Balanced Mix Design for Surface Asphalt Mixtures: Phase I: Initial Roadmap Development and Specification Verification

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16. Abstract:

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. The balanced mix design (BMD) method addresses this through the incorporation of performance criteria into mix design and acceptance. VDOT has committed to the implementation of the BMD method in an effort to improve asphalt mixture performance.

The purpose of this study was to continue advancing efforts toward VDOT's implementation of BMD by developing a performance-based mix design roadmap for application in Virginia. The proposed roadmap was developed to provide guidance on the specific needs and activities necessary for VDOT to adopt the BMD concept. A specific need outlined in the roadmap was to validate and/or refine the selected initial performance tests and associated test threshold criteria. To accomplish this, 13 asphalt mixtures were evaluated using performance-measuring laboratory tests. The results of these tests were used to assess the initial performance tests and test threshold criteria selected for BMD use.

The proposed roadmap is intended to be an evolving resource for outlining the agenda of activities necessary for implementation of BMD. The roadmap identified specific needs addressed in this study. Based on the results for the mixtures evaluated as part of those needs, the Asphalt Pavement Analyzer (APA) rut test (hereinafter "APA test"); indirect tensile cracking test (IDT-CT) (hereinafter "IDT-CT test"); and Cantabro mass loss test (hereinafter "Cantabro test") are suitable for continued use in BMD. The current threshold criteria for all three tests were reasonable, based on additional testing and analysis.

The study recommends that the roadmap for BMD continue to be refined to provide a clear direction of the activities necessary for implementation and serve as a resource to evaluate progress. VDOT should continue to use the APA, IDT-CT, and Cantabro tests for BMD. The APA and IDT-CT test results should be compared and correlated with those of fundamental rutting and cracking tests, respectively, and with performance predictions obtained from mechanistic-empirical pavement design simulations and field performance for full assurance that test threshold values are appropriate. In addition, the differences in test results attributable to mixture reheating and different specimen types, such as laboratory-compacted specimens and field cores, should be addressed. The study further recommends evaluating the Cantabro, IDT-CT, and APA test results to determine acceptable variability and establish precision statements.

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FINAL REPORT

BALANCED MIX DESIGN FOR SURFACE ASPHALT MIXTURES: PHASE I: INITIAL ROADMAP DEVELOPMENT AND SPECIFICATION VERIFICATION

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INTRODUCTION

Historically, the design of asphalt mixtures has been largely based on the volumetric properties of the mixture. The move to the Superpave mix design process in the mid-1990s continued to rely on these principles, which are used in both mix design and acceptance during production. Part of the initial Superpave mix design procedure included various degrees of asphalt mixture performance testing, especially for roads designed for moderate to high volumes. However, because of a number of factors, these performance tests were implemented on a limited basis. For many years, there has been a desire for owner agencies and the asphalt industry to have performance tests that can be used in the design process both to screen mixtures that may pass volumetric criteria but perform poorly in the field because of mixture deficiencies and to 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 the most common distresses such as rutting and cracking. The approach requires that a mix design pass performance criteria for approval. The approval process can take place at the mixture acceptance and/or construction acceptance level. The BMD is a significant step forward in the pursuit of better performing asphalt mixtures; however, these mixtures cannot compensate for an unsound underlying pavement structure or the selection of inappropriate maintenance treatments.

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. The BMD method addresses this 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. There are differing levels of application of the BMD method that allow implementation to occur in stages, as agencies and industry become more familiar with the process.

BMD is not yet a widely established method of design, and as such, there are not existing specifications readily available for widespread adoption. There is a need to develop a framework to address how VDOT can adopt this method and a need for specification language and requirements. In addition, a validation of proposed specification requirements is necessary, along with training activities to ensure agency and industry consistency in applying the new method and specifications.

In January 2018, an initial effort was undertaken by researchers at the Virginia Transportation Research Council (VTRC) to provide benchmark indications of performance for a number of asphalt mixtures produced and sampled in 2015 (Bowers and Diefenderfer, 2018). These mixtures were characterized in the laboratory using numerous performance tests. Based on the study, a suite of performance tests addressing different modes of pavement distress (i.e., durability, cracking, and rutting) was selected for use in the BMD method. This selection was based on several factors such as the degree of correlation of the tests to fundamental performance test methods or in-service performance; simplicity and repeatability of the tests; cost-effectiveness of the test methods associated with the procurement of test equipment; and time needed to perform each test. The selected tests were 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 durability, cracking potential, and rutting potential, respectively, of asphalt mixtures. In addition, initial performance threshold criteria were developed for the selected tests.

PURPOSE AND SCOPE

The purpose of this study was to build on previous efforts toward implementation of BMD by developing a draft roadmap to guide adoption of the BMD concept in Virginia. In addition, the study addressed specific needs for test and threshold criterion validation and refinement identified in the draft roadmap. This required the continued evaluation of current mixtures using performance-measuring laboratory tests and analysis of the resulting data to validate and refine the initial performance tests and test threshold criteria selected for BMD use.

METHODS

The following tasks were performed to achieve the study objectives:

1. A literature review was conducted, including a summary of Virginia’s BMD efforts to date.

2. A roadmap for BMD implementation was developed.

3. Plant-produced mixtures were sampled, and select paving projects were documented.

4. Laboratory testing was conducted and analyses were performed to validate and/or refine initial performance test selection and performance threshold criteria.

Literature Review

Literature related to BMD was identified by a search of various databases related to transportation engineering such as the Transport Research International Documentation (TRID) database. The identified literature was then reviewed in order to summarize findings from relevant work.

VDOT and VTRC began to investigate the application of BMD in 2018. A summary of relevant activities leading to specification development and the current effort is provided.

Roadmap Development

Based on the results of the literature review, project experiences, and initial VDOT activities, a draft roadmap was developed to outline necessary steps and activities for continued progress toward implementation of the BMD method.

Sampling and Documentation

Loose Mixtures

Thirteen plant-produced mixtures were collected from various plants in Virginia in 2018. The sampled mixtures were dense-graded surface mixtures (SMs) having a nominal maximum aggregate size (NMAS) of 9.5 mm and 12.5 mm that were being used in maintenance paving contracts. The mixtures were designated A through M.

Field Cores

Cores were collected from six paving sites during construction. These sites corresponded to plant-produced Mixtures A through F. Cores were taken approximately every 100 ft along the center of the lane. Air-void contents were determined in accordance with AASHTO T 269, Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures.

Paving Project Location

Project locations were documented for six of the Mixtures (A through F) in order 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 1.

Table 1. Paving Project Information

	Mix Type	RAP Content	Paving Date	District	Location
A	SM-9.5A	30%	6/28/2018	Hampton Roads	Settlers Landing Road, City of Hampton
B	SM-12.5A	30%	8/22/2018	Fredericksburg	US 3, Spotsylvania County
C	SM-12.5D	26%	9/12/2018	Lynchburg	SR 623, Nelson County
D	SM-9.5D	26%	10/2/2018	Salem	SR 100, Giles County
E	SM-9.5D	26%	10/31/2018	Salem	SR 122, Bedford County
F	SM-12.5A	30%	11/14/2018	Fredericksburg	SR 684, Essex County

RAP = reclaimed asphalt pavement.

Laboratory Testing and Evaluation

Laboratory testing was conducted on the sampled mixtures to achieve two objectives: (1) validate and/or refine the selection of suitable BMD performance tests, and (2) validate and/or refine the selected performance-based threshold criteria. All of the evaluated mixtures were typical production mixtures, designed under VDOT specifications for Superpave mixtures. Figure 1 summarizes the laboratory experimental plan.

Validation and refinement of the initially selected BMD performance tests were accomplished by evaluating six of the collected mixtures (A through F). Volumetric properties and gradations of the mixtures and the performance grade (PG) and rheological properties of the extracted and recovered asphalt binders were determined. The tests initially determined for use with BMD in Virginia were performed on reheated, laboratory-compacted specimens: the Cantabro test for durability, the APA test for rutting susceptibility, and the IDT-CT test for cracking susceptibility. For validation purposes, additional cracking tests were performed: the overlay test (OT), Illinois Flexibility Index test (I-FIT), and indirect tensile N_{flex} factor test. The cracking indices of the tests were further evaluated in terms of variability; discrimination potential and ranking among the selected asphalt mixtures; and correlation among each other. Finally, the mechanical properties in terms of dynamic modulus (E*) and phase angle (δ) were determined for the six mixtures using reheated, laboratory-compacted specimens. Parameters such as the Glover-Rowe ($G\text{-}R_m$) at intermediate temperature were determined and employed to evaluate and compare the cracking resistance of the mixtures. Further, because rutting distress has been proven to have a direct correlation with the structural responses of the mixtures to loading, the |E*| master curves were also used to estimate the rutting susceptibility of the mixtures.

Validation and refinement of the selected performance-based threshold criteria were accomplished by evaluating Mixtures A through F and seven additional plant-produced mixtures, Mixtures G through M. Volumetric properties and gradations were determined for all mixtures. The Cantabro, APA, and IDT-CT tests were conducted on reheated laboratory-compacted specimens for all mixtures. For some of the mixtures, the Cantabro, APA, and IDT-CT tests were conducted on non-reheated specimens compacted on-site in the contractor’s laboratory by VTRC staff and/or the producer’s staff. The APA and IDT-CT tests were also conducted on field-compacted specimens (i.e., cores) collected from the paving site. The resulting data were compared to the preliminary threshold criteria. In addition, the various specimen types (e.g., reheated vs. non-reheated) were used to evaluate the effect of reheating on the test variability and magnitude of the resulting indices.

