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Balanced Mix Design for Asphalt Surface Mixtures: 2019 Field Trials

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16. Abstract:

In 2017, the Virginia Department of Transportation (VDOT) began to evaluate the feasibility of introducing performance requirements into mix design using the balanced mix design (BMD) method. VDOT has since committed to the implementation of the BMD method in an effort to improve asphalt mixture performance. Through a collaborative effort with industry, VDOT developed two special provisions for use with field trials that use the BMD method to specify as-designed mixture performance. This study documented and evaluated the field trials that were the first applications of these specifications in 2019 to design, produce, and place BMD asphalt mixtures in Virginia. The analyses addressed the application of the BMD concept, production variability, comparisons of mixtures, and differences in specimen test response with and without reheating of the loose mixture for fabrication.

Nine mixtures were evaluated from the two field trials; the mixtures incorporated combinations of different reclaimed asphalt pavement (RAP) contents, two binder grades, two recycling agents, and two warm mix asphalt (WMA) additives. 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 a softer binder, WMA additives, 40% RAP, and recycling agents may be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements. The laboratory performance test results indicated that for some mixtures, WMA additives and a recycling agent may be expected to provide performance that is equal to or better than the performance of their counterpart mixtures containing only a WMA additive. In addition, results indicated that the evaluated asphalt mixtures containing 40% RAP and softer binders or a recycling agent can be expected to provide performance that is equal to or better than the performance of their counterpart mixtures with 30% RAP. The long-term field and laboratory performance of all of these mixtures needs to be evaluated to verify these early findings. The relationships between performance test results and mixture properties need further study, and improvements in test methods and criteria should be pursued.

Based on the outcomes of the study, it is necessary to determine the precision estimates for the Cantabro and APA tests. In addition, the development of different performance criteria for the Cantabro and IDT-CT tests to be applied to non-reheated specimen testing may be necessary. The performance of multiple Cantabro and IDT-CT performance tests for each lot during production may be necessary such that an average test value can be used in BMD quality control, quality assurance, or acceptance practices, because of the variability in individual test results. In light of the lack of failing test results among the mixtures, APA tests may not need to be performed as frequently as Cantabro and IDT-CT tests during production, although this needs to be investigated further.

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FINAL REPORT

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Nine mixtures were evaluated from the two field trials; the mixtures incorporated combinations of different reclaimed asphalt pavement (RAP) contents, two binder grades, two recycling agents, and two warm mix asphalt (WMA) additives. 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.

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INTRODUCTION

Currently, asphalt mixtures are primarily designed under the Superpave system where the aggregate and asphalt binder components are proportioned based on the volumetric properties of the resultant mixtures. Even when meeting these volumetric property requirements, mixtures can be designed with too little asphalt and may exhibit cracking and durability-related pavement distresses or be designed with too much asphalt and exhibit rutting and shoving-related pavement distresses. For many years, there has been a desire for owner agencies and the asphalt industry to introduce and implement performance tests that can be used in the design process to guarantee better-performing and longer-lasting asphalt mixtures in the field. Moreover, the introduction of such performance tests could facilitate the responsible use of innovative materials in the mix design process.

The balanced mix design (BMD) approach has been rapidly gaining attention on the national level. This method replaces some aspects of traditional volumetric design with performance testing criteria for most common distresses such as rutting and cracking. BMD was defined as “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” by the BMD task force, formed in September 2015 by the Federal Highway Administration Expert Task Group on Mixtures and Construction. Although BMD mixtures cannot compensate for an unsound underlying pavement structure or the selection of inappropriate maintenance treatments, BMD constitutes a significant step forward in the pursuit of better-performing asphalt mixtures.

The Virginia Department of Transportation (VDOT), as with many owner agencies, is interested in ways to facilitate the increased durability of asphalt mixtures in an effort to make its roadway network more sustainable, longer lasting, and more economical. Moreover, VDOT is extensively working to determine how best to incorporate recycled materials such as recycled asphalt pavement (RAP) into its roads without compromising quality. Concerns about the accuracy of volumetric properties (e.g., aggregate-specific gravity determinations) increase with the incorporation of RAP into mixtures, especially as the effect of the recycled binders and the interaction of the recycled virgin binders are not captured in the volumetric properties and are not well understood as part of the Superpave system. Therefore, the BMD method was proposed to address these challenges through the incorporation of performance criteria into mix design and acceptance. Instead of providing only recipe-type specifications for design and acceptance, the BMD method uses additional performance test criteria to assess and accept mixtures.

Although BMD is not yet a widely established method of design and no readily available specifications exist for widespread adoption, there was a need to develop a framework to address how VDOT can adopt this method and a need for specification language and requirements. Therefore, a preliminary comprehensive roadmap for BMD was developed to provide an all-inclusive picture of activities related to BMD. The vision for the proposed roadmap was the development of a mix design method and supporting tools to provide safe, durable, long-lasting asphalt mixtures in a more efficient, effective, environmentally sound, and economical manner. To address this, a program of research has been undertaken with a goal of systematic implementation of the BMD method through research and coordination with all stakeholders.

In 2017, 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 and Diefenderfer, 2018). The evaluation was conducted on specimens fabricated from reheated plant-produced mixtures. Numerous performance tests were considered in the laboratory to evaluate the selected mixtures. Three primary performance tests were recommended for use in the BMD method for VDOT: the Cantabro mass loss test (hereinafter “Cantabro test”); the indirect tensile cracking test (IDT-CT) (hereinafter “IDT-CT test”) at intermediate temperatures; and the Asphalt Pavement Analyzer (APA) rut test (hereinafter “APA test”) for assessing the durability, cracking potential, and rutting potential, respectively, of asphalt mixtures. Moreover, initial performance threshold criteria were developed for the selected tests.

Following this, 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. This was achieved by extensive evaluation of an additional 13 standard asphalt surface mixtures produced and sampled in 2018. This study validated that the IDT-CT and APA rut tests selected for use in the BMD method are in agreement with fundamental performance tests. Based on results from the mixtures tested in this study, the current performance criteria limiting Cantabro mass loss to a maximum of 7.5%, APA rut depth to a maximum of 8.0 mm, and the IDT CT index to a minimum of 70 were shown to be reasonable based on additional mixture testing. Moreover, the study highlighted the need to address the potential effects of mixture reheating on all performance test results.

In recognition of the impacts that BMD would have on the asphalt construction industry, in late 2018, VDOT and VTRC established a BMD technical committee to address the technical aspects of BMD collaboratively among VDOT, VTRC, and industry representatives. Through that collaboration, VDOT developed two special provisions for use with field trials that use BMD concepts to specify as-designed mixture performance (Diefenderfer et al., 2021). The initial application of those specifications to plant production occurred in 2019. The current study documents the first uses of these specifications to design, produce, and pave BMD asphalt mixtures in Virginia.

PURPOSE AND SCOPE

The purpose of this study was to document and assess the design and production of field trials using mixtures designed in accordance with the 2019 version of VDOT's *Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria* and VDOT's *Special Provision for Dense Graded Surface Mixtures Designed Using Performance Criteria* compared with typical standard mixtures used as controls. 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 mixtures, i.e., 30% RAP and 40% RAP mixtures with a recycling agent and softer binder and a typical surface mixture with recycling agents and different WMA additives
- differences in test responses of specimens fabricated from reheated mixtures compared to specimens prepared from non-reheated mixtures.

The 2019 trials served as the first application of the BMD special provisions to production. They provided an opportunity to begin evaluating the impact of the specifications on the design, production, quality control and assurance practices, and construction of surface mixtures (SMs). In addition, the trials will serve as a means to evaluate the long-term performance implications of using the BMD method.

METHODS

The following tasks were performed to achieve the study objectives:

1. Document the project selection, mix design, production, and construction processes.
2. Obtain producer-supplied design specimens 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.

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 both trial locations deviated from them.

Trials included control non-BMD typical dense-graded 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 2019 *Special Provision for Dense-Graded Surface Mixtures Designed Using Performance Criteria* and VDOT's 2019 *Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance* Criteria, which are presented in Appendices A and B, respectively. The contents are the same for both special provisions with the exception that RAP contents are limited to 30% or less for BMD SMs; in addition, the specification for "high RAP content surface mixtures" requires that such mixtures have a minimum RAP content of 40%. The special provisions cover requirements for materials, the job-mix formula (JMF), production testing, acceptance, and initial production. The requirements for performance, recommended by Bowers and Diefenderfer (2018), are summarized in the JMF requirements, which also define the two types of BMD approaches that VDOT is evaluating.

In the BMD special provisions, SMs 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, VTRC evaluated the proposed mix designs to determine their performance response, and the results were used by the specific VDOT district for mix design approval. All BMD mixtures were designed to meet the P+V designation. During production, specimens were fabricated at the plant without reheating for performance testing by VTRC and the producer in accordance with the special provision; however, producer performance test results are not included herein. 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 this is not discussed herein.

Table 1. Performance Testing Criteria

Distress	Test	Test Method	Specimens	Criteria
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.

During production and paving, standard equipment and practices were used. No operations-related issues were observed. Both producers crushed and screened their RAP prior to use. Producer A maintains coarse and fine RAP stockpiles and used two RAP feed bins during production. Producer B's plant had only one RAP stockpile and bin.

Materials

The field trials were constructed in two VDOT districts: the Northern Virginia District and the Lynchburg District. Nine total mixtures were evaluated, with five mixtures produced at the Northern Virginia District plant and four mixtures produced at the Lynchburg District plant. Two of the mixtures produced at the Lynchburg District plant were paved in the Salem District, and two were paved in the Lynchburg District. All sampled mixtures were SMs having an NMAS of 9.5 mm.

Mixtures were produced by two producers, designated A and B. Producer A designed, produced, and paved five mixtures, identified as Mixtures A-I through A-V. Producer B designed, produced, and paved four mixtures, identified as Mixtures B-I through B-IV.

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 non-BMD mixtures were required to meet current VDOT volumetric and gradation requirements. BMD mixtures used in this study met current VDOT volumetric and gradation requirements and the performance requirements of the *Special Provision for Dense-Graded Surface Mixtures Designed Using Performance Criteria* or the *Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria.*

Producer A submitted laboratory-produced, laboratory-compacted specimens to VDOT for Cantabro, IDT-CT, and APA testing for mixtures produced during the trial. Testing was performed by VTRC. Laboratory-produced, laboratory-compacted design specimens were not available for the mixtures from Producer B.

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 are summarized in Table 2. Figures 1 through 4 show the locations of core sampling during each day of paving for each mixture. The distance paved each day for each mixture was greater than that shown in the figures. No cores were collected for Mixture B-I.

Table 2. Project and Mixture Locations

Mixture	Paving Date	Paving Location	Mixture Type	Job-Mix Formula	Production Temp.
A-I	7/15-16, 24/2019	Catharpin Road, Prince William County	SM-9.5A 30% RAP PG 64S-22	9064-2019-78 WM	275-280°F
A-II	8/26-27/2019		SM-9.5A 30% RAP PG 58-28	9064-2019-V58-28-2 WM	280-285°F
A-III	8/22/2019		SM-9.5A 40% RAP PG 64S-22	9064-2019-V78 WM	275-280°F
A-IV	7/17-18/2019		SM-9.5A 40% RAP PG 58-28	9064-2019-V-58-28 WM	280-300°F
A-V	6/27-28/2019	Logmill Road, Prince William County	SM-9.5A 40% RAP PG 64S-22 Recycling agent	9064-2019-V-Rej WM	275-300°F
B-I	7/12/2019	US 460, Bedford County	SM-9.5D 26% RAP PG 64S-22 WMA A	3020-2019-248-WMA	295-310°F
B-II	7/17/2019		SM-9.5D 26% RAP PG 64S-22 WMA A and Recycling agent A	3020-2019-248 WMA BP+V	300-305°F
B-III	7/24/2019	US 60, Amherst County	SM-9.5D 26% RAP PG 64S-22 WMA B	3020-2019-248 BMDE	280-290°F
B-IV	7/25/2019		SM-9.5D 26% RAP PG 64S-22 WMA B and Recycling agent B	3020-2019-248-BMDE BP+V	275°F

SM = surface mixture; RAP = reclaimed asphalt pavement; PG = performance grade.

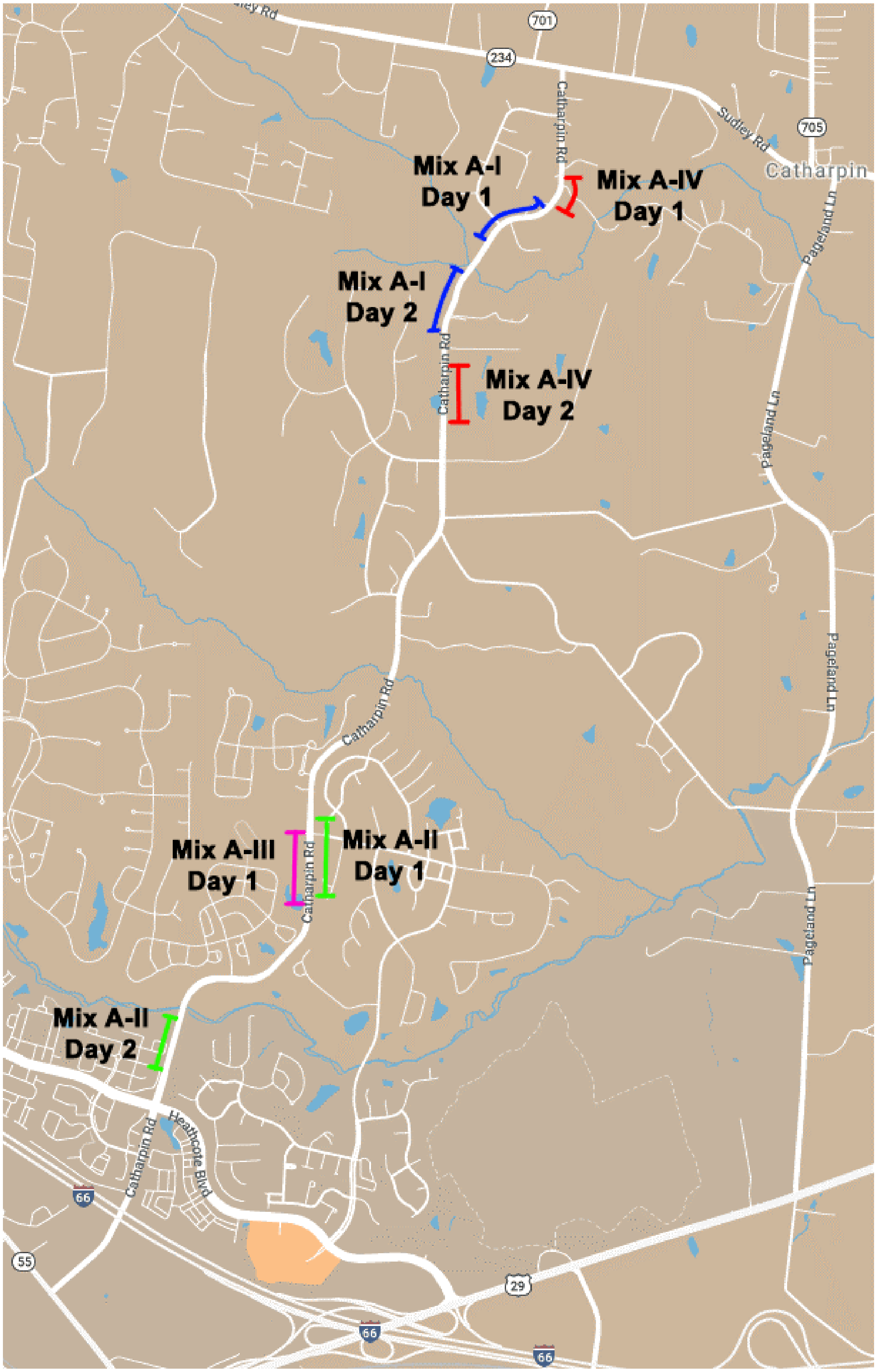

Figure 1. Sample Locations for Mixtures A-I Through A-IV on Catharpin Road

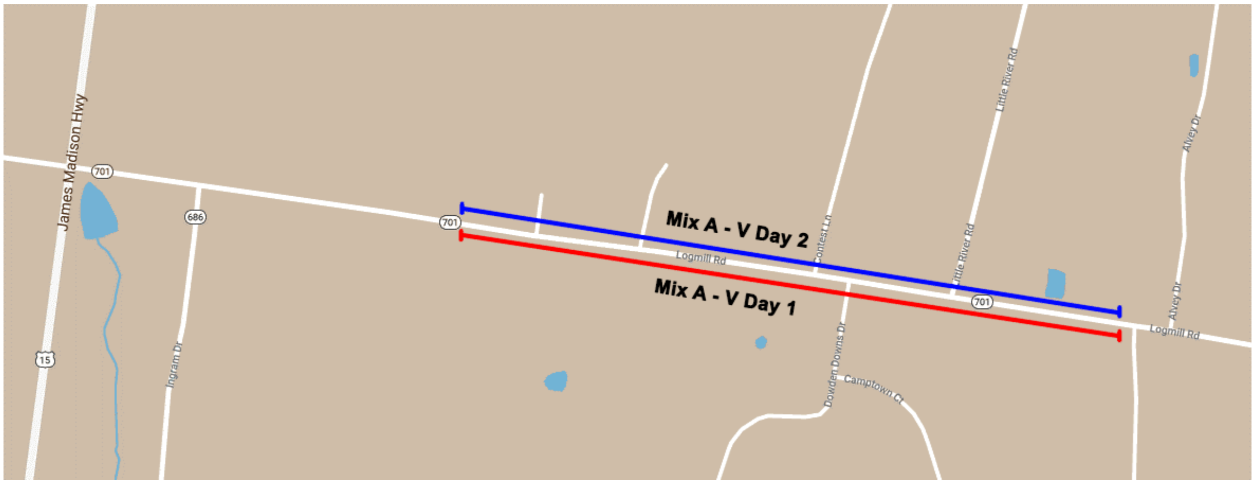

Figure 2. Sample Locations for Mixture A-V on Logmill Road

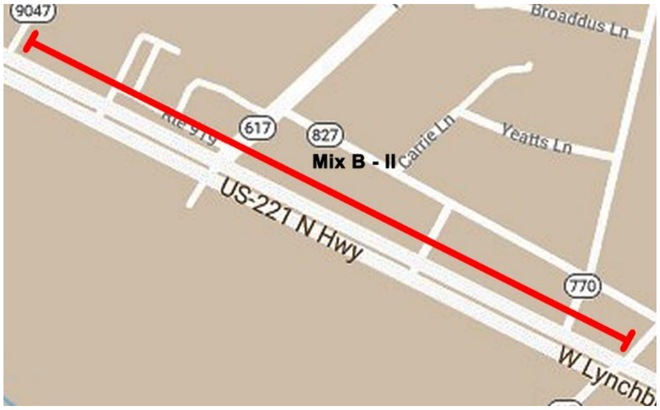

Figure 3. Sample Location for Mixture B-II on US 221

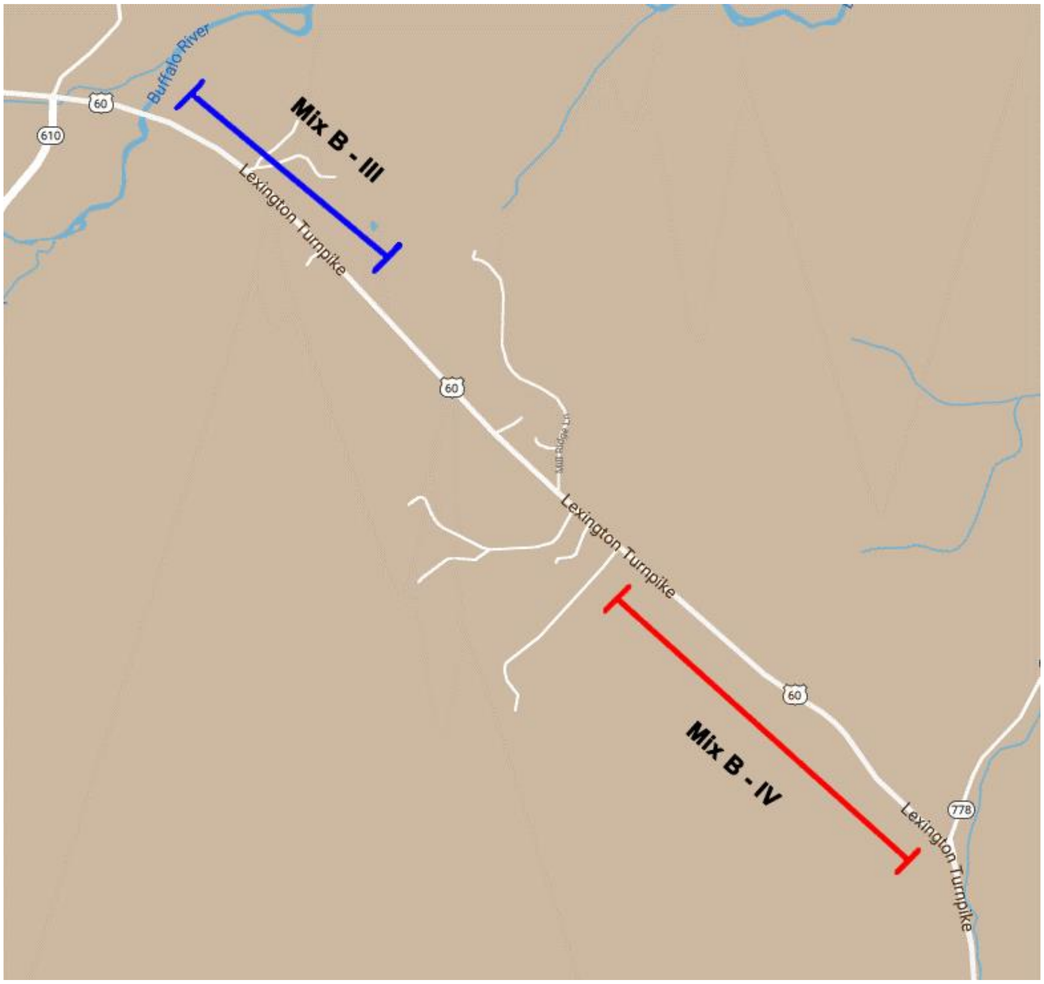

Figure 4. Sample Locations for Mixtures B-III and B-IV on US 60

Sampling

Loose mixture sampling was performed twice during each day of production. Table 3 presents the production sampling plan for each mixture. Some mixtures were produced for only a single day; for those mixtures, only two samples were collected. For the most part, sampling proceeded as planned, per Table 3; 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 Specimen Set 1 was fabricated from the first mixture sample).

Table 3. Production Sampling Plan

	Sample	**Plant Specimen**			**Loose Mixture**
Day	**Set**	**Cantabro**	**APA**	**IDT-CT**	**Boxes**
1	1	-	4	-	6
	2	3	4	5	12
2	3	-	4	-	6
	4	3	4	5	6

APA = Asphalt Pavement Analyzer; IDT-CT = indirect tensile cracking test; - = no specimens fabricated for VTRC testing.

Loose Mixture Samples

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

Plant-Compacted Specimens

Loose plant-produced mixture intended for specimens compacted without reheating at the plant was taken into the laboratory and immediately placed into ovens. The Rice mixture 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 criteria 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 air-void contents could be measured. Specimens cooled reasonably quickly if placed in front of a fan, preferably on an elevated perforated surface such as an oven shelf, so that air could move freely around all sides.

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.

