtures are presented in Table 6. Overall, no clear trends were observed for the PG high, intermediate, and low temperatures as a function of the RAP content and the use of softer binder, RA, and/or other types of additives.

**Table 6. Performance Grading Results of Extracted and Recovered Asphalt Binders**

| Property | | Mixture ID | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **A-1** | **A-2** | **A-3** | **B-1** | **B-2** | **B-3** | **C-1** | **D-1** | **D-2** | **D-3** | **E-1** | **E-2** |
| **Dynamic Shear, 10 rad/s, specification: \|G*\|/sin δ >2.20 kPa** | | | | | | | | | | | | | |
| RTFO \|G*\|/sin δ, kPa | 64°C | - | - | - | - | 4.22 | - | - | - | - | - | - | - |
| | 70°C | - | - | - | 3.24 | 1.95 | - | 3.28 | - | 2.52 | 2.48 | 2.44 | 3.87 |
| | 76°C | 3.54 | 2.41 | 2.93 | 1.53 | - | 2.46 | 1.60 | 2.44 | 1.23 | 1.22 | 1.18 | 1.85 |
| | 82°C | 1.81 | 1.19 | 1.44 | - | - | 1.22 | - | 1.21 | - | - | - | - |
| RTFO Failure Temperature, °C | | **80.3** | **76.8** | **78.4** | **73.1** | **69.1** | **77.0** | **73.3** | **76.9** | **71.1** | **71.0** | **70.9** | **74.6** |
| **Dynamic Shear, 10 rad/s, specification: \|G*\|·sin δ < 5,000 kPa** | | | | | | | | | | | | | |
| PAV \|G*\|·sin δ, kPa | 19°C | - | - | - | - | 6,190 | - | 6,130 | - | 6,550 | 6,380 | - | - |
| | 22°C | - | 5,950 | 6,300 | 5,770 | 4,400 | - | 4,380 | - | 4,550 | 4,500 | 6,160 | 5,960 |
| | 25°C | 5,040 | 4,250 | 4,560 | 4,170 | - | 5,270 | - | 6,300 | - | - | 4,520 | 4,260 |
| | 28°C | 3,670 | - | - | - | - | 3,810 | - | 4,620 | - | - | - | - |
| PAV Failure Temperature, °C | | **25.1** | **23.6** | **24.1** | **23.3** | **20.9** | **25.5** | **26.6** | **27.2** | **21.2** | **21.1** | **24.0** | **23.6** |
| **Creep Stiffness, 60 sec, specification: Stiffness (S) < 300 MPa and m-value > 0.300** | | | | | | | | | | | | | |
| Stiffness (S), MPa | -12ºC | 207 | 179 | 170 | 181 | 144 | 198 | 147 | 262 | 140 | - | 186 | 180 |
| | -18ºC | 403 | 350 | 326 | 366 | 296 | 393 | 310 | 499 | 307 | 280 | 359 | 375 |
| | -24ºC | - | - | - | - | 551 | - | - | - | 632 | 582 | - | - |
| m-value | -12ºC | 0.319 | 0.317 | 0.316 | 0.323 | 0.337 | 0.308 | 0.344 | 0.305 | 0.369 | - | 0.321 | 0.337 |
| | -18ºC | 0.269 | 0.270 | 0.274 | 0.276 | 0.288 | 0.265 | 0.293 | 0.254 | 0.310 | 0.310 | 0.268 | 0.290 |
| | -24ºC | - | - | - | - | 0.238 | - | - | - | 0.254 | 0.253 | - | - |
| Stiffness Failure Temperature ($T_S$), °C | | -15.3 | -16.6 | -17.2 | -16.3 | -18.1 | -15.6 | -17.7 | -13.3 | -17.8 | -18.6 | -16.4 | -16.2 |
| M-value Failure Temperature ($T_m$), °C | | -14.2 | -14.1 | -14.2 | -14.8 | -16.4 | -13.1 | -17.1 | -12.5 | -19.0 | -19.0 | -14.2 | -16.6 |
| PAV Low Failure Temperature, °C | | **-24.2** | **-24.1** | **-24.2** | **-24.8** | **-26.4** | **-23.1** | **-27.1** | **-22.5** | **-27.8** | **-28.6** | **-24.2** | **-26.2** |
| $\Delta Tc = T_S - T_m$, ºC | | -1.1 | -2.5 | -3.0 | -1.5 | -1.7 | -2.5 | -0.6 | -0.8 | +1.2 | +0.4 | -2.2 | +0.4 |
| **Performance Grade (AASHTO M 320)** | | **76-22** | **76-22** | **76-22** | **70-22** | **64-22** | **76-22** | **70-22** | **76-22** | **70-22** | **70-28** | **70-22** | **70-22** |
| **Multiple Stress and Creep Recovery (MSCR) Test at 64°C** | | | | | | | | | | | | | |
| $J_{nr}$, kPa$^{-1}$ | 0.1 kPa | 0.3392 | 0.6041 | 0.4553 | 1.1186 | 1.9722 | 0.5954 | 0.9147 | 0.7058 | 1.5551 | 1.3832 | 1.5436 | 0.9423 |
| | 3.2 kPa | 0.3937 | 0.6642 | 0.5010 | 1.2569 | 2.2392 | 0.6593 | 1.075 | 0.7777 | 1.7465 | 1.5993 | 1.7846 | 1.0565 |
| Avg. % Recovery, % | 0.1 kPa | 36.66 | 15.69 | 20.48 | 9.15 | 6.12 | 14.94 | 16.61 | 12.14 | 7.28 | 10.17 | 8.55 | 11.46 |
| | 3.2 kPa | 27.86 | 9.84 | 14.21 | 3.66 | 1.38 | 9.10 | 7.67 | 7.04 | 2.32 | 3.42 | 2.64 | 5.58 |
| **Performance Grade (AASHTO M 322)** | | **64E-22** | **64V-22** | **64V-22** | **64H-22** | **64S-22** | **64V-22** | **64H-22** | **64V-22** | **64H-22** | **64H-28** | **64H-22** | **64H-22** |

RTFO = rolling thin film oven; PAV = pressure aging vessel; Avg. = average, % = percent; - = no data collected.

For instance, binders A-2 and A-3 had lower continuous PG high and intermediate temperatures and similar continuous PG low temperatures when compared with the control binder A-1. Binders A-2 and A-3 were recovered from mixtures produced using 40% RAP, and binder A-1 was recovered from a mixture produced using 30% RAP. This clearly indicates a potential softening effect when softer binders or RAs are used. These observations held true only for binder B-2 when compared with the control binder B-1. In fact, binder B-3 (high RAP + RA2) had higher PG high, intermediate, and low temperatures when compared with those of binder B-1, which could be attributed to either the change in properties of the RAP stockpile and/or the efficiency (type and dosage) of the RA used. Major softening over all temperature ranges was observed for binders D-2 and D-3 when compared to binder D-1. It should be noted that mixtures D-2 and D-3 featured the use of multiple alternatives at the same time to alleviate the potential high stiffness induced with the use of a relatively high RAP content (i.e., softer binder + RA for mixture D-2 and softer binder + fiber + softening oil for Mixture D-3). Finally, binder E-2 had a high PG high temperature and a lower PG intermediate and low temperature when compared to binder E-1.

Binder grading was also performed 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 ($\%R_{3.2\,kPa}$) determined using the MSCR test. The MSCR test was conducted at 64°C, the average 7-day maximum pavement design temperature for Virginia. AASHTO M 332 specifies a maximum $J_{nr,\,3.2\,kPa}$ requirement for standard (S), heavy (H), very heavy (V), and extremely heavy (E) traffic of 4.5 $kPa^{-1}$, 2.0 $kPa^{-1}$, 1.0 $kPa^{-1}$, and 0.5 $kPa^{-1}$, respectively. Figures 35 and 36 show the MSCR testing data for all evaluated extracted and recovered binders. VDOT specifications call for a minimum of PG 64S-16 and PG 64H-16 "virgin" asphalt binders for surface mixtures with A and D designations, respectively (VDOT, 2016). The data in Figure 35 indicate that all extracted and recovered binders from the mixtures evaluated in this study met or exceeded the VDOT specification criteria in terms of asphalt binder properties. For example, slightly higher $J_{nr}$ and lower %R values were observed for binders A-2 and A-3 when compared with binder A-1; binder A-3 (incorporating the use of an RA) performed better than binder A-2 (which used a softer binder). Although binder A-1 met the extremely heavy (E) traffic requirement, this could be attributed to some elastomeric polymers present in the corresponding RAP stockpile given that %R for binder A-1 was low compared to typical polymer-modified asphalt binders. Binders A-2, A-3, B-3, and D-1 were in category V. Binders B-1, C-1, D-2, D-3, and E-1 were in category H. Binder B-2 was the only binder in category S. The %R values in Figure 36 were very low, which is commonly observed for typical unmodified binders.

Table 6 and Figure 37 present the ΔTc values for all evaluated binders. All binders had ΔTc values ranging from -3.0°C to +1.2°C, with none exceeding the traditional cracking zone of -5.0°C and with one binder (A-3) surpassing the cracking warning limit of -2.5°C (Yang et al., 2022). This indicates a promising resistance to non–load related cracking.

For example, the ΔTc decreased (more negative) with the use of softer binders followed by the blends that featured the use of RAs ($\Delta Tc_{A-1} > \Delta Tc_{A-2} > \Delta Tc_{A-3}$ and $\Delta Tc_{B-1} > \Delta Tc_{B-2} > \Delta Tc_{B-3}$). No clear trends for ΔTc were observed with the use of multiple alternatives at the same time. An improvement of ΔTc was observed for binder E-2 when compared with binder E-1 ($\Delta Tc_{E-2} > \Delta Tc_{E-1}$).

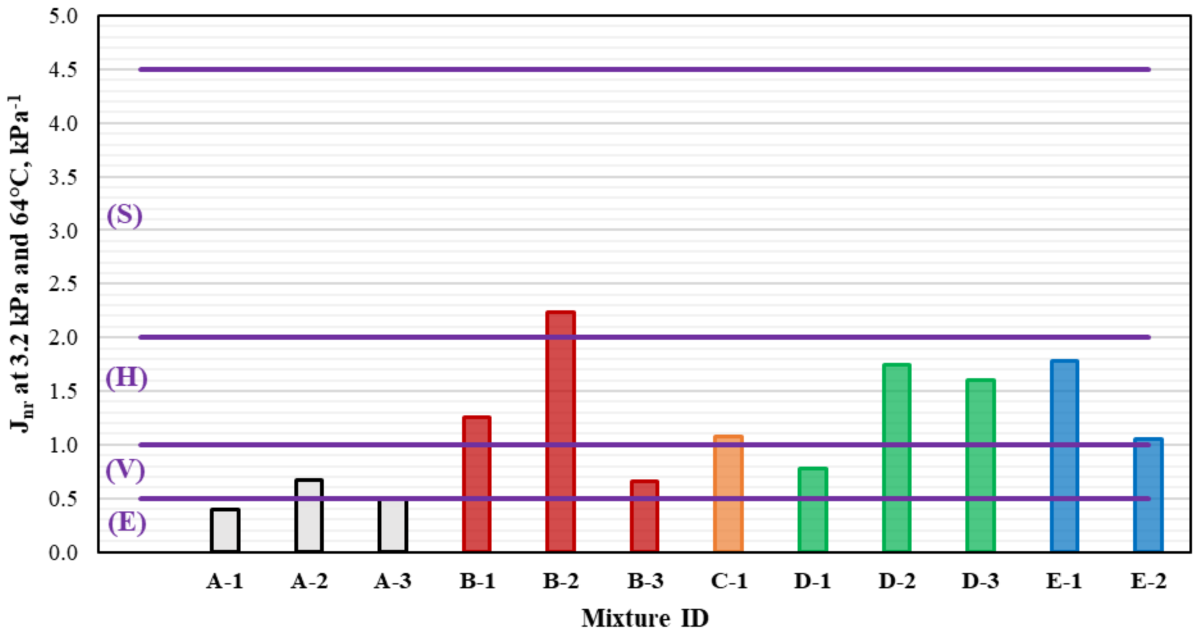


**Figure 35. Multiple Stress and Creep Relaxation (MSCR) Testing Data: Summary of Non-Recoverable Creep Compliance at 3.2 kPa ($J_{nr,\ 3.2\ kPa}$). Purple lines indicate specification limits. (S), (H), (V), and (E) are specification designations.**

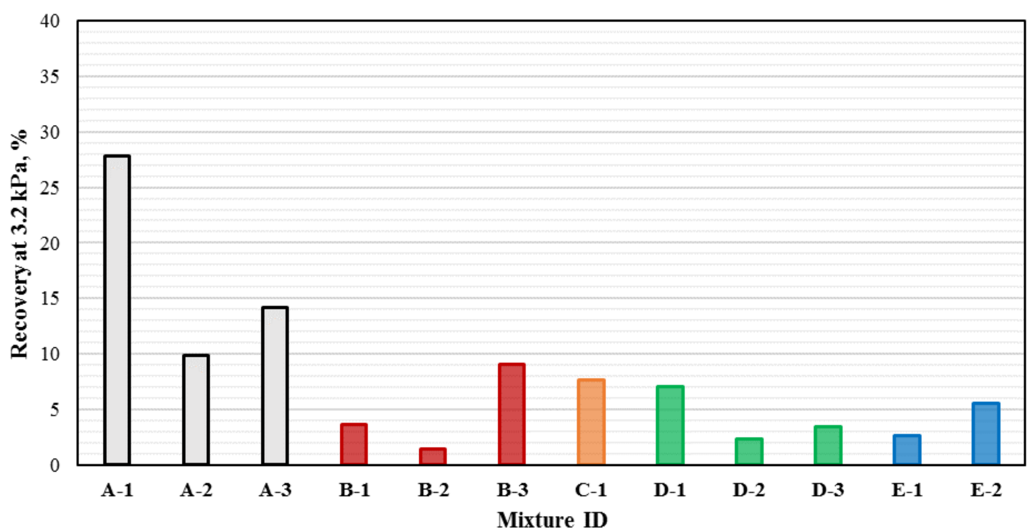


**Figure 36. Multiple Stress and Creep Relaxation (MSCR) Testing Data: Summary of Percent Recovery at 3.2 kPa ($\%R_{3.2\ kPa}$)**

The ongoing NCHRP Project 09-60 aims to address the impacts of changes in asphalt binder formulation and manufacturer on pavement performance through changes in the asphalt binder specification. As part of this study, the research team defined three new categories based on the measured ΔTc values: (1) the "passing" category, which features ΔTc values greater than

-2°C; (2) the "failing" category, which features ΔTc values lower than -6°C; and (3) the "to be determined" category, which features ΔTc values ranging from -2 to -6°C (Elwardany et al., 2020). In the case of the third category, the asphalt binder cracking device (ABCD) test should be used for further analysis. This test was not performed as part of this study since the VTRC laboratory does not have the ABCD test setup.