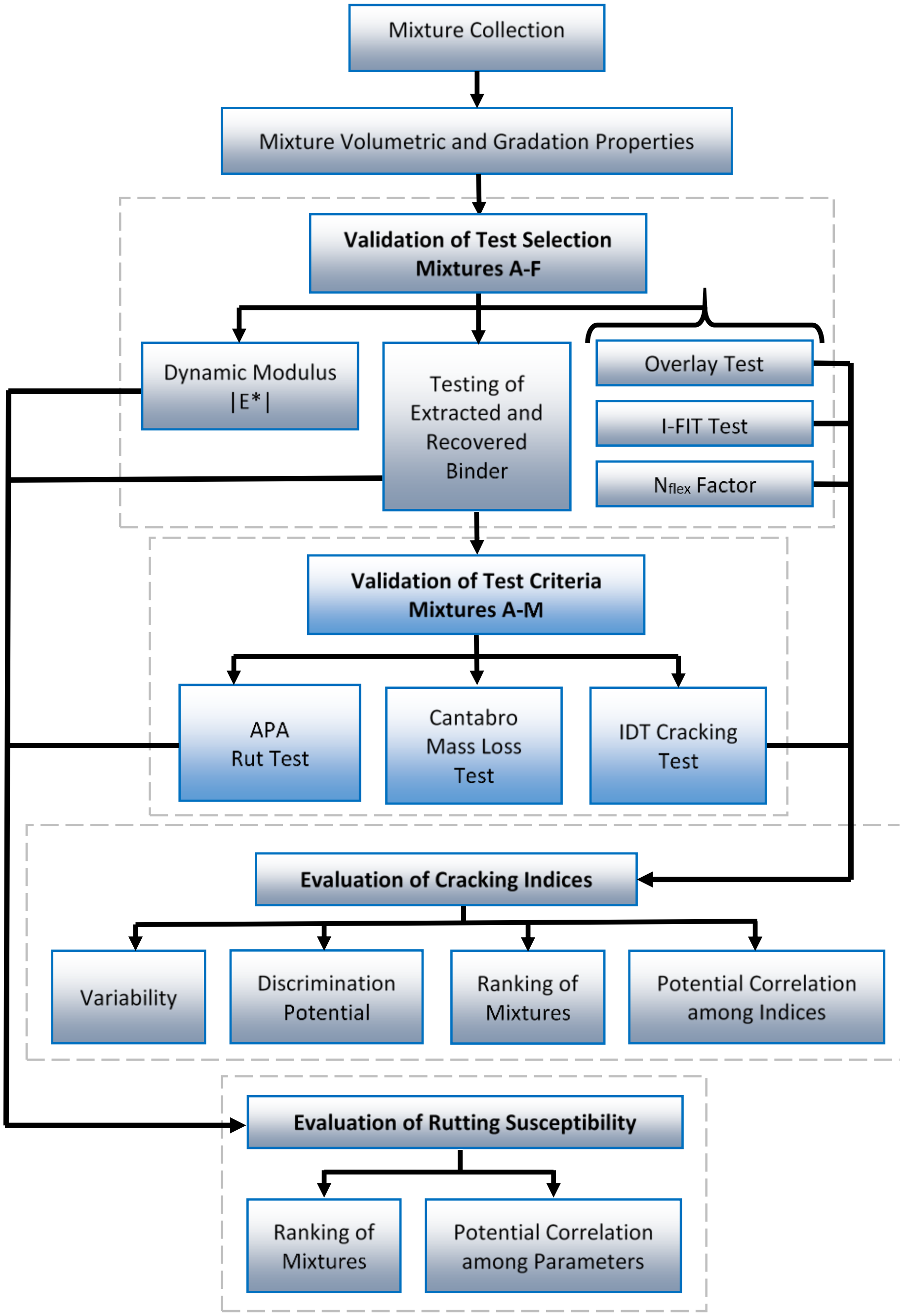


Figure 1. Flowchart of the Experimental Program. Bold titles in each light gray dashed box show the key evaluations performed.

Specimen Designations

Laboratory testing was conducted on several types of specimens fabricated from the mixture produced at the plant:

- *LCNR*. Laboratory-compacted non-reheated specimens were compacted on-site at the plant by VTRC staff without reheating loose mixture sampled at the plant.

- *LCNR-P. L*aboratory-compacted non-reheated specimens were compacted on-site at the plant by producer staff without reheating the loose mixture sampled at the plant.

- *LCR.* Laboratory-compacted reheated specimens were compacted in the VTRC laboratory by VTRC staff after reheating loose mixture sampled at the plant.

- *FC.* Field-compacted specimens were cored from the mat at the job site.

Specimens were designated “X-Y,” where “X” is the mixture designation (A-M) and “Y” is the specimen type (LCNR, LCNR-P, LCR, or FC).

Reheated specimens were fabricated by reheating the loose mixture in boxes until workable, splitting the material into specimen quantities, and then heating to the appropriate compaction temperature and compacting.

Mixture Volumetric Properties and Gradations

Volumetric and gradation analyses were performed to determine fundamental mixture properties. The data collected included asphalt content and gradation; bulk and Rice mixture specific gravities (G_{mb} and G_{mm}); air voids (voids in total mix [VTM]); voids in mineral aggregate (VMA); voids filled with asphalt (VFA); bulk and effective aggregate specific gravities (G_{sb} and G_{se}); dust/asphalt ratio; percent binder absorbed (P_{ba}); and effective binder content (P_{be}).

Asphalt Binder Extraction and Recovery

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

Asphalt Binder Testing

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

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.

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.

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, using an Instrotek Auto-SCB load frame with a 15 kN load cell. A minimum of three replicate specimens were tested.

Overlay Test

The OT was performed on mixtures to evaluate cracking in general and reflective cracking in particular generally in accordance with TX-248-F, Test Procedure for Overlay Test (Texas Department of Transportation [DOT], 2014). Test specimens were cut in pairs from the center of gyratory specimens that were 150 mm in diameter and 170 mm in height; care was taken to minimize any influence of an air-void differential between the top and bottom of the specimen. Testing was performed using a universal testing machine with a 25 to 100 kN loading capacity. A temperature of 25 ± 0.5°C was used for testing; loading was applied for 1,200 cycles or until a 93% reduction of the initial load was reached. Four replicate specimens were tested.

The OT was performed; however, the data quality checks indicated that the test results were flawed for four of the six mixtures tested. The test data for these mixtures showed a sudden drop in the load magnitude after two or three loading cycles followed by a very low (less than 1 kN) steady load magnitude until the test reached its termination point at 1,200 loading cycles. The adhesive agent used to glue test specimens to the test plates was the source of the flawed tests. The visual inspection of the test specimens indicated that adhesive failure occurred between the adhesive agent and the specimens during the tests because of the defective adhesive agent. The tests could not be repeated because sufficient materials were not available to fabricate additional test specimens. Thus, no data were reported.

Illinois Flexibility Index Test

The Semi-Circular Bend (SCB) I-FIT for cracking resistance was conducted in accordance with AASHTO TP 124-16, Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature. Tests were conducted at a temperature of 25 ± 0.5°C using an Instrotek Auto-SCB load frame with a 15 kN load cell. The analysis of the results was conducted using the I-FIT (IL-SCB) Analysis Tool developed by the Illinois Center for Transportation and the University of Illinois Urbana-Champaign. Four replicate specimens were tested.

N_{flex} Factor Test

The N_{flex} factor test was conducted in accordance with the method proposed by Yin et al. (2018). A gyratory N_{design} pill was cut to a 50-mm thickness and then loaded in the indirect tensile mode at 25 ± 0.5°C using an Instrotek Auto-SCB load frame with a 15 kN load cell. The load-displacement curve was converted to a stress-strain curve, and a series of mathematical equations were applied to calculate the N_{flex} factor. Four replicate specimens were tested for each mixture.

Dynamic Modulus Test

Dynamic modulus tests were performed using an Asphalt Mixture Performance Tester with a 25 to 100 kN loading capacity in accordance with AASHTO T 342, Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures. Tests were performed on 100-mm-diameter by 150-mm-high specimens compacted to 7.0 ± 0.5% air voids. Four test temperatures (4.4, 21.1, 37.8, and 54.4°C) and six test frequencies ranging from 0.1 to 25 Hz were used. All tests were conducted in the uniaxial mode without confinement. Stress vs. strain values were captured continuously and used to calculate dynamic modulus. Dynamic modulus was computed automatically using IPC |E*| software. Three replicate specimens were tested for each mixture, and results at each temperature-frequency combination were reported.

RESULTS AND DISCUSSION

Literature Review

The National Center for Asphalt Technology recently concluded a National Cooperative Highway Research Program (NCHRP) study on developing a framework for the BMD concept. The study included a survey to obtain information from state DOTs and asphalt contractors regarding the current practice on mix design, mixture performance testing, quality assurance through performance tests, and implementation of BMD. Three BMD approaches were identified and summarized (West et al., 2018):

- *Approach I: volumetric design with performance verification.* This approach involves performing a conventional volumetric mix design method and then applying performance tests to the volumetrically designed mixture. If the design does not meet the required performance criteria, the process is repeated.

- *Approach II: performance-modified volumetric design.* This approach uses volumetric design guidelines to establish the initial aggregate blend and asphalt content. The results of performance testing are then used to adjust the mixture proportions such that the resulting mix design meets performance criteria. In this case, the final design may not be required to meet traditional volumetric criteria.

- *Approach III: performance design.* This approach relies on establishing aggregate blends and asphalt contents that meet the performance testing criteria regardless of the volumetric properties and/or design guidelines.

At the core of the BMD approach is the identification of common pavement distress modes encountered and the identification of associated test methods to address these distresses. According to the survey conducted by West et al. (2018) at the National Center for Asphalt Technology, fatigue cracking, rutting, and thermal cracking were identified as the three main distresses to be addressed with mixture performance testing. Responses to the survey addressed testing requirements (West et al., 2018). A rutting test was required in the current mix design specifications for 24 state DOTs. Only 8 state DOTs mandated the use of a cracking test in design. Some of these DOTs intended to address one specific type of cracking, whereas the others focused on assessing the overall cracking resistance of asphalt mixtures. In terms of quality assurance, 14 state DOTs required performance testing on plant-produced mixtures. The survey noted that multiple concerns were identified by state DOTs and asphalt contractors regarding the implementation of BMD. These concerns included the validity of mixture performance tests, specimen preparation and testing time, and lack of acceptance testing protocols. Overall, 68% of state DOTs (34 of 50) showed interest in constructing BMD field trials. The intent of these demonstration sections was to compare the performance of asphalt mixtures designed following conventional methods (i.e., Superpave volumetric approach) vs. any of the BMD approaches.

A number of states including California, Illinois, Iowa, Louisiana, New Jersey, and Texas have already been experimenting with or implementing the BMD at the mixture acceptance and/or construction acceptance level. All of these states have followed BMD Approach I with the exception of California, which has followed BMD Approach II. No state reported following BMD Approach III.

State BMD Efforts

California has adopted a framework for BMD mixtures that includes performance-based specifications and its mechanistic empirical design program, CalME. These mixtures are typically designed and placed on very-high-volume roads, and the BMD specifications are applied to plant-produced mixtures. The performance testing protocol includes the repeated simple shear test, bending beam fatigue (BBF) test, and Hamburg wheel-track test (HWTT). The specification criteria were selected based on repetitions to 5% permanent deformation shear strain for the repeated simple shear test and 50% loss of stiffness and flexural stiffness at 20°C and a test frequency of 10 Hz for the BBF test (Harvey et al., 2014).