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 and 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. In addition, volumetric specimens were compacted and used for

Cantabro testing. 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 Set	Loose Mixture	Reheated Specimens		
		Boxes	Cantabro	APA	IDT-CT
1	1	6	3	4	5
	2	12	3	4	5
2	3	6	3	4	5
	4	6	3	4	5

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

Laboratory Testing and Evaluation

Laboratory testing was conducted on specimens fabricated from mixtures, as shown in Figure 5. In addition to the performance tests shown in Figure 1, mixture volumetric properties and gradation were determined for all plant-produced mixtures.

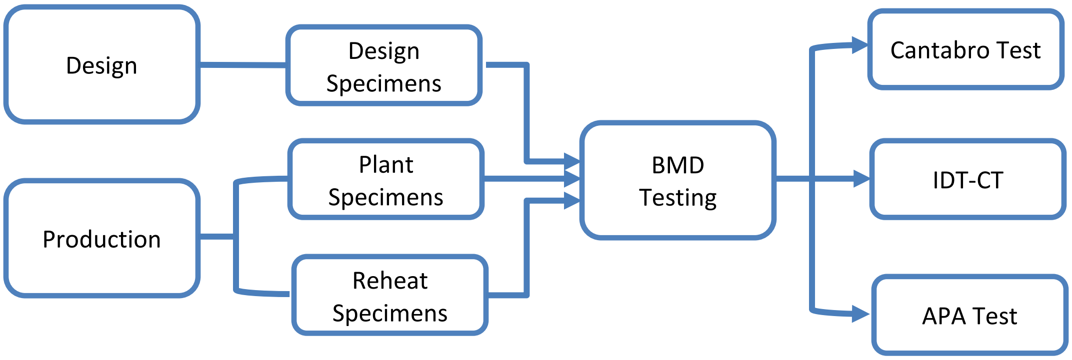

Figure 5. Experimental Plan for Laboratory- and Plant-Produced Mixtures. BMD = balanced mix design; IDT-CT = indirect tensile cracking test; APA = Asphalt Pavement Analyzer.

Specimen Designations

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

1. *Design:* 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.

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

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}); dust/asphalt 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.

Cantabro Mass Loss 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. Three to five replicate specimens were tested.

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), using a test temperature of 64 ± 0.5°C. An APA Jr. tester was used such that two replicate tests consisting of two specimens each were conducted for each mixture.

RESULTS AND DISCUSSION

The volumetrics and performance test results of the mixtures from Producers A and B are presented. Unless mentioned otherwise, no data were discarded from any tests presented in this report. 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 performed in this study were conducted at a 95% confidence interval and included checking the assumptions of normality and equal variances.

Mixtures From Producer A

Five mixtures were evaluated during the trial conducted with Producer A. All mixtures were designed to meet VDOT volumetric and gradation requirements (VDOT, 2016). Only

Mixture A-IV, containing 40% RAP and PG 58-28 binder, and Mixture A-V, containing 40% RAP and a recycling agent, were designed to meet VDOT's *Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria.*

Volumetric Properties and Gradation

The volumetric properties and gradations of Mixtures A-I through A-V are shown in Tables 5 through 9, respectively, for design, plant samples tested by the producer, and reheated samples tested by VTRC. VDOT specifications require that mixtures meet design criteria for volumetric properties (binder content, VTM, VFA, VMA, and FA) and aggregate gradations for specific sieve sizes depending on the mixture type (VDOT, 2016). The tables indicate that all mixtures from Producer A met VDOT mix design criteria as outlined in the specifications.

Mixture acceptance during production is based on the determination of asphalt content, gradation, and temperature along with in-place density. The means of the production results of asphalt content and gradation properties are checked against the tolerance allowed for the JMF as specified in the specification. Among all mixtures, only Mixture A-II did not meet such requirements for the No. 200 sieve for the reheat sets. The average percent passing the No. 200 sieve of the reheat sets for this mixture exceeded the maximum design criteria (i.e., 10%) and the production tolerance limit compared to the JMF. This was primarily due to Reheat Set 2 (Table 6). However, Mixture A-II plant sets met all production requirements.

Close inspection of the tables indicated that the volumetric properties and gradation showed variation from set to set throughout the production of Mixtures A-I through A-V. These variations were minimal for the majority of the mixtures. Variations for a few cases were outside the tolerance limits required by VDOT specifications. For example, the asphalt content of Mixture A-IV Reheat Set 3 (Table 8) did not meet the production tolerance limits (determined for four samples), as it was not within 0.3% of the asphalt content indicated by the JMF. For Mixture A-V (Table 9), reheat mixtures for Set 1 and both plant and reheat mixtures for Set 3 exceeded the VFA upper production limit of 85%. In addition, for the same mixture, the VTM for the Set 2 plant mixture was less than the minimum production limit of 2% as per the specifications. Although such comparison at the sample set level of test results is not VDOT practice (acceptance and pay are determined by lot average), this comparison was performed to provide an indication of the extent of production variability. The mixture average volumetric properties and gradations during production were within the allowable tolerances for Mixtures A-I through A-V with the exception of one mixture where only the percent passing the No. 200 sieve was outside the tolerance limit for the VTRC sets only.

In summary, the mixtures designed by Producer A incorporating 40% RAP and either a recycling agent or softer binder were in accordance with VDOT specifications. The production results indicated that these mixtures can be produced consistently in terms of volumetric properties and gradation. This observation is important to consider when the performance of the mixtures is evaluated.

Table 5. Volumetric Properties and Gradations for Mixture A-I

Mixture	**A-I**										
Mixture Type	**SM-9.5A**										
Virgin Binder Grade	**PG 64S-22**										
RAP Content, %	**30**										
Recycling Agent	**No**										
Sample	**JMF**	**Process Tolerance**[a]	**Set 1**		**Set 2**		**Set 3**		**Set 4**		**Set Average**	
Property			**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.60	±0.3	5.67	5.69	5.38	5.42	5.38	5.50	5.73	5.35	5.54	5.49
Rice SG (G_{mm})	2.651	-	2.664	2.668	2.658	2.659	2.658	2.650	2.658	2.653	2.660	2.657
VTM, %	3.9	2-5	3.5	3.9	3.5	3.6	3.5	3.2	3.3	2.9	3.5	3.4
VMA, %	17.8	Min. 16	17.6	18.0	16.8	17.0	16.8	16.8	17.5	16.2	17.2	17.0
VFA, %	78.0	70-85	80.0	78.1	79.0	78.7	79.0	81.2	81.0	82.3	79.8	80.1
FA Ratio	1.00	0.7-1.3	1.20	1.15	-	1.27	1.20	1.20	1.10	1.26	1.17	1.22
Mixture Bulk SG (G_{mb})	-	-	2.571	2.563	-	2.563	2.565	2.567	2.570	2.577	2.569	2.567
Aggregate Effective SG (G_{se})	-	-	2.945	2.950	-	2.924	2.920	2.917	2.941	2.912	2.935	2.926
Aggregate Bulk SG (G_{sb})	-	-	2.942	2.947	-	2.921	2.917	2.914	2.938	2.909	2.932	2.923
Absorbed Asphalt Content (P_{ba}), %	-	-	0.04	0.04	-	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Effective Asphalt Content (P_{be}), %	-	-	5.63	5.65	-	5.39	5.34	5.46	5.69	5.32	5.55	5.45
Gradation, percent passing												
½ in (12.5 mm)	100	±4.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in (9.5 mm)	95	±4.0	96.0	96.0	97.0	96.9	96.0	96.2	97.0	96.0	96.5	96.3
No. 4 (4.75 mm)	61	±4.0	63.0	63.7	62.0	**66.9**	61.0	61.3	62.0	62.2	62.0	63.5
No. 8 (2.36 mm)	40	±4.0	42.0	41.8	40.0	42.2	40.0	40.4	40.0	39.6	40.5	41.0
No. 16 (1.18 mm)	-	-	29.0	29.4	-	29.9	28.0	28.9	28.0	28.2	28.3	29.1
No. 30 (600 µm)	20	±3.0	21.0	21.3	20.0	21.5	20.0	20.7	20.0	20.4	20.3	21.0
No. 50 (300 µm)	-	±2.5	15.0	14.8	-	15.2	14.0	14.4	14.0	14.5	14.3	14.8
No. 100 (150 µm)	-	-	10.0	9.7	-	10.2	9.0	9.6	9.0	9.8	9.3	9.8
No. 200 (75 µm)	6	±1.0	6.5	6.5	6.4	6.9	6.3	6.6	6.4	6.7	6.4	6.7

Red text indicates value that did not meet allowable tolerance. PG = performance grade; 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, - = not available.

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

Table 6. Volumetric Properties and Gradations for Mixture A-II

Mixture	**A-II**										
Mixture Type	**SM-9.5A**										
Virgin Binder Grade	**PG 58-28**										
RAP Content, %	**30**										
Recycling Agent	**No**										
Sample	**JMF**	**Process Tolerance**[a]	**Set 1**		**Set 2**		**Set 3**		**Set 4**		**Set Average**	
Property			**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.60	±0.3	5.52	5.76	5.50	5.71	5.54	5.72	5.51	5.30	5.52	5.57
Rice SG (G_{mm})	2.650	-	2.652	2.652	2.652	2.665	2.662	2.657	2.656	2.661	2.656	2.659
VTM, %	3.9	2-5	3.7	3.1	3.7	4.0	3.5	3.4	3.9	3.7	3.7	3.6
VMA, %	17.6	Min. 16	17.3	17.4	17.3	18.1	17.2	17.6	17.5	16.8	17.3	17.4
VFA, %	78.0	70-85	79.0	82.3	79.0	77.8	80.0	80.6	78.0	77.8	79.0	79.5
FA Ratio	1.00	0.7-1.3	1.10	1.26	1.10	**2.08**	1.10	1.11	1.20	1.27	1.13	**1.43**
Mixture Bulk SG (G_{mb})	-	-	2.553	2.570	2.554	2.558	2.570	2.566	2.552	2.561	2.557	2.564
Aggregate Effective SG (G_{se})	-	-	2.921	2.934	2.920	2.948	2.935	2.939	2.925	2.920	2.925	2.933
Aggregate Bulk SG (G_{sb})	-	-	2.918	2.931	2.917	2.945	2.932	2.938	2.922	2.917	2.922	2.930
Absorbed Asphalt Content (P_{ba}), %	-	-	0.04	0.04	0.04	0.04	0.04	0.01	0.04	0.04	0.04	0.03
Effective Asphalt Content (P_{be}), %	-	-	5.48	5.72	5.46	5.67	5.50	5.70	5.47	5.27	5.48	5.54
Gradation, percent passing												
½ in (12.5 mm)	100	±4.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in (9.5 mm)	95	±4.0	96.0	95.7	96.0	96.6	97.0	96.6	97.0	96.7	96.5	96.4
No. 4 (4.75 mm)	61	±4.0	61.0	61.5	58.0	61.6	61.0	61.8	63.0	62.4	60.8	61.8
No. 8 (2.36 mm)	40	±4.0	40.0	40.0	37.0	41.1	39.0	39.3	41.0	40.6	39.3	40.3
No. 16 (1.18 mm)	-	-	28.0	-	26.0	30.9	28.0	28.0	28.0	29.2	27.5	32.0
No. 30 (600 μm)	20	±3.0	20.0	21.7	19.0	24.2	20.0	20.2	21.0	21.2	20.0	21.8
No. 50 (300 μm)	-	±2.5	14.0	15.4	13.0	18.8	14.0	14.2	14.0	14.9	13.8	15.8
No. 100 (150 μm)	-	-	9.0	10.2	9.0	14.5	9.0	9.4	9.0	9.9	9.0	11.0
No. 200 (75 μm)	6	±1.0	6.1	**7.2**	6.0	**11.8**	6.3	6.3	6.3	6.7	6.2	**8.0**

Red text indicates value that did not meet allowable tolerance. PG = performance grade; 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, - = not available.

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

Table 7. Volumetric Properties and Gradations for Mixture A-III

Mixture	**A-III**							
Mixture Type	**SM-9.5A**							
Virgin Binder Grade	**PG 64S-22**							
RAP Content, %	**40**							
Recycling Agent	**No**							
Sample	**JMF**	**Process Tolerance[a]**	**Set 1**		**Set 2**		**Set Average**	
Property			**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.50	±0.3	5.52	5.76	5.50	5.74	5.51	5.75
Rice SG (G_{mm})	2.655	-	2.664	2.661	2.654	2.654	2.659	2.657
VTM, %	2.8	2-5	3.5	3.1	2.8	2.8	3.2	3.0
VMA, %	16.7	Min. 16	17.3	17.5	16.5	17.1	16.9	17.3
VFA, %	82.0	70-85	80.0	82.0	83.0	83.6	81.5	82.8
FA Ratio	1.10	0.7-1.3	1.20	1.16	1.30	1.16	1.25	1.16
Mixture Bulk SG (G_{mb})	-	-	2.570	2.577	2.580	2.580	2.575	2.578
Aggregate Effective SG (G_{se})	-	-	2.936	2.946	2.922	2.936	2.929	2.941
Aggregate Bulk SG (G_{sb})	-	-	2.935	2.943	2.921	2.933	2.928	2.938
Absorbed Asphalt Content (P_{ba}), %	-	-	0.01	0.04	0.01	0.04	0.01	0.04
Effective Asphalt Content (P_{be}), %	-	-	5.51	5.72	5.49	5.70	5.5	5.7
Gradation, percent passing								
½ in (12.5 mm)	100	±5.7	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in (9.5 mm)	96	±5.7	97.0	96.3	98.0	96.6	97.5	96.4
No. 4 (4.75 mm)	65	±5.7	66.0	66.1	66.0	64.0	66.0	65.1
No. 8 (2.36 mm)	43	±5.7	44.0	44.1	44.0	42.3	44.0	43.2
No. 16 (1.18 mm)	-	-	31.0	31.7	31.0	30.2	31.0	31.0
No. 30 (600 µm)	22	±4.3	23.0	23.3	23.0	22.1	23.0	22.7
No. 50 (300 µm)	-	±3.6	16.0	16.0	16.0	15.3	16.0	15.7
No. 100 (150 µm)	-	-	10.0	10.0	10.0	9.9	10.0	10.0
No. 200 (75 µm)	6.2	±1.4	6.5	6.6	7.0	6.6	6.8	6.6

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; - = not available.

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

Table 8. Volumetric Properties and Gradations for Mixture A-IV

Mixture	**A-IV**											
Mixture Type	**SM-9.5A**											
Virgin Binder Grade	**PG 58-28**											
RAP Content, %	**40**											
Recycling Agent	**No**											
Sample	**JMF**	**Process Tolerance**[a]	**Set 1**		**Set 2**		**Set 3**		**Set 4**		**Set Average**	
Property			**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.50	±0.3	5.28	5.75	5.50	5.45	5.31	**5.97**	**5.19**	5.60	5.32	5.69
Rice SG (G_{mm})	2.655	-	2.649	2.653	2.661	2.663	2.655	2.667	2.665	2.662	2.658	2.661
VTM, %	2.8	2-5	2.9	3.1	3.5	4.2	3.5	3.6	3.7	3.4	3.4	3.6
VMA, %	16.7	Min. 16	16.1	17.4	17.2	17.7	16.7	18.4	16.6	17.4	16.7	17.7
VFA, %	83.0	70-85	82.0	82.2	80.0	76.0	79.0	80.6	78.0	80.4	79.8	79.8
FA Ratio	1.10	0.7-1.3	1.20	1.16	-	1.23	1.30	1.14	-	1.19	1.25	1.18
Mixture Bulk SG (G_{mb})	-	-	2.571	2.570	-	2.550	2.562	2.572	-	2.572	2.567	2.566
Aggregate Effective SG (G_{se})	-	-	2.903	2.935	-	2.931	2.913	2.966	-	2.939	2.908	2.943
Aggregate Bulk SG (G_{sb})	-	-	2.902	2.934	-	2.930	2.912	2.965	-	2.938	2.907	2.942
Absorbed Asphalt Content (P_{ba}), %	-	-	0.01	0.01	-	0.01	0.01	0.01	-	0.01	0.01	0.01
Effective Asphalt Content (P_{be}), %	-	-	5.27	5.74	-	5.43	5.30	5.95	-	5.59	5.29	5.68
Gradation, percent passing												
½ in (12.5 mm)	100	±4.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in (9.5 mm)	96	±4.0	97.0	97.7	96.0	96.6	97.0	96.6	96.0	96.5	96.5	96.9
No. 4 (4.75 mm)	65	±4.0	67.0	67.5	62.0	63.9	63.0	64.5	63.0	64.9	63.8	65.2
No. 8 (2.36 mm)	43	±4.0	45.0	45.2	42.0	41.5	42.0	42.3	42.0	42.5	42.8	42.9
No. 16 (1.18 mm)	-	-	31.0	32.2	-	29.6	30.0	30.2	-	30.4	30.5	30.6
No. 30 (600 µm)	22	±3.0	22.0	23.1	21.0	21.7	22.0	21.7	21.0	22.1	21.5	22.1
No. 50 (300 µm)	-	±2.5	15.0	15.6	-	15.2	15.0	15.0	-	15.3	15.0	15.3
No. 100 (150 µm)	-	-	10.0	10.0	-	10.0	10.0	10.0	-	10.0	10.0	10.0
No. 200 (75 µm)	6.2	±1.0	6.5	6.6	6.4	6.7	6.8	6.8	6.2	6.6	6.5	6.7

Red text indicates value that did not meet allowable 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.

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

Table 9. Volumetric Properties and Gradations for Mixture A-V

Mixture	**A-V**										
Mixture Type	**SM-9.5A with Recycling Agent**										
Virgin Binder Grade	**PG 64S-22**										
RAP Content, %	**40**										
Recycling Agent	**Yes**										
Sample	**JMF**	**Process Tolerance**[a]	**Set 1**		**Set 2**		**Set 3**		**Set 4**		**Set Average**	
Property			**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.50	±0.3	5.57	5.73	5.49	5.61	5.37	5.49	5.52	5.70	5.49	5.63
Rice SG (G_{mm})	2.655	-	2.650	2.647	2.663	2.648	2.645	2.656	2.653	2.662	2.653	2.653
VTM, %	2.8	2-5	2.5	2.1	3.2	2.7	**1.9**	2.3	2.8	3.1	2.6	2.5
VMA, %	16.7	Min. 16	16.5	16.5	16.9	16.7	**15.4**	16.1	16.6	17.4	16.4	16.6
VFA, %	82.0	70-85	85.0	**87.3**	81.0	83.9	**88.0**	**85.9**	83.0	82.1	84.3	84.8
FA Ratio	1.10	0.7-1.3	1.10	1.19	1.10	1.13	1.30	1.24	1.20	0.95	1.18	1.13
Mixture Bulk SG (G_{mb})	-	-	2.584	2.591	2.579	2.577	2.594	2.596	2.578	2.580	2.584	2.586
Aggregate Effective SG (G_{se})	-	-	2.922	2.926	2.933	2.921	2.903	2.924	2.922	2.944	2.920	2.929
Aggregate Bulk SG (G_{sb})	-	-	2.921	2.925	2.932	2.920	2.902	2.923	2.921	2.943	2.919	2.928
Absorbed Asphalt Content (P_{ba}), %	-	-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Effective Asphalt Content (P_{be}), %	-	-	5.57	5.71	5.48	5.60	5.36	5.47	5.51	5.69	5.48	5.62
Gradation, percent passing												
½ in (12.5 mm)	100	±4.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8 in (9.5 mm)	96	±4.0	96.0	97.0	97.0	95.5	97.0	96.4	96.0	96.6	96.5	96.3
No. 4 (4.75 mm)	65	±4.0	65.0	65.3	65.0	63.7	65.0	63.1	65.0	64.2	65.0	64.1
No. 8 (2.36 mm)	43	±4.0	43.0	43.2	43.0	42.3	44.0	42.5	44.0	42.3	43.5	42.6
No. 16 (1.18 mm)	-	-	30.0	31.0	31.0	30.5	32.0	30.7	31.0	30.0	31.0	30.6
No. 30 (600 µm)	22	±3.0	22.0	22.5	22.0	22.1	23.0	22.3	22.0	21.4	22.3	22.1
No. 50 (300 µm)	-	±2.5	15.0	15.6	15.0	15.1	16.0	15.6	15.0	14.3	15.3	15.2
No. 100 (150 µm)	-	-	10.0	10.2	9.0	9.6	11.0	10.4	10.0	8.8	10.0	9.8
No. 200 (75 µm)	6.2	±1.0	6.3	6.8	6.2	6.3	7.2	6.8	6.5	5.4	6.6	6.3

Red text indicates value that did not meet allowable 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.

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

Cantabro Test Results

Figure 6 presents the average Cantabro mass loss results for Mixture A-I. The red dashed line shows the current BMD special provision limit for Cantabro mass loss, an average maximum value of 7.5%. It can be seen that the design and production (both plant and reheat) results met the performance requirements except for reheat Set 1 whose mass loss was statistically and significantly higher than that of the other sets. The reason for such a high Cantabro mass loss for this set is unknown, as volumetric properties did not indicate any significant deviation from the design of other sets. The design Cantabro mass loss result was statistically similar to the results from the plant sets but statistically differed from the results of any of the reheat sets. The results of the plant sets (Sets 1 and 3) were statistically similar, as were the results among the reheat sets with the exception of reheat Set 1. In addition, the results of the plant and reheat Set 3 were statistically similar, which was not the case for the results from the Set 1 pair. The coefficient of variation (COV) for the Cantabro mass loss for this mixture ranged from 1.1% to 35%, with an average COV of 11.4%.

The average Cantabro mass loss results for Mixture A-II are shown in Figure 7. The mix design set with an average Cantabro mass loss of 8.8% did not meet the performance criteria, whereas the plant and reheat sets did. The analysis of variance results indicated that the design test results statistically differed from all plant and reheat test results. The plant results for Sets 1 and 3 were statistically similar. The reheat results formed two statistically similar groups. The results from reheat Sets 1 and 2 were statistically similar, as were the results from reheat Sets 3 and 4. The plant and reheat results for Set 3 were also statistically similar. For Set 1, the plant results were statistically higher than the reheat results. The COV for the Cantabro mass loss for this mixture ranged from 2.4% to 20.1%, with an average COV of 10.7%.