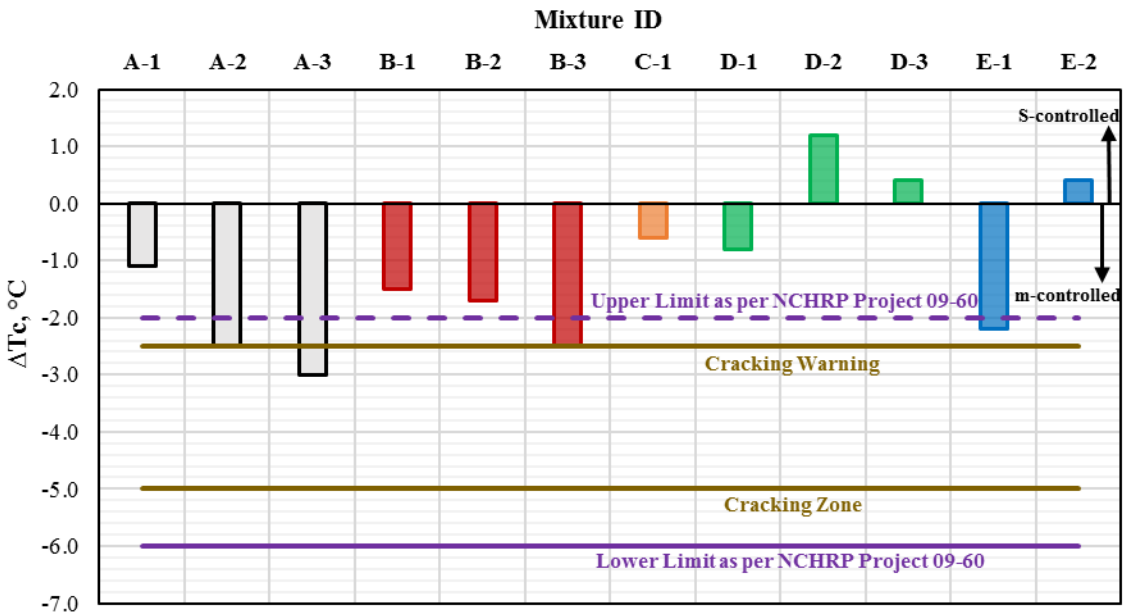


**Figure 37. Difference in Critical Low Temperature Performance Grade (ΔTc) for All Evaluated Extracted and Recovered Asphalt Binders. Purple solid and dashed lines indicate lower and upper limits recommended by Elwardany et al. (2020). Gold solid lines indicate the limits of warning and cracking zones.**

Overall, no binders had ΔTc values lower than -6°C. The majority of binders except for binders A-2, A-3, B-3, and E-1 had ΔTc values greater than -2°C, thus belonging to the passing category. The binders that belong to the "to be determined" category had ΔTc values very close to the -2°C passing criterion, again indicating a high resistance to non–load related cracking.

## G-R Parameter

Figure 38 shows G-R1 for all evaluated binders at the as-recovered and 20-hour PAV aging conditions. As expected, G-R1 significantly increased with aging (as-recovered vs. 20-hour PAV). A damage zone/range where cracking is likely to begin because of brittle rheological behavior is defined by a G-R1 between 180 (onset of cracking) and 600 kPa (significant cracking) that correlates to low ductility values of 5 to 3 cm, respectively. None of the binders had a G-R1 greater than 600 kPa. The majority of the binders (i.e., binders A-1, A-2, A-3, B-3, D-1, and E-1) fell in the damage cracking zone. Three binders (B-1, C-1, and E-2) had G-R1 values very close to the 180 kPa onset of cracking value. The remaining binders (B-2, D-2, and D-3) had G-R1 values much lower than 180 kPa, indicating a potential high resistance to non-load cracking.

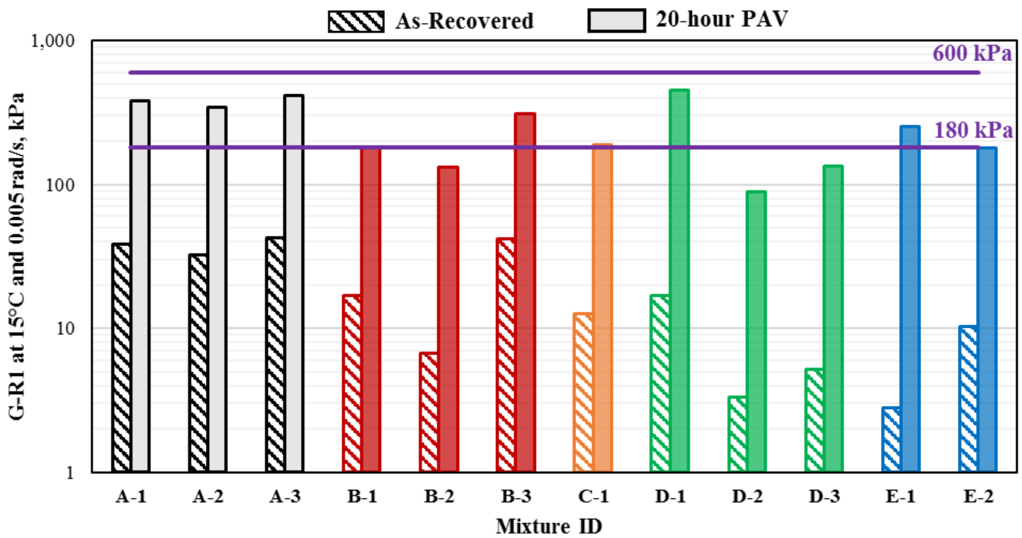


**Figure 38. Glover-Rowe (G-R1) Values at 15°C and 0.005 rad/s of the Evaluated Binders at the As-Recovered and 20-Hour PAV Aging Conditions. Purple lines indicate onset and significant cracking limits. PAV = pressure aging vessel.**

Figures 39 and 40 show the black space diagram of all evaluated binders. The orange dashed and green dashed dotted lines show the current PG boundaries for G* and δ for the as-recovered and 20-hr PAV aging conditions, respectively. It can be seen that all binders fell well within these criteria, although with aging, the binder G* increased and the δ decreased. The dashed and solid black lines show the G-R parameter limits, 180 kPa and 600 kPa, respectively, also seen in Figure 38, where the onset of cracking and significant cracking are expected to occur. It is anticipated that a lower G* and a lower δ represent lower susceptibility to cracking. In addition, a steeper slope between G* and δ represents lower susceptibility to long-term aging and resistance to the loss of flexibility.

Figure 41 shows G-R2 for all evaluated binders at the as-recovered and 20-hour PAV aging conditions. Similar to G-R1, G-R2 significantly increased with aging (as-recovered vs. 20-hour PAV). Christensen and Tran (2022) determined a maximum allowable value for G-R2 after a 20-hour PAV of 5,000 kPa. Seven of the 12 evaluated binders (A-1, A-2, A-3, B-3, D-1, D-3, and E-1) had G-R2 values greater than 5,000 kPa, thus indicating potential susceptibility for cracking. It is important to note that the proposed maximum G-R2 threshold value is still considered tentative. Revisions to this threshold should be performed based on extensive laboratory evaluation of materials typically used in Virginia and corresponding local field validations.

Figure 42 shows the black space diagram of all evaluated binders and compares the properties of the binders to the G-R2 limit of 5,000 kPa and G*sinδ limit of 5,000 kPa. The G*sinδ limit of 5,000 kPa is what is currently being used as part of the binder Superpave specifications at intermediate temperatures. The majority of the binders met the G*sinδ limit of 5,000 kPa except binder D-1. However, as mentioned previously, 7 of 12 binders did not meet the G-R2 limit of 5,000 kPa. These binders are more likely to have lower phase angles causing them to fail the G-R2 criterion, although they may have previously met the G*sinδ specification criterion.

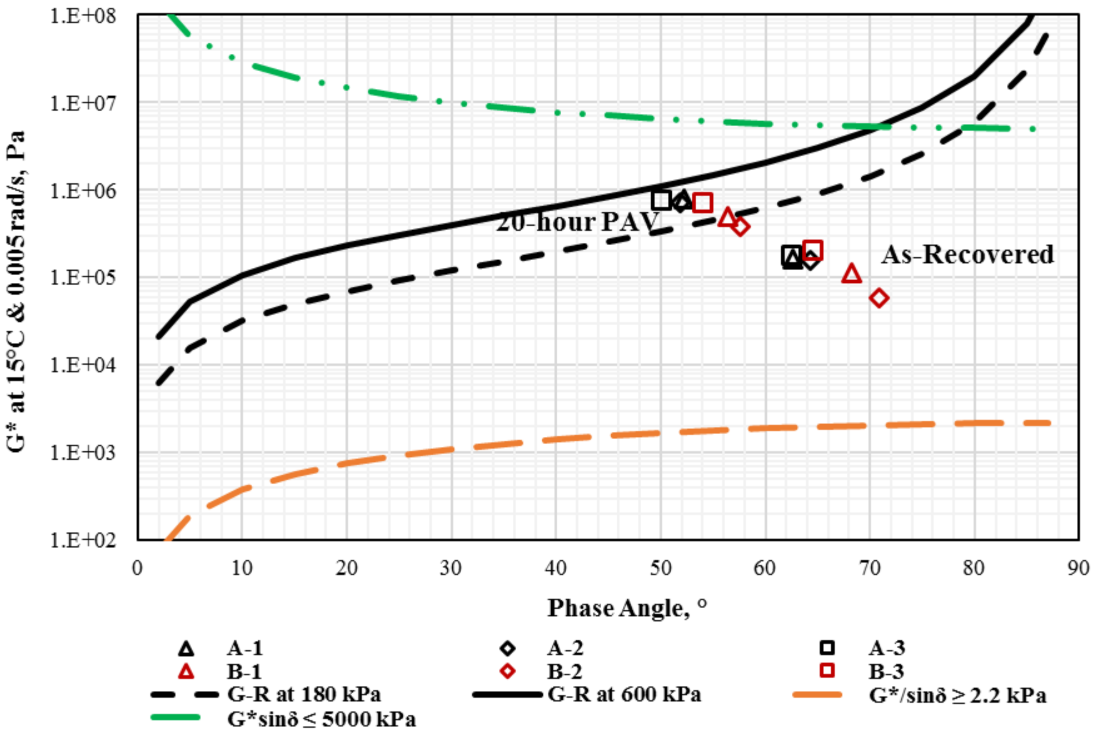


**Figure 39. Black Space Diagram in Terms of Glover-Rowe (G-R1) Values at 15°C and 0.005 rad/s for Binders A-1, A-2, A-3, B-1, B-2, and B-3 at the As-Recovered and 20-Hour PAV Aging Conditions. PAV = pressure aging vessel; G* = complex shear modulus; δ = phase angle.**

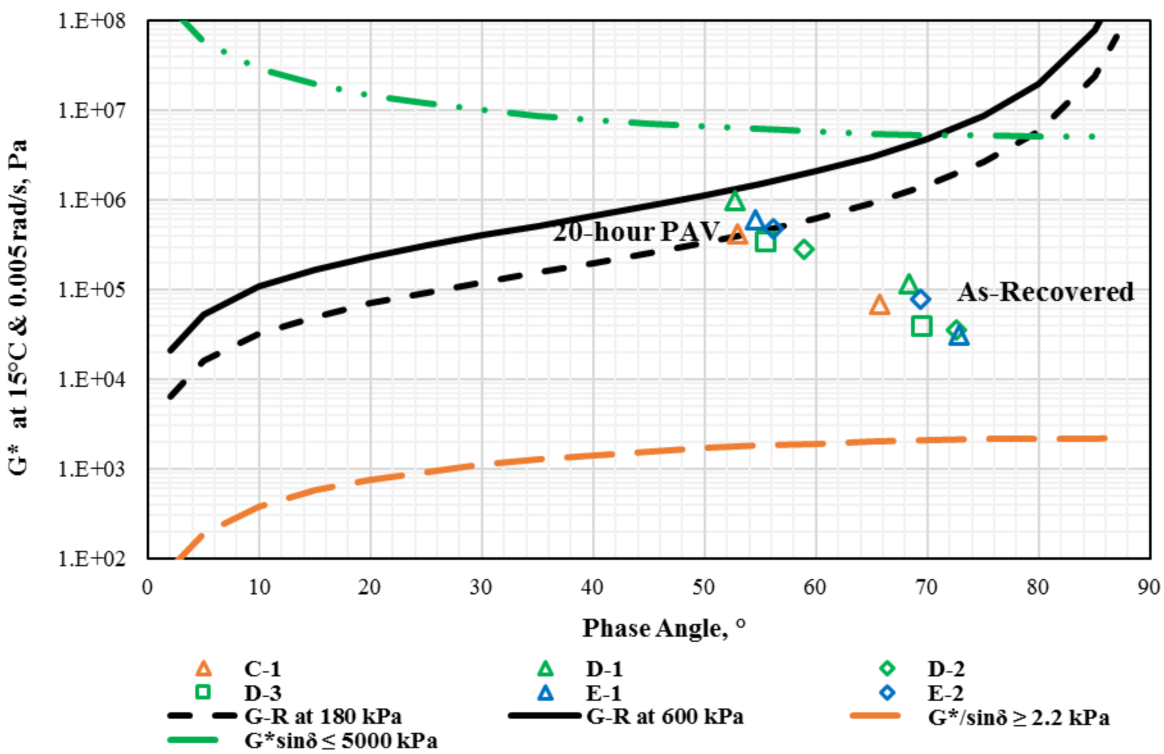


**Figure 40. Black Space Diagram in Terms of Glover-Rowe (G-R1) Values at 15°C and 0.005 rad/s for Binders C-1, D-1, D-2, D-3, E-1, and E-2 at the As-Recovered and 20-Hour PAV Aging Conditions. PAV = pressure aging vessel; G* = complex shear modulus; δ = phase angle.**