The Illinois DOT is in the process of implementing BMD Approach I. The DOT requires performing the HWTT, I-FIT, and a modified version of the tensile strength ratio test to evaluate rutting, fatigue, and moisture susceptibility, respectively. A long-term aging protocol for implementation of the I-FIT was recently published (Al-Qadi et al., 2019). This effort recommended using aging compacted specimens in forced-draft ovens. Three days of oven aging at 95°C was chosen as the key component of the long-term aging protocol. For acceptance, laboratory-produced laboratory-compacted specimens must have a mean flexibility index (FI) for unaged and oven-aged specimens greater than 8.0 and 5.0, respectively. In addition, plant-produced laboratory-compacted specimens must have a mean FI for unaged and oven-aged specimens greater than 8.0 and 4.0, respectively. Contractors were also provided an optional approach to use oven aging for 1 day at 95°C to screen for problematic mixtures; a minimum FI of 6 should be met for this approach (Al-Qadi et al., 2019).

The Iowa DOT designs the majority of its asphalt mixtures following the conventional Superpave volumetric approach. However, mixtures designed for very-high-volume traffic and/or produced using a particular aggregate mineralogy must be evaluated for rutting resistance using the HWTT by the contractor or a third-party mix design laboratory. The HWTT testing temperature is a function of the asphalt binder PG high temperature. The current specifications require a minimum stripping inflection point of 10,000 cycles and 14,000 cycles for plant-produced mixtures with traffic designation Standard (S), and High (H) or Very High (V), respectively. Additional performance testing and acceptance criteria might be required for special types of asphalt mixtures. Moreover, the Iowa DOT is currently considering the addition of the disc-shaped compact tension test as part of their BMD effort to evaluate mixture resistance to thermal cracking (West et al., 2018).

The Louisiana DOT has implemented BMD Approach I using conventional volumetric criteria along with loaded wheel tracking (LWT) and SCB tests to evaluate rutting and intermediate temperature cracking, respectively, as part of their simplified performance-based specifications. The roadway acceptance test sampling consists of collecting 25 random cores from five sublots, with five random cores per sublot. Some of these cores undergo density measurement and verifications, and others are subjected to LWT and SCB testing (Mohammad et al., 2016). For rutting, the current specifications require an LWT test at 50°C and 20,000 cycles to be lower than 6 mm for mixtures containing polymer and crumb rubber modified asphalt binders and lower than 10 mm for mixtures containing unmodified binders. For cracking, the current specifications require the SCB fracture energy (SCB-J_c) at 25°C to be greater than 0.5 kJ/m^2 and 0.6 kJ/m^2 for unmodified and modified asphalt mixtures, respectively (Cooper et al., 2016). Efforts related to evaluating the changes in test parameters from different specimen types (mix design vs. plant produced vs. field cores), developing an accelerated aging protocol, and implementing the SCB test into quality control are ongoing.

The New Jersey DOT currently uses BMD Approach I on several types of asphalt mixtures including high reclaimed asphalt pavement (RAP), high-performance thin overlay, binder-rich intermediate course, bottom-rich base course, and bridge deck waterproofing surface course mixtures. The performance-testing matrix at both the mix design and plant-production stages includes APA testing at 64°C, tensile strength ratio and OT testing at 25°C, and BBF testing at 15°C. The maximum APA rut depths after 8,000 cycles at 64°C for high RAP mixtures are 4.0 mm and 7.0 mm for modified and unmodified asphalt binders, respectively. In addition, the minimum number of cycles to failure using the OT for high RAP SMs is 275 cycles for modified mixtures and 200 cycles for unmodified mixtures. For high RAP intermediate and base mixtures, the required number of overlay cycles is reduced to 150 for modified mixtures and 100 for unmodified mixtures. Binder-rich intermediate course and high-performance thin overlay mixtures must have APA rut depths not exceeding 6.0 mm and 4.0 mm and minimum numbers of 700 and 600 overlay cycles, respectively. With the shift to using quicker and simpler tests such as the IDT at intermediate and high temperature to evaluate cracking and rutting, tentative thresholds for IDT strength at high temperature and the cracking tolerance index (CT_{index}) at intermediate temperature have been determined and are undergoing further evaluation for possible implementation (Bennert et al., 2020).

The Texas DOT currently uses BMD Approach I for premium asphalt mixtures such as porous friction courses, stone matrix asphalt, thin overlay mixtures, and hot in-place recycling of asphalt concrete surfaces. They require the use of the HWTT and OT to evaluate mixture resistance to rutting/moisture damage and reflection/bottom-up cracking, respectively. The Superpave volumetric mix design criteria are used to determine an optimum binder content (OBC). The HWTT and OT are then used to evaluate specimens at three binder contents (OBC, OBC + 0.5%, and OBC + 1.0%). The final optimum OBC is selected to satisfy the requirements of both tests. The minimum number of HWTT passes to 12.5 mm rut depth at a test temperature of 50°C are 10,000 cycles, 15,000 cycles, and 20,000 cycles for mixtures produced with high-temperature binder PG of 64°C and lower, 70°C, and 76°C and higher, respectively. The requirements for the OT include a minimum critical fracture energy of 1 in-lb/in^2 and a maximum crack propagation rate of 0.45 (Texas DOT, 2019). Zhou et al. (2020) recommended a quality control/quality assurance (QC/QA) acceptance protocol using practical performance-related tests suitable for production QC such as the IDT at intermediate and high temperatures. This includes sampling and conditioning produced loose mixtures at 135°C for 2 hours and then compacting performance test specimens to an air-void level of 7 ± 0.5%. A minimum CT_{index} at 25°C of 105 and a minimum IDT shear strength of 1.02 MPa at 50°C were recommended as QC production acceptance criteria (Zhou et al., 2020).

A growing number of states including Florida, Georgia, Indiana, Minnesota, Nebraska, New Hampshire, New Mexico, Ohio, Oklahoma, Oregon, South Dakota, Utah, and Wisconsin, among others, have ongoing efforts related to BMD. Table 2 summarizes some of the recently completed and current ongoing efforts.

Virginia BMD Efforts

VDOT has continuously supported efforts to improve mixture durability. In an effort to address rutting in Marshall mixtures, the Superpave system began to be adopted in 1997 with the use of PG binders. Adoption continued as VDOT began using Superpave to design mixtures in 2000, and full implementation occurred in 2002. However, it was quickly noted that many of the early Superpave-designed mixtures were coarse and dry, resulting in lives that were shorter than desired. This began an effort to improve service life. Maupin (2003) found that as much as 0.5% binder could be added to nine studied mixtures to obtain beneficial results. To increase binder contents, VDOT changed the gyratory compaction effort from the AASHTO-specified traffic-dependent level to 65 gyrations. Additional work by Maupin (2011) found that binder contents determined during the Superpave design had not significantly changed from those of the previous Marshall mixtures, although differences in mixture gradations may have influenced the results. Following this, VDOT made additional changes to mix design requirements, including further reducing the design gyrations to 50 along with making gradation and volumetric adjustments (Diefenderfer et al., 2018).

Table 2. States With Efforts to Address BMD and/or Performance Testing

State	Description of Efforts
Florida (West et al., 2018)	• Use FN, HWTT, and APA rut tests to evaluate rutting • Use IDT energy ratio and OT to evaluate cracking
Georgia (West et al., 2018)	• Use APA and moisture susceptibility test as part of the mix design approval and field verification of all asphalt mixtures • Use different APA test temperatures depending on mix location in pavement structure • Currently looking into CT_{index} and FI parameters
Minnesota (Newcomb and Zhou, 2018)	• Use the DCT fracture energy, G_f, to evaluate cracking performance • Require DCT testing on both mix design and production mix samples • Considering applying the DCT as a mix design test and the IDT as a QC/QA test • Need further work to define failure criteria for all cracking tests
New Mexico (West et al., 2018)	• Constructed test sections on existing projects by using asphalt mixtures designed following a BMD procedure • Use HWTT to evaluate rutting and stripping potentials of asphalt mixtures
Ohio (Rodezno et al., 2018)	• Use APA testing for mixtures with more than 15% fine aggregates and that do not meet the fine aggregate angularity criteria • Use BBF tests for bridge deck waterproofing mixtures • Selected the I-FIT to assess the cracking resistance and durability of mixtures with recycled materials; however, with the emergence of the IDT, are evaluating the suitability of both tests for implementation in mix design approval and QC/QA. Will recommend specification limits and test standards.
Oklahoma (Cross and Li, 2019)	• Are considering potential implementation of BMD Approach II • Constructed several BMD trial projects in spring 2018 • Use the HWTT, I-FIT, IDT, and Cantabro test to evaluate mix design and production samples • Recommended the IDT if Oklahoma DOT decides to move forward with BMD • Recommended a minimum CT_{index} of 80 as the criterion for short-term aged specimens; recommended consideration of dropping the binder grade in case failure to meet this criterion occurs
Oregon (Coleri et al., 2020)	• Previous research efforts established a performance-based BMD framework that suggested the use of the I-FIT with typical FI values ranging from 9-14 for production mixtures • Recently completed efforts developed a long-term aging protocol to be implemented consisting of aging mixtures at 95°C for 24 hours to simulate not more than 3-5 years of aging in the field; FI threshold was refined to a minimum of 6 for Level 3 mixtures (1-10 million ESALs on rural highways and 1-3 million ESALs on urban highways) and 8 for Level 4 mixtures (>10 million ESALs on rural highways and >3 million ESALs on urban highways). A rut depth threshold of 3 mm for Level 3 mixtures and 2.5 mm for Level 4 mixtures was recommended.
South Dakota (West et al., 2018)	• Currently follows the conventional Superpave volumetric mix design • Uses APA and TSR tests to evaluate rutting and moisture damage of asphalt mixtures, respectively
Utah (West et al., 2018)	• Uses Superpave volumetric approach to design asphalt mixtures • Uses HWTT to evaluate resistance to rutting • Is exploring the use of the BBR sliver test and I-FIT to evaluate the mixture resistance to low-temperature and intermediate-temperature cracking, respectively
Wisconsin (West et al., 2018)	• Lowered the mixture design air-void target from 4.0% to 3.5% • Increased the minimum TSR requirement from 0.70 to 0.75 • Uses HWTT to evaluate moisture susceptibility and rutting • Uses DCT test to evaluate low temperature cracking • Uses SCB test for fatigue cracking • Evaluates the PG grading of the recovered asphalt binder • Is exploring and evaluating the feasibility of using the HWTT, confined FN, and SCB tests at intermediate and low temperatures • Identified potential for increase of asphalt contents by regressed air voids using the HWTT, DCT, and I-FIT tests

APA = Asphalt Pavement Analyzer; BBF = bending beam fatigue; BBR = bending beam rheometer; BMD = balanced mix design; DCT = disk-shaped compact tension; ESALs = equivalent single axle loads; FI = flexibility index; FN = flow number; HWTT = Hamburg wheel-tracking test; IDT = indirect tensile test; OT = overlay test; PG = performance grade; QC/QA = quality control/quality assurance; SCB = semi-circular bend; TSR = tensile strength ratio.