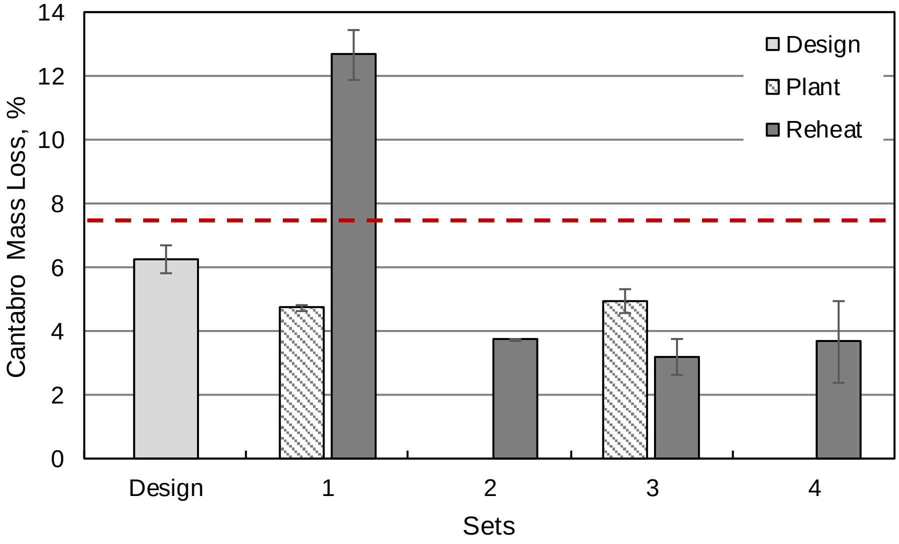

Figure 6. Cantabro Mass Loss Results for Mixture A-I. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

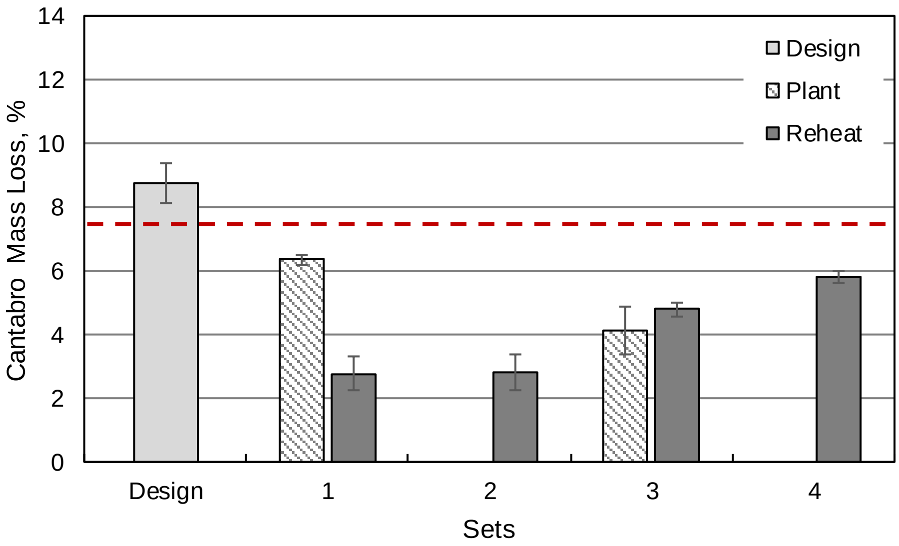

Figure 7. Cantabro Mass Loss Results for Mixture A-II. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Figure 8 shows the average Cantabro mass loss results for Mixture A-III. No plant sets for the Cantabro test were available for this mixture. The results indicated that the design results did not meet the performance criteria whereas the reheat results did. In addition, the results of the sets were significantly different. The average COV for Cantabro mass loss for this mixture was 8.7%.

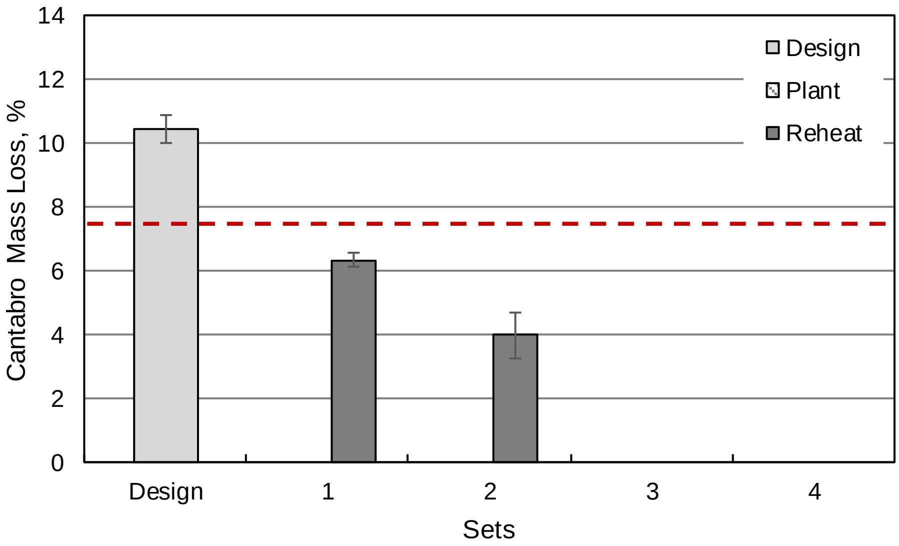

Figure 8. Cantabro Mass Loss Results for Mixture A-III. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

The average Cantabro mass loss results for Mixture A-IV are presented in Figure 9. The results show that this mixture satisfied the performance criteria during design and production with the exception of reheat Sets 2 and 4. The statistical analysis showed that the design results statistically differed from both the plant and the reheat results. The plant results for Sets 1 and 3 were statistically similar, as were the plant and reheat results for Set 3. No other statistical similarities were observed. The average COV for Cantabro mass loss values for this mixture was 5.8%, with a maximum observed COV of 10%.

Figure 10 shows the average Cantabro mass loss results for Mixture A-V. All sample sets satisfied the performance criteria except for reheat Set 4. The design results statistically differed from the results of plant Set 1 and reheat Set 4. No statistical differences were found among the results of the plant sets. This was also the case for the reheat sets with the exception of reheat Set 4. No statistical differences existed between the results of the plant and reheat sets. The COV for this mixture ranged from 4.8% to 22.7%, with an average COV of 13.6%.

The Cantabro mass loss results for Mixtures A-I through A-V indicated that design test results for two of the five mixtures (Mixtures A-II and A-III) did not pass the performance requirements, based on one set of three replicate design specimens. These two mixtures were not BMD designs, so this was not unexpected. For the plant (non-reheat) testing, each of Mixtures A-I, A-II, A-IV, and A-V had two plant sets of three replicate specimens from production (plant test results for Mixture A-III were not available). None of these mixtures had failing performance results in the plant specimen sets, nor did the plant set results statistically differ from each other for any of the mixtures. However, the design results statistically differed from the results of the plant sets for Mixtures A-II, A-III, and A-IV. The exceptions were Mixture A-I, wherein all design and plant results were not statistically different, and Mixture A-V, in which the design results significantly differed from one (Set 1) of the two sets of plant results.

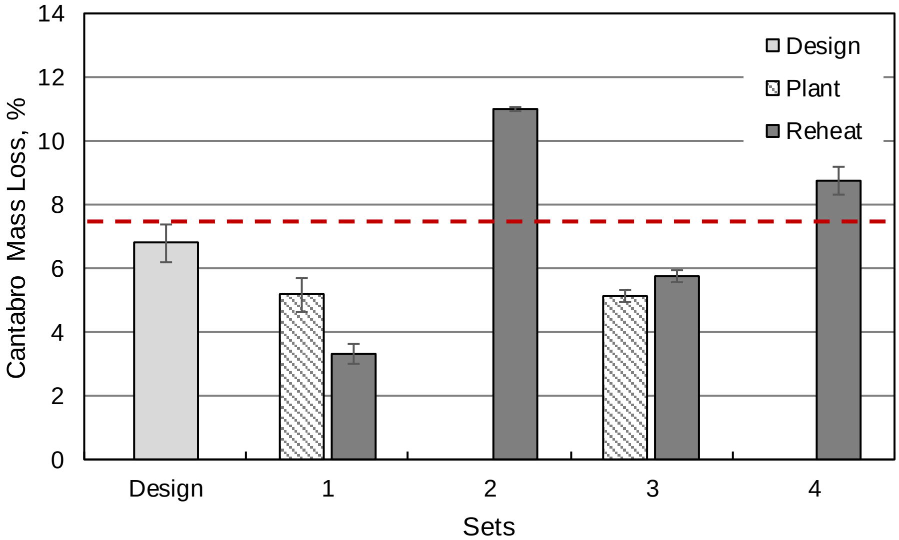

Figure 9. Cantabro Mass Loss Results for Mixture A-IV. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

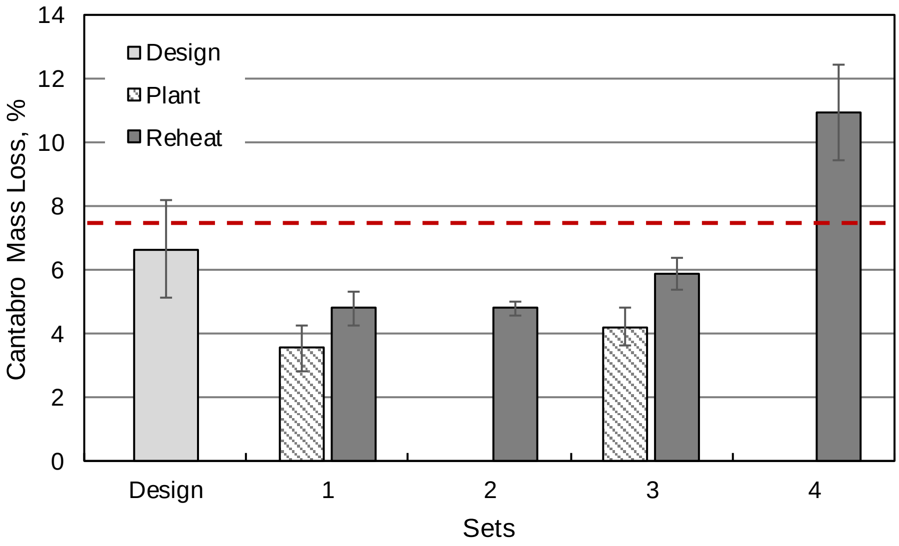

Figure 10. Cantabro Mass Loss Results for Mixture A-V. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Cantabro reheat testing for each mixture consisted of four sets of three replicate specimens sampled throughout production with the exception of Mixture A-III, from which only two samples were collected. The two mixtures failing during design testing (Mixtures A-II and A-III) had passing results from all reheat sets sampled throughout the production. However, for the other three mixtures (A-I, A-IV, and A-V) that showed passing design results, each had one or two failing results among the four reheat sets sampled throughout the production. The results from the reheat sets indicated statistical differences among the sets of each mixture sampled throughout production. Pairwise comparison of the reheated sets showed that one or two of four sets per mixture were statistically different, but the remaining sets were statistically similar. For all mixtures, design results statistically differed from all results of the reheat sets except for Mixture A-V, for which the design and reheat Set 4 results were statistically similar. There were also statistically significant differences between the plant and reheat sets. One of two sets of plant-reheat comparisons was significantly different for Mixtures A-I, A-II, and A-IV, whereas no statistical differences between the results of the plant and reheat sets were found for Mixture A-V.

In summary, given that the individual reheat sets throughout production consisted of failing and passing test results for several mixtures and statistically differed from each other, multiple tests for each lot will be needed in order to use an average performance test value against the performance criteria for acceptance or BMD quality control and assurance practices for the Cantabro test. The differences between laboratory mix design and plant production such as differences in aging conditions, as well as the inherent variability during plant production and associated changes in volumetric properties, provide additional cause for multiple sample measurements for this test. The mixture reheating produced mixed results for the Cantabro mass loss; no consistent trend in mass loss was found between the non-reheat and reheat processes. This finding may result in a need for a different performance criterion for the plant (non-reheat) mixtures. Finally, the average COV for all Cantabro test results performed on Mixtures A-I through A-V was 10.1%, with a standard deviation of 8%. Although this average COV is a promising indication for a test method to be used in quality measurement practices, it is a precision estimate of the VTRC laboratory and not the precision estimates (i.e., single operator and multi-laboratory) of the Cantabro test. Thus, the precision estimates of this test need to be determined for proper implementation of the BMD concept.

Comparisons Between Mixtures

Figure 11 shows the Cantabro mass loss results of Mixtures A-I through A-V averaged from the results of the design, plant, and reheat set tests. The design results are based on one set of test specimens consisting of three replicates. The plant results are the averages of two sets sampled throughout production. Likewise, the reheat results are the averages of four sets sampled throughout production with the exception of Mixture A-III, which only had two sample sets. The standard deviation of each mixture was calculated from the averages of these sets.

Based on the results shown in Figure 11, the following observations were made from the averaged design Cantabro mass loss values of Mixtures A-I through A-V:

- Of the five mixtures, only Mixture A-II (30% RAP with PG 58-28) and Mixture A-III (40% RAP with PG 64S-22) did not satisfy the performance criterion for Cantabro durability. Neither of these mixtures was designed to meet BMD requirements.

- The mixture with the lowest Cantabro mass loss was Mixture A-I (30% RAP with PG 64S-22). This mixture met volumetric and gradation requirements but was not designed to meet BMD requirements.

- The use of a softer binder did not result in an improved performance for Mixture A-II (30% RAP with PG 58-28) as compared to Mixture A-I (30% RAP with PG 64S-22).

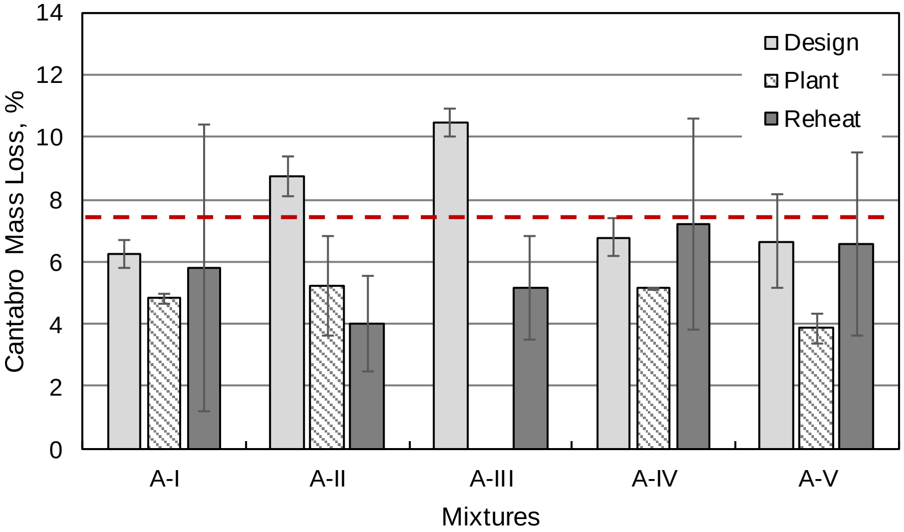

Figure 11. Average Cantabro Mass Loss for Mixtures A-I Through A-V. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

- In fact, despite the softer binder, the mixture failed to meet the Cantabro performance criterion during design testing.

- However, the use of a softer binder improved the performance for Mixture A-IV (40% RAP with PG 58-28) compared to Mixture A-III (40% RAP with PG 64S-22). This improvement was statistically and practically significant as Mixture A-IV met the Cantabro mass loss criterion. Mixture A-IV was designed to meet BMD criteria.

- Similarly, the use of a recycling agent to Mixture A-V (40% RAP with recycling agent) statistically and practically improved the performance compared to Mixture A-III (40% RAP with PG 64S-22). Mixture A-V was designed to meet BMD criteria.

- Mixture A-V (40% RAP with a recycling agent) had a slightly lower Cantabro mass loss than Mixture A-IV (40% RAP with PG 58-28), although the difference was not statistically significant.

- Mixture A-I (30% RAP with PG 64S-22) statistically had the same Cantabro mass loss as Mixture A-IV (40% RAP with PG 58-28) and Mixture A-V (40% RAP with a recycling agent); all three mixtures met the Cantabro mass loss criterion. This indicated that these 40% RAP mixtures containing a softer binder or a recycling agent should have a performance that is equal to the performance of their counterpart 30% RAP mixtures in terms of durability as measured by the laboratory Cantabro test.

Based on the results shown in Figure 11, the following observations were made from the averaged plant Cantabro test results of Mixtures A-I, A-II, A-IV, and A-V:

- All four mixtures met the performance criterion for Cantabro durability.

- There were no statistically significant differences among plant results for these mixtures. This indicated that these 40% RAP mixtures containing a softer binder or recycling agent should have a performance that is equal to the performance of the 30% RAP mixtures containing standard or softer binder in terms of durability as measured by the laboratory Cantabro test.

- Mixture A-V (40% RAP with recycling agent) had the lowest Cantabro mass loss, although all mixtures were statistically similar and met the Cantabro performance criterion.

- The use of a softer binder did not result in improved performance for Mixture A-II (30% RAP with PG 58-28) as compared to Mixture A-I (30% RAP with PG 64S-22), although both mixtures were statistically similar and met the Cantabro performance criterion. The results from Mixture A-III were not available for comparison to its counterpart mixtures (A-IV and A-V).

- Mixture A-V (40% RAP with a recycling agent) showed improved performance compared to Mixture A-IV (40% RAP with PG 58-22), although both mixtures met the Cantabro performance criterion and were statistically similar.

Based on the results shown in Figure 11, the following observations were made from the averaged reheat Cantabro mass loss testing of Mixtures A-I though A-V:

- All five mixtures satisfied the performance criteria for Cantabro durability.

- There were no statistically significant differences among the mixtures. This was partly due to high variations in the results across sets sampled throughout production. Nevertheless, this indicated that these 40% RAP mixtures containing a standard binder, softer binder, or recycling agent should have a performance that is equal to the performance of their counterpart 30% RAP mixtures in terms of durability as measured by the laboratory Cantabro test.

- Despite the statistical similarity and passing performance of all mixtures, the mixture with the lowest Cantabro mass loss was Mixture A-II (30% RAP with PG 58-28).

- The use of a softer binder resulted in improved performance for Mixture A-II (30% RAP with PG 58-28) compared to Mixture A-I (30% RAP with PG 64S-22), although both mixtures were statistically similar and met the Cantabro performance criterion. However, this was not the case for Mixture A-IV (40% RAP with PG 58-28) in comparison to Mixture A-III (40% RAP with PG 64S-22), although again, both mixtures met the Cantabro performance criterion and were statistically similar.

- The use of a recycling agent in Mixture A-V (40% RAP with a recycling agent) did not improve performance compared to Mixture A-III (40% RAP with PG 64S-22). However, Mixture A-V did have improved performance compared to its counterpart mixture containing a softer binder, Mixture A-IV (40% RAP with PG 58-28). All three mixtures were statistically similar and met the Cantabro performance criterion.

- Overall, for a given mixture, there were no statistical differences between the design and reheat Cantabro test results and the plant and reheat Cantabro test results. Despite the statistical similarity, for a given mixture, the reheat average mass loss value was less than or similar to the design mass loss value and higher than the plant average mass loss value.

It was seen that 40% RAP mixtures containing a standard binder, softer binder, or recycling agent should have a performance that is equal to the performance of their counterpart 30% RAP mixtures in terms of durability as measured by the laboratory Cantabro test. It is also evident that the use of the BMD concept can successfully allow inclusion of these materials to provide improved mixture durability. However, the long-term laboratory and field performance of these mixtures should be evaluated to confirm these findings.

IDT-CT Test Results

Figure 12 shows the average CT index values for Mixture A-I. The dashed red line indicated an average minimum CT index value of 70 as required by the current BMD special provision. As shown, all sets exceeded the performance criteria with the exception of reheat Set 4, which had an average CT index value of 69. The CT index results for the design and reheat sets were statistically similar but significantly lower than the CT index results for the plant sets. This was likely attributable to the effects of reheating. Although the plant and reheat results for Set 1 and Set 3 each differed significantly with respect to each other, the two plant sets and four reheat sets of CT index results remained statistically similar throughout production. The average COV for the CT index for this mixture was 16.4%. The design and reheat Set 4 test results exceeded the single operator precision of 20.7% established as part of a previous study based on five replicate measurements (Diefenderfer et al., 2020).

Figure 13 presents the average CT index values for Mixture A-II. The design results for this mixture were not available. It can be seen from the figure that all of the plant and reheat sets exceeded the performance criterion for the CT index. The results for the plant sets were statistically higher than the results for the reheat sets, likely an indication of the effect of reheating. No statistical differences were found among the plant results and among the reheat results throughout production. The average COV for the reheat sets was 13.3%. The average COV was 33.5% for the plant sets, which was significantly higher than the single-operator precision of 20.7%.

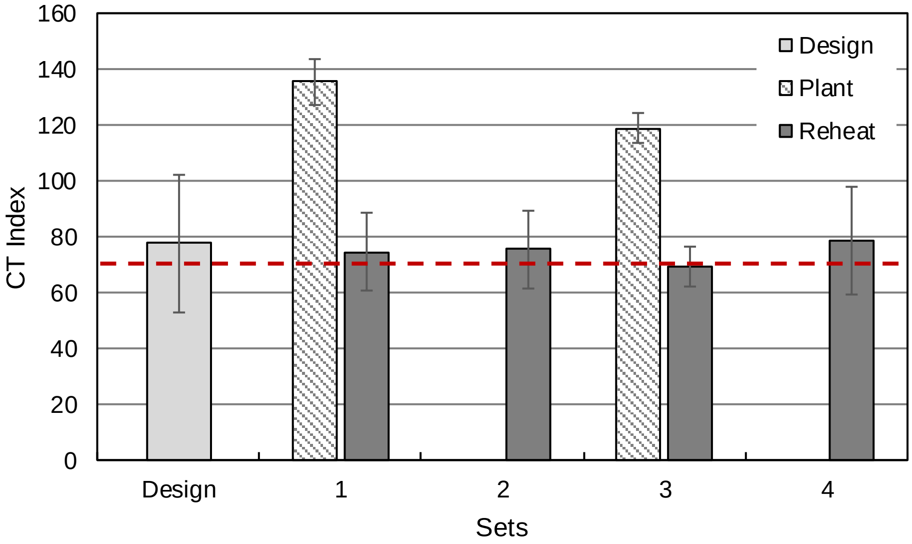

Figure 12. CT Index Results for Mixture A-I. Values are the average of four to six replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

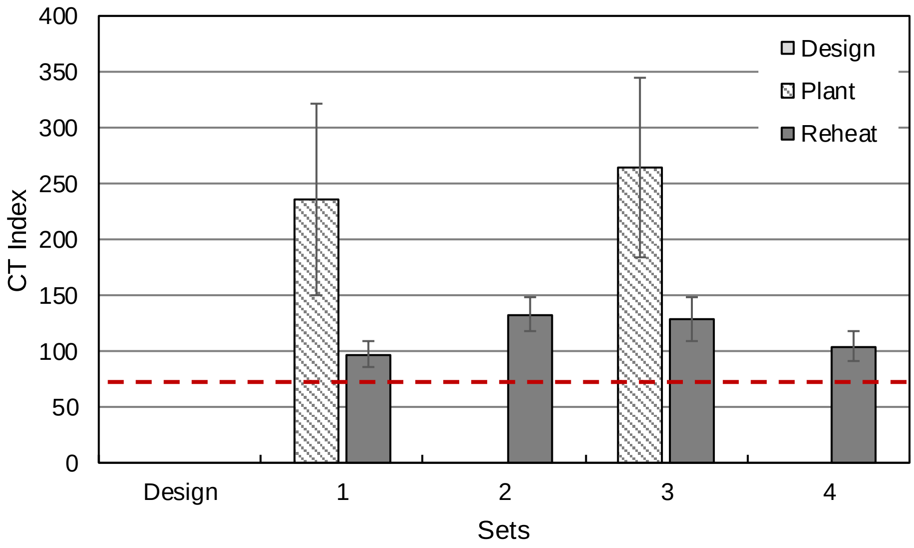

Figure 13. CT Index Results for Mixture A-II. Values are the average of four to six replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Figure 14 displays the average CT index values for Mixture A-III. Two reheat sets and one plant set were available for testing for this mixture. The plant and reheat results from Set 2 satisfied the performance criteria. Although reheat Set 1 failed to meet the CT index performance criterion, it was not statistically different than reheat Set 2, which passed the criteria. The CT index for the plant set was statistically higher than the CT index values for the reheat sets, indicating the potential effect of reheating on the test results. The average COV for the reheat sets was 16.7% and that for the plant set was 30.9%, exceeding the single-operator precision of 20.7%.