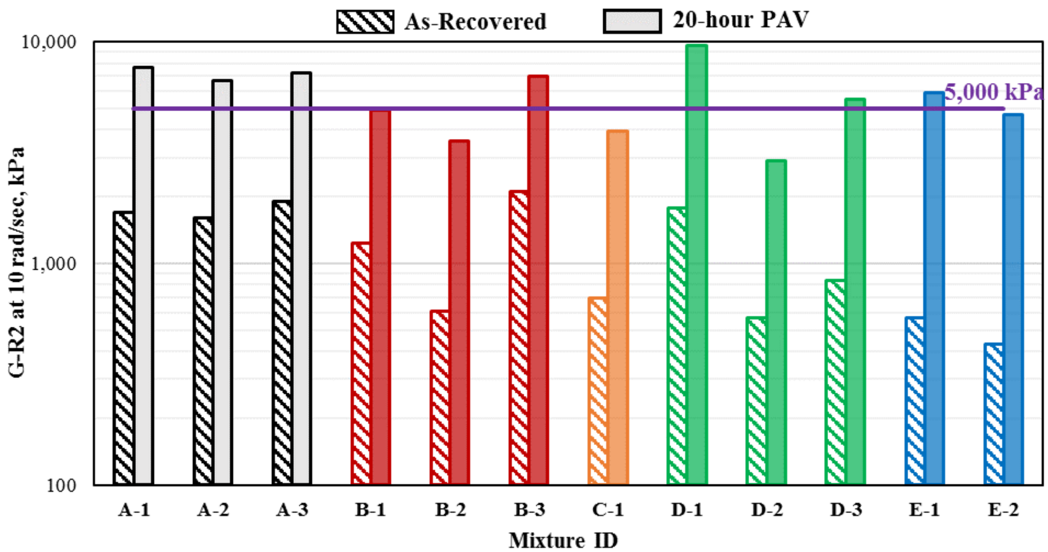


**Figure 41. Glover-Rowe (G-R2) Values at the Corresponding Binder Fatigue Test Temperature and 10 rad/s of the Evaluated Binders at the As-Recovered and 20-Hour PAV Aging Conditions. Purple line indicates the recommended specification limit. PAV = pressure aging vessel.**

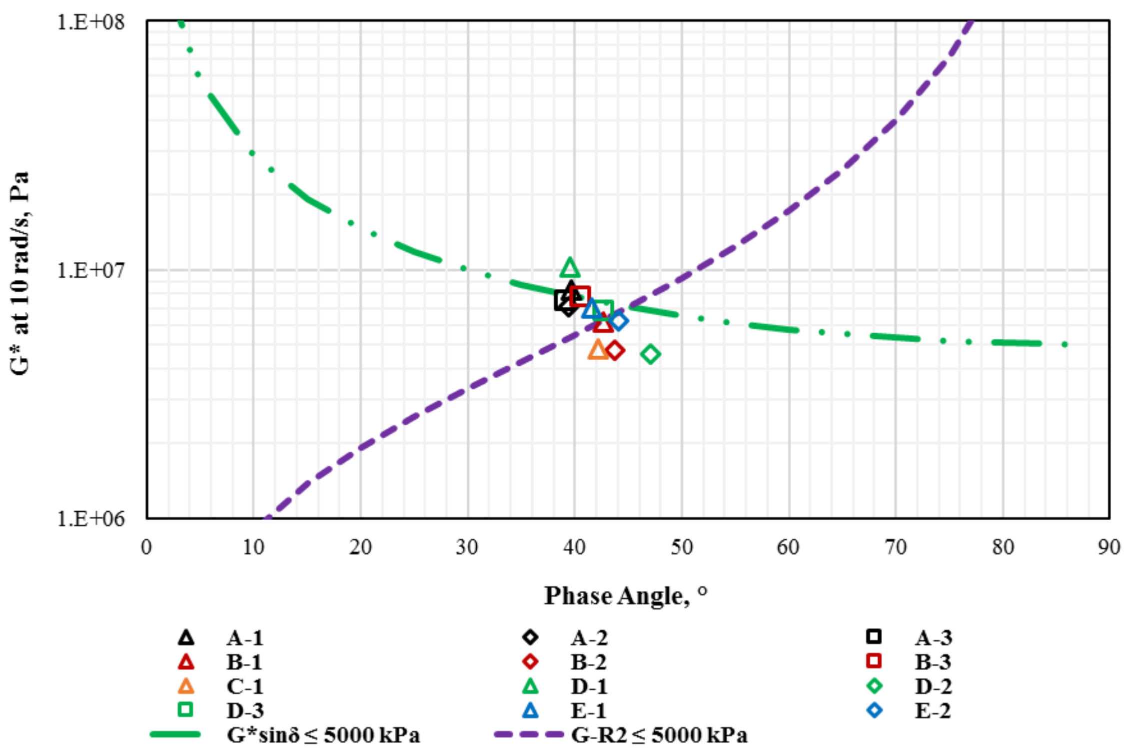


**Figure 42. Black Space Diagram in Terms of Glover-Rowe (G-R2) Values at the Corresponding Binder Fatigue Test Temperature and 10 rad/s of the Evaluated Binders at the 20-Hour PAV Aging Conditions. PAV = pressure aging vessel; G* = complex shear modulus; δ = phase angle.**

The aging index based on G-R values is defined as the ratio of G-R parameters determined at the 20-hour PAV and as-recovered aging conditions. Figure 43 shows that all aging indices were greater than 1, as expected, confirming that the G-R parameter increased with aging. Similar aging indices were observed for binders A-1, A-2, and A-3 and binders D-1, D-2, and D-3 regardless of the definition of the G-R parameter. Greater and lower aging indices were observed for binders B-2 and B-3, respectively, when compared with the one for the control binder B1, indicating a potential higher susceptibility to aging for mixtures produced with a softer binder grade when compared with a mixture containing RAs. Finally, a lower aging index determined using G-R1 was observed for binder E-2 when compared with binder E-1. However, both binders (E-1 and E-2) had similar aging indices when determined using G-R2.

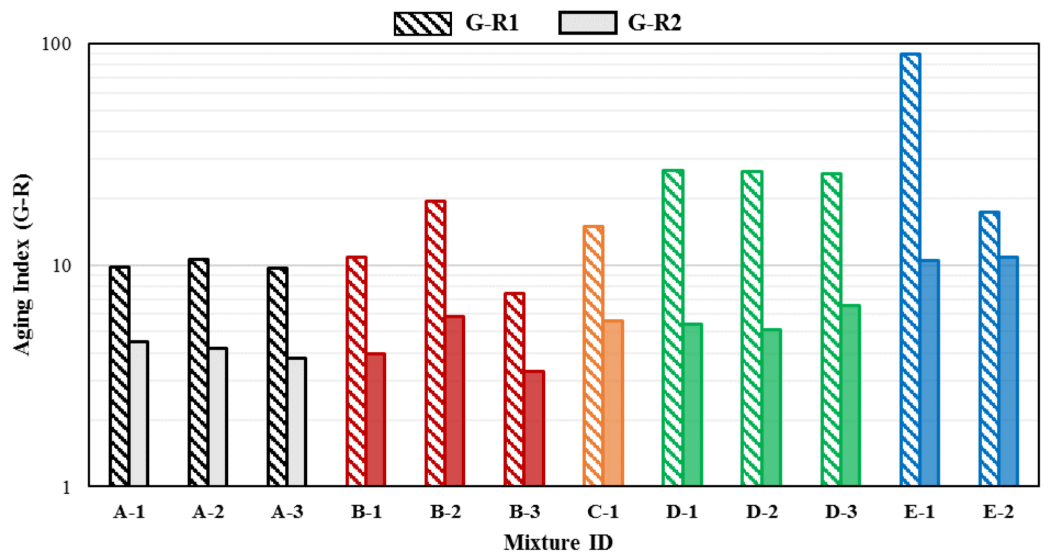


**Figure 43. Aging Index for the Glover-Rowe Parameters G-R1 and G-R2 for All Evaluated Binders**

## R-Value and Crossover Frequency ($w_c$)

Figure 44 shows R-Value1 and R-Value2 for all evaluated binders. In general, high R-values can result in poor fatigue performance at lower temperature for thin pavements. Low R-values can result in poor fatigue performance for thick pavements. For all evaluated binders, R-Value1 was in a relatively close range. Christensen and Tran (2022) defined an allowable range for R-Value2 from 1.5 to 2.5 for binders at the 20-hour PAV aging condition. All evaluated binders had an R-Value2 within the 1.5 to 2.5 range.

Figure 45 shows the crossover frequency ($w_c$) for all evaluated binders. In general, as $w_c$ decreases, the hardness of the binder increases. As expected, $w_c$ for all binders decreased with aging (20-hour PAV vs. as-recovered). Similar $w_c$ values were observed for binders A-1, A-2, and A-3. Greater and lower $w_c$ values were observed for binders B-2 and B-3, respectively, when compared with binder B-1, indicating a potential higher hardening effect with the use of the RA. Binder D-3 had a $w_c$ value greater than that of binder D-2 followed by that of binder D-1. It should be noted that mixtures D-2 and D-3 featured the use of multiple alternatives to address the use of higher RAP contents at the same time.

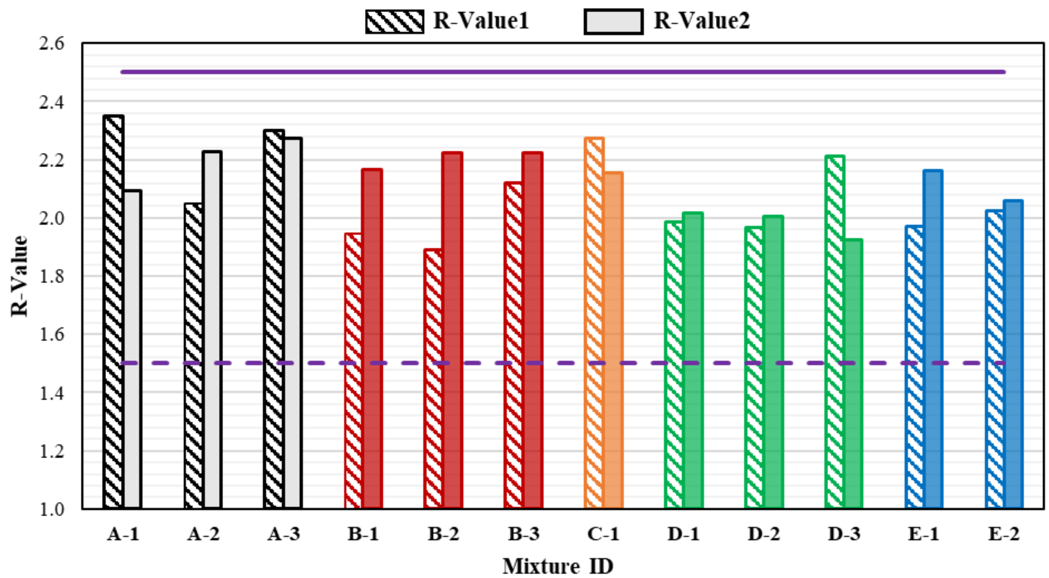


**Figure 44. R-Value1 and R-Value2 for All Evaluated Binders at the 20-Hour PAV Aging Condition. PAV = pressure aging vessel. Purple dashed and solid lines indicate minimum and maximum recommended values, respectively, for R-Value2.**

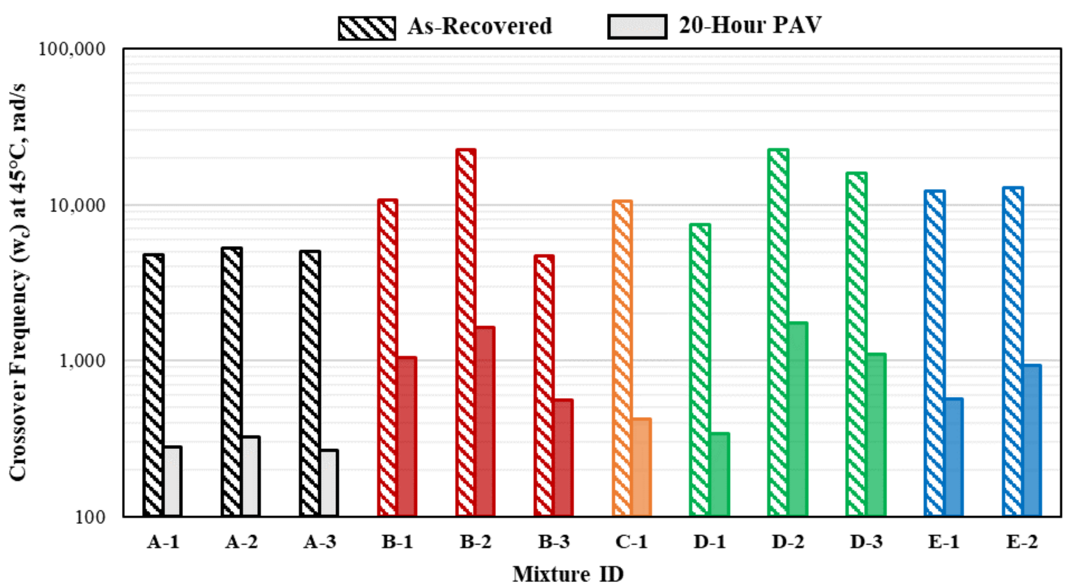


**Figure 45. Crossover Frequency ($w_c$) Values at 45°C for All Evaluated Binders at the As-Recovered and 20-Hour PAV Aging Conditions. PAV = pressure aging vessel.**

## Crossover Temperature ($T_{\delta=45°}$)

Figure 46 presents the crossover temperature ($T_{\delta=45°}$) of all evaluated binders at the 20-hour PAV aging condition. Martin et al. (2019) recommended a maximum $T_{\delta=45°}$ of 32°C after a 20-hour PAV to evaluate binder blends of mixtures featuring the use of high RAP and RAs. All evaluated binders met the 32°C recommended threshold except binder A-3, with a $T_{\delta=45°}$ of 33.3°C. It should be noted that binder A-3 featured the use of an RA.

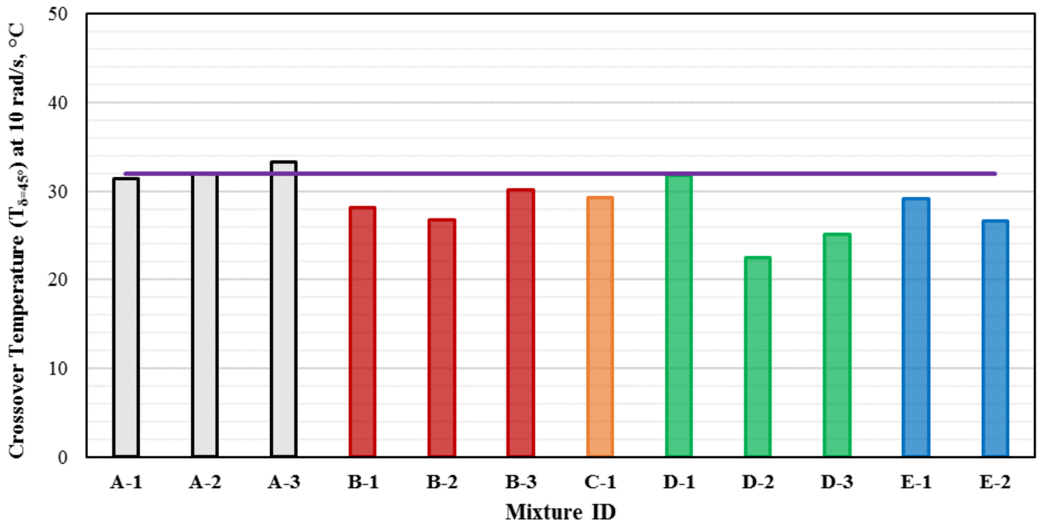


**Figure 46. Crossover Temperature ($T_{\delta=45°}$) Values at 10 rad/s for All Evaluated Binders at the 20-Hour PAV Aging Condition. Purple line indicates the recommended specification limit. PAV = pressure aging vessel.**

Overall, similar or lower $T_{\delta=45°}$ values were observed for binders extracted from mixtures featuring the use of softer binder grades when compared to those extracted from control mixtures (i.e., mixture A-2 compared to mixture A-1; mixture B-2 compared to mixture B-1; mixture D-2 compared to mixture D-1; and mixture E-2 compared to mixture E-1). Further, binder D-2 had the lowest $T_{\delta=45°}$ value among all evaluated binders, which could be attributed to the dual effect of using softer binder and RA at the same time in mixture D-2.