In addition to the efforts to improve durability, VDOT has been responding to increased interest in the use of RAP. Beginning in 2007, VDOT allowed the use of up to 30% RAP (by weight of mixture) in certain dense-graded SMs (Maupin et al., 2008). By 2017, interest from industry in pursuing even higher SM RAP contents, up to 40% and above, had grown, and the need to address this topic and the ongoing desire to achieve longer service lives prompted VDOT and VTRC to begin investigating the BMD concept.

Asphalt Mixture Benchmarking

As previously discussed, the BMD method replaces some aspects of traditional volumetric design with performance testing criteria for most common distresses such as rutting and cracking. The approach requires that a mix design pass performance criteria for approval. However, since no data were available to determine what performance tests should be used or what the threshold criteria should be in order to provide the appropriate lifespan, the effort began by performing benchmarking testing on asphalt mixtures meeting current specifications using potential performance tests. An extensive suite of laboratory tests was performed on specimens fabricated from asphalt mixtures collected during a 2015 study (Diefenderfer et al., 2018) published by VTRC. Loose plant-produced mixtures were collected and evaluated in terms of mixture volumetrics, aggregate gradation, and binder grade. The loose mixture was reheated and compacted to fabricate test specimens for performance testing including the Cantabro test, the APA test, the I-FIT, the OT, the N_{Flex} factor, and the IDT-CT test (Bowers and Diefenderfer, 2018).

After the benchmarking data were evaluated and several approaches were applied to the test selection, Diefenderfer and Bowers (2019) recommended the Cantabro, APA, and IDT-CT tests for consideration in the BMD specification for Virginia. Further analysis was undertaken to determine threshold values for each selected performance test (Bowers and Diefenderfer, 2018). A maximum value of 7.5% was recommended for the Cantabro mass loss threshold to assess general durability. All of the evaluated mixtures had mass loss values within a reasonable range based on the literature (Cox et al., 2017). A maximum rutting threshold of 8.0 mm for APA rut testing was recommended. This limit was near the maximum rut depth exhibited and was selected because Virginia has not experienced any consistent rutting issues in its modern asphalt mixtures. A minimum CT_{index} of 70 was recommended to evaluate the cracking susceptibility. This recommendation was based on the study benchmarking results and the results presented by Zhou et al. (2017). Zhou et al. (2017) included CT_{index} values for mixtures used on the Federal Highway Administration Accelerated Loading and subsequent full-scale test cracking results. It was noted that the worst performing asphalt mixtures had CT_{index} values below 70 whereas the best performing asphalt mixtures had CT_{index} values greater than 100. More information and analysis details can be found elsewhere (Bowers and Diefenderfer, 2018).

Specification Development

The adoption of BMD will not only have VDOT-wide impacts, it will also affect the asphalt construction industry. As part of VDOT's effort to address BMD, two committees were created to coordinate efforts within VDOT and with industry in late 2018. A BMD advisory group was initiated to address BMD at the executive level, manage VDOT-wide communication, determine final policies, and make other relevant decisions. Committee members include VDOT and industry representatives. In addition, a technical committee was established to address the technical aspects of BMD collaboratively among VDOT, VTRC, and industry representatives.

The initial products of the technical committee were the 2019 versions of two special provisions for BMD SFs: (1) Special Provision for Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria, and (2) Special Provision for High RAP Content Surface Mixtures Designed Using Performance Criteria. These are presented in the Appendix. 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, "high RAP content surface mixtures" are defined as having a minimum RAP content of 40%. The provisions cover requirements for materials, job-mix formula (JMF), production testing, acceptance, and initial production. The requirements for performance, recommended from the benchmarking effort, 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 NMAS of the designated mixture type. For both mixtures, performance test results must be reported in the design submission:

- *Cantabro testing:* mass loss at design binder content and 0.5% below design binder contents.

- *IDT-CT testing:* CT_{index} at design binder content, at 0.5% above design binder content, and 0.5% below design binder contents.

- *APA rut testing:* rut depth at design binder content and at 0.5% above design binder contents.

The varying binder content required for each test is intended to provide an indication of how sensitive the mix design is to changes in the binder content. If a mixture is too sensitive, it is likely the mixture could fail the performance criteria during production because of the inherent variability during production. In addition, the performance qualities (as defined in Table 3) for the P and/or P+V JMF must show improvement over the original JMF specifically through a higher CT_{Index}, a lower rutting depth, and less Cantabro mass loss. This is intended to support the goal of improved mixture performance.

P+V mixtures are designed to meet the volumetric requirements in Section 211.03 of the VDOT specifications (VDOT, 2016) and the criteria summarized in Table 3 at the design binder content.

Table 3. Performance Testing Requirements

Test	Procedure	Specimens	Criteria
AASHTO TP 108: Standard Method of Test for Determining the Abrasion Loss of Asphalt Mixture Specimens (Cantabro)	300 rotations 30-33 rotations/min	• 3 replicates • Gyratory pill: 150 mm diameter, 115 ± 5 mm height • Compact to N_{design}, report air voids • Lab-produced mix: condition loose mix for 2 hr at design compaction temperature prior to compacting	Mass loss ≤ 7.5%
AASHTO T 340: Method of Test for Determining Rutting Susceptibility of HMA Using the Asphalt Pavement Analyzer (APA)	8,000 passes at 64°C	• 2 replicates of 2 pills (APA Jr.) • Gyratory pill: 150 mm diameter, 75 ± 2 mm height • Compact to 7 ± 0.5% air voids • Lab-produced mix: condition loose mixture for 2 hr at design compaction temperature prior to compacting • Plant-produced mix: Minimize any cooling, bring specimens to compaction temperature, and compact immediately	Rutting ≤ 8.0 mm
ASTM D 8225: Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature (CT_{index})	• Condition specimens at 25 ± 1°C for 2 hr ± 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/min, record load to peak and through failure, and analyze	• 5 replicates • Gyratory pill: 150 mm diameter, 62 ± 2 mm height • Compact to 7 ± 0.5% air voids • Lab-produced mix: condition loose mix for 4 hr at the design compaction temperature prior to compacting	$CT_{index} \geq 70$

P mixtures are designed to meet the requirements of Section 211.03 of the VDOT specifications (VDOT, 2016) except that volumetric requirements are waived. The JMF for P mixtures must establish a single percentage of aggregate passing each required sieve, a single percentage of liquid asphalt material to be added to the mixture, the ranges for which the Superpave volumetric properties will be held to during production, and the mixture production temperature.

Based on the literature and experience gained through Virginia's BMD efforts, the need for further development of a roadmap was identified. The purpose of this roadmap was to provide a detailed plan to address all aspects of VDOT's initial implementation of BMD. This roadmap needed be a dynamic document and be able to accommodate changes as the effort continued and new developments occurred. The intent behind the roadmap presented herein was to identify the broad categories under which specific efforts are required to implement BMD. An initial example is presented showing detailed tasks and questions or knowledge gaps to address. Further details are presented to show how several of these tasks were addressed in this study.

Roadmap for BMD Implementation

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. Since then, interest in the BMD concept has continued to grow. To provide guidance and resources for state agencies, NCHRP 20-07/Task 406 was initiated to develop a framework addressing approaches to develop and implement BMD procedures (West et al., 2018). The products included draft AASHTO practices and specifications that were fully adopted as AASHTO PP 105, Standard Practice for Balanced Design of Asphalt Mixtures, and AASHTO MP 46, Standard Specification for Balanced Mix Design.

AASHTO PP 105 presents a general framework for BMD that introduces the available approaches to BMD and details the processes followed for each. AASHTO MP 46 presents a selection of tests available to address and assess mixture susceptibility to rutting, cracking, and moisture damage. Where available, the method of practice reports test criteria being used by various entities; however, no criteria are recommended in AASHTO MP 46 at this time.

Despite a lack of available guidance at the time, in late 2017, VDOT's Materials Division determined that the potential benefits of implementing BMD were compelling and developed a general roadmap delineating the general strategy and timeline to achieve initial BMD implementation, shown in Figure 2. This timeline has guided the initial efforts and progress toward BMD implementation. However, the complexity of the implementation effort cannot be captured in such a simplified form. Therefore it was determined that a comprehensive roadmap for BMD should be developed to provide an all-inclusive picture of activities related to BMD. This roadmap was intended to be a living and evolving resource for outlining the agenda of activities necessary for implementation of BMD. The next step in advancing this roadmap is to gather a group of stakeholders from VDOT, VTRC, and industry and continue the process of refining the outline presented herein.

Figure 3 introduces the initial proposed roadmap for BMD. The vision for the proposed roadmap is 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. The roadmap efforts are necessary because the current asphalt mix design method has resulted in the design of some mixtures having shortened lifespans that do not meet performance expectations while curtailing the use of new technologies and innovations developed to improve performance. 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.

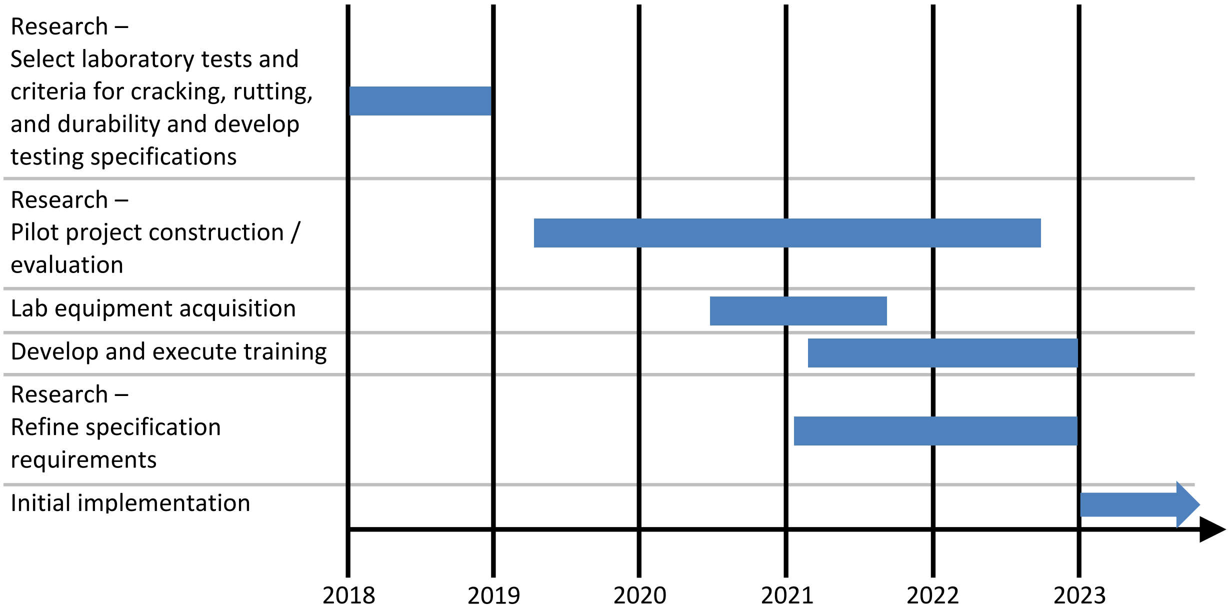


Figure 2. Timeline for Initial Implementation

The initial proposed roadmap shown in Figure 3 is structured into five broad focal categories under which specific necessary efforts are identified. Each proposed effort should be broken down further into detailed tasks and questions or knowledge gaps to address. This is important as the accuracy of the scope and details required to accomplish each task or project in the roadmap will determine the accuracy of determining project timelines and costs and affect the level of efficiency that can be achieved in optimizing task assignments and managing the logistics of implementation.