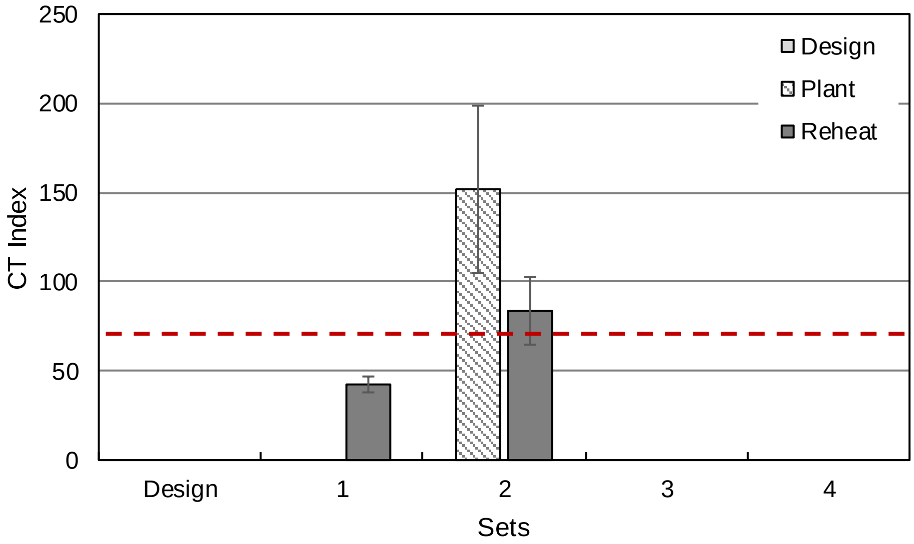

Figure 14. CT Index Results for Mixture A-III. Values are the average of four to six replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Figure 15 shows the average CT index values for Mixture A-IV. As shown, all sets exceeded the minimum CT index limit with the exception of reheat Set 1 and Set 2. All sets were statistically similar. Despite the statistical similarity, the average CT index values for the plant sets were higher than those for the reheat sets, indicating the potential effect of reheating on the test results. The average COV for the CT index for this mixture was 23.9%; all sets exceeded the single-operator precision of 20.7% except for the two plant sets.

The average CT index values for Mixture A-V are presented in Figure 16. All sets passed the CT index performance criterion of 70. The CT index for the design set was statistically similar to the plant and reheat CT index values with the exception of plant Set 1. The CT index values between the reheat sets were also statistically similar, as were the CT index values for the plant sets. There was a significant difference between the Set 1 plant and reheat values; no significant difference was found between the Set 3 plant and reheat values. The average COV for Mixture A-V was 19.5%, with COV values for plant Set 1 (20.8%) and reheat Set 3 (43.4%) exceeding the single-operator precision limit (20.7%).

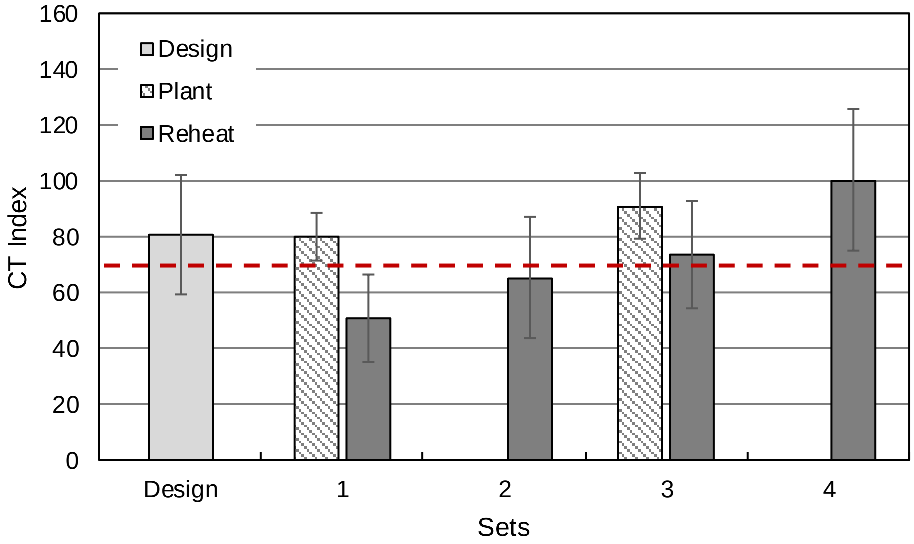

Figure 15. CT Index Results for Mixture A-IV. Values are the average of four to six replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

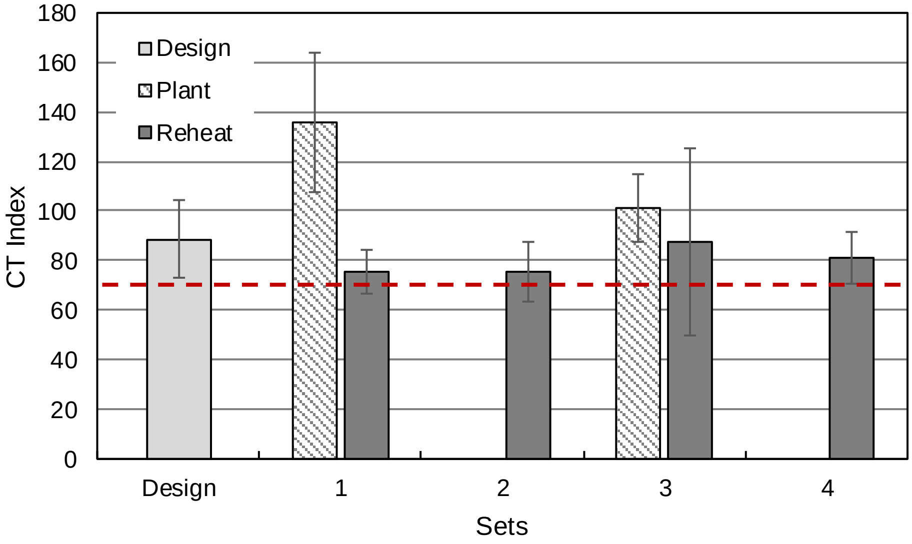

Figure 16. CT Index Results for Mixture A-V. Values are the average four to six replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Mixtures A-I, A-II and A-V had average CT index values for design that met the CT index criterion; Mixtures A-III and A-IV did not have design data available. All five mixtures showed average plant CT index values that met the performance criterion. In addition, the CT index values were not significantly different among each mixture's plant sets during production. Further, there was no statistical difference between CT index values for the design and each plant set for all mixtures except Mixture A-I and Mixture A-V, where the design value and Set 1 plant values were significantly different. This statistical outcome was a result of the high variation in the test results of Mixtures A-I through A-V. Despite the statistical similarity, the CT index values for the plant sets were higher than for the design sets.

Two mixtures (A-II and A-V) had reheat CT index values that met the performance criterion; Mixtures A-I and A-III each had one failing CT index set among the reheat sets, although the failing value for the Mixture A-I reheat Set 3 almost met the criterion, with a value of 69. One mixture, A-IV, had two reheat sets that did not meet the criterion. Mixtures A-I through A-V had 18 reheat sets tested, of which 14 met the CT index criterion. The design CT index values statistically differed from the reheat set values only for Mixture A-V; the difference was between the design value and one reheat set value. Similar to the results for the plant sets, the CT index values among the reheat sets of each mixture did not statistically differ throughout production, although individual failing CT index values were observed among the sets of some mixtures. The effect of reheating on the CT index values was evident. For three mixtures (A-I, A-II, and A-III), the plant set CT index values were all significantly higher than those for the reheat sets. No significant difference was observed for one mixture, A-IV, but the magnitude of the CT index values for the plant sets was larger than for the reheat sets. For the remaining mixture, A-V, plant and reheat values from one set had a significant difference and the other set of plant and reheat values did not; in both cases, the plant CT index values were higher than the reheat CT index values. The average COV for individual sample measurements from Mixtures A-I through A-V was 20.1%, although 43% of the observations did not satisfy the single-operator precision estimate of 20.7% for the CT index.

In summary, given that the individual reheat sets throughout production had failing and passing test results for several mixtures and they statistically differed, multiple tests for each lot will be needed in order to use an average performance test value against the performance criteria for acceptance of asphalt mixtures or BMD quality control and assurance practices for the IDT-CT test. In addition, the differences between laboratory mix design and plant production such as differences in aging conditions, as well as the inherent variability during plant production and associated changes in volumetric properties, support multiple sample measurements for this test.

The plant (non-reheat) mixture testing yielded higher CT index values than for the reheat mixture testing, and a passing CT index during plant testing does not guarantee a passing CT index during reheat testing. This finding may suggest a need for a different performance criterion for the plant (non-reheat) mixtures.

Finally, the average COV for the Producer A mixtures was high. Alternative cracking indices from the IDT-CT test that can provide low variability can be evaluated to overcome the high-variability issue. In a previous study (Seitllari et al., 2020), it was shown that use of the fracture strain tolerance index as a performance indicator resulted in significantly lower variability compared to the CT index while providing the same performance ranking, a better performance discrimination potential of asphalt mixtures, and a high correlation with the CT index.

Comparisons Among Mixtures

Figure 17 presents the average design, plant, and reheat CT index results for Mixtures A-I through A-V. The design results are based on one set of specimens consisting of five replicates. The plant results are the averages of two sets sampled throughout production except for Mixture A-III, which consisted of only one sample set. The reheat results are the averages of four sets sampled throughout production with the exception again of Mixture A-III, which had two sample sets. The standard deviation of each mixture was calculated from the averages of these sample sets.

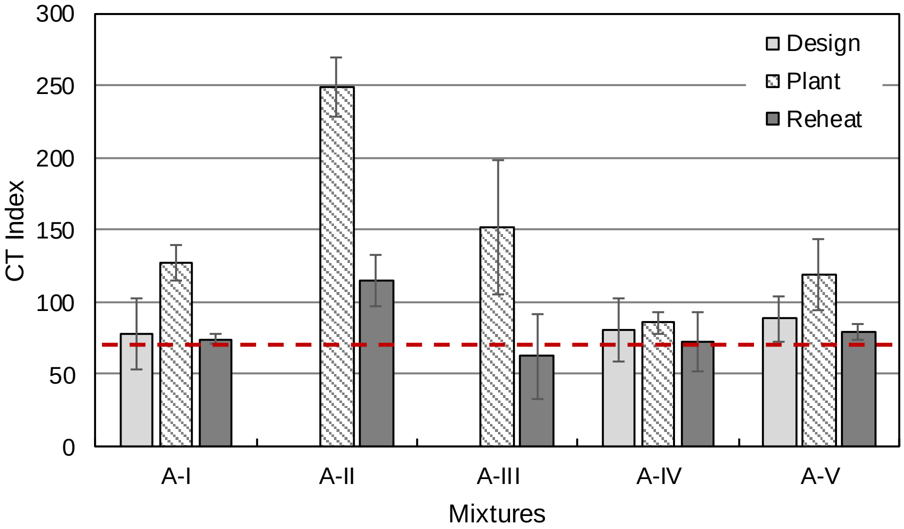

Figure 17. Average CT Index Results for Mixtures A-I Through A-V. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Based on the results presented in Figure 17, the following observations were made from the average design CT index values of Mixtures A-I, A-IV, and A-V:

- All three mixtures had design values that met the performance criterion for cracking. Mixture A-I was not designed to meet BMD criteria, although Mixtures A-IV and A-V were.

- There were no statistically significant differences among the design values for these mixtures. This indicated that no difference in cracking susceptibility was shown at design between the mixture with 30% RAP (Mixture A-I) and the mixtures with 40% RAP (Mixtures A-IV and A-V).

- The mixture with the highest design CT index was Mixture A-V (40% RAP with a recycling agent).

- The use of a recycling agent in Mixture A-V (40% RAP with a recycling agent) showed improved cracking resistance relative to the counterpart mixture containing a softer binder, Mixture A-IV (40% RAP with PG 58-28), although the difference was not significant.

Based on the results presented in Figure 17, the following observations were made from the average plant values of Mixtures A-I through A-V:

- All five mixtures had average plant values that satisfied the CT index performance criterion for cracking.

- There were no statistically significant differences among the mixture plant values except for Mixture A-II (30% RAP with PG 58-28), which significantly differed from the others. This indicated that these 40% RAP mixtures incorporating a standard binder, softer binder, or recycling agent should have a performance that is equal to the performance of their counterpart mixture with 30% RAP and a standard binder in terms of cracking susceptibility as measured by the laboratory IDT-CT test.

- The mixture with the highest CT index was Mixture A-II (30% RAP with PG 58-28).

- The use of a softer binder resulted in a statistically significant improvement in the average plant CT index for Mixture A-II (30% RAP with PG 58-28) compared to Mixture A-I (30% RAP with PG 64S-22).

- Conversely, the use of a softer binder did not improve the performance test results for Mixture A-IV (40% RAP with PG58-28) compared to Mixture A-III (40% RAP with PG 64-22). However, the Mixture A-III test results showed high variability.

- The use of a recycling agent in Mixture A-V (40% RAP with a recycling agent) did not result in an improved performance compared to Mixture A-III (40% RAP with

PG 64-22); however, it did when compared to Mixture A-IV (40% RAP with PG 58-28).

Based on the results shown in Figure 17, the following observations were made from the average reheat CT index values of Mixtures A-I though A-V:

- Of the five mixtures, only the average reheat value for Mixture A-III (40% RAP with PG 6S4-22) failed to meet the performance criterion for cracking.

- Although the average reheat value for Mixture A-III did not meet the performance criterion, there were no statistically significant differences among the mixtures with the exception of Mixture A-II. This indicated that these 40% RAP mixtures using a standard binder, softer binder, or recycling agent should have a performance that is equal to the performance of the counterpart mixture with 30% RAP using a standard binder in terms of cracking susceptibility as measured by the laboratory IDT-CT test.

- The mixture with the highest reheat CT index was Mixture A-II (30% RAP with PG 58-28).

- The use of a softer binder resulted in a statistically significant improved reheat performance for Mixture A-II (30% RAP with PG 58-28) as compared to Mixture A-I (30% RAP with PG 64S-22). The improvement in reheat value from the use of a softer binder was also seen when Mixture A-IV (40% RAP with PG 58-28) was compared to Mixture A-III (40% RAP with PG 64S-22). This improvement in reheat value was practically significant, as Mixture A-IV met the CT index criterion and Mixture A-III did not.

- The use of a recycling agent in Mixture A-V (40% RAP with a recycling agent) improved the reheat performance compared to Mixture A-III (40% RAP with PG 64S-22), which was practically significant, as Mixture A-V met the CT index criterion. The use of a recycling agent also resulted in improved reheat performance over that of the counterpart mixture with a softer binder, Mixture A-IV (40% RAP with PG 58-28).

For a given mixture, no significant differences were found between the average reheat and design values; however, the average reheat and plant values for some of the mixtures were significantly different. In addition, the average plant CT index values were higher than the average reheat CT index values. Further, Mixture A-III had an average plant CT index value that met the performance criterion but an average reheat CT index value that did not. This observation and the findings indicated that further evaluation of the effects of conditioning or aging is necessary. In addition, the findings suggested that consideration of different CT index performance criteria may be justified related to the various mixture aging conditions during design and production, although further evaluation of additional mixtures is necessary.

It was seen that these 40% RAP mixtures containing a standard binder, softer binder, or recycling agent can have a performance that is equal to the performance of their counterpart 30%

RAP mixtures in terms of cracking as measured by the laboratory IDT-CT test. It is also evident that the use of the BMD concept can successfully allow inclusion of these materials to provide improved mixture cracking performance. However, the long-term laboratory and field performance of these mixtures should be evaluated to confirm these findings.

APA Rut Test Results

Figure 18 presents the average rut depths for Mixture A-I. The red dashed line indicates the current BMD special provision limit requirement for the APA test, an average maximum value of 8 mm. None of the Mixture A-I sets failed to meet the APA test criterion. Statistical analysis indicated no significant differences among the set values. The COV for this test for this mixture ranged from 2.5% to 23.8%, with an average COV of 9.7%.

The average rut depths for Mixture A-II are presented in Figure 19. Rut depths for the plant and reheat sets for this mixture were below the maximum performance limit. Statistical analysis indicated no differences among the plant set values; however, statistical differences were found among the reheat sets. Rut depths for reheat Sets 1 and 3 were statistically similar, but rut depths for reheat Sets 2 and 4 were significantly different. The rut depths between the pairs of plant and reheat sets were statistically similar with the exception of the Set 2 plant and reheat values. The COV for this mixture ranged from 5.1% to 35.6%, with an average COV of 14.7%.

Figure 20 presents the average rut depths for Mixture A-III. Two reheat sets and one plant set were available for this mixture. All sets had a rut depth less than the maximum criterion. The analysis of variance indicated no significant differences among the sets. The average COV was 4.8% for this mixture.

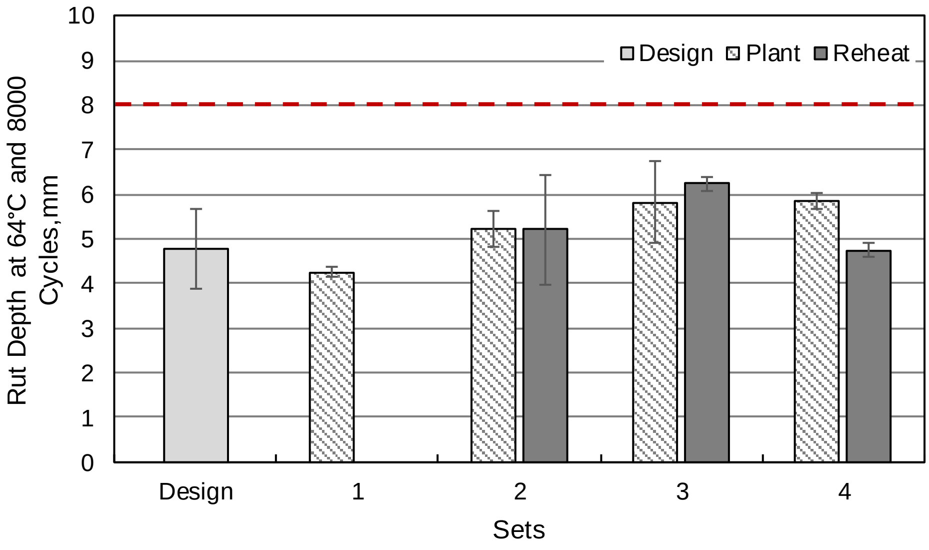

Figure 18. APA Rut Depths for Mixture A-I. Values are the average of two sets of two replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

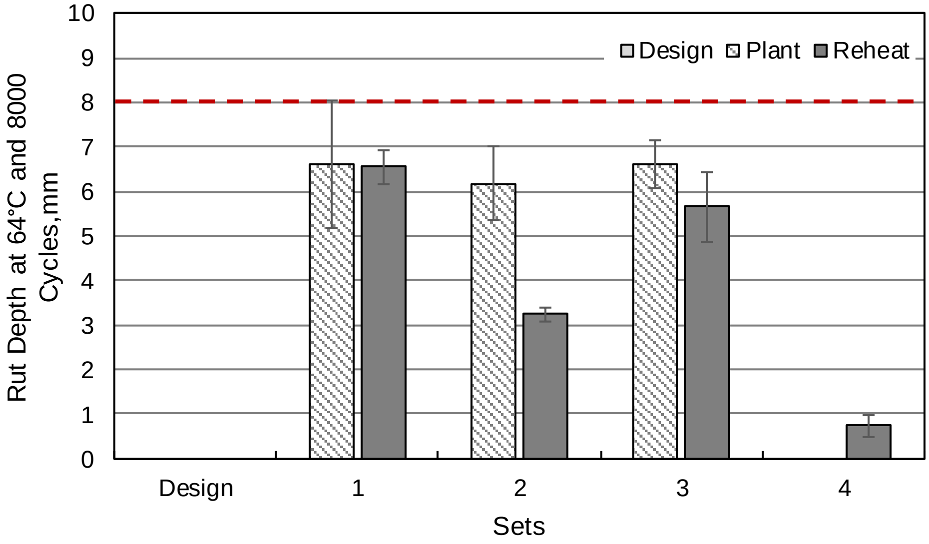

Figure 19. APA Rut Depths for Mixture A-II. Values are the average of two sets of two replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

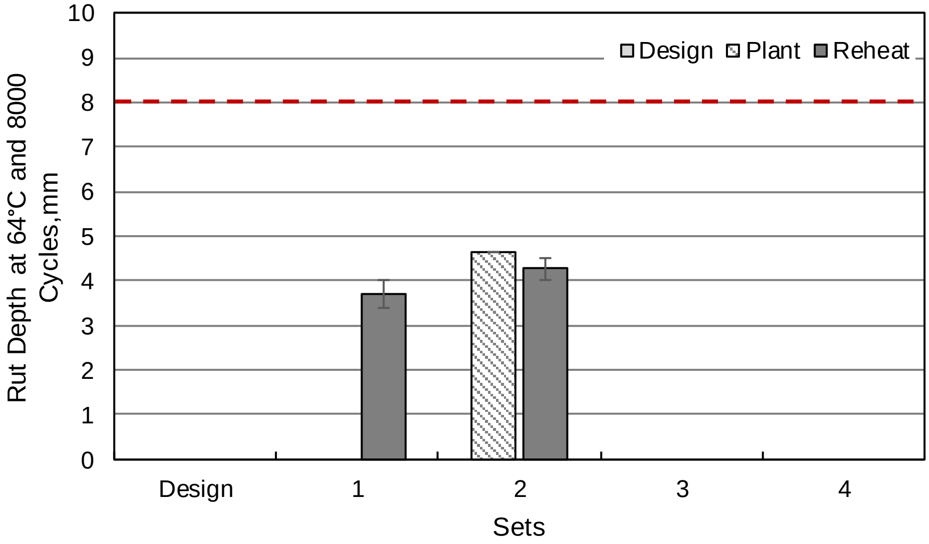

Figure 20. APA Rut Depths for Mixture A-III. Values are the average of two sets of two. I-bars indicate ±1 standard deviation. Red dashed = BMD special provision limit; BMD = balanced mix design.

The average rut depths for Mixture A-IV are shown in Figure 21. All sets had rut depths that met the performance criterion. The design results were statistically similar to the results of the plant and reheat sets except reheat Set 1. The results of the plant sets did not significantly differ; neither did the results of the reheat sets. The pairwise comparison of the rut depths between the plant and reheat sets indicated a statistical difference for the Set 1 plant and reheat pair only. The plant set values were higher than the reheat set values, indicating the potential effect of reheating on the results. The COV for this mixture ranged from 0.3% to 36.5%, with an average COV of 15.2%.

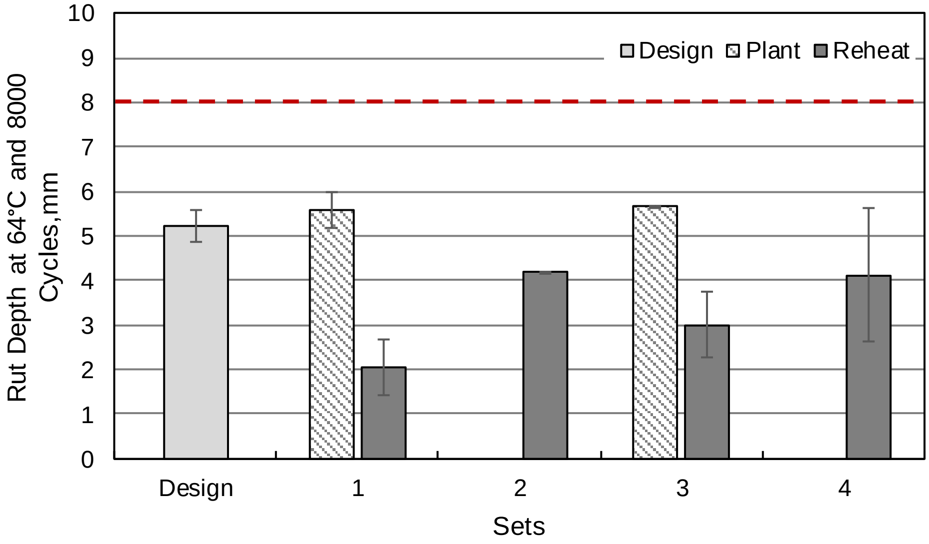

Figure 21. APA Rut Depths for Mixture A-IV. Values are the average of two sets of two replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Figure 22 shows the average rut depths for Mixture A-V. All sets (design, plant, and reheat) of this mixture satisfied the performance criterion. The analysis of variance results indicated statistical similarity among all sets. The COV for this mixture ranged from 0.4% to 20.5%, with an average COV of 7%. Mixtures A-I, A-IV, and A-V had average design rut depth values that were lower than the 8 mm performance criterion; Mixtures A-II and A-III did not have design results available. Average plant rut depth values were available for all five mixtures, and all results met the APA performance criterion. The rut depths were not significantly different among each mixture's plant sets throughout production. In addition, the rut depths from design testing were not significantly different from the rut depths from the plant sets. In general, although not significantly different, the plant rut depths were slightly higher than the design rut depths.