## Linear Amplitude Sweep (LAS) Test

The fatigue life of a given asphalt binder can be predicted using the LAS test results coupled with the viscoelastic continuum damage model. The power function, expressed in Equation 5, relates the binder fatigue performance $N_f$ to the maximum strain amplitude. The "A" and "B" parameters are directly associated with the fatigue resistance of the evaluated binder. The model parameter A in the power function refers to inherent fatigue resistance of the asphalt binder (Yang et al., 2022). Johnson and Bahia (2010) demonstrated that the model parameter A is related to the field fatigue performance of the Long-Term Pavement Performance project. Overall, a high A parameter indicates a better fatigue resistance of the asphalt binder.

Figure 47 shows the A parameter for all evaluated binders. Overall, all binders had higher A parameter values as compared to that of the control binder except for binder A-2 when compared with control binder A-1. The parameter B indicates the damage evolution rate. Figure 48 shows the B parameter for all evaluated binders. Overall, the B parameters were similar for the mixtures produced by the same contractor at the same plant. This indicates that parameter B could be directly related to the material used to produce the corresponding mixtures. Mannan et al. (2015) showed that a relatively higher amplitude strain provided more reasonable ranking results for a long-term aged binder. Based on this, the predicted fatigue lives for 5% and 10% strain were computed and analyzed.

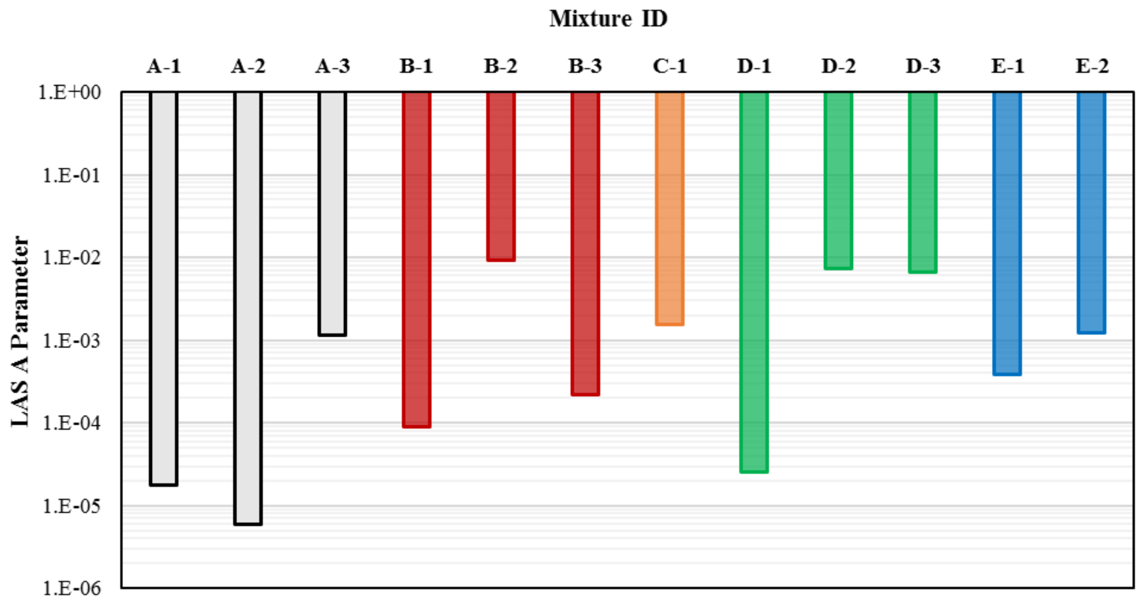


**Figure 47. LAS A Parameter for All Evaluated Binders at the 20-Hour PAV Aging Condition. LAS = linear amplitude sweep; PAV = pressure aging vessel.**

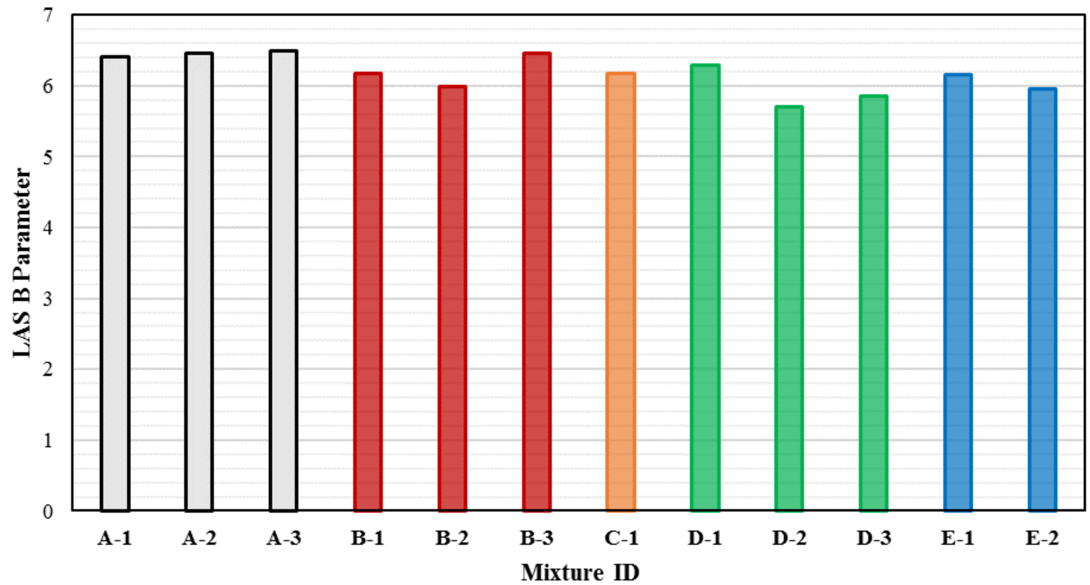


**Figure 48. LAS B Parameter for All Evaluated Binders at the 20-Hour PAV Aging Condition. LAS = linear amplitude sweep; PAV = pressure aging vessel.**

Figure 49 shows the LAS binder fatigue parameter for all evaluated binders at 5% and 10% strain. As expected, $N_f$ decreased with the increase of induced strain, which indicates that the LAS is sensitive to asphalt binder blends featuring the use of softer binder, RAs, and/or other additives. The observations for the LAS A parameter remained valid for the $N_f$ parameter at 10%. This indicated that high RAP asphalt mixtures produced using a softer binder and/or an RA, if designed properly (in this case using the BMD framework), could have better cracking performance as compared to the control design.

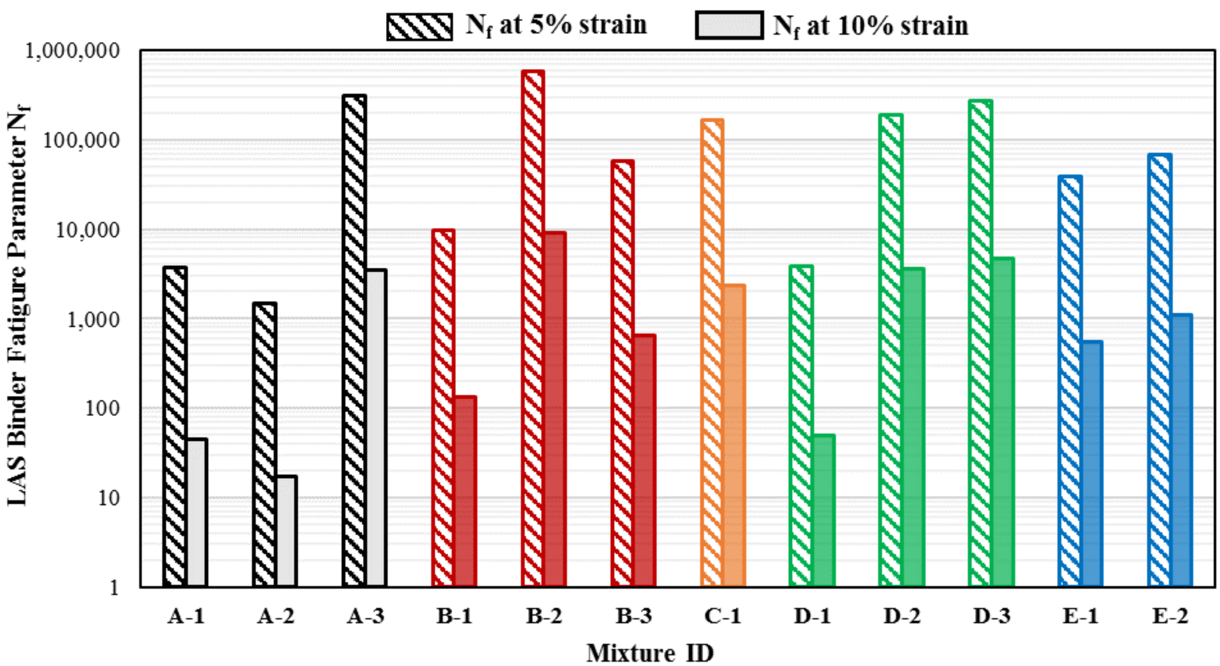


**Figure 49. LAS Binder Fatigue Parameter for All Evaluated Binders at the 20-Hour PAV Aging Condition at 5% and 10% Induced Strain. LAS = linear amplitude sweep; PAV = pressure aging vessel.**

## Mixture and Binder Properties: Initial Relationships

In this study, three fast, simple, and practical test methods were used to assess the durability, cracking, and rutting potential of 12 non-BMD and high RAP BMD mixtures. In parallel, corresponding extracted and recovered asphalt binders from the 12 mixtures were evaluated using several test methods and corresponding parameters at high, intermediate, and low temperatures. Table 7 summarizes initial trends and relationships between the mixtures and binder properties tested in the laboratory. Binders were extracted and recovered from sample 2 of each mixture, and since reheating was applied to perform extraction and recovery, the comparisons were limited to the properties of and data for mixture reheat sample 2. When mixtures and binders were evaluated at relatively high temperatures, APA rut depth and ($J_{nr}$, %R) showed similar trends for all evaluated binders except binders B-2 and B-3. When mixtures and binders were evaluated at relatively intermediate and low temperatures, binder parameters seemed to distinguish among evaluated binders and showcased better/worse performance when corresponding CT index values showed statistical similarities. It should be noted that these observations were based on statistical analyses performed on mixtures and not on binders because of data limitations.

**Table 7. Initial Relationships Between Mixture and Binder Properties**

| Mixture/ Binder ID | Mixture Properties | | | Extracted and Recovered Binder Properties | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Reheat Sample 2 | | | High Temperature As-Recovered | | | Intermediate Temperature After 20-hr PAV | | | | | | | | | Low Temperature After 20-hr PAV | |
| | Mass Loss | Rut Depth | CT Index | High PG | $J_{nr, 3.2 kPa}$ | %R | Int. PG | G-R1 | G-R2 | R-Value1 | R-Value2 | $w_c$ | $T_{\delta=45°}$ | LAS A | LAS $N_f$ | Low PG | ΔTc |
| A-1 | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C |
| A-2 | ↓ | ↑ | ↔ | ↓ | ↑ | ↓ | ↓ | ↔ | ↔ | ↓ | ↑ | ↔ | ↔ | ↓ | ↓ | ↔ | ↓ |
| A-3 | ↓ | ↑ | ↔ | ↓ | ↑ | ↓ | ↓ | ↔ | ↔ | ↓ | ↑ | ↔ | ↑ | ↑ | ↑ | ↔ | ↓ |
| B-1 | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C |
| B-2 | ↓ | ↔ | ↑ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↓ | ↑ | ↑ | ↓ | ↑ | ↑ | ↓ | ↔ |
| B-3 | ↓ | ↔ | ↔ | ↑ | ↓ | ↑ | ↑ | ↑ | ↑ | ↑ | ↑ | ↓ | ↑ | ↓ | ↓ | ↑ | ↓ |
| C-1 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| D-1 | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C |
| D-2 | ↓ | ↑ | ↑ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↔ | ↔ | ↑ | ↓ | ↑ | ↑ | ↓ | ↑ |
| D-3 | ↓ | ↑ | ↑ | ↓ | ↑ | ↓ | ↓ | ↓ | ↓ | ↑ | ↓ | ↑ | ↓ | ↑ | ↑ | ↓ | ↑ |
| E-1 | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C |
| E-2 | ↑ | ↓ | ↔ | ↑ | ↓ | ↑ | ↔ | ↓ | ↓ | ↑ | ↓ | ↑ | ↓ | ↑ | ↑ | ↓ | ↑ |

PAV = pressure aging vessel; C = control; CT = cracking tolerance; PG = performance grade; $J_{nr, 3.2 kPa}$ = non-recoverable creep compliance at 3.2 kPa; %R = recovery; Int. = intermediate; G-R1 and G-R2 = Glover-Rowe parameters; $w_c$ = crossover frequency; $T_{\delta=45°}$ = crossover temperature; LAS = linear amplitude sweep; A = model parameter; $N_f$ = binder fatigue performance parameter; ΔTc = difference in critical low temperature performance grade; ↑ = response value increased compared to control; ↓ = response value decreased compared to control; ↔ = no difference in response value compared to control.

## CONCLUSIONS

- *Mixtures containing 35% or greater RAP contents, softer binders, RAs, and/or fiber may be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements.* The long-term aged laboratory performance and in-service field performance of these mixtures need to be evaluated to verify further the findings in this study, as the scope of work was limited to short-term laboratory-aged and plant-produced material.