Several of the tasks are already underway or complete and are shown in bold text in Figure 3. It is suggested that the proposed roadmap be refined and further developed as the proposed version is not comprehensive and inclusive of all details. It is very likely that additional tasks will be need to be considered and incorporated. This refinement should be undertaken by a group consisting of stakeholders with diverse backgrounds and experiences so that the resulting product provides robust and effective guidance in support of BMD implementation. It is anticipated that this group could be constituted from members of the BMD technical committee and other key stakeholders determined by VTRC and VDOT's Materials Division to provide continuity in all areas and all parties collaborating in this effort.

Example Roadmap Application

The proposed roadmap includes tasks that have already been completed and identifies needs yet to be addressed. The technical efforts presented in this study are composed of several of the tasks identified in the proposed roadmap.

Initial Roadmap for Balanced Mix Design

Vision

Develop 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.

Problem Statement

The current asphalt mix design method has resulted in the design of some mixtures having shortened lifespans that do not meet performance expectations while curtailing the use of new technologies and innovations developed to improve performance.

Goal

Achieve systematic implementation of the balanced mix design method through research and coordination with all stakeholders.

Establish Communications and Transparency with All Stakeholders

- **Identify champion(s) and key stakeholders**
- **Establish joint committees – VDOT/VTRC/Industry**

Identify and Address Knowledge Gaps

- Confirm the current performance cycle length for dense-graded mixtures using PMS data
- Install and monitor mixtures on structurally sound pavements to assess mixture performance cycle
- Develop performance metrics to assess and measure improvements in service life
- **Identify/develop tests suitable for laboratory evaluation and performance testing**
- Consider potential for integration with pavement design and maintenance

Initiate Research Efforts

- **Select and evaluate potential performance tests**
- **Conduct benchmarking or shadow evaluation of current mixtures**
- **Select recommended tests for performance assessment**
- **Determine preliminary test acceptance criteria**
- **Develop sampling and testing plan**
- **Conduct precision/variability studies**
- **Conduct production data analysis**
- **Verify and/or refine test acceptance criteria**
- Refine sampling and testing plan
- Develop process to address mixture QC/QA, acceptance, and payment

Initiate Operational Efforts

- **Acquire equipment**
- **Conduct trial/demonstration projects (no cost)**
- Update training program and laboratory accreditation process
- Conduct pilot projects (bid)
- Perform final analysis and specification revisions

Implementation

- Use a phased approach
- Revisit processes, review metrics, and assess improvement
- Implement further refinements and advancements

Figure 3. Initial Proposed Roadmap for Balanced Mix Design. Tasks in bold text are underway or complete.

An example of using the proposed roadmap to identify needs for research can be shown for the first item listed under “Initiate Research Efforts”: *Select and evaluate potential performance tests*. This objective can be broken down into a number of more specific tasks, as shown in Figure 4. Although this list may not be comprehensive at this time, further refinement of the roadmap will remedy that as stakeholder input is incorporated.

Several of the tasks shown in Figure 4 are addressed in this study and are shown in bold font in the figure. Additional production mixtures were sampled and evaluated to provide additional benchmark data. Various specimen types including non-reheated specimens, reheated specimens, and field cores were evaluated to assess the impact of the different fabrication methods. The performance tests selected by Diefenderfer and Bowers (2019) were validated by considering relationships to fundamental properties and comparing test quality factors. The test criteria determined in the previous benchmarking study (Bowers and Diefenderfer, 2018) were also validated and the differences in specimen fabrication methods were assessed. These are discussed in detail in the following sections.

Validation and Refinement of BMD Performance Test Selection

Mixtures A through F were used to validate and/or refine the selection of suitable BMD performance tests. This was accomplished by first comparing the ranking and expected performance of the mixtures determined by the selected BMD tests (IDT-CT and APA) with fundamental mechanical responses and parameters measured from binder and mixture rheological testing. The choice of cracking test was further evaluated by assessing the IDT-CT, OT, I-FIT, and N_{flex} factor tests in terms of variability, discrimination potential and ranking among the selected asphalt mixtures, and correlation among each other. The volumetric properties and gradations of Mixtures A through F are shown in Table 5, along with those of Mixtures G through M, which will be addressed later.

The PG and rheological properties of the extracted and recovered asphalt binders from Mixtures A through F are presented in Table 6. Binder grading was performed in accordance with AASHTO M 332, which incorporates the non-recoverable creep compliance at 3.2 kPa ($J_{nr,3.2kPa}$) from the MSCR test. MSCR testing was conducted at 64°C, the average 7-day maximum pavement design temperature for Virginia. AASHTO M 332 specifies a maximum $J_{nr,3.2kPa}$ requirement for standard (S), heavy (H), very heavy (V), and extremely heavy (E) traffic of 4.0, 2.0, 1.0, and 0.5 kPa^{-1}, respectively. VDOT specifications call for a minimum of PG 64S-16 and PG 64H-16 asphalt binders for SMs with the A and D designation, respectively. Table 6 shows that Mixture B and Mixture E binders were in the extremely high traffic (E) category; Mixture C, D, and F binders fell under the very heavy traffic (V) category; and the Mixture A binder was adequate for heavy traffic (H) loading. This indicates that all of the mixtures used in this study met or exceeded VDOT specification criteria from the standpoint of binder properties. The percentage recovery at the 3.2 kPa stress level for all binders was very low, an expected outcome for unmodified binders.

Select and evaluate potential performance tests

- Identify target failure mechanisms to be addressed by performance testing
  - Rutting. cracking, durability
- Identify the potential pool of tests relevant to each failure mechanism
  - Rutting - APA rut test, Hamburg wheel track test, dynamic modulus, binder properties
  - Cracking - IDT-CT, Overlay test, I-FIT, N_{flex} test, Bending Beam Fatigue test, dynamic modulus, binder properties
  - Durability - Cantabro test
- Initial screening to identify the most promising test candidates
  - Preliminary benchmarking
  - Determine if relationships exist between tests and mix performance
  - Are the tests practical to perform in terms of cost, effort, and time
- Benchmark typical production mixtures
  - **Collect test data for analysis and further evaluation and screening of tests**
  - **Establish a reference baseline of performance test results for known mixtures**
  - **Assess impact of specimen type - reheated, non-reheated, core**
- Evaluate and compare test quality factors
  - **Variability of results**
  - **Discrimination potential**
  - **Ranking capability**
  - **Correlation or relationship with fundamental tests**
  - **Correlation to field performance**
- Eliminate poorly ranked tests from consideration
  - **Consider applications - mix design, QC, QA, acceptance, pay**
  - **Eliminating impractical tests**
- Verify and/or refine performance test criteria
  - **Do criteria compare well with current mixtures**
  - Do criteria relate to field performance

Figure 4. Example Tasks and Activities Necessary to Select and Evaluate Potential Performance Tests. Activities in bold were conducted as part of this study.

Table 6 also presents the critical low temperature difference (ΔT_c) values for the binders after 20 hours of aging in a pressure-aging vessel (PAV). The ΔT_c is calculated as the difference in continuous PG temperature for stiffness (T_S) and relaxation (T_m) properties in the BBR. It provides insight into the relaxation properties of a binder that can be used to indicate susceptibility to non-load related cracking or other age-related embrittlement distresses in an asphalt pavement, especially for unmodified binders (Asphalt Institute, 2019; Martin et al., 2019). Generally, for ΔT_c, a minimum threshold of -2.5°C is recommended for the cracking warning limit and -5.0°C is recommended for the cracking limit, both after 20-hour PAV aging (Anderson et al., 2011; Asphalt Institute, 2019). In a draft AASHTO specification prepared under the NCHRP 9-58 study, the ΔT_c value of -5 after 20-hour PAV aging is proposed as a requirement to evaluate the low-temperature performance of binder blends (Martin et al., 2019).