All reheat sets from all mixtures met the performance criterion. For Mixtures A-I, A-IV, and A-V, there were no statistical differences between rut depth values for the design and each reheat set; this was not the case for Mixture A-IV, where the design and reheat Set 1 values were significantly different. Statistically significant differences existed among the reheat sets only for Mixture A-II. The differences between the pairs of plant and reheat sets were statistically significant for only 2 of 11 sets: Mixture A-II Set 2, and Mixture A-IV Set 1. The rut depths of the plant sets for 9 of the 11 pairs were slightly higher or nearly equivalent to the rut depths of the reheat sets, evidence of the effect of reheating, although the differences were significant for only 2 of the 9.

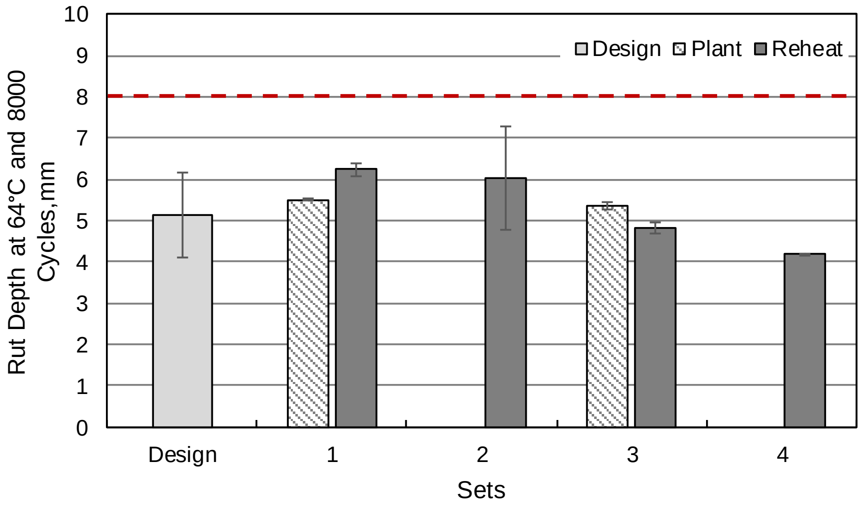

Figure 22. APA Rut Depths for Mixture A-V. Values are the average of two sets of two replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

In summary, although none of the sets tested for the Producer A mixtures failed or varied significantly for rutting performance, because of the production variability, multiple tests per lot will still be needed for this test for acceptance of asphalt mixtures or BMD quality control and assurance practices. However, because of the passing performance and consistent results throughout the production, the APA test may not need to be performed as frequently as the other two performance tests (Cantabro and IDT-CT). This would be convenient for both VDOT and the industry because of the cost and time required to perform the test. Alternative simple and rapid tests such as the high temperature IDT test may also be used for evaluating the rutting performance of mixtures, especially during production. In addition, since there were no significant differences between the reheat and design rut depth values, or between the reheat and plant rut depth values, and since all sets had passing rut depths, it appears that either plant or reheat test results may be used to evaluate the mixtures. However, further studies are needed to confirm this conclusion.

Finally, the average COV for all APA tests performed on Mixtures A-I through A-V was 10.9%, with a standard deviation of 10.7%. Although this average COV is a promising indication for a test method to be used in quality measurement practices, it is a precision estimate for the VTRC laboratory and not the precision estimates (i.e., single operator and multi-laboratory) of the APA test. Thus, the precision estimates of this test need to be determined for proper implementation of the BMD concept.

Comparisons Among Mixtures

Figure 23 shows the average design, plant, and reheat rut depth results for Mixtures A-I through A-V. The design results are based on one set of specimens having four replicates. The plant results are the averages of one to four sets sampled throughout production. The reheat results are the averages of four sets sampled throughout production except for Mixture A-III, which had only two sample sets. The standard deviation of each mixture was calculated from the averages of these sets.

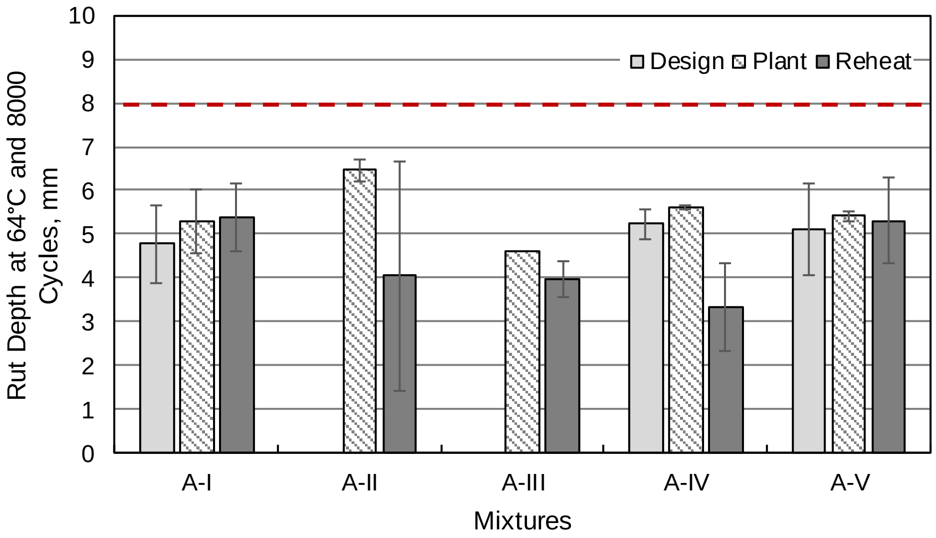

Figure 23. Average Rut Depth Results for Mixtures A-I Through A-V. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Based on the results presented in Figure 23, the following observations were made from the average design rut depth values of Mixtures A-I, A-IV, and A-V:

- The design rut depth values for Mixtures A-I, A-IV, and A-V met the performance criterion for rutting, although Mixture A-I was not designed to meet BMD criteria.

- There were no statistically significant differences among the design values of the three mixtures. This indicated that no difference in rutting susceptibility was shown at design for Mixture A-I (30% RAP with PG 64S-22) or Mixtures A-IV (40% RAP with PG 58-28) and A-V (40% RAP with a recycling agent).

- The mixture with the lowest design rut depth value was Mixture A-I (30% RAP with PG 6S4-22).

- The use of a recycling agent in Mixture A-V (40% RAP with a recycling agent) provided statistically similar rutting resistance at design as the counterpart mixture with a softer binder, Mixture A-IV (40% RAP with PG 58-28).

Based on the results presented in Figure 23, the following observations were made from the average plant values of Mixtures A-I through A-V:

- All five mixtures had average plant values that satisfied the performance criteria for rutting.

- There were no significant differences among the mixture plant rut depth values except for Mixture A-II (30% RAP with PG 58-28), which significantly differed from the other mixtures. This indicated that these high RAP mixtures incorporating a standard binder, softer binder, or recycling agent should have a performance that is equal to the performance of the counterpart mixture with low RAP and a standard binder in terms of rutting susceptibility as measured by the laboratory APA test.

- The mixture with the lowest rut depth was Mixture A-III (40% RAP with PG 64S-22).

- The use of a softer binder resulted in a significantly increased rut depth for Mixture A-II (30% RAP with PG 58-28) as compared to Mixture A-I (30% RAP with PG 64S-22). A decrease in performance was also observed for Mixture A-IV (40% RAP with PG 58-28) compared to Mixture A-III (40% RAP with PG 64S-22), although the difference was not significant. All plant values met the performance criterion.

- The use of a recycling agent in Mixture A-V (40% RAP with a recycling agent) resulted in decreased performance compared to Mixture A-III (40% RAP with PG 64S-22); however, performance was slightly improved compared to Mixture A-IV (40% RAP with PG 58-28).

Based on the results presented in Figure 23, the following observations were made from the average reheat rut depth values of Mixtures A-I through A-V:

- All five mixtures satisfied the performance criterion, with statistically similar average reheat rut depth values. This indicated that all mixtures should perform equally in terms of rutting resistance as measured by the laboratory APA test.

- The mixture with the lowest rut depth was Mixture A-III (40% RAP with PG 64S-22).

- The use of a softer binder resulted in improved performance for Mixture A-II (30% RAP with PG 58-28) compared to Mixture A-I (30% RAP with PG 64S-22) and for Mixture A-IV (40% RAP with PG 58-28) compared to Mixture A-III (40% RAP with PG 64S-22). All had rut depth results that met the performance criterion.

- The use of a recycling agent in Mixture A-V (40% RAP with a recycling agent) resulted in decreased performance compared to Mixture A-III (40% RAP with PG 64S-22) and Mixture A-IV (40% RAP with PG 58-28).

- For a given mixture, no significant differences were found between the reheat and design rut depth values or between the reheat and plant rut depth values.

It was seen that 40% RAP mixtures containing a standard binder, softer binder, or recycling agent can have a performance that is equal to the performance of their counterpart 30% RAP mixtures in terms of rutting as measured by the laboratory APA test. It was also evident that the use of the BMD concept can successfully allow inclusion of these materials to provide improved mixture rutting performance. However, the long-term laboratory and field performance of these mixtures should be evaluated to confirm these findings.

From the laboratory testing, it was clear that these mixtures, although having similar volumetric properties and gradations, showed differences in response when subjected to the BMD testing performed in this study. This demonstrated how volumetric properties and gradations alone cannot differentiate mixture performance. Performance testing can capture the influence of binder properties/grades and the use of a recycling agent on the mixture response that volumetrics do not address. This is indicative of the usefulness and importance of the BMD concept wherein the performance of mixtures can be measured and addressed.

Overall, based on laboratory testing, the performance test results of Mixtures A-I through A-V indicated that asphalt mixtures with 40% RAP can be designed and produced such that their performance is at least equal to the performance of their counterpart 30% RAP mixtures. In addition, softer binders or recycling agents can be incorporated into asphalt mixtures with the use of the BMD concept.

Mixtures From Producer B

Four mixtures were produced and paved by Producer B. As noted previously, Mixtures B-I and B-II were paved on the same route in the Salem District, and Mixtures B-III and B-IV were paved on another route in the Lynchburg District. Aside from the presence or absence of a warm mix additive or recycling agent, the four mixtures had the same basic design. Design performance test results were not available for Mixtures B-I through B-IV. During production, one set of plant specimens was fabricated for each mixture and two sets of loose mixture samples were collected for each mixture for reheat testing.

Volumetric Properties and Gradation

The volumetric properties and gradation of Mixtures B-I through B-IV are presented in Tables 10 through 13, respectively, for design, plant samples tested by the producer, and reheated samples tested by VTRC. All mixtures from Producer B met VDOT mix design criteria as outlined in the specifications.

Close examination of the tables indicated that VFA determined by VTRC for Mixture B-I, Set 2 (Table 9), exceeded the production limit (i.e., 85%). VMA from the producer for Mixture B-II, Set 1 (Table 10), was less than the minimum production limit criterion of 16%; unfortunately, producer volumetric results for Set 2 were not available. Samples of Mixture B-II, Set 2, tested by VTRC met all volumetric requirements including VMA. Most VFA values for Mixture B-III (Table 11) exceeded the production limit, based on both producer and VTRC data. For Set 1 of Mixture B-III, the VMA determined by VTRC was less than the minimum production criterion. No issues were observed with regard to Mixture B-IV (Table 12). Aside from these specific observations, the variability of volumetric properties and gradations were within acceptable limits throughout production. In addition, average volumetric properties and gradation during the production for each mixture were within the allowable tolerance with the exception of Mixture B-III where VFA exceeded the tolerance limit for both producer and VTRC data.

Table 10. Volumetric Properties and Gradations for Mixture B-I

Mixture	**B-I**							
Mixture Type	**SM-9.5D**							
Virgin Binder Grade	**PG64S-22**							
RAP Content, %	**26**							
Additive or Recycling Agent	**WMA A**							
Sample	**JMF**	**Process**	**Set 1**		**Set 2**		**Set Average**	
Property		**Tolerance**[a]	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.70	±0.43	5.94	5.81	5.75	6.03	5.85	5.92
Rice SG (G_{mm})	2.606	-	-	2.613	2.622	2.617	2.622	2.615
VTM, %	4.0	2-5%	-	2.6	3.3	2.4	3.3	2.5
VMA, %	17.0	Min. 16	-	16.4	16.9	16.8	16.9	16.6
VFA, %	78.0	70-85	-	83.9	80.0	**85.7**	80	84.8
FA Ratio	1.20	0.7-1.3	-	1.08	1.10	1.15	1.1	1.1
Mixture Bulk SG (G_{mb})	-	-	-	2.544	2.535	2.554	2.535	2.549
Aggregate Effective SG (G_{se})	-	-	-	2.887	2.895	2.905	2.895	2.896
Aggregate Bulk SG (G_{sb})	-	-	-	2.867	2.875	2.885	2.875	2.876
Absorbed Asphalt Content (P_{ba}), %	-	-	-	0.25	0.25	0.25	0.25	0.25
Effective Asphalt Content (P_{be}), %	-	-	-	5.58	5.51	5.79	5.51	5.68
Gradation, percent passing								
½ in (12.5 mm)	100	±5.7	100.0	98.3	99.0	99.2	99.5	98.7
3/8 in (9.5 mm)	93	±5.7	96.0	92.6	95.0	95.5	95.5	94.0
No. 4 (4.75 mm)	63	±5.7	65.0	62.4	64.0	66.8	64.5	64.6
No. 8 (2.36 mm)	42	±5.7	44.0	42.5	44.0	46.0	44.0	44.3
No. 16 (1.18 mm)	-	-	31.0	30.3	31.0	32.3	31.0	31.3
No. 30 (600 µm)	21	±4.3	21.0	21.2	21.0	22.4	21.0	21.8
No. 50 (300 µm)	-	±3.6	14.0	13.7	14.0	14.6	14.0	14.2
No. 100 (150 µm)	-	-	9.0	8.7	9.0	9.5	9.0	9.1
No. 200 (75 µm)	6.3	±1.4	6.3	6.0	6.2	6.7	6.3	6.3

Red text indicates value that did not meet allowable 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; - = not available.
[a] Process tolerance for two tests from Table II-15 (VDOT, 2016).

In summary, this producer was able to design mixtures incorporating recycling agents and WMA additives in accordance with VDOT specifications. The production results also indicated that these mixtures could be produced consistently throughout production in terms of volumetric properties and gradation. In addition, as seen in the tables, the asphalt content and gradation of the mixtures were very close, if not the same, especially in the light of the inherent production variability.

Cantabro Test Results

Figure 24 shows the average Cantabro mass loss values for Mixture B-I (26% RAP with WMA A). Plant Set 1 and reheat Set 2 both met the Cantabro mass loss performance criterion, and reheat Set 1 did not. The results between reheat Sets 1 and 2 were statistically different, as were the plant and reheat Set 1 mass loss values. However, the Cantabro mass loss values for plant Set 1 and reheat Set 2 were statistically similar. The average COV for Cantabro mass loss for this mixture was 10%.

Table 11. Volumetric Properties and Gradations for Mixture B-II

Mixture	**B-II**							
Mixture Type	**SM-9.5D**							
Virgin Binder Grade	**PG64S-22**							
RAP Content, %	**26**							
Additive or Recycling Agent	**WMA A + Recycling Agent A**							
Sample	**JMF**	**Process**	**Set 1**		**Set 2**		**Set Average**	
Property		**Tolerance**[a]	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.70	±0.43	5.52	5.82	5.75	5.99	5.64	5.90
Rice SG (G_{mm})	2.606	-	2.613	2.627	-	2.632	2.613	2.629
VTM, %	4.0	2-5%	2.5	3.0	-	2.6	2.5	2.8
VMA, %	17.0	Min. 16	**15.6**	16.8	-	16.9	**15.6**	16.9
VFA, %	78.0	70-85	84.0	82.1	-	84.8	84	83.5
FA Ratio	1.20	0.7-1.3	1.00	1.10	-	1.12	1	1.1
Mixture Bulk SG (G_{mb})	-	-	2.548	2.547	-	2.565	2.548	2.556
Aggregate Effective SG (G_{se})	-	-	2.871	2.905	-	2.922	2.871	2.913
Aggregate Bulk SG (G_{sb})	-	-	2.851	2.885	-	2.902	2.851	2.893
Absorbed Asphalt Content (P_{ba}), %	-	-	0.25	0.25	-	0.24	0.25	0.24
Effective Asphalt Content (P_{be}), %	-	-	5.28	5.59	-	5.76	5.28	5.67
Gradation, percent passing								
½ in (12.5 mm)	100	±5.7	99.0	99.2	100.0	99.3	99.5	99.2
3/8 in (9.5 mm)	93	±5.7	92.0	93.6	95.0	93.8	93.5	93.7
No. 4 (4.75 mm)	63	±5.7	63.0	66.1	63.0	65.4	63.0	65.8
No. 8 (2.36 mm)	42	±5.7	42.0	44.6	43.0	44.5	42.5	44.5
No. 16 (1.18 mm)	-	-	30.0	31.5	30.0	31.1	30.0	31.3
No. 30 (600 µm)	21	±4.3	21.0	21.9	21.0	21.7	21.0	21.8
No. 50 (300 µm)	-	±3.6	13.0	14.1	14.0	14.1	13.5	14.1
No. 100 (150 µm)	-	-	8.0	9.0	9.0	9.2	8.5	9.1
No. 200 (75 µm)	6.3	±1.4	5.5	6.2	6.2	6.5	5.9	6.3

Red text indicates value that did not meet allowable 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; - = not available.

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

The average Cantabro mass loss values for Mixture B-II (26% RAP with WMA A and recycling agent A) are presented in Figure 25. None of the sets failed to meet the performance criterion, and there were no statistically significant differences among any of the sets. The average COV for Cantabro mass loss for Mixture B-II was 8%.

Figure 26 displays the average Cantabro mass loss values for Mixture B-III (26% RAP with WMA B). All sets satisfied the performance criterion. The results for plant Set 1 statistically differed from the results for reheat Sets 1 and 2. Reheat Sets 1 and 2 were not significantly different. Mixture B-III had an average COV for Cantabro mass loss of 10.9%.

The average Cantabro mass loss values for Mixture B-IV (26% RAP with WMA B and recycling agent B) are shown in Figure 27. All sets satisfied the performance criterion. No statistical differences were found among any of the sets. The average COV for Cantabro mass loss for this mixture was 18%, with a maximum COV of 22.6%.

Table 12. Volumetric Properties and Gradations for Mixture B-III

Mixture	**B-III**							
Mixture Type	**SM-9.5D**							
Virgin Binder Grade	**PG64S-22**							
RAP Content, %	**26**							
Additive or Recycling Agent	**WMA B**							
Sample	**JMF**	**Process**	**Set 1**		**Set 2**		**Set Average**	
Property		**Tolerance**[a]	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.70	±0.43	5.93	5.68	6.04	6.03	5.99	5.85
Rice SG (G_{mm})	2.606	-	2.608	2.608	2.595	2.597	2.602	2.602
VTM, %	4.0	2-5%	2.4	2.0	2.3	2.3	2.4	2.1
VMA, %	17.0	Min. 16	16.5	**15.5**	16.6	16.5	16.6	16.0
VFA, %	78.0	70-85	85.0	**87.3**	**86.0**	**86.3**	**85.5**	**86.8**
FA Ratio	1.20	0.7-1.3	1.00	1.10	1.00	1.10	1.00	1.10
Mixture Bulk SG (G_{mb})	-	-	2.545	2.556	2.535	2.538	2.54	2.547
Aggregate Effective SG (G_{se})	-	-	2.887	2.873	2.876	2.878	2.8815	2.875
Aggregate Bulk SG (G_{sb})	-	-	2.867	2.853	2.856	2.858	2.8615	2.855
Absorbed Asphalt Content (P_{ba}), %	-	-	0.25	0.25	0.25	0.25	0.25	0.25
Effective Asphalt Content (P_{be}), %	-	-	5.69	5.44	5.81	5.79	5.75	5.62
Gradation, percent passing								
½ in (12.5 mm)	100	±5.7	100.0	99.2	100.0	98.9	100.0	99.0
3/8 in (9.5 mm)	93	±5.7	93.0	90.4	93.0	93.4	93.0	91.9
No. 4 (4.75 mm)	63	±5.7	64.0	60.1	64.0	63.0	64.0	61.6
No. 8 (2.36 mm)	42	±5.7	42.0	40.8	42.0	42.3	42.0	41.5
No. 16 (1.18 mm)	-	-	29.0	28.5	29.0	28.9	29.0	28.7
No. 30 (600 µm)	21	±4.3	20.0	19.7	20.0	19.8	20.0	19.7
No. 50 (300 µm)	-	±3.6	13.0	12.9	13.0	13.0	13.0	12.9
No. 100 (150 µm)	-	-	8.0	8.5	8.0	8.8	8.0	8.7
No. 200 (75 µm)	6.3	±1.4	5.7	6.0	5.7	6.4	5.7	6.2

Red text indicates value that did not meet allowable tolerance. WMA = warm mix asphalt; 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; - = not available.

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

The Cantabro mass loss results for Mixtures B-I through B-IV indicated that only 1 of 12 sample sets (inclusive of both plant and reheat sets) failed to meet the performance criterion during production. The results for the reheat sets were not statistically different for any mixture except Mixture B-I. There were significant differences between two of the four plant and reheat sets (Mixtures B-I and B-IV).

In summary, given that several plant and reheat sets statistically differed throughout production, multiple tests for each lot will be needed in order to use an average performance test value against the performance criteria for acceptance or BMD quality control and assurance practices for the Cantabro test. The differences between laboratory mix design and plant production such as differences in aging conditions, as well as the inherent variability during plant production and associated changes in volumetric properties, provide additional evidence of the need for multiple sample measurements for this test.