- *The laboratory performance of the mixtures evaluated in this study indicate that some mixtures that are volumetrically designed under current VDOT specifications can meet BMD requirements.*

- *Expected trends in the mixture performance testing were not always observed*. The trends may have been masked by variability in test results that was due to specimen fabrication practices or that was inherent in the test under consideration.

- *The precision estimates for the Cantabro and APA tests need to be established.* These are necessary to evaluate the acceptability of test data, and they have not been developed for the test methods. The precision estimates for the IDT-CT were not used to evaluate the acceptability of the IDT-CT data in this study because the estimates were not available at the time the trials were constructed and testing occurred.

- *There appear to be moderate linear relationships between non-reheat and reheat values for the Cantabro test and the IDT-CT for the mixtures evaluated in this study*. Additional data points and advanced statistical analyses are necessary to evaluate further and validate these relationships. The data collected and corresponding relationships presented in this study provide initial assurance that performance criteria can be determined for different specimen aging conditions.

- *The use of softer binder (PG 58-28) and/or RAs resulted in changes to the mixture binder grade when compared to the control binder*. The changes were not seen consistently across the PG high, intermediate, and low temperatures, indicating differences in efficacy of various RAs (types and dosage) and the impact of different RAP sources/stockpiles.

- *The results of comparisons between extracted and recovered binders from the control mixture and corresponding BMD mixtures depended on the particular binder test under consideration.* Further efforts are needed to determine what binder test is best correlated with field performance.

## RECOMMENDATIONS

1. *VDOT's Materials Division and VTRC should pursue efforts to establish a validated testing protocol that truly evaluates the performance of RAs when used in BMD mixtures*. This protocol will help provide quality assurance/acceptance programs with validated

performance-based parameter(s) and threshold criteria that help screen a given “good”- and “bad”-performing RA.

2. *VTRC should pursue efforts to determine the effect of asphalt binder properties on the overall performance of asphalt mixtures with a primary focus on cracking and durability.* This effort is necessary to evaluate the need to revise the current binder specifications by considering additional/newer binder parameters beyond the linear viscoelastic region. These parameters could have a more promising potential in discriminating the performance of the corresponding asphalt mixtures.

It should be pointed out that the 2020 trials reported in this study built upon the experiences from the 2019 trials presented in detail in *Balanced Mix Design for Asphalt Surface Mixtures: 2019 Field Trials* (Diefenderfer et al., 2021). The recommendations provided in that study remain applicable to this study. To avoid redundancy, only recommendations resulting from the data collected and corresponding analyses in this study are provided 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, VTRC Project No. 117566, Evaluating Recycling Agents’ Acceptance for Virginia: Test Protocols and Performance-Based Threshold Criteria, is ongoing. The objective of that project is to identify and/or develop a testing protocol to evaluate the effectiveness of RAs in alleviating the brittleness of high RAP asphalt mixtures. In addition, performance-based parameter(s) with threshold limits / criteria will be developed to enable the acceptance or rejection of RA products. Both objectives will facilitate the responsible use of innovative materials as part of Virginia’s BMD initiative. The outcomes of this effort are expected to be available in August 2023.

Regarding Recommendation 2, VTRC will draft and submit a research needs statement to the VTRC Pavement Research Advisory Committee by no later than Fiscal Year 2024.

### Benefits

Regarding Recommendation 1, the development of testing protocols and performance-based parameters with criteria will allow VDOT to develop specifications to address the use of RAs. This will provide a means for VDOT to evaluate and accept these materials such that their use in innovative mixtures can be allowed in a manner that preserves the goals of sustainable, longer-lasting, and cost-effective pavements.

Regarding Recommendation 2, improvements in binder specifications will allow VDOT to specify better-performing binders for use in asphalt mixtures. This will allow for the further optimization of mixture properties that should result in improved mixture performance.

## ACKNOWLEDGMENTS

The authors are grateful to the following individuals who served on the technical review panel for this study: Robert Crandol (Project Champion and Assistant State Maintenance Engineer, VDOT), Kwame Adu-Gyamfi (District Materials Engineer, Fredericksburg District, VDOT), Angela Beyke (Assistant State Materials Engineer, VDOT), Don French (District Materials Engineer, Lynchburg District, VDOT), Sungho Kim (formerly of VDOT), Jason Provines (Senior Research Scientist, VTRC), Tommy Schinkel (District Materials Engineer, Richmond District, VDOT), and Tom Tate (District Materials Engineer, Hampton Roads District, VDOT). The authors also appreciate the assistance of all participating contractors and their staff. The authors thank Drew Barbour of VDOT and Troy Deeds, Derek Lister, Danny Martinez, and Jennifer Samuels of VTRC for their outstanding efforts in sample collection and testing. Appreciation is also extended to Linda Evans of VTRC for her editorial assistance.

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# APPENDIX A

# SPECIAL PROVISION FOR HIGH RECLAIMED ASPHALT PAVEMENT (RAP) CONTENT SURFACE MIXTURES DESIGNED USING PERFORMANCE CRITERIA

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

March 18, 2020

## I. Description

These Specifications cover the requirements and materials used to produce High RAP Content Surface Mixtures, containing 40% RAP and higher, 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 be in accordance with Section 211.02 of the Specifications with the exception that Recycled Asphalt Shingles (RAS) shall not be allowed in these mixes.

## III. Job-Mix Formula

**Mix Types SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D may be designed to meet eithe**r the Performance + Volumetric (P+V) criteria or the Performance Only (P) criteria included in this section. Each mix type used shall meet the requirements of Section 211 and any related Special Provisions included in the contract, except the maximum RAP percentages as indicated in TABLE II-14A shall be waived. 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.

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

For all pilot mix types, a set of 5 CTindex specimens shall be prepared from long-term aged loose mix during design and submitted with the JMF. 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. Specimens shall be heated to compaction temperature following aging and then compacted.

**Type Performance + Volumetric (P+V) asphalt mixtures** shall be designed to conform to Section 211.03 of the Specifications as well as Table 1.

**Type Performance Only (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 are waived. However, the grading and Superpave volumetric properties shall be reported in the mix design submittal in accordance with AASHTO R35, and shall include the varying AC analysis.

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

- Cantabro testing: at design and 0.5% below design binder content
- $CT_{Index}$ testing: at design, at 0.5% above, and 0.5% below the design binder content
- APA rut testing: at design and 0.5% above the design binder content

The JMF shall meet the nominal max aggregate size (NMAS) of the designated mix type.

**Table 1**
**Performance Testing Requirements**

| Test | Procedure | Specimens | Criteria |
|---|---|---|---|
| **AASHTO T 340**<br>Method of Test for Determining Rutting Susceptibility of HMA Using the Asphalt Pavement Analyzer (APA) | 8,000 passes @ 64ºC | • 2 replicates of 2 pills (APA Jr)<br>• Gyratory pill: 150 mm dia., 75 ± 2 mm ht.<br>• Compact to 7±0.5% air voids<br>• Lab produced mix: condition loose mix for 2 hours at the design compaction temperature prior to compacting<br>• Plant produced mix: Minimize any cooling of and bring specimens to the compaction temperature and compact immediately. | Rutting ≤ 8.0mm |
| **AASHTO TP 108**<br>Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens (Cantabro) | 300 rotations<br>30-33 rot/min | • 3 replicates<br>• Gyratory pill: 150 mm dia., 115 ± 5 mm ht.<br>• Compact to $N_{design}$, report air voids<br>• Lab-produced mix – condition loose mix for 2 hours at the design compaction temperature prior to compacting | Mass loss ≤ 7.5% |
| **ASTM D8225**<br>Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature ($CT_{index}$ a.k.a. "Ideal CT") | • Condition specimens 25±1°C for 2 hours ± 10 min. Specimens must remain dry; if conditioning in a water bath, specimens must be sealed in plastic bags.<br>• Apply load using load-line displacement control at rate of 50 mm/minute, record load to peak and through failure; analyze. | • 5 replicates<br>• Gyratory pill- 150mm dia., 62 ± 2mm ht.<br>• Compact to 7±0.5% air voids<br>• Lab-produced mix – condition loose mix for 4 hours at the design compaction temperature prior to compacting | $CT_{index}$ ≥ 70 |

The job-mix formula for (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 (P) JMF shall exhibit improvement over the type (P+V) JMF, specifically: higher CT Index, lower rutting depth, and less mass loss on Cantabro.

## IV. Production Testing

The contractor and the Department will conduct testing as required by Section 211.05 and 211.06 but with the frequencies defined in Table 2.

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.

**Table 2**
**Production Testing Frequency[1]**

| Entity | Gradation/AC | Volumetrics | APA rutting | Cantabro | $CT_{index}$ |
|---|---|---|---|---|---|
| Producer | 500T | 500T | - | 500T | 500T |
| VDOT | 500T | 1,000T | - | 1000T[2] | 1000T[2] |
| VTRC | 500T | 500T | 500T[2] | 500T (reheat) | 500T (reheat) |

[1]With a minimum of 1 sample per day, per entity, per test.
[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. Specimens shall be fabricated and provided to the Department by the Contractor.

## V. Acceptance

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

Field density shall be determined in accordance with the Special Provision for Density Determination.