Table 5. Volumetric Properties and Gradations for All Mixtures

Mixture	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**
Mixture Type	**SM-9.5A**	**SM-12.5A**	**SM-12.5D**	**SM-12.5D**	**SM-9.5A**	**SM-12.5A**	**SM-9.5A**	**SM-12.5A**	**SM-9.5A**	**SM-12.5A**	**SM-9.5A**	**SM-9.5A**	**SM-9.5A**
RAP Content, %	**30**	**30**	**26**	**26**	**26**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
Property													
NMAS, mm	9.5	12.5	12.5	9.5	9.5	12.5	9.5	12.5	9.5	12.5	9.5	9.5	9.5
Asphalt Content, %	5.64	5.04	5.39	6.19	5.47	5.95	5.74	5.70	5.14	5.31	5.62	5.50	5.51
Rice SG (G_{mm})	2.435	2.670	2.634	2.447	2.587	2.491	2.431	2.507	2.720	2.587	2.656	2.629	2.632
VTM, %	3.3	3.1	3.0	2.2	4.5	1.9	4.4	2.5	4.3	3.1	3.4	4.0	4.7
VMA, %	16.1	15.3	15.8	16.3	17.5	14.9	17.1	16.0	17.1	15.9	17.3	17.4	17.9
VFA, %	79.5	79.6	81.3	86.2	74.2	87.5	74.5	84.4	74.6	80.3	80.3	76.7	74.0
FA Ratio	0.87	1.28	1.36	1.03	1.25	1.06	1.15	1.12	2.08	1.14	0.97	1.22	1.18
Mixture Bulk SG (G_{mb})	2.355	2.586	2.556	2.392	2.470	2.444	2.325	2.444	2.602	2.506	2.565	2.523	2.509
Aggregate Effective SG (G_{se})	2.651	2.916	2.890	2.691	2.834	2.736	2.650	2.745	2.986	2.827	2.932	2.890	2.894
Aggregate Bulk SG (G_{sb})	2.648	2.901	2.872	2.680	2.830	2.702	2.642	2.745	2.978	2.823	2.929	2.885	2.889
Absorbed Asphalt Content (P_{ba}), %	0.04	0.18	0.22	0.16	0.05	0.47	0.12	0.00	0.09	0.05	0.04	0.06	0.06
Effective Asphalt Content (P_{be}), %	5.59	4.87	5.18	6.04	5.42	5.50	5.63	5.70	5.05	5.26	5.59	5.44	5.45
Effective Film Thickness (F_{be}), µm	9.7	7.8	8.4	10.4	8.4	9.8	8.2	9.4	6.3	8.5	10.5	9.3	9.4
Gradation, percent passing													
¾ in (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
½ in (12.5 mm)	98.9	97.3	99.3	100.0	99.4	96.0	98.9	98.0	99.6	98.2	99.9	99.5	99.7
3/8 in (9.5 mm)	93.3	86.6	92.0	91.9	94.7	85.7	95.0	87.0	90.7	90.8	94.9	91.1	94.0
No. 4 (4.75 mm)	60.7	55.6	58.5	56.7	65.9	58.1	71.2	58.1	57.4	59.4	56.9	58.3	60.9
No. 8 (2.36 mm)	43.9	39.2	39.6	40.6	47.1	40.9	52.3	40.0	38.0	41.8	37.0	40.5	41.4
No. 16 (1.18 mm)	35.0	30.3	28.4	33.3	34.9	29.9	39.8	29.6	25.8	31.2	26.2	29.4	30.2
No. 30 (600 µm)	25.8	23.5	20.1	25.0	24.5	21.2	28.6	21.9	18.1	23.5	18.8	20.7	20.9
No. 50 (300 µm)	17.0	16.8	13.7	13.1	15.4	13.4	19.0	15.2	12.4	16.4	13.0	12.5	12.5
No. 100 (150 µm)	8.4	10.3	9.8	8.0	9.5	8.3	10.3	9.7	8.0	10.1	8.5	8.6	8.5
No. 200 (75 µm)	4.9	6.2	7.1	6.2	6.8	5.8	6.5	6.4	5.3	6.0	5.4	6.7	6.4
Extracted and Recovered Asphalt Binder													
Performance Grade (PG)	64H-22	64E-16	64V-16	64H-16	64E-16	64V-16	-	-	-	-	-	-	-

RAP = recycled asphalt pavement; 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; - = extraction not performed.

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

Property		**Mixture**					
		A	**B**	**C**	**D**	**E**	**F**
Dynamic Shear, 10 rad/sec, specification: |G*|/sin δ >2.20 kPa							
RTFO |G*|/sin δ	70°C	2.24	7.12	6.41	3.97	9.44	6.01
	76°C	1.08	3.40	3.06	1.90	4.57	2.81
	82°C	-	1.68	1.51	-	2.26	1.36
	88°C	-	-	-	-	1.17	-
RTFO Failure Temperature, °C		70.1	79.7	78.8	74.8	82.4	78.1
Dynamic Shear, 10 rad/sec, specification: |G*|·sin δ < 5000 kPa							
PAV |G*|·sin δ	22°C	5418	-	-	5989	-	-
	25°C	3861	6109	5166	4337	-	6082
	28°C	-	4500	3894	-	5035	4354
	31°C	-	-	-	-	3832	3051
PAV Failure Temperature, °C		22.7	27.0	25.4	23.7	28.1	26.7
Creep Stiffness, 60 sec, specification: Stiffness < 300 MPa and m-value > 0.300							
Stiffness, S	-6ºC	-	126	106	101	126	131
	-12ºC	157	206	214	189	226	249
	-18ºC	340	-	-	-	-	-
M-value, m	-6ºC	-	0.318	0.325	0.338	0.301	0.33
	-12ºC	0.313	0.275	0.29	0.297	0.273	0.286
	-18ºC	0.265	-	-	-	-	-
ΔTc, ºC		-3.4	-8.1	-4.6	-4.9	-8.7	-3.6
Performance Grade (AASHTO M 320)		70-22	76-16	76-16	70-16	82-16	76-16
Multiple Stress and Creep Recovery (MSCR) Test at 64°C							
J_{nr}, kPa^{-1}	0.1 kPa	1.652	0.395	0.465	0.908	0.261	0.546
	3.2 kPa	1.851	0.429	0.504	1.000	0.283	0.589
Avg. % Recovery, %	0.1 kPa	8.1	21.9	19.8	12.1	2.9	14.6
	3.2 kPa	2.7	15.8	14.2	6.3	2.3	9.6
Performance Grade (AASHTO M322)		64H-22	64E-16	64V-16	64H-16	64E-16	64V-16

RTFO = rolling thin film oven; PAV = pressure aging vessel; - = no data collected.

From Table 6, Mixtures A, C, D, and F had ΔT_c values ranging from -3.6 to -4.9°C, all exceeding the cracking warning limit. For Mixtures B and E, the corresponding ΔT_c values exceeded the cracking limit of -5.0°C indicating a high susceptibility to non-load related cracking.

Dynamic Modulus Test

The dynamic modulus (|E*|) and phase angle (δ) of Mixtures A through F were measured on three replicate specimens, and the average results at each temperature-frequency combination were reported. An overall average coefficient of variation (COV) of 11.2% for the |E*| measurements and a COV of 3.3% for the δ measurements were observed across all temperature-frequency test combinations.

The dynamic modulus (|E*|) and phase angle (δ) of the six mixtures are presented in Figure 5 and Figure 6, respectively. These curves were constructed at a reference temperature (T_r) of 21°C using the generalized logistic models (for both |E*| and δ data) along with the polynomial shift factor, which provide a better fit to the measured data compared to a conventional sigmoid function implemented in the current mechanistic-empirical pavement design software (Boz and Solaimanian, 2019; Boz et al., 2017a, b; Oshone et al., 2017; Rowe et al., 2016; Tavassoti-Kheiry et al., 2017). In general, a higher |E*| value at higher temperatures (and lower frequencies) is often attributed to a higher rutting resistance potential of asphalt mixtures. Conversely, a higher |E*| value and lower δ at lower temperatures (and higher frequencies) is often associated with a higher cracking susceptibility potential of asphalt mixtures. A visual inspection of Figure 5 shows that Mixtures A and D have lower |E*| values (lower stiffness) and Mixture E has higher |E*| values (higher stiffness) across the loading spectrum. As seen in Figure 6, Mixture D has higher δ values and Mixture E has lower δ values (lower relaxation capability), indicating a higher cracking potential for Mixture E among the six mixtures.

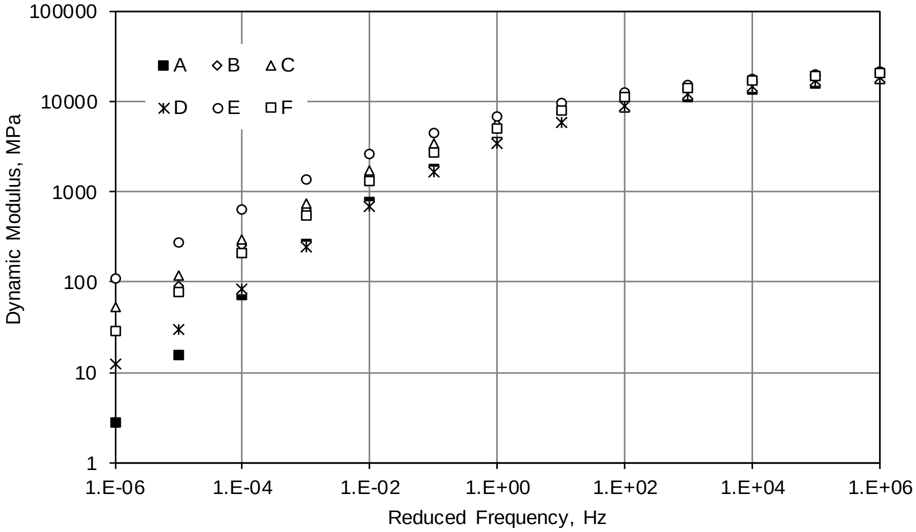


Figure 5. Dynamic Modulus |E*| Master Curves

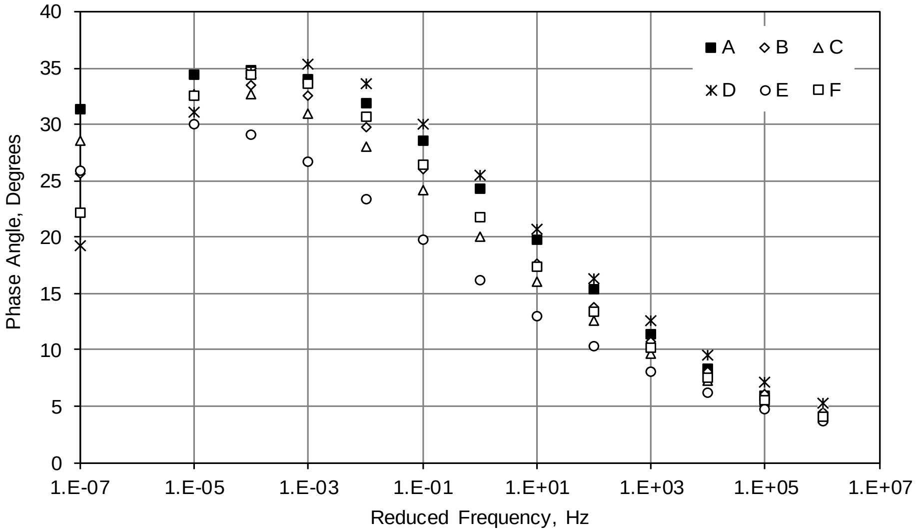


Figure 6. Phase Angle (δ) Master Curves

In recent years, various index parameters from |E*| and δ master curves have been developed to quantify rutting and fatigue performance of asphalt concrete mixtures (Apeagyei, 2011; Apeagyei et al., 2011; Boz et al., 2017c; Martin et al., 2019; Ogbo et al., 2019; Pellinen and Witczak, 2002; Zhang et al., 2020). Apeagyei et al. (2011) reported that the |E*| measured at 38°C and 0.1 Hz along with some gradation parameters indicated good correlation to the rutting resistance potential of asphalt mixtures, as quantified by the flow number test performed in accordance with AASHTO TP 79 (now AASHTO T 378). For simplicity, the |E*| values at 38°C and 0.1 Hz are plotted in Figure 7 to quantify the rutting potential of the mixtures tested in this study. As can be seen from the figure, Mixture E was the most rut-resistant mixture and Mixture D was potentially the most susceptible to rutting.