Table 13. Volumetric Properties and Gradations for Mixture B-IV

Mixture	**B-IV**							
Mixture Type	**SM-9.5D**							
Virgin Binder Grade	**PG64S-22**							
RAP Content, %	**26**							
Additive or Recycling Agent	**WMA B + Recycling Agent B**							
Sample	**JMF**	**Process**	**Set 1**		**Set 2**		**Set Average**	
Property		**Tolerance**[a]	**Producer**	**VTRC**	**Producer**	**VTRC**	**Producer**	**VTRC**
NMAS, mm	9.5	-	9.5	9.5	9.5	9.5	9.5	9.5
Asphalt Content, %	5.70	±0.43	5.52	5.42	5.43	5.13	5.48	5.27
Rice SG (G_{mm})	2.606	-	2.626	2.624	2.628	2.631	2.627	2.627
VTM, %	4.0	2-5%	3.7	3.4	3.9	4.3	3.8	3.9
VMA, %	17.0	Min. 16	16.7	16.2	16.7	16.3	16.7	16.2
VFA, %	78.0	70-85	78.0	78.9	77.0	73.5	77.5	76.2
FA Ratio	1.20	0.7-1.3	1.10	1.17	1.20	1.28	1.15	1.20
Mixture Bulk SG (G_{mb})	-	-	2.529	2.534	2.525	2.518	2.527	2.526
Aggregate Effective SG (G_{se})	-	-	2.887	2.879	2.885	2.873	2.886	2.876
Aggregate Bulk SG (G_{sb})	-	-	2.867	2.859	2.865	2.853	2.866	2.856
Absorbed Asphalt Content (P_{ba}), %	-	-	0.25	0.25	0.25	0.25	0.25	0.25
Effective Asphalt Content (P_{be}), %	-	-	5.28	5.18	5.19	4.89	5.24	5.03
Gradation, percent passing								
½ in (12.5 mm)	100	±5.7	100.0	99.3	100.0	99.8	100.0	99.6
3/8 in (9.5 mm)	93	±5.7	94.0	91.3	94.0	93.8	94.0	92.5
No. 4 (4.75 mm)	63	±5.7	64.0	64.0	65.0	63.8	64.5	63.9
No. 8 (2.36 mm)	42	±5.7	43.0	43.4	44.0	42.8	43.5	43.1
No. 16 (1.18 mm)	-	-	30.0	30.1	30.0	30.2	30.0	30.1
No. 30 (600 µm)	21	±4.3	20.0	20.6	21.0	20.8	20.5	20.7
No. 50 (300 µm)	-	±3.6	13.0	13.4	13.0	13.4	13.0	13.4
No. 100 (150 µm)	-	-	8.0	8.7	9.0	8.9	8.5	8.8
No. 200 (75 µm)	6.3	±1.4	5.8	6.1	6.3	6.3	6.1	6.2

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; - = not available.
[a] Process tolerance for two tests from Table II-15 (VDOT, 2016).

The average COV for all Cantabro tests performed on Mixtures B-I through B-4 was 11.7%, with a standard deviation of 4.9%. Although this average COV is a promising indication for a test method to be used in quality measurement practices, it is a precision estimate of the VTRC laboratory and not the precision estimates (i.e., single operator and multi-laboratory) of the Cantabro test. Thus, the precision estimates of this test need to be determined for proper implementation of the BMD concept.

Comparisons Among Mixtures

Figure 28 presents the Cantabro mass loss results for Mixtures B-I through B-IV averaged from the results of the plant and reheat set tests. The plant results are based on one set of three replicates, and the reheat results are the averages of two sets sampled during production.

The standard deviation of the plant set for each mixture was calculated from three replicates, whereas the standard deviation of the reheat sets for each mixture was calculated from the averages of the two sets.

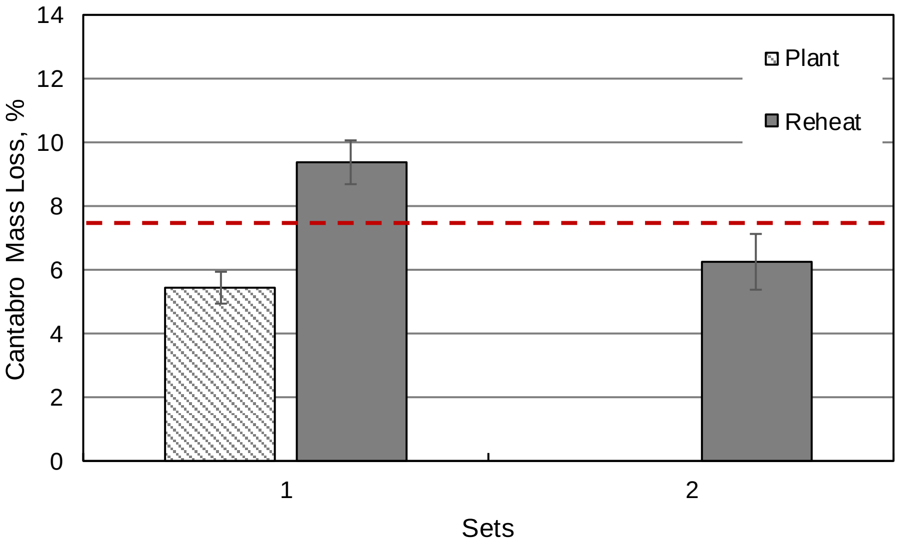

Figure 24. Cantabro Mass Loss Results for Mixture B-I. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

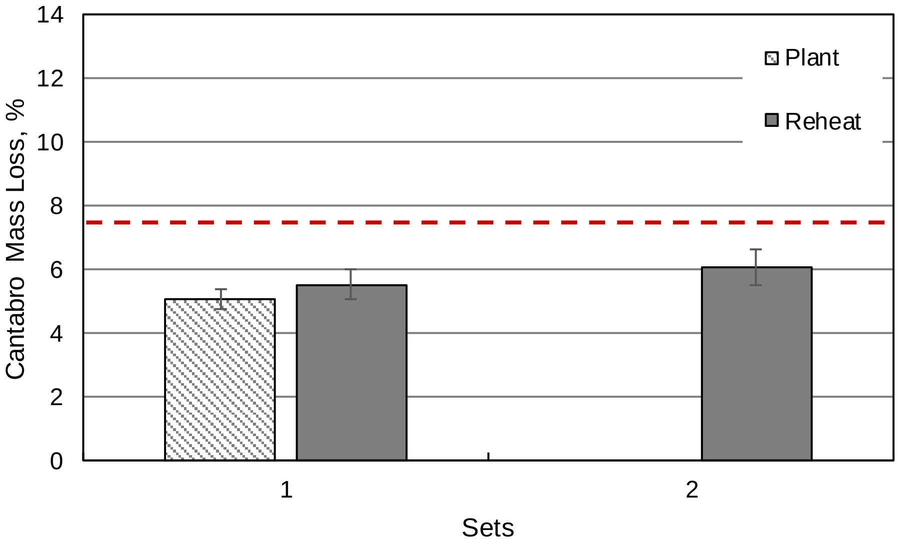

Figure 25. Cantabro Mass Loss Results for Mixture B-II. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

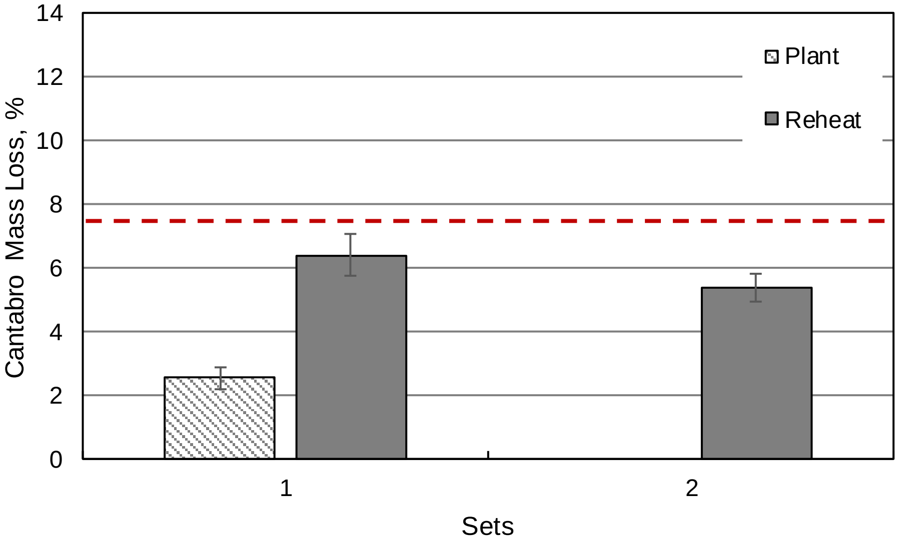

Figure 26. Cantabro Mass Loss Results for Mixture B-III. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

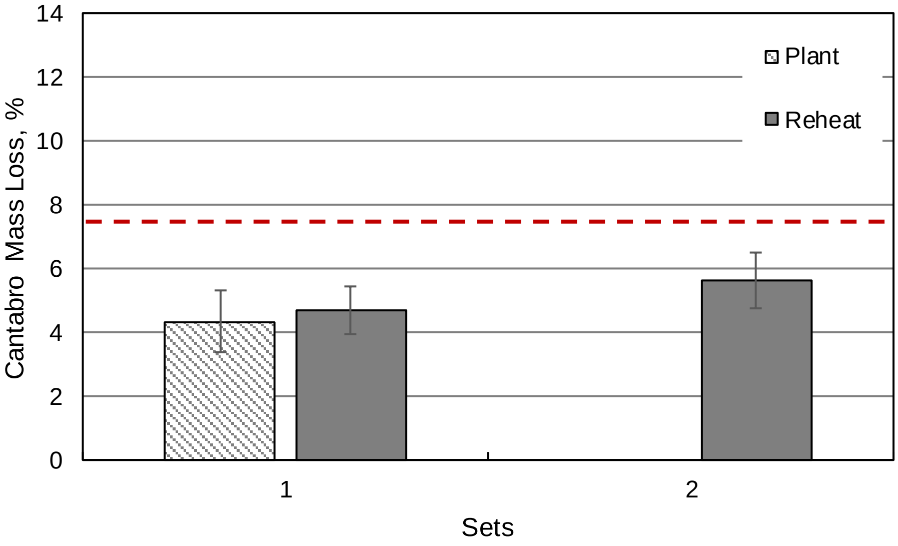

Figure 27. Cantabro Mass Loss Results for Mixture B-IV. Values are the average of three replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

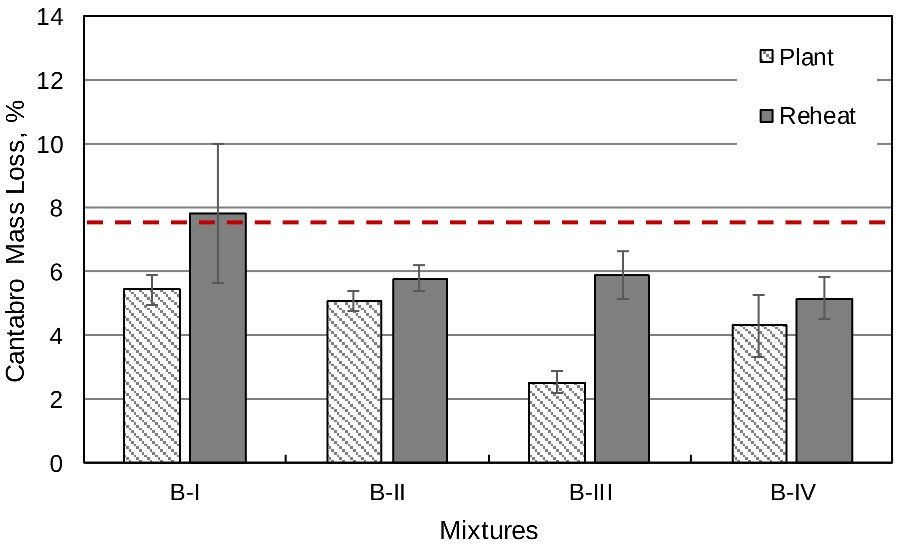

Figure 28. Average Cantabro Mass Loss for Mixtures B-I Through B-IV. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

From Figure 28, the following observations were made from the average plant Cantabro mass loss results for Mixtures B-I through B-IV:

- All mixtures satisfied the performance criterion for durability.

- There were no statistically significant differences among these mixtures except for Mixture B-III.

- The mixture with the lowest Cantabro mass loss was Mixture B-III (26% RAP with WMA B).

- The use of a recycling agent or WMA additive resulted in reductions of mass loss values for Mixtures B-II (26% RAP with WMA A and recycling agent A), B-III (26% RAP with WMA B), and B-IV (26% RAP with WMA B and recycling agent B) compared to Mixture B-I (26% RAP with WMA A). The reductions in mass loss for Mixtures B-II and B-IV were not significant; however, the mass loss reduction was significant for Mixture B-III.

The following observations were made from the averaged reheat Cantabro mass loss values for Mixtures B-I through B-IV, based on the results presented in Figure 28:

- All mixtures satisfied the performance criterion for durability except for the value for the reheat set from Mixture B-I, which was averaged from one set that did not meet the Cantabro criterion and a second set that did meet the criterion.

- There were no statistically significant differences among the reheat Cantabro mass loss values for the mixtures. This was partly due to high variations in the results across the sets throughout production.

- The mixture with the lowest Cantabro mass loss value was Mixture B-IV (26% RAP with WMA B and recycling agent B).

- The use of recycling agents or a WMA additive resulted in lower mass loss values for Mixtures B-II (26% RAP with WMA A and a recycling agent A), B-III (26% RAP with WMA B), and B-IV (26% RAP with WMA B and recycling agent B) compared to Mixture B-I (26% RAP with WMA A).

- For each mixture, no significant differences were found between the plant and reheat Cantabro test results except for Mixture B-III. For each mixture, the Cantabro mass loss values for the average reheat sets were higher than the values for the plant sets, potentially indicating the effect of reheating.

These findings indicated that SMs containing a WMA additive and a recycling agent can have a performance that is equal to the performance of their counterpart mixtures containing a WMA additive only in terms of durability as measured by the laboratory Cantabro test. It is also evident that the use of the BMD concept can successfully allow inclusion of these materials to provide improved mixture durability. However, the long-term laboratory and field performances of such mixtures need to be evaluated to confirm this finding.

IDT-CT Test Results

Figure 29 presents the average CT index values for Mixture B-I. Both of the reheat sets satisfied the performance criterion, but the plant set did not.

Reheat Set 1 had a significantly higher CT index value when compared with the plant set. The reason for this counterintuitive result is unknown. The CT index results for reheat Sets 1 and 2 were statistically different. The average COV for the CT index for Mixture B-I was 12.1%, with a maximum COV of 20.6%.

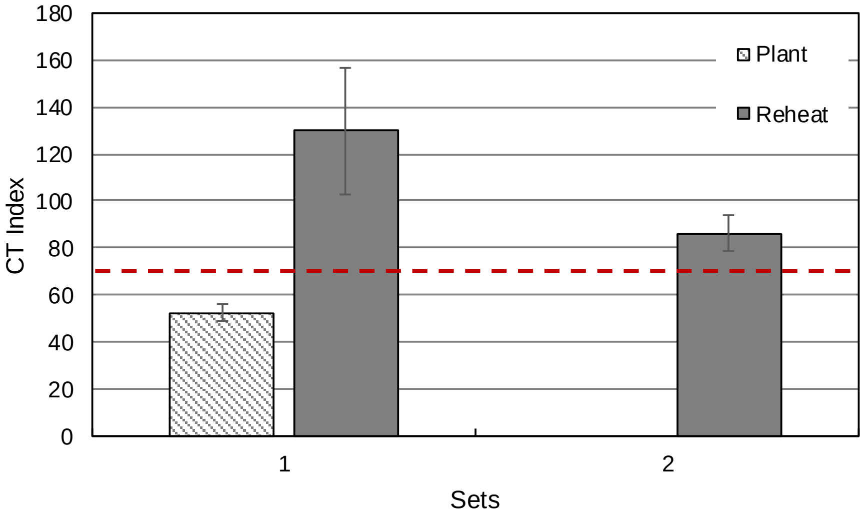

Figure 29. CT Index Results for Mixture B-I. Values are the average of three to five replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Figure 30 shows the average CT index values for Mixture B-II. Only results from plant Set 1 and reheat Set 2 were available. The results from both sets exceeded the CT index performance criterion and were significantly different. Although from different sets, the plant CT index value was significantly higher than the reheat CT index value, indicating the potential effect of reheating on the test results. The average COV for the plant set was 17.1%; that for the reheat set was 1.2%.

Figure 31 shows the average CT index values for Mixture B-III. The results from both the plant and reheat sets satisfied the performance criterion. Although the results between the reheat sets were statistically different, there was no statistical difference between the results of the plant and reheat set. In addition, the CT index for the reheat set was slightly higher than the CT index for the plant set. The average COV for the CT index for Mixture B-III was 10.3%.

Figure 32 shows the average CT index values for Mixture B-IV. The plant and reheat Set 1 values exceeded the minimum CT index criterion and were not significantly different. However, the reheat Set 2 CT index value failed to meet the performance criterion and was significantly different from the other two sets. The CT index value for reheat Set 1 was higher than the CT index value for plant Set 1. The average COV for the CT index for Mixture B-IV was 13.4%.

The IDT-CT test results for Mixtures B-I through B-IV showed that 9 of 11 specimen sets had an average CT index that exceeded the performance criterion of 70 during production. Plant Set 1 from Mixture B-I was the only plant set from the mixtures with a CT index value that did not meet the performance criterion. Reheat Set 2 from Mixture B-IV was the only reheat set from the mixtures to have a CT index that did not meet the performance criterion.

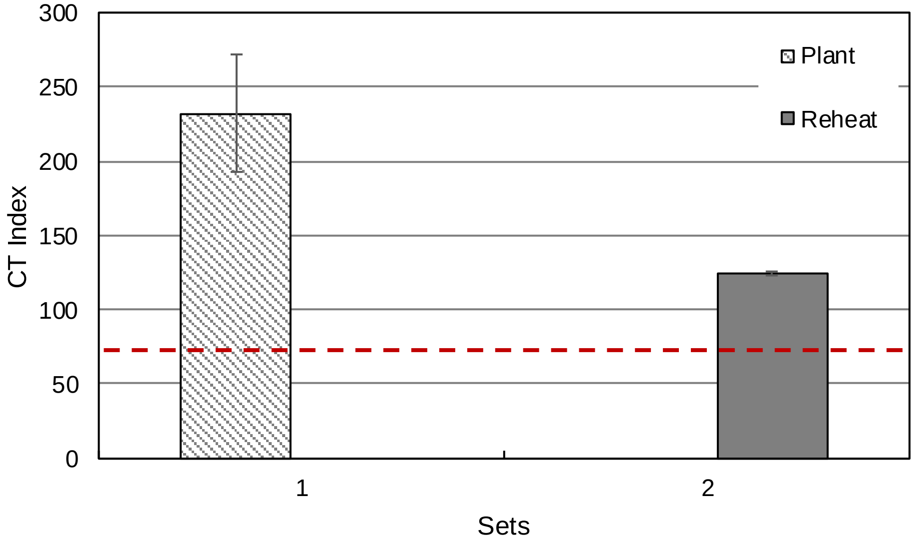

Figure 30. CT Index Results for Mixture B-II. Values are the average of three to five replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

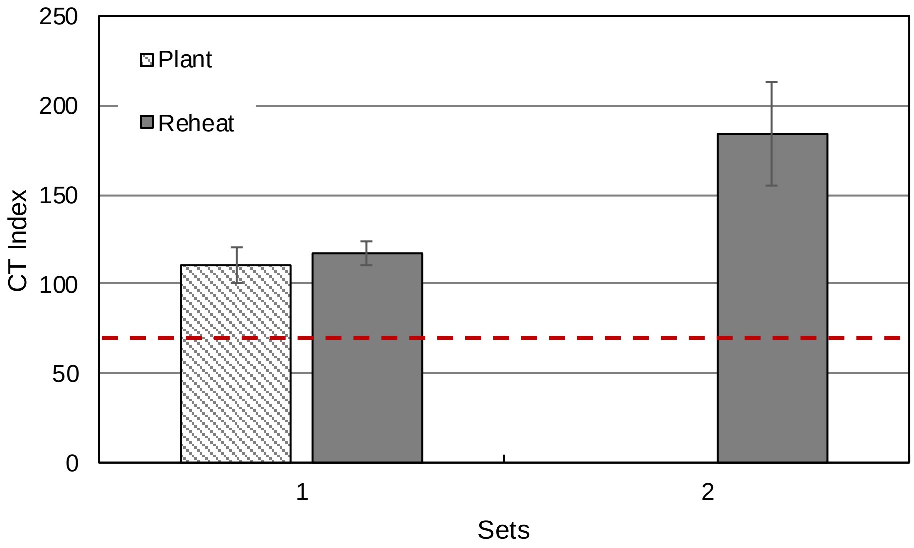

Figure 31. CT Index Results for Mixture B-III. Values are the average of three to five replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

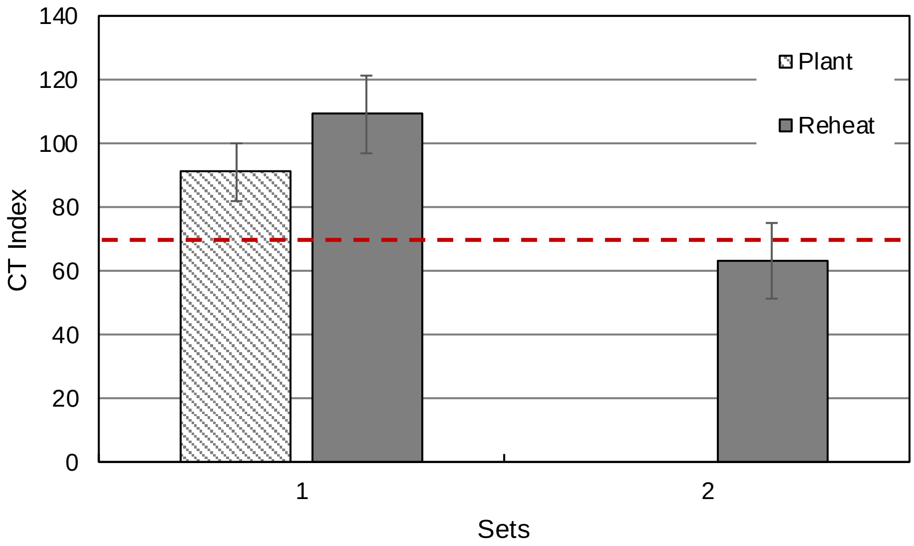

Figure 32. CT Index Results for Mixture B-IV. Values are the average of three to five replicates at 7 ± 0.5% air void content. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

Of the three mixtures with plant and reheat results from the same sample set, only Mixture B-I had a pair of plant and reheat values that were significantly different; for this set, the plant CT index value was less than the reheat value. For the other two mixtures, B-III and B-IV, the plant CT index values were also lower than the reheat CT index values; however, the differences were not significant. The reason for this counterintuitive trend is unknown. The CT index results from each mixture's reheat sets statistically differed throughout production. The average COV for the CT index for Mixtures B-I through B-IV was 11.4%; none of the observations exceeded the single-operator precision estimate of 20.7%.

In summary, given that the CT index values for individual reheat sets throughout production statistically differed, multiple tests for each lot will be needed in order to use an average performance test value to compare against the performance criteria for acceptance of asphalt mixtures or BMD quality control and assurance practices for the IDT-CT test. In addition, the inherent variability during plant production such as deviations in materials' compositions (aggregates and asphalt content) and associated changes in volumetric properties warrant consideration of multiple sample measurements for this test.

Comparisons Among Mixtures

Figure 33 shows the CT index results for Mixtures B-I through B-IV averaged from the results of the plant and reheat set tests. The plant results are based on one sample set with five replicates, and the reheat results are the averages of two sets sampled throughout production except for Mixture B-II that had only one sample set. The standard deviation of each mixture's plant set average was calculated from five replicates, whereas the standard deviation of the reheat set average was calculated from the averages of the mixture Sets 1 and 2 except for Mixture B-II in which the standard deviation was calculated from the replicate measurements of the single plant set.

From Figure 33, the following observations were made from the averaged plant CT index results for Mixtures B-I through B-IV:

- All mixtures except Mixture B-I (26% RAP with WMA A) satisfied the performance criterion for cracking.

- There were statistically significant differences among the mixtures except between Mixture B-III (26% RAP with WMA B) and Mixture B-IV (26% RAP with WMA B and recycling agent B).

- The mixture with the highest plant CT index was Mixture B-II (26% RAP with WMA A and recycling agent A).