## VI. Initial Production

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

# APPENDIX B

## TRIAL PROJECT AND MIXTURE LOCATION

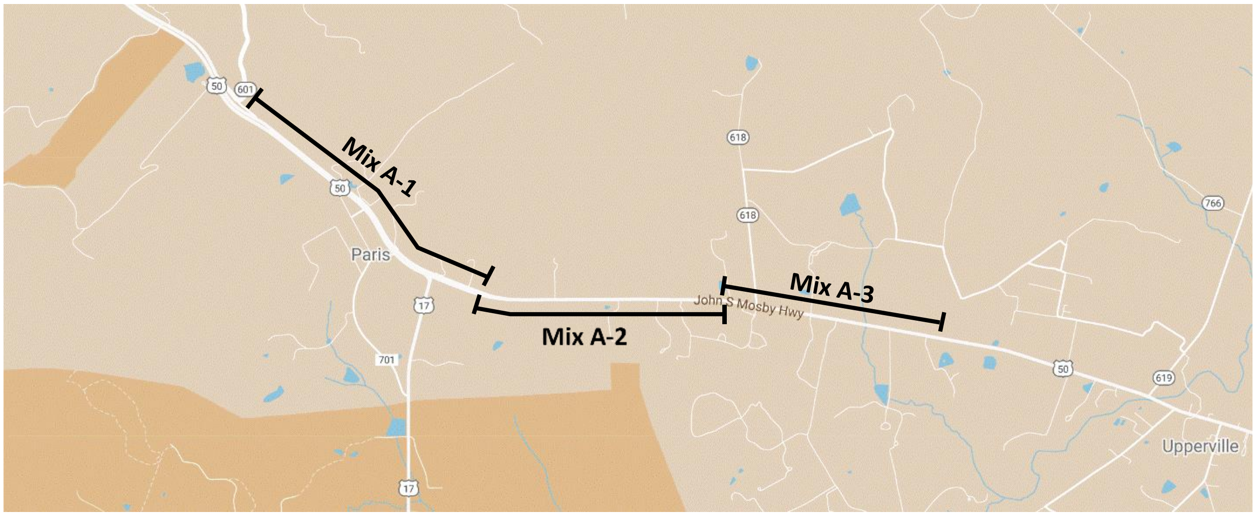

**Figure B1. Sample Locations for Mixtures A-1 Through A-3 on US 50 in Loudoun County**

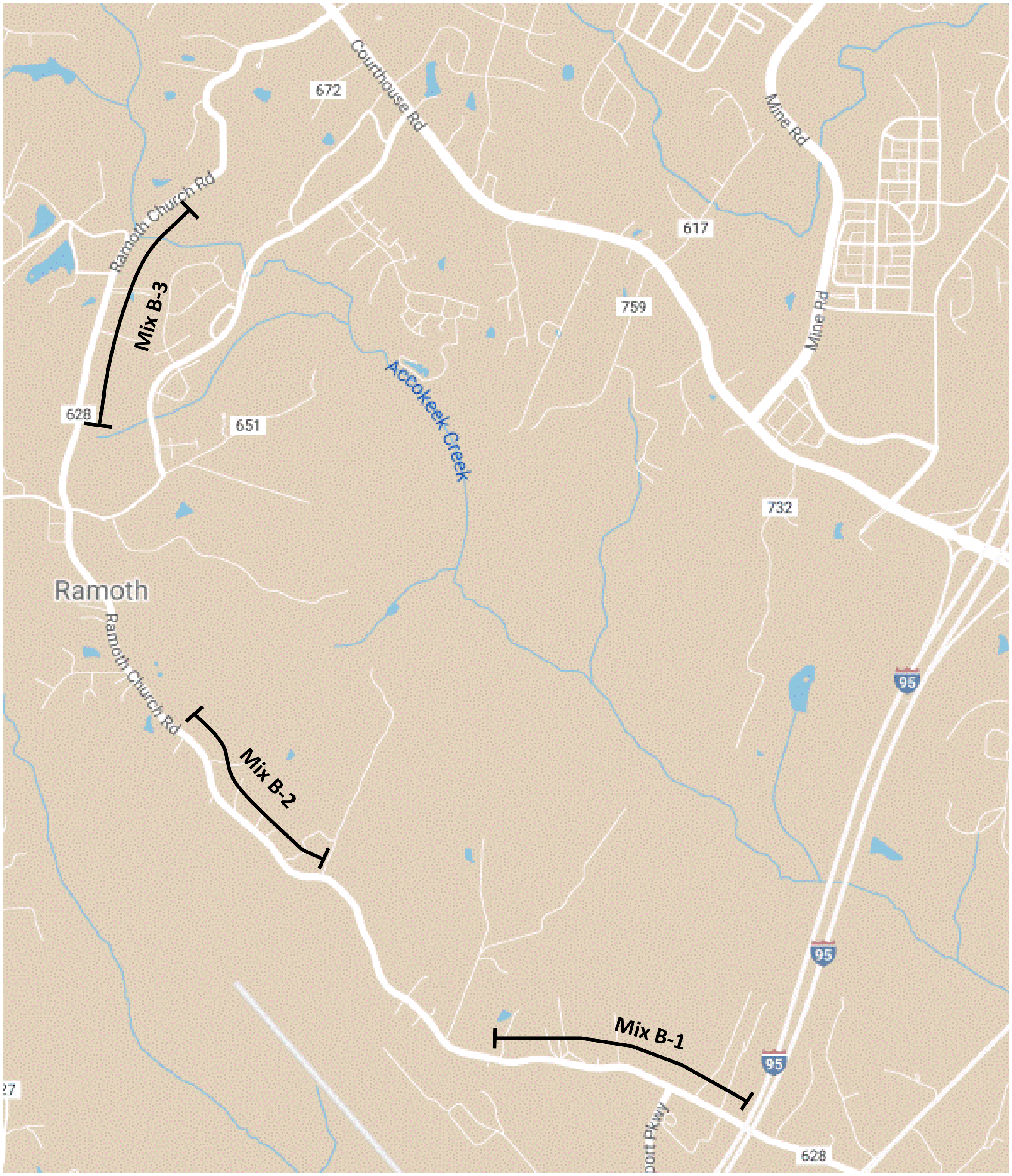


**Figure B2. Sample Locations for Mixtures B-1 Through B-3 on SR 628 in Stafford County**

**Figure B3. Sample Locations for Mixture C-1 on SR 623 in Goochland County**

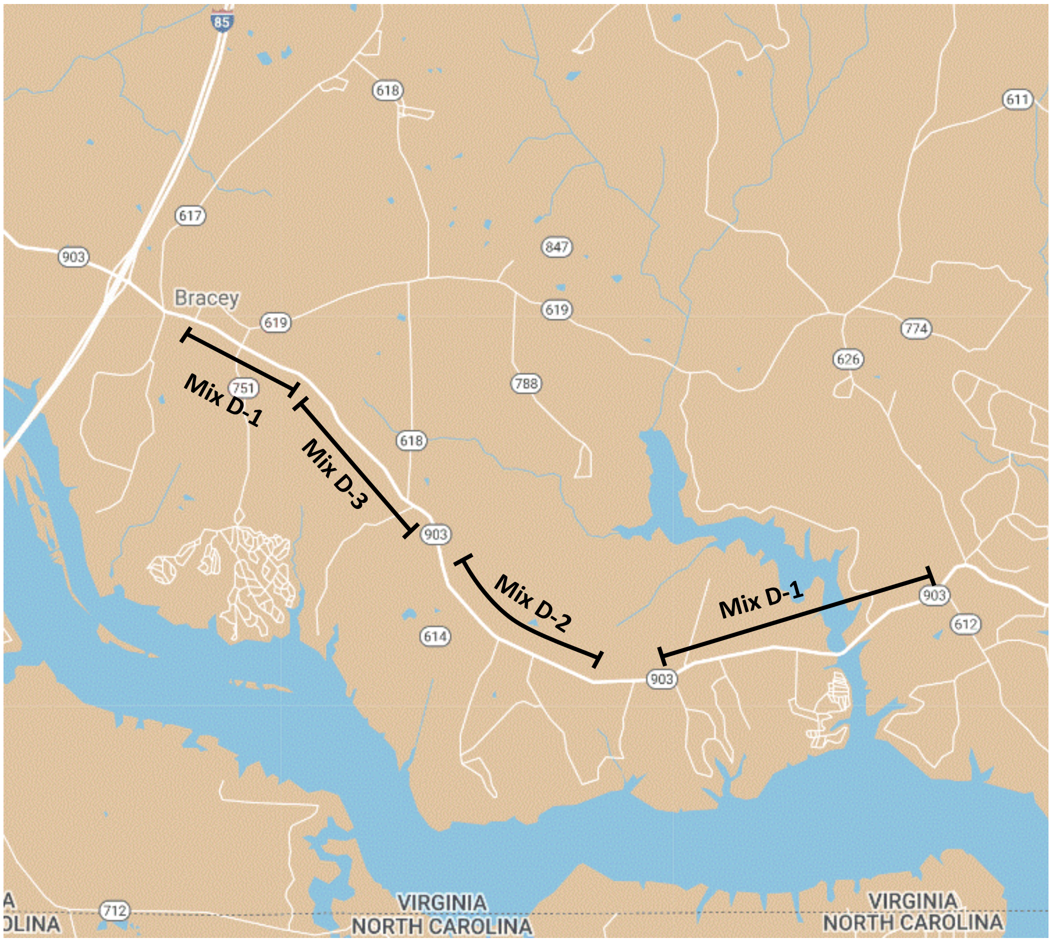


**Figure B4. Sample Locations for Mixtures D-1 Through D-3 on SR 903 in Mecklenburg County**


**Figure B5. Sample Locations for Mixtures E-1 and E-2 on US 360 in Chesterfield County**

# APPENDIX C

# MIXTURE VOLUMETRIC PROPERTIES AND GRADATIONS

**Table C1. Production Properties for Mixture A-1**

| **Mixture** | A-1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mixture Type** | SM-9.5D | | | | | | | | | |
| **NMAS, mm** | 9.5 | | | | | | | | | |
| **Virgin Binder Grade** | PG 64S-22 | | | | | | | | | |
| **RAP Content, %** | 30 | | | | | | | | | |
| **Recycling Agent** | No | | | | | | | | | |
| **Sample** | **Production JMF** | **Process Tolerance[a]** | **Sample 1 Producer** | **Sample 1 VTRC** | **Sample 2 Producer** | **Sample 2 VTRC** | **Sample 3 Producer** | **Sample 3 VTRC** | **Sample 4 Producer** | **Sample 4 VTRC** |
| Asphalt Content, % | 5.5 | ± 0.3 | 5.75 | 5.39 | 5.49 | 5.29 | 5.73 | 5.62 | 5.72 | 5.45 |
| VTM, % | 4 | 2-5 | 4.1 | 3.1 | 4.5 | 3.6 | 3.4 | 2.1 | 2.4 | 2.4 |
| VMA, % | - | Min. 16 | 18.5 | 16.7 | 18.2 | 16.8 | 17.8 | *15.4* | 16.9 | 16.2 |
| VFA, % | - | 70-85 | 78 | 81 | 75 | 79 | 81 | *87* | *86* | 85 |
| FA Ratio | - | 0.7-1.3 | 1.00 | 1.09 | 1.00 | 1.11 | 1.00 | 1.09 | 1.10 | 1.20 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.72 | 5.36 | 5.46 | 5.26 | 5.70 | 5.23 | 5.69 | 5.41 |
| Rice SG, $G_{mm}$ | 2.693 | - | 2.711 | 2.685 | 2.700 | 2.688 | 2.698 | 2.678 | 2.694 | 2.691 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.600 | 2.602 | 2.578 | 2.591 | 2.606 | 2.622 | 2.630 | 2.628 |
| **Gradation, percent passing** | | | | | | | | | | |
| 1/2 in (12.5 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | *97* | 100 | 100 |
| 3/8 in (9.5 mm) | 92 | ±4.0 | 93 | 92 | 92 | 93 | 88 | *85* | 93 | 93 |
| No. 4 (4.75 mm) | 60 | ±4.0 | 63 | 58 | 58 | 59 | 59 | 58 | *65* | 62 |
| No. 8 (2.36 mm) | 40 | ±4.0 | 42 | 39 | 38 | 39 | 40 | 39 | 44 | 43 |
| No. 16 (1.18 mm) | - | - | 29 | 28 | 27 | 28 | 27 | 27 | 30 | 31 |
| No. 30 (0.6 mm) | 19 | ±3.0 | 20 | 20 | 19 | 20 | 19 | 19 | 21 | 22 |
| No. 50 (0.3 mm) | - | ±2.5 | 14 | 13 | 13 | 14 | 13 | 13 | 15 | 15 |
| No. 100 (0.15 mm) | - | - | 9 | 9 | 8 | 9 | 9 | 9 | 10 | 10 |
| No. 200 (0.075 mm) | 5.8 | ±1.0 | 5.7 | 5.8 | 5.4 | 5.8 | 5.8 | 5.7 | 6.3 | 6.5 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C2. Production Properties for Mixture A-2**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mixture** | A-2 | | | | | | | | | |
| **Mixture Type** | SM-9.5D | | | | | | | | | |
| **NMAS, mm** | 9.5 | | | | | | | | | |
| **Virgin Binder Grade** | PG 58-28 | | | | | | | | | |
| **RAP Content, %** | 40 | | | | | | | | | |
| **Recycling Agent** | No | | | | | | | | | |
| **Sample** | **JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | | **Sample 4** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 5.6 | ± 0.3 | 5.63 | 5.63 | 5.74 | 5.61 | 5.35 | 5.39 | 5.55 | 5.34 |
| VTM, % | 4.0 | 2-5 | 2.4 | 2.1 | 3.0 | 3.0 | 4.7 | 3.7 | 4.0 | 4.0 |
| VMA, % | - | Min. 16 | 16.3 | 16.0 | 17.2 | 16.9 | 17.7 | 16.9 | 17.6 | 17.1 |
| VFA, % | - | 70-85 | 85 | *87* | 83 | 82 | 73 | 78 | 77 | 77 |
| FA Ratio | - | 0.7-1.3 | 1.10 | 1.14 | 1.00 | 1.07 | 1.10 | 1.12 | 1.10 | 1.12 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.52 | 5.52 | 5.63 | 5.49 | 5.24 | 5.27 | 5.44 | 5.22 |
| Rice SG, $G_{mm}$ | 2.648 | - | 2.659 | 2.663 | 2.667 | 2.681 | 2.677 | 2.676 | 2.674 | 2.681 |
| Mixture Bulk SG, Gmb | - | - | 2.596 | 2.607 | 2.586 | 2.601 | 2.550 | 2.577 | 2.567 | 2.573 |
| **Gradation, percent passing** | | | | | | | | | | |
| 1/2 in (12.5 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 3/8 in (9.5 mm) | 94 | ±4.0 | 93 | 93 | 94 | 93 | 95 | 92 | 95 | 94 |
| No. 4 (4.75 mm) | 64 | ±4.0 | 61 | 61 | 63 | 63 | 65 | 64 | 68 | 66 |
| No. 8 (2.36 mm) | 45 | ±4.0 | *40* | *40* | 41 | 41 | 44 | 44 | 46 | 44 |
| No. 16 (1.18 mm) | - | - | 27 | 28 | 28 | 29 | 30 | 31 | 31 | 31 |
| No. 30 (0.6 mm) | 22 | ±3.0 | 20 | 20 | 20 | 20 | 21 | 22 | 22 | 22 |
| No. 50 (0.3 mm) | - | ±2.5 | 14 | 14 | 14 | 14 | 14 | 14 | 15 | 15 |
| No. 100 (0.15 mm) | - | - | 10 | 10 | 9 | 9 | 9 | 9 | 9 | 9 |
| No. 200 (0.075 mm) | 5.9 | ±1.0 | 6.2 | 6.3 | 5.9 | 5.9 | 5.8 | 5.9 | 5.9 | 5.8 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C3. Production Properties for Mixture A-3**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mixture** | A-3 | | | | | | | | | |
| **Mixture Type** | SM-9.5D With Recycling Agent | | | | | | | | | |
| **NMAS, mm** | 9.5 | | | | | | | | | |
| **Virgin Binder Grade** | PG 64S-22 | | | | | | | | | |
| **RAP Content, %** | 40 | | | | | | | | | |
| **Recycling Agent** | RA1 | | | | | | | | | |
| **Sample** | **JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | | **Sample 4** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 5.6 | ± 0.3 | 5.49 | 5.54 | 5.81 | 5.43 | 5.50 | 5.33 | 5.45 | 5.36 |
| VTM, % | 4.0 | 2-5 | 3.9 | 3.5 | 3.9 | 3.9 | 3.1 | 2.6 | 3.3 | 3.2 |
| VMA, % | - | Min. 16 | 17.3 | 17.1 | 18.2 | 17.2 | 16.7 | *15.8* | 16.8 | 16.5 |
| VFA, % | - | 70-85 | 77 | 79 | 79 | 78 | 81 | 84 | 80 | 81 |
| FA Ratio | - | 0.7-1.3 | 1.20 | 1.16 | 1.10 | 1.18 | 1.10 | 1.2 | 1.10 | 1.21 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.38 | 5.42 | 5.70 | 5.32 | 5.39 | 5.21 | 5.34 | 5.24 |
| Rice SG, Gmm | 2.648 | - | 2.671 | 2.677 | 2.686 | 2.689 | 2.684 | 2.686 | 2.690 | 2.695 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.568 | 2.583 | 2.581 | 2.585 | 2.600 | 2.618 | 2.600 | 2.608 |
| **Gradation, percent passing** | | | | | | | | | | |
| 1/2 in (12.5 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 3/8 in (9.5 mm) | 94 | ±4.0 | 97 | 96 | 96 | 93 | 92 | 93 | 95 | 93 |
| No. 4 (4.75 mm) | 64 | ±4.0 | *76* | *71* | *72* | *70* | 65 | 65 | 67 | 66 |
| No. 8 (2.36 mm) | 45 | ±4.0 | *52* | 49 | 49 | 48 | 45 | 44 | 45 | 44 |
| No. 16 (1.18 mm) | - | - | 35 | 35 | 34 | 34 | 31 | 31 | 31 | 31 |
| No. 30 (0.6 mm) | 22 | ±3.0 | 24 | 24 | 24 | 24 | 22 | 22 | 21 | 22 |
| No. 50 (0.3 mm) | - | ±2.5 | 16 | 16 | 16 | 16 | 15 | 15 | 15 | 15 |
| No. 100 (0.15 mm) | - | - | 10 | 10 | 10 | 10 | 10 | 10 | 9 | 10 |
| No. 200 (0.075 mm) | 5.9 | ±1.0 | 6.3 | 6.3 | 6.3 | 6.2 | 6.1 | 6.2 | 5.9 | 6.4 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C4. Production Properties for Mixture B-1**

| | |
|---|---|
| **Mixture** | B-1 |
| **Mixture Type** | SM-12.5A |
| **NMAS, mm** | 12.5 |
| **Virgin Binder Grade** | PG 64S-22 |
| **RAP Content, %** | 30 |
| **Recycling Agent** | No |