Another performance indicator parameter that can be calculated from the |E*| and δ master curves of asphalt mixtures is the mixture G-Rm parameter, which is an adopted form of the binder Glover-Rowe (G-R) parameter (Mensching et al., 2017; Ogbo et al., 2019; Zhang et al., 2020). The G-Rm parameter is simply the same as the binder G-R parameter but it used mixture dynamic modulus (|E*|) and phase angle (δ) in lieu of the binder complex shear modulus and phase angle; it is expressed in Equation 1.

$$\text{G-Rm}=\frac{|E^*|\times(\cos\delta)^2}{\sin\delta} \qquad \text{[Eq. 1]}$$

This parameter, calculated at 20°C and 5 Hz, has been used to evaluate the resistance of asphalt mixtures to cracking and their susceptibility to aging, especially with changes in recycled content and recycling agent type and dosage (Martin et al., 2019; Ogbo et al., 2019; Zhang et al., 2020).

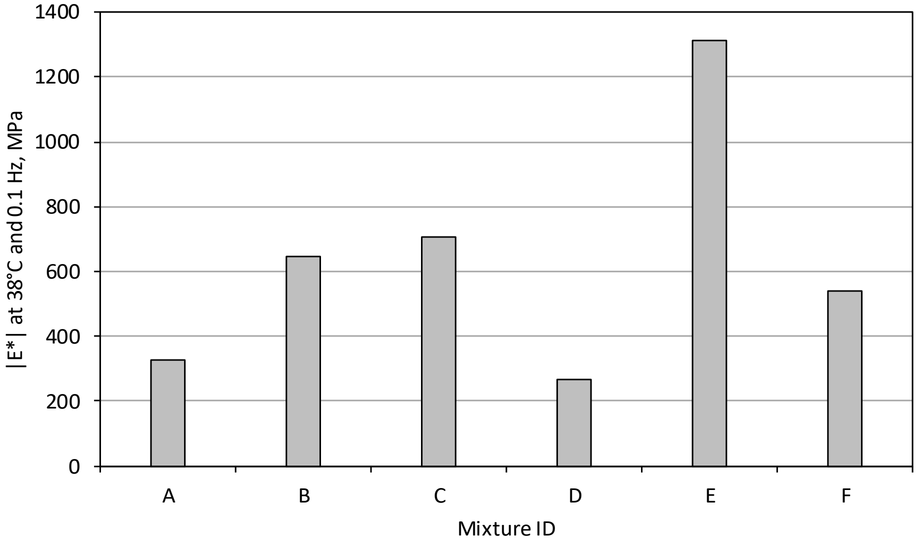


Figure 7. Dynamic Modulus |E*| at 38°C and 0.1 Hz

In a draft AASHTO specification proposed in the NCHRP 09-58 study (Martin et al., 2019), this parameter was recommended as a mixture performance evaluation parameter at intermediate temperatures to minimize the cracking potential of asphalt mixtures. A maximum G-Rm parameter value of 8,000 MPa was recommended for laboratory-made mixtures subjected to short-term oven-aging for 2 hours at the specified compaction temperature. A maximum G-Rm parameter value of 19,000 MPa was recommended for long-term oven-aged laboratory-made mixtures in accordance with either AASHTO R 30 or the proposed standard method for long-term conditioning of hot mix asphalt for performance testing in NCHRP Project 09-54 (Kim et al., 2018).

Figure 8 shows the G-Rm parameter calculated for the mixtures used in this study. It can be seen that the G-Rm parameter values for all mixtures are more comparable to the recommended threshold value (19,000 MPa) for long-term oven-aged laboratory-made mixtures than that for short-term oven-aged laboratory-produced mixtures (8,000 MPa). Since these mixtures were plant-produced and subjected to reheating, a process known to result in higher stiffness (Daniel et al., 2019), neither threshold is directly applicable to the mixtures as no recommendations have been made for plant-produced mixtures. Nevertheless, a relative comparison among the mixtures indicated that Mixtures E and D ranked as the most and least crack-susceptible mixtures, respectively.

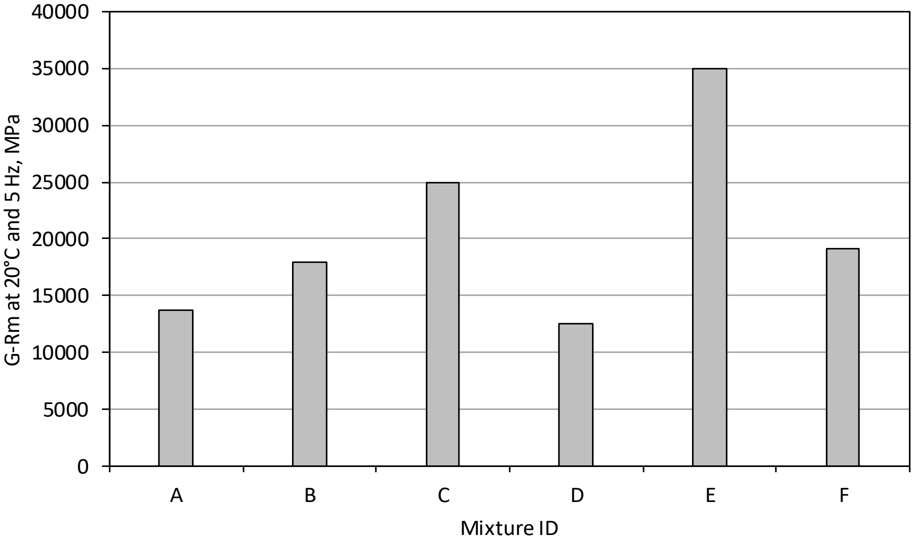


Figure 8. Glover-Rowe (G-Rm) Parameter at 20°C and 5 Hz

Asphalt Pavement Analyzer Test

The APA test is used as part of VDOT's BMD implementation efforts. VDOT's provisional BMD specification limits the deformation depth in the APA test at 64°C and 8,000 cycles to 8 mm for SMs with A and D designations. Figure 9 shows the APA test results for the six mixtures. With the exception of Mixture D, all mixtures had a rut depth lower than 8 mm, indicating adequate resistance to rutting.

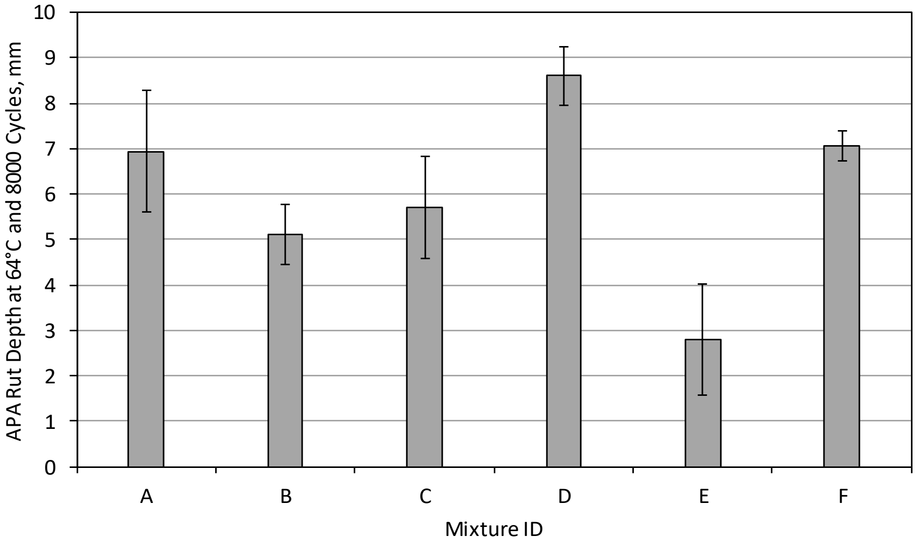


Figure 9. APA Test Results at 64°C and 8,000 cycles. I-bars indicate 1 standard deviation. APA = asphalt pavement analyzer.

The rut results from the APA test were compared to the rut parameters obtained from the mixture |E*| and binder tests. Figure 10 shows the correlation between the APA rut depth and |E*| values at 38°C and 0.1 Hz. As seen, the APA rut depth is highly correlated with the |E*| rutting parameter and the correlation trend is in the right direction (i.e., the higher the stiffness, the lower the rutting potential). Similarly, the APA rut depth was correlated with the binder |G*|/sin δ and $J_{nr,3.2kPa}$ parameters as shown in Figures 11 and 12, respectively. In both cases, the correlation was moderate with a coefficient of determination (R^2) of about 50% to 60%. However, the extent of correlation significantly increased (R^2 of about 96%) when one of the mixtures (encircled in the figures) was removed.