- The addition of a recycling agent or WMA additive resulted in statistically significant improvements in performance for Mixtures B-II (26% RAP with WMA A and recycling agent A), B-III (26% RAP with WMA B), and B-IV(26% RAP with WMA B and recycling agent B) (compared to Mixture B-I (26% RAP with WMA A). The improvements were also practically significant as the mixtures achieved CT index values meeting the performance criterion.

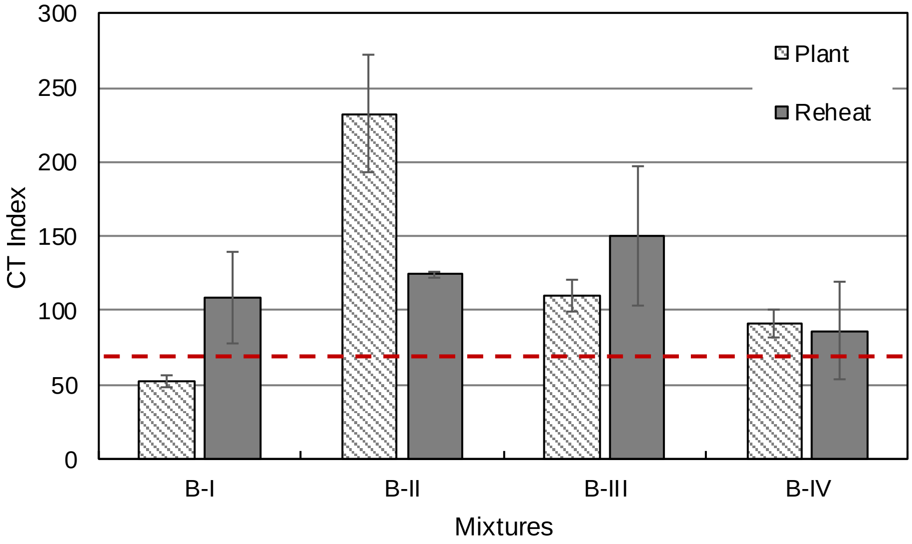

Figure 33. Average CT Index Results for Mixtures B-I Through B-IV. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

The following observations were made from the averaged reheat CT index values of Mixtures B-I through B-IV, based on the results presented in Figure 33:

- All mixtures satisfied the performance criterion for cracking.
- There were no statistically significant differences among the mixtures.
- The mixture having the highest CT index was Mixture B-III (26% RAP with WMA B).
- The addition of a recycling agent or WMA additive resulted in improved performance for Mixtures B-II (26% RAP with WMA A and recycling agent A) and B-III (26% RAP with WMA B) when compared to Mixture B-I (26% RAP with WMA A). Mixture B-IV (26% RAP with WMA B and recycling agent B) had slightly decreased performance compared to Mixture B-I. However, none of the differences between the mixtures was significant.

There were statistically significant differences between the plant and reheat CT index values for two of the four mixtures: Mixtures B-I and B-II. However, the trends of these differences were opposing. Three of the four mixtures (B-I, B-III, and B-IV) showed a trend of decreased CT index values for the reheat sets compared to the plant sets, potentially indicating the effect of reheating; however, only one of the differences was significant. The Mixture B-II CT index was significantly different between the plant and reheat sets but contradicted the trend. As the influence of the effects of conditioning or aging can be significant, as shown, additional evaluation is needed. Further, the use of a different CT index performance criterion should be considered, pending further evaluation of additional mixtures

These findings from the plant and reheat CT index results for Mixtures B-I through B-IV indicated that the mixtures containing a WMA additive or a WMA additive with a recycling agent should perform equally well in terms of cracking susceptibility as measured by the IDT-CT test. It is also evident that the use of the BMD concept can successfully allow inclusion of these materials to provide improved mixture cracking performance. However, the long-term laboratory and field performance of such mixtures needs to be evaluated to confirm this finding.

APA Rut Test Results

Figure 34 shows the average rut depth results for Mixture B-I. It can be seen that only the reheat results from Set 2 were available for this mixture; the average rut depth satisfied the performance criterion. The COV for the rut depth measurements for this mixture was 14.7%.

The average rut depths for Mixture B-II are presented in Figure 35. Rut depths for all of the plant and reheat sets for this mixture were below the maximum performance limit. The statistical analysis indicated that no differences existed among the plant sets. The rut depth from plant Set 1 was higher than the rut depth from reheat Set 1, although there was no statistically significant difference between the results. The average COV for the rut depths for this mixture was 14.6%.

Figure 36 shows the average rut depths for Mixture B-III. All sets had a rut depth meeting the performance criterion, and no statistical differences were found among any of the sets. The average COV was 8.2% for this mixture.

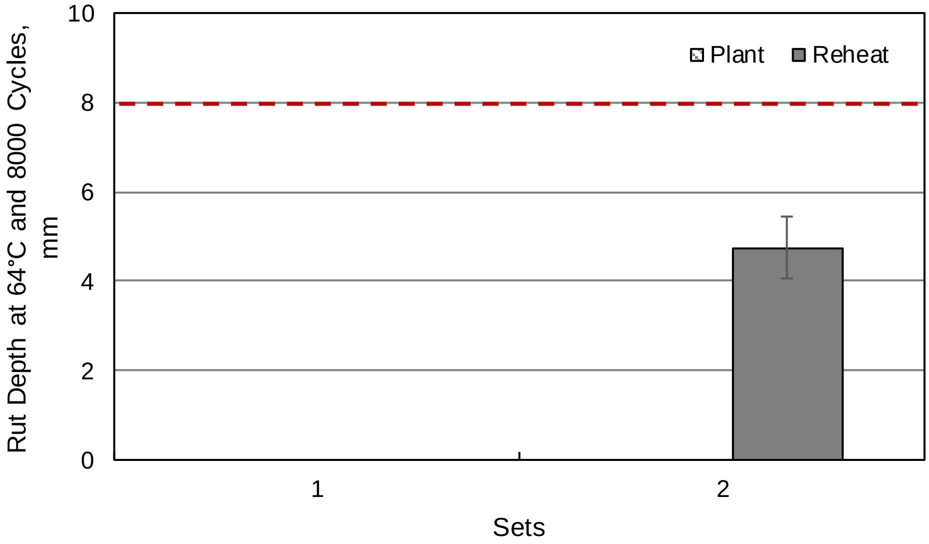

Figure 34. APA Rut Depths for Mixture B-I. Values are the average of two sets of two. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

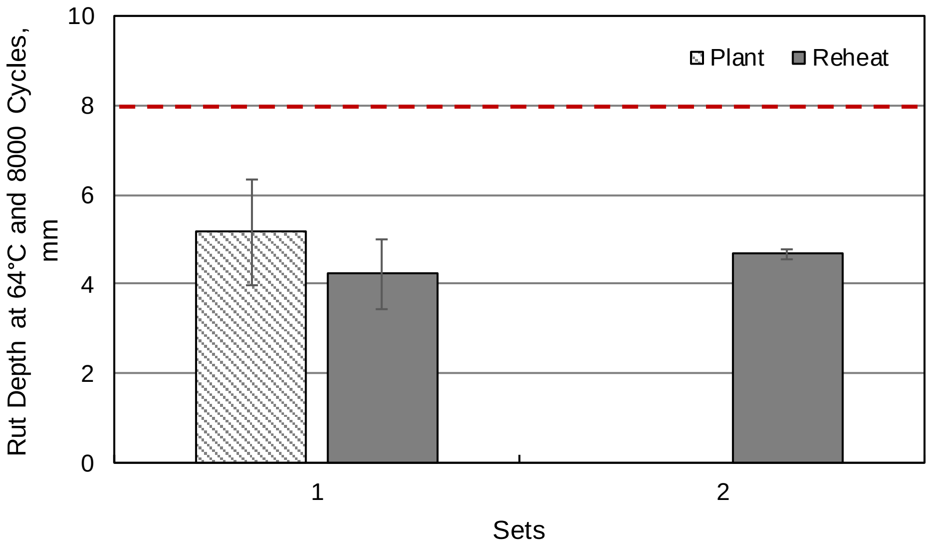

Figure 35. APA Rut Depths for Mixture B-II. Values are the average of two sets of two replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

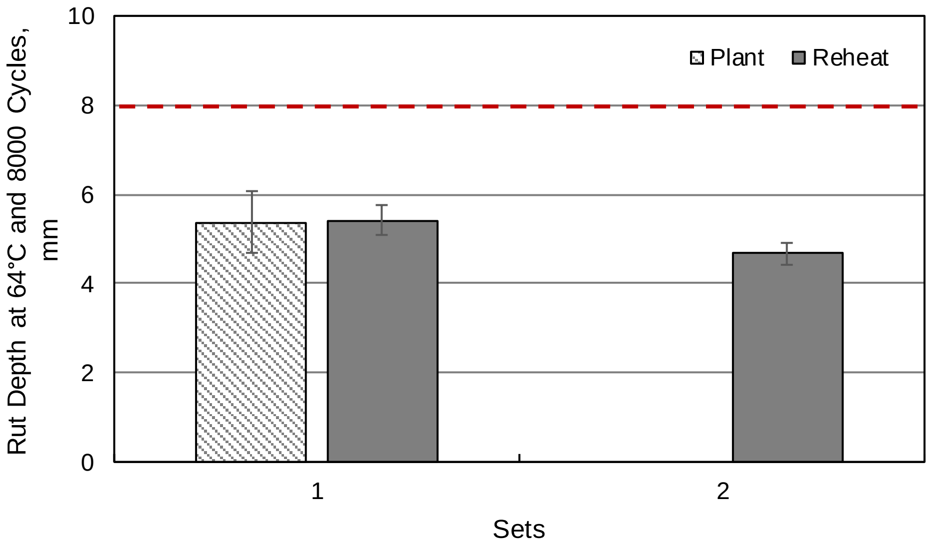

Figure 36. APA Rut Depths for Mixture B-III. Values are the average of two sets of two replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

The average rut depths for Mixture B-IV are presented in Figure 37. All sets of this mixture met the performance criterion. The results between the reheat sets did not significantly differ, but the rut depth from plant Set 1 significantly differed from and was higher than the rut depths of the reheat sets. The average COV for the rut depths for this mixture was 2.8%.

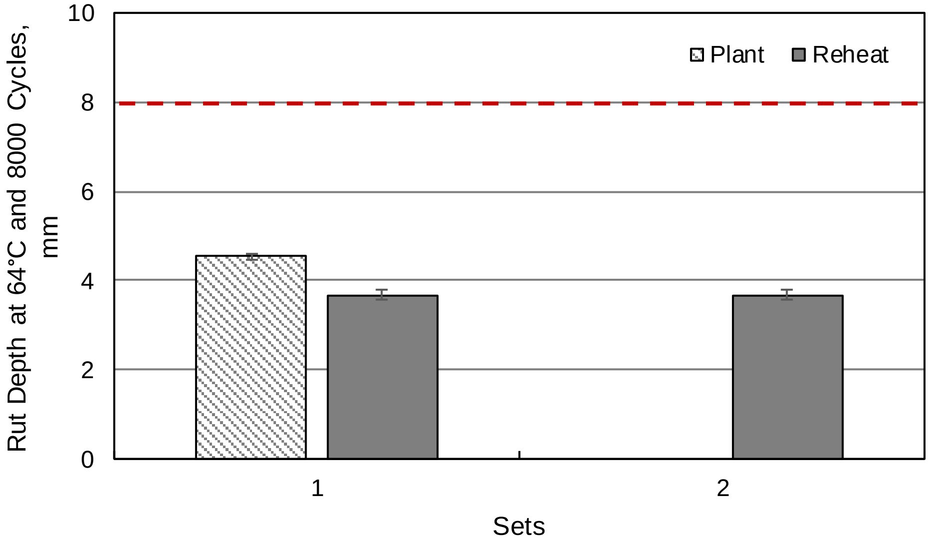

Figure 37. APA Rut Depths for Mixture B-IV. Values are the average of two sets of two replicates. I-bars indicate ±1 standard deviation. Red dashed line = BMD special provision limit; BMD = balanced mix design.

The APA rut depth results of Mixtures B-I through B-IV indicated that all sets had an average rut depth that met the maximum 8 mm performance criterion throughout production. For each mixture, none of the reheat sets statistically differed from each other throughout production. The same was found for the plant and reheat sets, except for that of Mixture IV. In general, despite the statistical similarity, the rut depths from the plant sets were slightly higher than that of the reheat sets.

In summary, none of the sets tested for Producer B mixtures failed the rutting performance criterion and only one mixture had a significant difference between plant and reheat sets. However, the difference in one of four otherwise consistent mixtures indicated that production variability can be a concern; thus, multiple tests for each lot will still be needed for acceptance of asphalt mixtures or BMD quality control and assurance practices. The APA test may not need to be performed as frequently as the Cantabro and IDT-CT tests because of the passing performance and mostly consistent results throughout production.

The average COV for individual set measurements of Mixtures B-I through B-IV was 9.2%, with a standard deviation of 7.5%. This value is the precision estimate for the VTRC laboratory and not the precision estimates (i.e., single operator and multi-laboratory) of the APA test, although it is a promising indication for this test method to be used in quality measurement practices. As the precision estimates for the APA test have not been determined, there is a need to establish them for proper implementation of the BMD concept.

Comparisons Among Mixtures

Figure 38 presents the rut depth results for Mixtures B-I through B-IV averaged from the results of plant and reheat set tests.

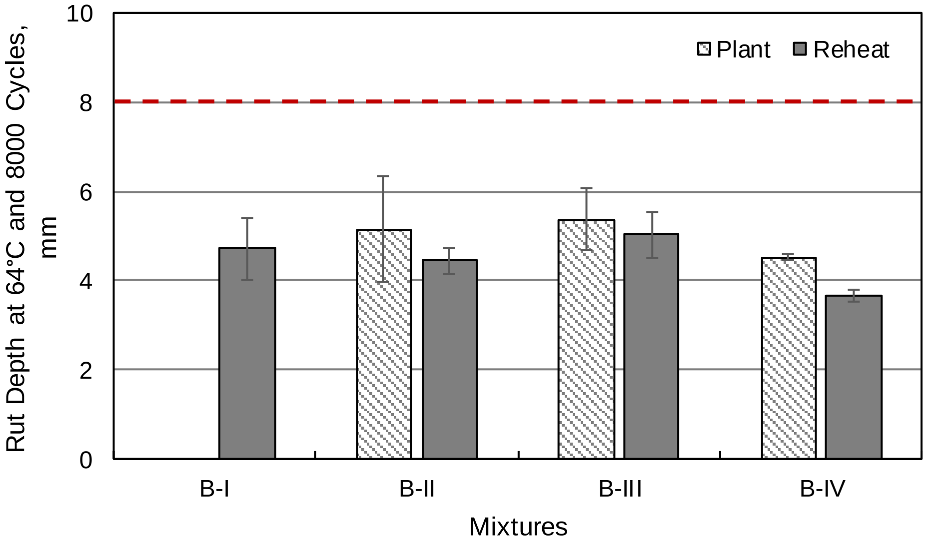

Figure 38. Average Rut Depth Results for Mixtures B-I Through B-IV. I-bars indicate ±1 standard deviation. Red dashed line =BMD special provision limit; BMD = balanced mix design.

The plant results are based on test results from one sample set having four replicates. The reheat results are the averages of two sets sampled throughout production except for Mixture B-I that had only one sample set. The standard deviation for each mixture for the plant test was calculated from four replicates, whereas the standard deviation for each mixture for the reheat test was calculated from the averages of the two sets except for Mixture B-I, for which the standard deviation was calculated from the replicate measurements of that set.

From Figure 38, the following observations were made from the averaged plant values of Mixtures B-II through B-IV:

- All mixtures tested satisfied the performance criterion for rutting.
- There were no statistically significant differences among the mixtures.
- The mixture with the lowest rut depth was Mixture B-IV (26% RAP with WMA B and recycling agent B).

The following observations were made from the averaged reheat values of Mixtures B-I through B-IV, based on the results presented in Figure 38:

- All mixtures satisfied the performance criterion and had statistically similar rut depth values except for Mixture B-IV (26% RAP with WMA B and recycling agent B).
- The mixture with the lowest rut depth was Mixture B-IV (26% RAP with WMA B and recycling agent B).
- The addition of a recycling agent resulted in improved performance for Mixture B-II (26% RAP with WMA A and recycling agent A) and Mixture B-IV (26% RAP with

WMA B and recycling agent B) as compared to Mixture B-I (26% RAP with WMA A) and Mixture B-III (26% RAP with WMA B), respectively. The improvement was statistically significant only for Mixture B-IV (26% RAP with WMA B and recycling agent B).

- The magnitude of rut depths from the plant mixtures was slightly higher than that of the rut depths from the reheat mixtures, although the only significant difference was between the plant and reheat rut depth values for Mixture B-IV (26% RAP with WMA B and recycling agent B).

These findings from the testing of Producer B mixtures indicated that a mixture containing a recycling agent and a WMA additive can have a performance that is equal to or better than the performance of its counterpart mixture containing only a WMA additive from the standpoint of rutting performance. It was also evident that the use of the BMD concept can successfully allow inclusion of these materials to provide improved mixture rutting performance. However, the long-term laboratory and field performance of such mixtures needs to be evaluated to confirm this finding.

Overall, based on laboratory testing, the performance test results of Mixtures B-I through B-IV indicated that asphalt mixtures incorporating a WMA additive and a recycling agent can be designed and produced such that their performance is at least equal to the performance of their counterpart mixtures produced with a WMA additive. In addition, recycling agents and WMA additives can be incorporated into asphalt mixtures with the use of the BMD concept.

Preliminary Evaluation of Relationship Between Non-Reheat and Reheat Specimen Test Results

The relationship between the results of non-reheat (plant) and reheat sets was analyzed for each of the performance tests by combining the data from both trial projects. In the preceding sections, it was shown that the effect of reheating loose mixture on the test results was statistically significant for the majority of sample sets of the mixtures. The objective of the analysis in this section was to investigate whether a shift factor exists that can relate test results for reheat mixtures with test results of the corresponding plant mixtures and vice versa.

Figure 39 compares the Cantabro test results between the reheat and plant sets, using mixtures from both producers. The results indicated that there is no relationship between the Cantabro mass loss for the plant and reheat sets of the mixtures. For 9 of the 12 sets of data points, the reheat results indicated greater mass loss than the plant results; of those, 2 sets had very large increases in mass loss after reheating such that they exceeded the 7.5% mass loss criterion. Overall, it was seen that reheating prior to compaction generally leads to an increase in mass loss.

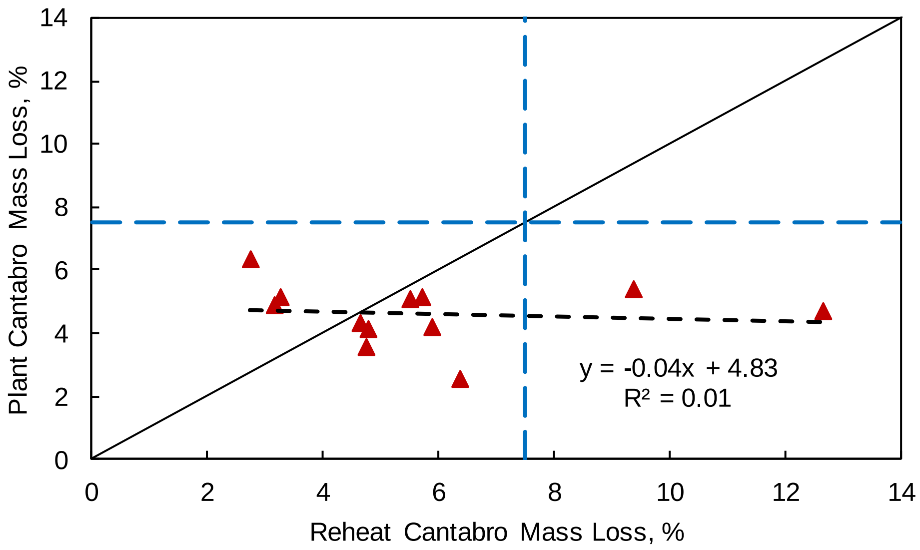

Figure 39. Effect of Reheating on Cantabro Mass Loss. Blue dashed line = BMD special provision limit; BMD = balanced mix design.

One interesting observation from Figure 39 was the increased discrimination potential of the performance of the mixtures through testing of the reheat mixtures. In other words, the range of Cantabro mass loss values was wider for the reheat testing of the mixtures than for the plant testing. Within the mixtures tested in this study, this indicated that for quality assurance purposes, evaluating the durability of mixtures might be better achieved by testing reheated mixtures. Unfortunately, the lack of relationship shown in Figure 38 precludes the use of a relationship to establish a performance threshold limit for the plant (non-reheat) test results or to guaranty that using the plant test results with respect to the durability performance criterion established from the reheat testing of mixtures will lead to satisfactory durability performance. Further work with additional mixtures is needed to confirm these results and support developing relationships.

Figure 40 compares the plant CT index values with their paired reheat CT index values, combining the data from both producers. The results indicated that there was no relationship between the CT index values of the plant and reheat sets of the mixtures. Overall, reheating prior to compaction generally led to a decrease in the CT index caused by an increase in brittleness, indicating a potential susceptibility of the mixture to cracking. This was supported by the data in Figure 40, as 8 of the 11 sets had reheat CT index values lower than the plant CT index values. In addition, 2 of the sets had failing reheat CT index values and passing plant CT index values. Further, if the current CT index criterion of 70 (which was developed from reheat data) is applied to the plant sets, one plant set would also have a failing CT index value. For the mixtures tested in this study, this supported the observation that a passing CT index from a plant mixture does not always result in a passing CT index from the reheat mixture. This indicated the need to establish a performance criterion for non-reheated specimens if non-reheated testing is to be adopted in quality assurance practices. The data presented in Figure 40 do not provide enough information to establish a performance threshold limit for the plant (non-reheat) test results. Further work with additional mixtures is needed to confirm these results and support developing relationships.

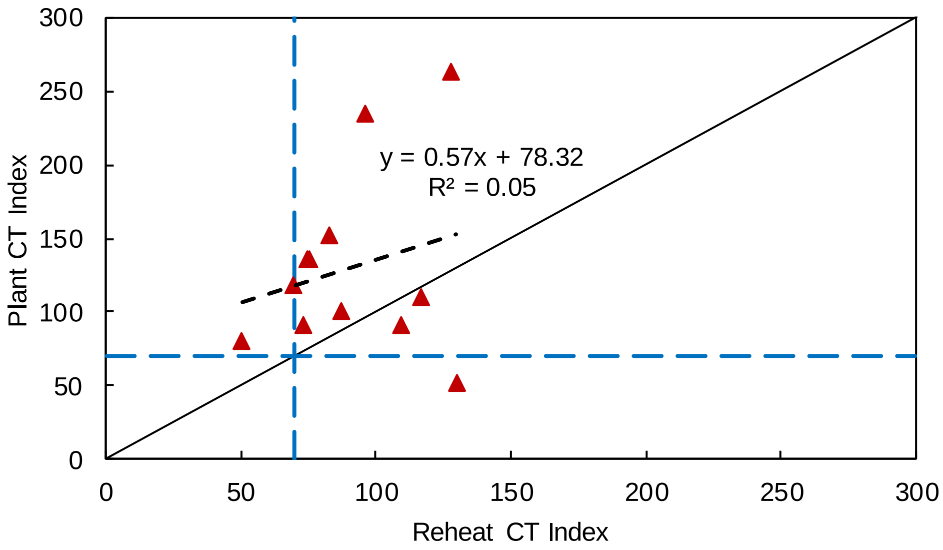

Figure 40. Effect of Reheating on CT Index. Blue dashed line = BMD special provision limit; BMD = balanced mix design.