| **Sample** | **Production JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | | **Sample 4** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 5.3 | ± 0.3 | 5.56 | *5.61* | 5.30 | *5.20* | 5.35 | *5.24* | 5.34 | 5.42 |
| VTM, % | 4.0 | 2-5 | 2.2 | 2.4 | 3.5 | 4.3 | 4.2 | 3.5 | 2.4 | 3.2 |
| VMA, % | - | Min. 15 | 16.0 | 16.3 | 16.5 | 15.0 | 17.3 | 16.5 | 15.7 | 16.6 |
| VFA, % | - | 70-85 | *86* | 85 | 79 | 71 | 76 | 79 | 85 | 81 |
| FA Ratio | - | 0.7-1.3 | 1.0 | 1.0 | 1.0 | 1.2 | 0.9 | 1.0 | 1.0 | 1.1 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.47 | 5.52 | 5.21 | 4.28 | 5.26 | 5.15 | 5.25 | 5.33 |
| Rice SG, $G_{mm}$ | 2.641 | - | 2.655 | 2.669 | 2.671 | 2.688 | 2.685 | 2.680 | 2.666 | 2.685 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.597 | 2.605 | 2.577 | 2.573 | 2.572 | 2.586 | 2.601 | 2.600 |
| **Gradation, percent passing** | | | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 97 | ±4.0 | 99 | 97 | 98 | 97 | 97 | 98 | 97 | 98 |
| 3/8 in (9.5 mm) | 90 | ±4.0 | 92 | 90 | 89 | 87 | 91 | 88 | 89 | 89 |
| No. 4 (4.75 mm) | 59 | ±4.0 | 62 | 62 | 58 | 57 | 61 | 57 | 61 | 62 |
| No. 8 (2.36 mm) | 40 | ±4.0 | 41 | 41 | 38 | 37 | 39 | 38 | 42 | 42 |
| No. 16 (1.18 mm) | - | - | 29 | 29 | 26 | 26 | 27 | 27 | 30 | 31 |
| No. 30 (0.6 mm) | 22 | ±3.0 | 22 | 22 | 20 | 19 | 20 | 20 | 22 | 23 |
| No. 50 (0.3 mm) | - | ±2.5 | 15 | 16 | 14 | 14 | 14 | 14 | 16 | 16 |
| No. 100 (0.15 mm) | - | - | 9 | 10 | 9 | 9 | 9 | 9 | 10 | 10 |
| No. 200 (0.075 mm) | 5.5 | ±1.0 | 5.3 | 5.6 | 5.0 | 5.1 | 4.9 | 5.0 | 5.5 | 5.8 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C5. Production Properties for Mixture B-2**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mixture** | B-2 | | | | | | | | | |
| **Mixture Type** | SM-12.5A | | | | | | | | | |
| **NMAS, mm** | 12.5 | | | | | | | | | |
| **Virgin Binder Grade** | PG 58-28 | | | | | | | | | |
| **RAP Content, %** | 40 | | | | | | | | | |
| **Recycling Agent** | No | | | | | | | | | |
| **Sample** | **Production JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | | **Sample 4** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 5.60 | ± 0.3 | 5.56 | 5.51 | 5.62 | 5.43 | 5.38 | *5.21* | 5.39 | 5.40 |
| VTM, % | 4.0 | 2-5 | *1.2* | *1.3* | *0.9* | *1.6* | 2.5 | 3.1 | 2.1 | 2.8 |
| VMA, % | - | Min. 15 | *14.9* | *14.9* | *14.8* | 15.0 | 15.7 | 15.8 | 15.3 | 16.0 |
| VFA, % | - | 70-85 | *92* | *91* | *94* | *89* | 84 | 81 | *86* | 83 |
| FA Ratio | - | 0.7-1.3 | 1.1 | 1.2 | 1.1 | 1.1 | 1.2 | 1.2 | 1.1 | 1.2 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.35 | 5.30 | 5.41 | 5.22 | 5.18 | 5.01 | 5.18 | 5.19 |
| Rice SG, $G_{mm}$ | 2.680 | - | 2.653 | 2.667 | 2.656 | 2.677 | 2.682 | 2.700 | 2.672 | 2.690 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.620 | 2.631 | 2.632 | 2.634 | 2.614 | 2.617 | 2.616 | 2.616 |
| **Gradation, percent passing** | | | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 98 | ±4.0 | 98 | 97 | 96 | 96 | 98 | 97 | 96 | 97 |
| 3/8 in (9.5 mm) | 90 | ±4.0 | 90 | 87 | 87 | 84 | 91 | 87 | 88 | 89 |
| No. 4 (4.75 mm) | 58 | ±4.0 | 57 | 55 | *53* | *50* | *64* | 61 | 61 | 62 |
| No. 8 (2.36 mm) | 38 | ±4.0 | 39 | 38 | 35 | *33* | *43* | 41 | 41 | 42 |
| No. 16 (1.18 mm) | - | - | 29 | 29 | 25 | 25 | 30 | 30 | 28 | 30 |
| No. 30 (0.6 mm) | 19 | ±3.0 | 22 | 21 | 19 | 18 | 22 | 22 | 21 | 22 |
| No. 50 (0.3 mm) | - | ±2.5 | 16 | 15 | 14 | 14 | 16 | 15 | 15 | 15 |
| No. 100 (0.15 mm) | - | - | 10 | 10 | 9 | 9 | 10 | 10 | 9 | 10 |
| No. 200 (0.075 mm) | 5.8 | ±1.0 | 6.1 | 6.1 | 5.7 | 5.9 | 6.0 | 5.9 | 5.8 | 6.3 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C6. Production Properties for Mixture B-3**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mixture** | B-3 | | | | | | | | | |
| **Mixture Type** | SM-12.5A with Recycling Agent | | | | | | | | | |
| **NMAS, mm** | 12.5 | | | | | | | | | |
| **Virgin Binder Grade** | PG 64S-22 | | | | | | | | | |
| **RAP Content, %** | 40 | | | | | | | | | |
| **Recycling Agent** | RA2 | | | | | | | | | |
| **Sample** | **JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | | **Sample 4** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 5.60 | ± 0.3 | *4.82* | *4.92* | 5.49 | *5.27* | 5.33 | *5.01* | *5.26* | 5.54 |
| VTM, % | 4.0 | 2-5 | 4.4 | 4.8 | 2.9 | 3.1 | 2.7 | 3.3 | 2.3 | 2.7 |
| VMA, % | - | Min. 15 | 16.0 | 16.7 | 16.3 | 15.9 | 15.7 | 15.5 | 15.1 | 16.3 |
| VFA, % | - | 70-85 | 73 | 71 | 82 | 81 | 83 | 79 | 85 | 83 |
| FA Ratio | - | 0.7-1.3 | 1.3 | *1.4* | 1.1 | 1.2 | 1.2 | 1.3 | 1.2 | 1.3 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 4.62 | 4.72 | 5.23 | 5.07 | 5.13 | 4.81 | 5.05 | 5.34 |
| Rice SG, $G_{mm}$ | 2.680 | - | 2.704 | 2.720 | 2.688 | 2.694 | 2.682 | 2.706 | 2.674 | 2.697 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.58 | 2.589 | 2.610 | 2.611 | 2.610 | 2.617 | 2.613 | 2.623 |
| **Gradation, percent passing** | | | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 98 | ±4.0 | 97 | 98 | 98 | 97 | 98 | 97 | 98 | 98 |
| 3/8 in (9.5 mm) | 90 | ±4.0 | 90 | 89 | 90 | 88 | 90 | 88 | 89 | 90 |
| No. 4 (4.75 mm) | 58 | ±4.0 | *63* | *64* | *63* | 60 | *64* | 61 | 62 | *65* |
| No. 8 (2.36 mm) | 38 | ±4.0 | 42 | *43* | *43* | 41 | *43* | 41 | 42 | *44* |
| No. 16 (1.18 mm) | - | - | 29 | 31 | 30 | 30 | 30 | 29 | 29 | 31 |
| No. 30 (0.6 mm) | 19 | ±3.0 | 22 | 22 | 22 | 22 | 22 | 21 | 22 | *23* |
| No. 50 (0.3 mm) | - | ±2.5 | 15 | 16 | 16 | 15 | 15 | 15 | 16 | 16 |
| No. 100 (0.15 mm) | - | - | 10 | 11 | 10 | 10 | 10 | 10 | 10 | 11 |
| No. 200 (0.075 mm) | 5.8 | ±1.0 | 6.1 | 6.5 | 6.0 | 6.1 | 6.0 | 6.2 | 6.3 | 6.8 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C7. Production Properties for Mixture C-1**

| **Mixture** | C-1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mixture Type** | SM-12.5A | | | | | | | | | |
| **NMAS, mm** | 12.5 | | | | | | | | | |
| **Virgin Binder Grade** | PG 58-28 | | | | | | | | | |
| **RAP Content, %** | 35 | | | | | | | | | |
| **Recycling Agent** | No | | | | | | | | | |
| **Sample** | **JMF** | **Process Tolerance**[a] | **Sample A** | | **Sample B** | | **Sample C** | | **Sample D** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 6.20 | ± 0.3 | 6.30 | 6.25 | 6.07 | *5.39* | 6.24 | *5.61* | *5.86* | *5.78* |
| VTM, % | 3.4 | 2-5 | *5.1* | 4.3 | 4.9 | 5.0 | *5.2* | 5.0 | *5.9* | 4.5 |
| VMA, % | - | Min. 15 | 18.8 | 18.0 | 18.1 | 16.7 | 18.8 | 17.3 | 18.6 | 17.2 |
| VFA, % | - | 70-85 | 73 | 76 | 73 | 70 | 72 | 71 | *68* | 74 |
| FA Ratio | - | 0.7-1.3 | 0.9 | 1.4 | 0.8 | 1.0 | 0.9 | 1.0 | 0.9 | 0.9 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 6.08 | 6.02 | 5.84 | 5.16 | 6.01 | 5.38 | 5.63 | 5.55 |
| Rice SG, $G_{mm}$ | 2.458 | - | 2.449 | 2.454 | 2.448 | 2.461 | 2.455 | 2.467 | 2.468 | 2.460 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.324 | 2.348 | 2.328 | 2.338 | 2.328 | 2.343 | 2.323 | 2.349 |
| **Gradation, percent passing** | | | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 97 | ±4.0 | 96 | 97 | 96 | 94 | 96 | 95 | 96 | 94 |
| 3/8 in (9.5 mm) | 85 | ±4.0 | 88 | 89 | 86 | 82 | 89 | 84 | 87 | 82 |
| No. 4 (4.75 mm) | 49 | ±4.0 | *55* | *54* | 51 | 48 | *54* | 49 | 51 | 47 |
| No. 8 (2.36 mm) | 32 | ±4.0 | 35 | 36 | 34 | 32 | 35 | 32 | 33 | 32 |
| No. 16 (1.18 mm) | - | - | 26 | 28 | 24 | 24 | 25 | 24 | 24 | 24 |
| No. 30 (0.6 mm) | 16 | ±3.0 | 18 | *20* | 17 | 17 | 17 | 16 | 17 | 16 |
| No. 50 (0.3 mm) | - | ±2.5 | 11 | 14 | 10 | 10 | 11 | 10 | 11 | 10 |
| No. 100 (0.15 mm) | - | - | 7 | 10 | 7 | 7 | 7 | 7 | 7 | 7 |
| No. 200 (0.075 mm) | 4.8 | ±1.0 | 5.4 | *8.3* | 4.9 | 4.9 | 5.5 | 5.2 | 5.2 | 5.2 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C8. Production Properties for Mixture D-1**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Mixture** | D-1 | | | | | | | | |
| **Mixture Type** | SM-12.5A | | | | | | | | |
| **NMAS, mm** | 12.5 | | | | | | | | |
| **Virgin Binder Grade** | PG 64S-22 | | | | | | | | |
| **RAP Content, %** | 30 | | | | | | | | |
| **Recycling Agent** | No | | | | | | | | |
| **Sample** | **Production JMF** | **Process Tolerance**[a] | **Sample 1 Producer** | **VTRC** | **Sample 2 Producer** | **VTRC** | **Sample 3 Producer** | **VDOT** | **Sample 4 Producer** |
| Asphalt Content, % | 5.8 | ± 0.3 | 5.98 | 5.89 | 5.96 | 5.88 | 5.49 | 5.40 | 5.99 |
| VTM, % | 4 | 2-5 | 2.1 | *1.9* | 3.0 | 2.3 | 3.9 | 4.1 | 2.6 |
| VMA, % | - | Min. 15 | 15.8 | 15.5 | 16.6 | 15.8 | 16.3 | 16.3 | 16.3 |
| VFA, % | - | 70-85 | *87* | *88* | 82 | 85 | 76 | 75 | 84 |
| FA Ratio | - | 0.7-1.3 | 1.0 | 1.0 | 0.9 | 1.0 | 0.8 | 0.9 | 0.9 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.88 | 5.78 | 5.86 | 5.77 | 5.39 | 5.30 | 5.89 |
| Rice SG, $G_{mm}$ | 2.470 | - | 2.460 | 2.467 | 2.471 | 2.472 | 2.478 | 2.485 | 2.468 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.408 | 2.419 | 2.397 | 2.415 | 2.382 | 2.384 | 2.405 |
| **Gradation, percent passing** | | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 97 | ±4.0 | 97 | 99 | 98 | 98 | 97 | 97 | 98 |
| 3/8 in (9.5 mm) | 88 | ±4.0 | 90 | 89 | 90 | 88 | 87 | 84 | 88 |
| No. 4 (4.75 mm) | 61 | ±4.0 | *56* | 61 | 63 | 61 | 58 | *55* | 60 |
| No. 8 (2.36 mm) | 41 | ±4.0 | 43 | 43 | 44 | 43 | 38 | 39 | 41 |
| No. 16 (1.18 mm) | - | - | 31 | 32 | 32 | 32 | 28 | 28 | 31 |
| No. 30 (0.6 mm) | 23 | ±3.0 | 23 | 24 | 23 | 24 | 21 | 21 | 23 |
| No. 50 (0.3 mm) | - | ±2.5 | 16 | 17 | 16 | 17 | 14 | 14 | 16 |
| No. 100 (0.15 mm) | - | - | 9 | 10 | 9 | 10 | 8 | 8 | 9 |
| No. 200 (0.075 mm) | 4.8 | ±1.0 | 5.7 | *5.9* | 5.0 | *5.9* | 4.5 | 4.7 | 5.1 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C9. Production Properties for Mixture D-2**

| **Mixture** | D-2 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mixture Type** | SM-12.5A | | | | | | | | | |
| **NMAS, mm** | 12.5 | | | | | | | | | |
| **Virgin Binder Grade** | PG 58-28 | | | | | | | | | |
| **RAP Content, %** | 35 | | | | | | | | | |
| **Recycling Agent** | RA3 | | | | | | | | | |
| **Sample** | **JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | | **Sample 4** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VDOT** | **Producer** | **VTRC** |
| Asphalt Content, % | 6.20 | ± 0.3 | 6.00 | 5.98 | 6.35 | 6.20 | 6.12 | *5.71* | 6.12 | 5.94 |
| VTM, % | 1.9 | 2-5 | *1.7* | *1.7* | *1.5* | *1.3* | 2.5 | 2.2 | 2.1 | *1.7* |
| VMA, % | - | Min. 15 | 15.0 | 15.0 | 15.7 | 15.1 | 16.1 | *14.8* | 15.7 | *14.9* |
| VFA, % | - | 70-85 | *89* | *89* | *90* | *92* | 84 | 85 | *87* | *89* |
| FA Ratio | - | 0.7-1.3 | 1.0 | 1.1 | 1.0 | 1.1 | 0.9 | 0.9 | 1.0 | 1.1 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.67 | 5.64 | 6.02 | 5.87 | 5.79 | 5.37 | 5.79 | 5.61 |
| Rice SG, $G_{mm}$ | 2.471 | - | 2.468 | 2.472 | 2.462 | 2.462 | 2.472 | 2.474 | 2.469 | 2.470 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.426 | 2.429 | 2.424 | 2.430 | 2.409 | 2.419 | 2.416 | 2.428 |
| **Gradation, percent passing** | | | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 98 | ±4.0 | 98 | 98 | 99 | 99 | 98 | 98 | 99 | 99 |
| 3/8 in (9.5 mm) | 90 | ±4.0 | 91 | 88 | 92 | 90 | 91 | *84* | 92 | 89 |
| No. 4 (4.75 mm) | 61 | ±4.0 | 61 | 58 | 64 | 61 | 61 | *55* | 64 | 57 |
| No. 8 (2.36 mm) | 42 | ±4.0 | 42 | 40 | 44 | 42 | 42 | 39 | 43 | 40 |
| No. 16 (1.18 mm) | - | - | 31 | 31 | 33 | 33 | 31 | 29 | 32 | 30 |
| No. 30 (0.6 mm) | 25 | ±3.0 | 24 | 24 | 26 | 26 | 24 | *21* | 24 | 24 |
| No. 50 (0.3 mm) | - | ±2.5 | 18 | 18 | 18 | 19 | 17 | 14 | 17 | 17 |
| No. 100 (0.15 mm) | - | - | 10 | 11 | 11 | 12 | 10 | 9 | 10 | 10 |
| No. 200 (0.075 mm) | 5.7 | ±1.0 | 5.8 | 6.2 | 6.0 | 6.5 | 5.4 | 5.0 | 5.7 | 5.9 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C10. Production Properties for Mixture D-3**

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Mixture** | D-3 | | | | | | | | | |
| **Mixture Type** | SM-12.5A | | | | | | | | | |
| **NMAS, mm** | 12.5 | | | | | | | | | |
| **Virgin Binder Grade** | PG 58-28 | | | | | | | | | |
| **RAP Content, %** | 35 | | | | | | | | | |
| **Recycling Agent** | Fiber + Softening oil | | | | | | | | | |
| **Sample** | **JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | | **Sample 4** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 6.20 | ± 0.3 | 6.17 | *5.88* | 6.18 | 6.02 | 6.13 | *5.78* | 5.70 | *5.30* |
| VTM, % | 2.1 | 2-5 | *1.6* | *1.7* | *1.6* | *1.8* | *1.4* | *1.7* | 2.5 | 2.1 |
| VMA, % | - | Min. 15 | 15.5 | *14.9* | 15.5 | 15.3 | 15.2 | *14.7* | 15.1 | *14.0* |
| VFA, % | - | 70-85 | *90* | *89* | *90* | *88* | *91* | *89* | 83 | 85 |
| FA Ratio | - | 0.7-1.3 | 1.0 | 1.1 | 1.0 | 1.1 | 1.0 | 1.1 | 1.0 | 1.1 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.88 | 5.59 | 5.89 | 5.73 | 5.84 | 5.49 | 5.41 | 5.03 |
| Rice SG, $G_{mm}$ | 2.469 | - | 2.470 | 2.477 | 2.465 | 2.473 | 2.472 | 2.485 | 2.475 | 2.471 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.431 | 2.436 | 2.425 | 2.428 | 2.437 | 2.444 | 2.414 | 2.419 |
| **Gradation, percent passing** | | | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 98 | ±4.0 | 99 | 99 | 99 | 98 | 99 | 99 | 99 | 99 |
| 3/8 in (9.5 mm) | 90 | ±4.0 | 92 | 91 | 91 | 89 | 92 | 89 | 90 | 89 |
| No. 4 (4.75 mm) | 61 | ±4.0 | 62 | 60 | 61 | 59 | 63 | 58 | 61 | 57 |
| No. 8 (2.36 mm) | 42 | ±4.0 | 42 | 42 | 42 | 41 | 43 | 41 | 43 | 41 |
| No. 16 (1.18 mm) | - | - | 32 | 32 | 32 | 32 | 33 | 32 | 32 | 31 |
| No. 30 (0.6 mm) | 25 | ±3.0 | 25 | 25 | 25 | 25 | 25 | 25 | 24 | 24 |
| No. 50 (0.3 mm) | - | ±2.5 | 18 | 18 | 18 | 18 | 18 | 18 | 17 | 17 |
| No. 100 (0.15 mm) | - | - | 10 | 11 | 10 | 11 | 10 | 11 | 10 | 10 |
| No. 200 (0.075 mm) | 5.7 | ±1.0 | 5.8 | 6.2 | 5.7 | 6.0 | 5.9 | 6.1 | 5.5 | 5.7 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C11. Production Properties for Mixture E-1**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Mixture** | E-1 | | | | | | |
| **Mixture Type** | SM-12.5A | | | | | | |
| **NMAS, mm** | 12.5 | | | | | | |
| **Virgin Binder Grade** | PG 64S-22 | | | | | | |
| **RAP Content, %** | 30 | | | | | | |
| **Recycling Agent** | No | | | | | | |
| **Sample** | **JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 5.9 | ± 0.3 | 6.11 | 5.61 | 5.94 | 5.90 | 6.01 | 5.87 |
| VTM, % | 4.0 | 2-5 | 4.2 | 4.1 | 2.0 | *1.6* | 2.0 | *1.9* |
| VMA, % | - | Min. 15 | 17.7 | 16.5 | 15.4 | 15.0 | 15.6 | 15.2 |
| VFA, % | - | 70-85 | 76 | 75 | *87* | *90* | *87* | *87* |
| FA Ratio | - | 0.7-1.3 | 1.1 | 1.2 | 1.2 | 1.3 | 1.2 | 1.2 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.78 | 5.27 | 5.61 | 5.56 | 5.68 | 5.53 |
| Rice SG, $G_{mm}$ | 2.485 | - | 2.511 | 2.516 | 2.514 | 2.520 | 2.515 | 2.515 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.405 | 2.412 | 2.463 | 2.481 | 2.465 | 2.467 |
| **Gradation, percent passing** | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 99 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 95 | ±4.0 | 96 | 93 | 93 | 93 | 94 | 94 |
| 3/8 in (9.5 mm) | 85 | ±4.0 | 85 | 82 | 84 | 85 | 84 | 85 |
| No. 4 (4.75 mm) | 58 | ±4.0 | 55 | *49* | 56 | 55 | 57 | 55 |
| No. 8 (2.36 mm) | 37 | ±4.0 | 34 | *32* | 38 | 38 | 37 | 37 |
| No. 16 (1.18 mm) | - | - | 24 | 23 | 27 | 28 | 27 | 27 |
| No. 30 (0.6 mm) | 18 | ±3.0 | 17 | 16 | 20 | 20 | 20 | 20 |
| No. 50 (0.3 mm) | - | ±2.5 | 12 | 12 | 14 | 15 | 14 | 14 |
| No. 100 (0.15 mm) | - | - | 9 | 9 | 10 | 11 | 10 | 10 |
| No. 200 (0.075 mm) | 6.0 | ±1.0 | 6.4 | 6.2 | 6.8 | *7.3* | 7.0 | 6.8 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

**Table C12. Production Properties for Mixture E-2**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Mixture** | E-2 | | | | | | | |
| **Mixture Type** | SM-12.5A | | | | | | | |
| **NMAS, mm** | 12.5 | | | | | | | |
| **Virgin Binder Grade** | PG 58-28 | | | | | | | |
| **RAP Content, %** | 35 | | | | | | | |
| **Recycling Agent** | No | | | | | | | |
| **Sample** | **JMF** | **Process Tolerance**[a] | **Sample 1** | | **Sample 2** | | **Sample 3** | |
| | | | **Producer** | **VTRC** | **Producer** | **VTRC** | **Producer** | **VTRC** |
| Asphalt Content, % | 5.80 | ± 0.3 | 5.90 | 5.74 | 5.87 | 5.48 | 5.97 | 5.83 |
| VTM, % | 2.8 | 2-5 | 2.1 | *1.8* | 2.0 | 3.0 | 3.3 | 3.4 |
| VMA, % | - | Min. 15 | 16.0 | 15.3 | 15.7 | 15.7 | 17.1 | 16.8 |
| VFA, % | - | 70-85 | *87* | *88* | *87* | 81 | 81 | 80 |
| FA Ratio | - | 0.7-1.3 | 1.1 | 1.1 | 1.0 | 1.1 | 1.0 | 1.0 |
| Eff. Asphalt Content ($P_{be}$), % | - | - | 5.80 | 5.64 | 5.77 | 5.38 | 5.87 | 5.72 |
| Rice SG, $G_{mm}$ | 2.479 | - | 2.511 | 2.508 | 2.495 | 2.516 | 2.507 | 2.506 |
| Mixture Bulk SG, $G_{mb}$ | - | - | 2.458 | 2.463 | 2.446 | 2.441 | 2.425 | 2.422 |
| **Gradation, percent passing** | | | | | | | | |
| 3/4 in (19.0 mm) | 100 | ±1.0 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1/2 in (12.5 mm) | 96 | ±4.0 | 94 | 94 | 97 | 94 | 97 | 96 |
| 3/8 in (9.5 mm) | 89 | ±4.0 | 86 | *83* | 88 | *83* | 90 | 89 |
| No. 4 (4.75 mm) | 53 | ±4.0 | 54 | 54 | *58* | 51 | 57 | 56 |
| No. 8 (2.36 mm) | 35 | ±4.0 | 38 | 37 | 38 | 35 | 36 | 36 |
| No. 16 (1.18 mm) | - | - | 27 | 27 | 27 | 26 | 25 | 26 |
| No. 30 (0.6 mm) | 17 | ±3.0 | 20 | 20 | 20 | 18 | 18 | 19 |
| No. 50 (0.3 mm) | - | ±2.5 | 14 | 14 | 13 | 13 | 13 | 13 |
| No. 100 (0.15 mm) | - | - | 9 | 9 | 9 | 9 | 9 | 9 |
| No. 200 (0.075 mm) | 5.2 | ±1.0 | 6.1 | 6.2 | 5.8 | 5.8 | 5.8 | 5.8 |

Red italic values indicate result exceeds allowable process tolerance. RAP = reclaimed asphalt pavement; JMF = job-mix formula; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA = fines to aggregate; Eff. = effective.

[a] Process tolerance for four tests from Table II-15 (VDOT, 2016).

# APPENDIX D

## STATISTICAL COMPARISON TABLES

**Table D1. Comparison of Variability in Mass Loss for Reheat Samples**

| Sample | A-1 | A-2 | A-3 | B-1 | B-2 | B-3 | C-1 | D-1 | D-2 | D-3 | E-1 | E-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | a | a | a | a | a | a | a | a | a | a | a | a |
| 2 | a b | a | a | b | a | a | a | a | a | a | a b | b |
| 3 | a | a | a | a b | b | a | a | - | a | a | b | a |
| 4 | b | a | a | a b | a | a | a | - | a | a | - | - |

The results of samples with the same letters in a column are not statistically different. - = no data available.

**Table D2. Comparison of JMF, Average Plant, and Average Reheat Mass Loss for Each Mixture**

| Mixture | A-1 | A-2 | A-3 | B-1 | B-2 | B-3 | C-1 | D-1 | D-2 | D-3 | E-1 | E-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JMF | a | a | a | a | a | a | a | - | a | a | - | a |
| Plant | b | b | b | b | b | a | b | a | a | a | a | b |
| Reheat | a | a | a | c | a b | a | c | a | b | b | a | a |

The results for samples with the same letters in a column are not statistically different. - = no data available.

**Table D3. Comparison of Average Reheat Mass Loss for Control (Mixture 1) and BMD Mixtures (Mixtures 2 and 3)**

| Mixture | Producer | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 1 | a | a | - | a | a |
| 2 | a | a | - | b | a |
| 3 | a | a | - | b | - |

The results for samples with the same letters in a column are not statistically different. - = no data available.

**Table D4. Comparison of Variability of Rut Depth Reheat Samples**

| Sample | A-1 | A-2 | A-3 | B-1 | B-2 | B-3 | C-1 | D-1 | D-2 | D-3 | E-1 | E-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | a | a | a b | a | a | a | a | a | a | a | a | a |
| 2 | a | a | a | a | a | a | - | a | a | a | a | a |
| 3 | a | a | b | a | a | a | a | - | a | a | a | a |
| 4 | a | a | a b | a | a | a | a | - | a | a | - | - |

The results for samples with the same letters in a column are not statistically different. - = indicates no data available.

**Table D5. Comparison of JMF, Average Plant, and Average Reheat Rut Depths for Each Mixture**

| Mixture | A-1 | A-2 | A-3 | B-1 | B-2 | B-3 | C-1 | D-1 | D-2 | D-3 | E-1 | E-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JMF | a | a | a | a | a | a | a | - | a | a | - | a |
| Plant | a | a | b | a | a | a | a | a | a | a | a | a b |
| Reheat | a | a | c | a | a | a | a | a | a | b | a | b |

The results for samples with the same letters in a column are not statistically different. - indicates no data available.

**Table D6. Comparison of Average Reheat Rut Depths for Control (Mixture 1) and BMD Mixtures (Mixtures 2 and 3)**

| Mixture | Producer | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 1 | a | a | - | a | a |
| 2 | b | a | - | a | a |
| 3 | a b | a | - | a | - |

The results for samples with the same letters in a column are not statistically different. - = no data available.

**Table D7. Comparison of CT Index Reheat Sample Variability**

| Sample | A-1 | A-2 | A-3 | B-1 | B-2 | B-3 | C-1 | D-1 | D-2 | D-3 | E-1 | E-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | a | a | a | a | a | a | a b | a | a | a | a | a |
| 2 | a | a | a | a b | a | b | a b | b | b | a | a | b |
| 3 | b | a | b | a b | b | c | a | - | a | a | a | a |
| 4 | a | b | b | b | b | c | b | - | a | a | - | - |

The results for samples with the same letters in a column are not statistically different. - = indicates no data available.

**Table D8. Comparison of JMF, Average Plant, and Average Reheat CT Index for Each Mixture**

| Mixture | A-1 | A-2 | A-3 | B-1 | B-2 | B-3 | C-1 | D-1 | D-2 | D-3 | E-1 | E-2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| JMF | a b | a | a | a | a | a | a | - | a | a | - | a |
| Plant | a | b | b | b | a | a | a b | a | a b | a | a | b |
| Reheat | b | a | a | c | a | a | b | a | b | a | a | b |

The results for samples with the same letters in a column are not statistically different. - = no data available.

**Table D9. Comparisons of Average Reheat CT Index for Control (Mixture 1) and BMD Mixtures (Mixtures 2 and 3)**

| Mixture | Producer | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| 1 | a | a b | - | a | a |
| 2 | a | a | - | b | a |
| 3 | a | b | - | a b | - |

The results for samples with the same letters in a column are not statistically different. - = no data available.