Figure 41 compares the rut depth values between the reheat and plant sets for data from both producers. The results showed that no relationship exists between the rut depths of the plant and reheat specimen sets for the mixtures. Overall, it was seen that reheating prior to compaction generally led to an increase in the rut depth of the mixtures, but the majority of the increases were not statistically significant and the performance outcome did not change. For the mixtures evaluated in this study, this suggests that evaluating the rutting performance of asphalt mixtures might be achieved through APA testing of reheated or non-reheated specimens with the same threshold value. Further work with additional mixtures is needed to confirm these results and support developing relationships.

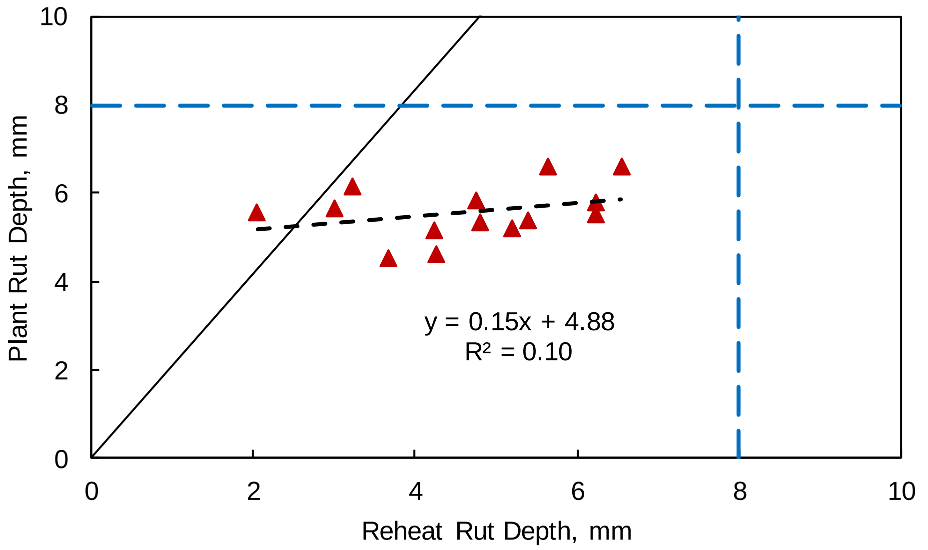

Figure 41. Effect of Reheating on APA Rut Depth. Blue dashed line = BMD special provision limit; APA = Asphalt Pavement Analyzer; BMD = balanced mix design.

Summary of Findings

Mixtures From Producer A

- From the laboratory testing of Mixtures A-I through A-V, it was clear that these mixtures, although possessing similar and acceptable volumetric properties and gradations, showed differences in response when subjected to the BMD testing performed in this study. This demonstrated how volumetric properties and gradations alone cannot differentiate mixture performance. Performance testing can capture the influence of binder properties/grades and use of a recycling agent on the mixture response that volumetrics do not address. The ability of the BMD concept to address and measure mixture performance is a central benefit of the adoption of this method.

Volumetrics

- All mixtures, including those incorporating 40% RAP and a recycling agent or softer binder, were designed in accordance with VDOT specifications.

- Production results indicated that all mixtures could be produced consistently in terms of volumetric properties and gradation.

Cantabro Test Results

- Statistical differences and inconsistent pass-fail trends for mixture reheat results for the same mixture suggested that multiple tests for each lot will be needed in order to use an average performance test value against the performance criteria for acceptance or BMD quality control and assurance practices for the Cantabro test.

- Mixture reheating produced mixed results for the Cantabro mass loss; no consistent trend between the non-reheat and reheat processes was found. This indicated the potential need for a different performance criterion for the non-reheated mixtures. Although the COV results for the Cantabro test performed at VTRC were promising, there is no precision estimate for the test method, hindering the ability to assess acceptable results for single-operator and multi-laboratory conditions.

- The passing performance results and lack of statistically significant differences in the design results for Mixtures A-I, A-IV, and A-V; the plant results for Mixtures A-I, A-II, A-IV, and A-V; and the reheat results for Mixtures A-I through A-V indicated that these 40% RAP mixtures containing a softer binder or recycling agent should have a performance that is equal to the performance of their counterpart 30% RAP mixtures containing a standard binder in terms of durability as measured in the laboratory using the Cantabro test. The use of the BMD concept successfully allowed inclusion of a softer binder and recycling agent to provide improved mixture durability.

IDT-CT Test Results

- Statistical differences and inconsistent pass-fail trends for mixture reheat results for the same mixture suggested that multiple tests for each lot will be needed in order to use an average performance test value against the performance criteria for acceptance or BMD quality control and assurance practices for the IDT-CT test.

- The differences between plant and reheat values for individual mixtures and the observations that a passing CT index during the plant testing did not guarantee a passing CT index during the reheat testing suggested that consideration of different performance criteria may be justified for non-reheated specimens. These findings also indicated the need for further evaluation of the effects of conditioning or aging.

- The average COV for the Producer A mixtures was high, suggesting a need to consider alternative cracking indices obtained from the IDT-CT test that can provide lower variability.

- The passing performance results and lack of significant differences in the design results for Mixtures A-I, A-IV, and A-V; in the plant results for Mixtures A-I and A-III through A-V; and in the reheat results for Mixtures A,I, A-IV, and A-V indicated that these 40% RAP mixtures incorporating a softer binder or recycling agent should have a performance that is equal to the performance of their counterpart 30% RAP mixture with a standard binder in terms of cracking susceptibility as measured in the laboratory using the IDT-CT test.

- The use of PG 58-28 binder significantly improved the plant CT index values of the 30% RAP mixture compared to the use of PG 64S-22 binder. The use of PG 58-28 binder did not improve the plant CT index values of the 40% RAP mixture compared to the use of PG 64S-22 binder.

- The use of PG 58-28 binder in both the 30% and 40% RAP mixtures significantly improved the reheat CT index values compared to those of the same RAP content mixture incorporating PG 64S-22 binder.

- The use of a recycling agent improved the reheat performance of the 40% RAP mixture compared to the performance of 40% RAP mixtures produced with either PG 58-22 or PG 64S-22 binder.

APA Rut Test Results

- Although none of the sets tested for Producer A mixtures failed or varied significantly for rutting performance, because of production variability, multiple tests for each lot will still be needed for this test for acceptance of asphalt mixtures or BMD quality control and assurance practices. However, because of the passing performance and consistent results throughout production, the APA test may not need to be performed as frequently as the Cantabro and IDT-CT tests.

- There were no significant differences between the reheat and design rut depth values or between the reheat and plant rut depth values, and all sets had passing rut depths. From this, it appears that either plant or reheat test results may be used to evaluate the mixtures. However, further studies are needed to confirm this outcome.

- Although COV results for the APA test performed at VTRC were promising, there is no precision estimate for the test method, hindering the ability to assess acceptable results for single-operator and multi-laboratory conditions.

- The passing performance results and lack of significant differences in the design results for Mixtures A-I, A-IV, and A-V; in the plant results for Mixtures A-I, A-III, A-IV, and A-V; and in the reheat results for Mixtures A-I through A-V indicated that these 40% RAP mixtures incorporating a standard binder, softer binder, or recycling agent should have a performance that is equal to the performance of their counterpart 30% RAP mixture with a standard binder in terms of rutting susceptibility as measured in the laboratory using the APA test.

Mixtures From Producer B

- From the laboratory testing of Mixtures B-I through B-IV, it was clear that these mixtures, although possessing similar and acceptable volumetric properties and gradations, showed differences in response when subjected to the BMD testing performed in this study. This demonstrated how volumetric properties and gradations alone cannot discriminate mixture performance. Performance testing can capture the influence of the use of WMA additives and recycling agents on the mixture response that volumetrics do not address. The ability of the BMD concept to address and measure mixture performance is a central benefit of the adoption of this method.

Volumetrics

- All mixtures, including those incorporating a recycling agent and/or WMA additive, were designed in accordance with VDOT specifications.

- Production results indicated that all mixtures could be produced consistently in terms of volumetric properties and gradation.

Cantabro Test Results

- Several sets of the plant and reheat sets throughout production statistically differed, indicating that multiple tests for each lot will be needed in order to use an average performance test value against the performance criteria for acceptance or BMD quality control and assurance practices for the Cantabro test.

- Although COV results for the Cantabro test performed at VTRC were promising, the test method lacks a precision estimate, inhibiting the assessment of acceptable results for single-operator and multi-laboratory conditions.

- Mixture reheating did not have a significant effect on results, although reheat mass losses were less than non-reheated plant mass losses.

- The passing performance results and the lack of significant differences in the plant results for Mixtures B1, B-II and B-IV and in the reheat results for Mixtures B1 through B-IV indicated that the mixtures in this study containing WMA additives and those containing WMA and a recycling agent should perform equally in terms of durability as measured in the laboratory by the Cantabro test.

- The Cantabro mass loss results also indicated that the use of the BMD concept may successfully allow inclusion of recycling agents and WMA additives to provide improved mixture durability.

IDT-CT Test Results

- The CT index values for individual reheat sets throughout production statistically differed, indicating that multiple tests for each lot will be needed in order to compare an average performance test value against the performance criteria for acceptance of asphalt mixtures or BMD quality control and assurance practices for the IDT-CT test.

- Mixture reheating produced mixed results in CT index values; no consistent trend was found between the plant and reheat results. This indicated that further evaluation of the effect of conditioning or aging is needed and suggests that the use of different CT index performance criteria may need to be considered.

- The plant and reheat CT index results for Mixtures B-I through B-IV indicated that the mixtures containing a recycling agent and WMA additive should perform equally to or better than their counterpart mixture containing a WMA additive in terms of cracking susceptibility as measured by the IDT-CT test.

- The results also indicated that the use of the BMD concept may successfully allow inclusion of these materials to provide improved mixture cracking performance. However, the long-term laboratory and field performance of such mixtures needs to be evaluated to confirm this.

APA Rut Test Results

- Mixture reheating had a significant effect on the results from only one mixture, and reheat rut depth values were less than plant rut depth values.

- None of the sets tested for Producer B mixtures failed the rutting performance criterion, and only one mixture had a significant difference between plant and reheat sets. However, the difference in one of four otherwise consistent mixtures indicated that production variability can be a concern; thus, multiple tests for each lot will still be needed for acceptance of asphalt mixtures or BMD quality control and assurance practices. In addition, the APA test may not need to be performed as frequently as the Cantabro and IDT-CT tests because of the passing performance and mostly consistent results throughout production. The COV for the

APA rut tests performed at VTRC were promising; however, the test method lacks a precision estimate, preventing the verification of acceptable results for single-operator and multi-laboratory conditions.

- The plant and reheat rut depth results for Mixtures B-I through B-IV indicated that the mixtures containing a recycling agent and WMA additive should perform equally to or better than their counterpart mixture containing the same WMA additive in terms of rutting susceptibility as measured in the laboratory by the APA test.

- The rut depth results indicated that the use of the BMD concept may successfully allow inclusion of these materials to provide improved mixture rutting performance.

Preliminary Evaluation of Relationships Between Non-Reheat and Reheat Test Results

- The evaluation of additional mixtures having more varied performance responses is needed to provide a robust dataset to confirm or prove false the findings indicating no relationships between non-reheat and reheat test results for the Cantabro, IDT-CT, and APA tests.

Cantabro Test Results

- Overall, the mixtures in this study indicated that reheating prior to compaction generally leads to an increase in mass loss.

- The wider range of reheat mass loss results for the mixtures in this study compared to the range of plant mass loss results may indicate the possibility of increased discrimination potential for mixture performance by testing reheated test specimens.

- The lack of relationship between plant and reheat mass loss results does not provide a means to establish a performance threshold limit for plant test results or validate that evaluating the plant test results with respect to the durability performance criterion established from the reheat testing of mixtures will provide satisfactory performance.

IDT-CT Test Results

- Reheating prior to compaction generally leads to a decrease in the CT index, likely caused by an increase in brittleness, which indicated a greater potential susceptibility of the mixture to cracking.

- CT index data indicated the need to establish a performance criterion for non-reheated specimens if non-reheat testing is to continue to be used. The data from the study do not provide enough information to establish that performance threshold limit.

APA Rut Test Results

- For the mixtures evaluated in this study, the lack of significant differences in test results between reheated or non-reheated specimens suggested that evaluating the rutting performance of asphalt mixtures might be achieved through APA testing of reheated or non-reheated specimens with the same threshold value.

- Additional APA rut depth data are needed from mixtures with a wider range of rutting performance to provide better information to evaluate differences and relationships between non-reheated and reheated specimen test results and to validate further the rutting performance criterion.

CONCLUSIONS

- *Mixtures containing a softer binder, WMA additives, 40% RAP, and recycling agents may be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements.*

- *The laboratory performance test results from the mixtures in this study indicate that 26% RAP mixtures containing WMA additives and a recycling agent may be designed and produced such that their performance is equal to or better than the performance of their counterpart mixtures containing only a WMA additive.* However, the long-term laboratory and field performance of such mixtures needs to be evaluated.

- *The laboratory performance test results from the mixtures in this study indicate that these asphalt mixtures containing 40% RAP and PG 64S-22 binder, PG 58-28 binder, or PG 64S-22 binder and a recycling agent may be designed and produced such that their performance is equal to or better than the performance of their counterpart 30% RAP mixtures.* However, the long-term laboratory and field performance of such mixtures needs to be evaluated.

- *The precision estimates for the Cantabro and APA tests need to be established.* Both test methods lack precision estimates, preventing the evaluation of results for acceptability under single-operator and multi-laboratory conditions. This information is necessary for the development of acceptance specifications.

- *The development of different performance criteria for Cantabro and IDT-CT tests to be applied to non-reheated specimen testing may be necessary.* Results from the mixtures in the study suggested that when Cantabro and IDT-CT test results during design met the performance criteria, generally, it could be anticipated that reheat test results would also meet the performance criteria, although no relationship between the design and reheat test results was found. This trend did not hold true for non-reheated specimen results, implying that these results may need to be compared to condition-specific criteria.

- *The mixture performance test results for the mixtures in each trial project varied, in some cases statistically and practically, although the overall asphalt content and gradations of the asphalt mixtures produced for each project were similar.* Additional efforts to determine how volumetric and gradation properties influence the results of each performance test across a wide variety of mixtures are needed.

- *Because of the variability in individual test results, multiple Cantabro and IDT-CT tests for each lot may be necessary such that an average test value can be used in BMD quality control, quality assurance, or acceptance practices*. In addition, the differences between laboratory and plant production such as aging conditions, as well as the inherent variability during plant production and associated changes in volumetric properties, provide additional justification of the need for multiple performance test measurements.

- *Because of the lack of failing test results among the mixtures in this study, APA tests may not need to be performed as frequently as Cantabro and IDT-CT tests during production.* This would be convenient for both industry and VDOT, considering the cost and time required to perform the test. Alternative simple and fast tests such as the high temperature IDT test may also be used for evaluating the rutting performance of mixtures, especially during production.

RECOMMENDATIONS

1. *VDOT's Materials Division and VTRC should continue to collaborate on the planned implementation of the BMD process for mix design.* There are still significant issues to address as implementation approaches and greater experience leads to new questions. Continued evaluation of the potential use of various additives and alternative materials is needed to understand their impact on performance.

2. *VTRC should pursue efforts to determine precision estimates for the Cantabro and APA tests*. These efforts may be through participation in externally administered interlaboratory studies or the development of interlaboratory studies to be administered by VTRC.

3. *VTRC should monitor the field performance of these test sites to track the short- and long-term field and laboratory performance of these mixtures.* Monitoring of in-service performance is necessary to validate that the performance criteria selected are appropriate to provide an improvement in mixture performance compared to that of current mixtures.

4. *VTRC should continue to evaluate the relationships between mixture properties and performance test results.* It is clear that volumetrics and material properties such as aggregate type and gradation, binder type, and RAP properties play a role in mixture performance, but the details are still unclear. There is a need to determine how material changes such as aggregate type, gradation, mixture structure, asphalt content and type, RAP properties, inclusion of additives, and the interactive mixture response of such changes can specifically change the laboratory measures of performance: mass loss, cracking index, and rut depth.

5. *VTRC should continue to evaluate improvements to BMD performance tests and criteria.* Further simplification of the APA test or determination of a surrogate test for production testing is needed. Given the high variability of the results, further study is necessary to validate the current thresholds for acceptable designs. Adjustments to the initial thresholds for BMD mix design acceptability may be necessary as additional data become available.

Additional efforts to validate current performance criteria with respect to in-service performance are also necessary.

6. *VTRC should evaluate the impacts of short- and long-term laboratory aging on the results of BMD performance tests.* Performance testing is clearly affected by the aging state of test specimens. There is a need to determine the appropriate laboratory conditioning to simulate particular aging states during production and to determine the appropriate performance criteria under those conditions or states that will relate to in-service performance.

IMPLEMENTATION AND BENEFITS

Implementation

Regarding Recommendation 1, VDOT's Materials Division has targeted initial implementation of BMD beginning in 2023. VTRC is dedicated to supporting this effort and will continue to collaborate and provide research support. Staff from the Materials Division and VTRC jointly chair the BMD Technical Committee that provides a collaborative space for discussion and feedback among VDOT, VTRC, and industry participants. Additional paving trials are underway for the 2021 construction season, and the development of plans and specifications for 2022 projects are ongoing. A draft roadmap for BMD implementation has been developed by Diefenderfer at al. (2021) and is being refined collaboratively to serve as a guide to the activities necessary for implementation and a resource to evaluate progress.

Regarding Recommendation 2, VTRC completed Project 116473, Round Robin Testing Program for the Indirect Tensile Cracking Test at Intermediate Temperature—Phase I, in August 2020 that developed precision estimates for ASTM D8225 based on prefabricated test specimens. Project 118733, Round Robin Testing Program for the Indirect Tensile Cracking Test (IDT-CT) at Intermediate Temperature, is ongoing and will address the effects of specimen fabrication on the precision estimates of ASTM D8225. Additional efforts to address precision estimates for AASHTO TP 108, Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens, and AASHTO T 340, Method of Test for Determining Rutting Susceptibility of HMA Using the Asphalt Pavement Analyzer (APA), are anticipated for the future as soon as resources allow.

Regarding Recommendations 3, 4, 5, and 6, VTRC has ongoing projects and anticipates additional future work to meet these needs. Project 117566, Evaluating Recycling Agents' Acceptance for Virginia: Test Protocols and Performance-Based Threshold Criteria, is developing a testing protocol to evaluate the effectiveness of recycling agents in alleviating the brittleness of high RAP asphalt mixtures and developing a performance-based parameter(s) with criteria to allow acceptance of products and will be complete in 2023. Project 117336, Feasibility of Using Monotonic Loading-Based Tests to Evaluate Rutting Performance of Asphalt Mixtures, is ongoing. The study is extensively analyzing the IDT test as a surrogate test for the APA test and will be completed in late 2022. Monitoring the in-service performance of

BMD mixtures is planned as part of the draft roadmap for BMD implementation, along with work to assess the effects of aging and laboratory conditioning, as soon as resources allow.

Benefits

Improving the durability of asphalt mixtures is a priority for VDOT. The BMD concept is intended to improve durability through the incorporation of performance criteria into mix design and acceptance. This provides VDOT with a new approach for specifying asphalt mix designs in an effort to make its roadway network more sustainable, longer lasting, and more economical. By incorporating performance criteria in the mix design process, mixtures will be optimized to provide resistance to deterioration, although it must be understood that these mixtures cannot be expected to compensate for unsound underlying pavement structures or inappropriate selection of maintenance treatments. The goals of BMD implementation include extending the lifespan of dense-graded SMs. Further, use of a BMD should allow for the development of new, innovative methods to increase pavement recyclability and enhance pavement performance through the application of new additives and technologies and through other means.

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APPENDIX A

SPECIAL PROVISION FOR BALANCED MIX DESIGN (BMD) SURFACE MIXTURES DESIGNED USING PERFORMANCE CRITERIA

Rev. 3 7/1/2019

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR

BALANCED MIX DESIGN (BMD) SURFACE MIXTURES DESIGNED USING PERFORMANCE CRITERIA

I. Description

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

II. Materials

All materials shall be in accordance with Section 211.02 of the Specifications.

III. Job-Mix Formula

Mix Types SM-9.5A, SM-9.5D, SM-9.5E SM-12.5A, SM-12.5D, SM-12.5E may be designed to meet either the Performance + Volumetric (BP+V) criteria or the Performance Only (BP) criteria included in this section. Each mix type used shall meet the requirements of Section 211 and any related Special Provisions included in this contract.

Type Performance + Volumetric (BP+V) asphalt mixtures shall be designed to meet the requirements of Section 211.03 of the Specifications as well as the requirements of Table 1.

Type Performance Only (BP) 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 T340 – 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) Gyratory pill: 150 mm dia., 75 ± 2 mm ht. Compact to 7±0.5% air voids Lab produced mix: condition loose mix for 2 hours at the design compaction temperature prior to compacting Plant produced mix: Minimize any cooling of and bring specimens to the compaction temperature and compact immediately.	Rutting ≤ 8.0mm
AASHTO TP 108-14 (2018) Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens (Cantabro)	300 rotations 30-33 rot/min	3 replicates Gyratory pill: 150 mm dia., 115 ± 5 mm ht. Compact to N_{design}, report air voids Lab-produced mix – condition loose mix for 2 hours at the design compaction temperature prior to compacting	Mass loss ≤ 7.5%
ASTM D8225 (2019) 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 2hours ± 10 min. Specimens must remain dry, if conditioning in a water bath, specimens must be sealed in plastic bags. Apply load using load-line displacement control at rate of 50 mm/minute, record load to peak and through failure; analyze.	3 replicates Gyratory pill- 150mm dia., 62 ± 2mm ht. Compact to 7±0.5% air voids Lab-produced mix – condition loose mix for 4 hours at the design compaction temperature prior to compacting	$CT_{index} \geq 70$

The job-mix formula for (BP) 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 R35 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 (BP and/or BP+V) JMF shall exhibit improvement over original JMF (Control), 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.

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.

Note: No changes to the standard lot sizes as defined in Sections 211 and 315

V. Acceptance

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

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

VI. Initial Production

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

APPENDIX B

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

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 either 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 this contract, expect the maximum RAP percentages as indicated in TABLE II-14A shall be waived. Approval from the Engineer is required if the use of a PG binder grade not currently approved, or an asphalt rejuvenator is used 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.

Type Performance + Volumetric (P+V) asphalt mixtures shall be designed to meet the requirements of Section 211.03 of the Specifications as well as the requirements of 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 T340 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) • Gyratory pill: 150 mm dia., 75 ± 2 mm ht. • Compact to 7±0.5% air voids • Lab produced mix: condition loose mix for 2 hours at the design compaction temperature prior to compacting • Plant produced mix: Minimize any cooling of and bring specimens to the compaction temperature and compact immediately.	Rutting ≤ 8.0mm
AASHTO TP 108-14 (2018) Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens (Cantabro)	300 rotations 30-33 rot/min	• 3 replicates • Gyratory pill: 150 mm dia., 115 ± 5 mm ht. • Compact to N_{design}, report air voids • Lab-produced mix – condition loose mix for 2 hours at the design compaction temperature prior to compacting	Mass loss ≤ 7.5%
ASTM D8225 2019 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 2hours ± 10 min. Specimens must remain dry, if conditioning in a water bath, specimens must be sealed in plastic bags. • Apply load using load-line displacement control at rate of 50 mm/minute, record load to peak and through failure; analyze.	• 3 replicates • Gyratory pill- 150mm dia., 62 ± 2mm ht. • Compact to 7±0.5% air voids • Lab-produced mix – condition loose mix for 4 hours at the design compaction temperature prior to compacting	$CT_{index} \geq 70$

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 R35 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.

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.

Note: No changes to the standard lot sizes as defined in Sections 211 and 315.

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.