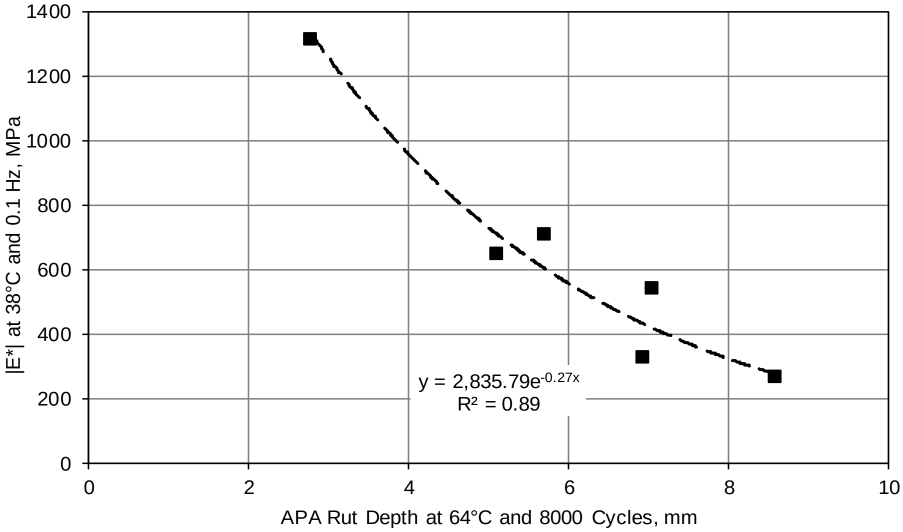


Figure 10. Correlation Between APA Rut Depth and |E*| at 38°C and 0.1 Hz

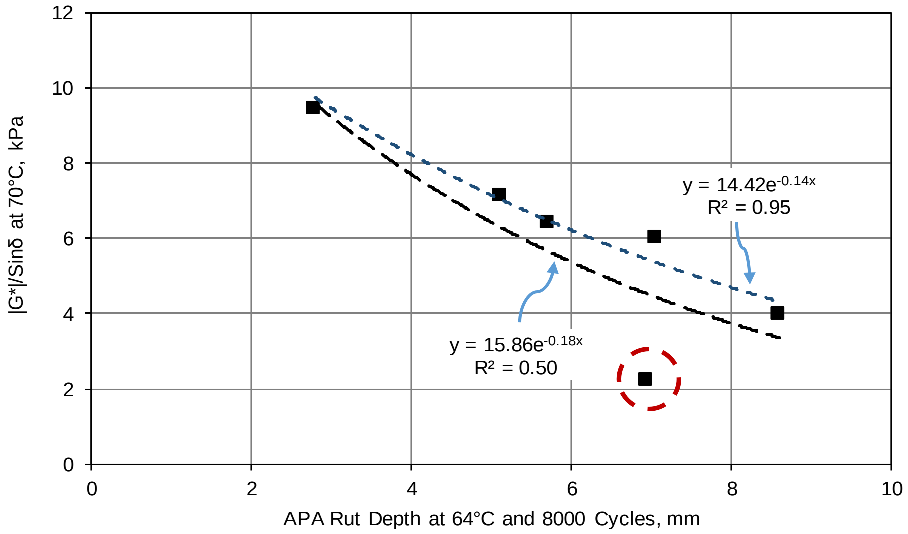


Figure 11. Correlations Between APA Rut Depth and |G*|/sin δ. The circled data point appears to be an outlier. R^2 improves from 0.50 (lower curve) to 0.95 (upper curve) when the circled point is removed from the analysis.

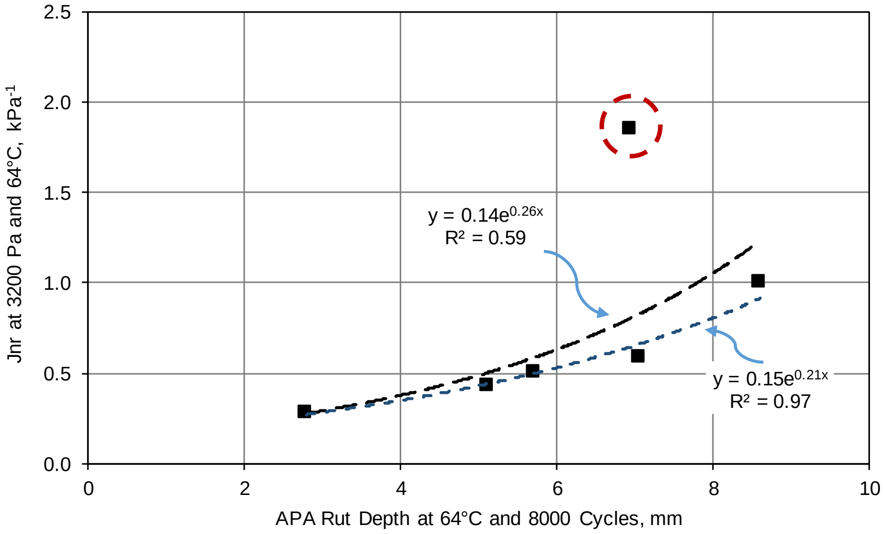


Figure 12. Correlations Between APA Rut Depth and $J_{nr,3.2KPa}$. The circled data point appears to be an outlier. R^2 improves from 0.59 (upper curve) to 0.97 (lower curve) when the circled point is removed from the analysis.

Although it is unclear why that specific binder test parameter deviated from the general trend seen, the behavior can be attributed to differences in binder vs. mixture properties (such as mixture heterogeneity, aggregate and binder interactions including blending of RAP and virgin binder) or an experimental error during the process of extraction, recovery, or testing of the binder.

Nevertheless, for the mixtures tested in this study, the APA test overall provides the expected trend of rutting potential in relation to that determined from the other mixture and binder tests used in this study. However, for further verification that APA test threshold values are appropriate, results should also be compared and correlated with test results from fundamental rut tests such as the flow number test and rut depths obtained from mechanistic-empirical pavement design simulations and field performance.

Cracking Tests

As indicated earlier, several cracking tests addressing different pavement deterioration modes were initially considered for the development of BMD specifications in Virginia (Bowers and Diefenderfer, 2018), including the OT and several monotonic loading tests (indirect tensile test [IDT] and I-FIT). As a result, the IDT-CT test and the associated CT_{index} calculated in accordance with ASTM D 8225, was selected based on several factors including performance ranking, test repeatability, the ease of specimen preparation, speed of testing, and minimal cost of equipment.

For this study, these tests and associated indices were re-evaluated in an effort to validate and/or refine the previous findings. To achieve this, the tests considered in this study were evaluated in terms of several factors:

- test variability
- performance discrimination potential of the mixtures
- performance ranking of the mixtures and correlations among the indices
- correlation of the indices to the G-Rm parameter from the dynamic modulus test.

The cracking indices evaluated as part of this study were the CT_{index} (ASTM D8225), N_{flex} factor (Yin et al., 2018), and FI (AASHTO TP 124). All tests were conducted at 25°C using a constant loading rate of 50 ± 2 mm/min.

Variability

Figure 13 presents the results of the cracking tests, and the I-bars represent 1 standard deviation around the mean. Each test consisted of three to five replicates. During the SCB testing of Mixture D, machine-related issues were encountered and the test results had to be discarded. Additional specimens for retesting could not be made because of insufficient material. Thus, the FI analysis included five mixtures and the analysis of the other indices included six mixtures. No data trimming (removal of outlier or minimum and maximum values of the replicates) was applied; the test data were analyzed including all tested replicates.

As the magnitude of the indices differed significantly, the variability of each index was evaluated using the COV parameter. The COV for the CT_{index} ranged from 9.1% to 40.7%, with an average COV of 21.4%. The range of the COV observed in this study for the CT_{index} was slightly higher than the range reported in previous studies (Bowers et al., 2019; Diefenderfer et al., 2019; Seitllari et al., 2019, 2020). The average COV for the FI was 33.5% with a minimum and maximum COV of 21.2% to 49.3%, respectively. The COV for the N_{flex} factor ranged from 5.8% to 24.6% with an average COV of 11.1%.

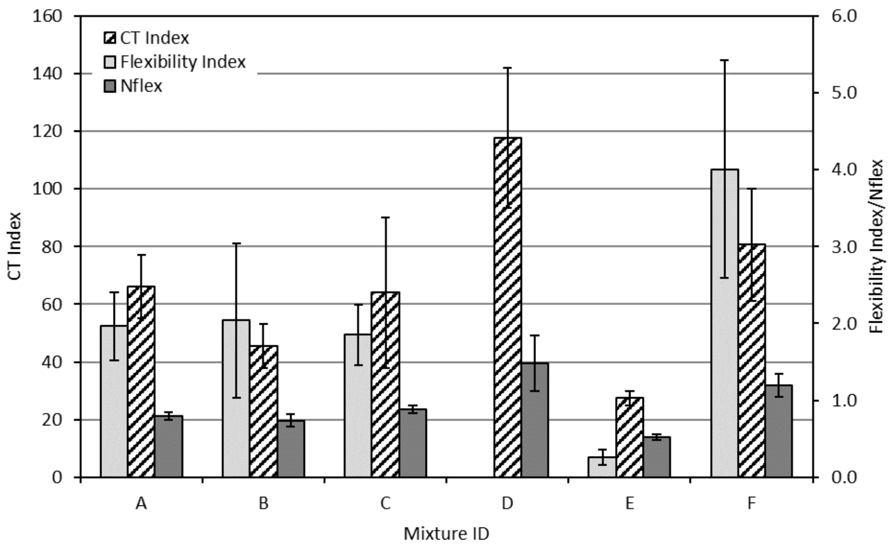


Figure 13. Cracking Test Results at 25°C

The results confirmed the findings of Seitllari et al. (2020), as among the three indices considered, the N_{flex} factor had the lowest variability followed by the CT_{index} and the FI had the highest variability. The high variability observed with the FI can be associated with several factors such as the confounding effects of stress concentration at the tip of the notch, the crack propagation path, the spatial distribution of aggregates and their orientation along the crack tip and path, and their impact on the resulting load-displacement curve (Seitllari et al., 2020).

Performance Discrimination Potential

The performance discrimination potential of the cracking indices among the six mixtures was assessed through statistical analysis. The assumptions of normality and equal variances at a 95% confidence interval were first checked. The results indicated that the data from all cracking indices were normally distributed, but only CT_{index} data had equal variances. Thus, Welch's analysis of variance (ANOVA) was performed for the N_{flex} and FI and the standard one-way ANOVA was conducted for the CT_{index}; all were conducted at a 95% confidence interval. The ANOVA results showed that statically significant differences existed for the indices among the mixtures. The Tukey and Games-Howell pairwise comparison tests at a 95% confidence interval were performed for the indices with and without equal variances, respectively. The results of the analysis are shown in Table 7.

Table 7. Pairwise Statistical Comparisons of Evaluated Cracking Tests

	Cracking Index		
Mixture	**CT_{index}**	**N_{flex}**	**Flexibility Index**
A	b/c	a	a/b
B	b/c	a	a/b
C	b/c	a	a/b
D[a]	a	a	-
E	c	a	b
F	a/b	a	a

[a] FI data for Mixture D were not available.

The mixtures that do not share a letter indicate a statistically significant difference in their mean value. As seen, the CT_{index} resulted in three groupings and the FI resulted in two groupings among the mixtures evaluated in this study. The N_{flex} factor did not statistically discriminate the cracking performance of the mixtures. The results showed that the CT_{index} was the most sensitive index among the ones considered in this study.

Ranking and Correlation Among Considered Indices

The indices were compared in terms of their potential to rank the cracking performance of the mixtures. This was done by sorting the average mean value of each index from the highest to the lowest to determine the order of the performance rank of the mixtures. Table 8 shows the order ranking of the mixtures in descending order for each index. As seen from Table 8, all of the indices indicated that Mixture E was the most susceptible to cracking. The CT_{index} and N_{flex} ranked Mixture D as the most resistant to cracking. The FI ranked Mixture F as the most resistant to cracking in the absence of Mixture D data. It is also seen that the order of the ranking for the FI differed slightly from that of the CT_{index} and N_{flex} factor. However, this difference was deemed irrelevant, as the order of ranking was not statistically or practically different when the results were evaluated with respect to the discrimination potential discussed in the preceding section.

Figure 14 shows a very strong linear relationship among the indices. In combination with the performance ranking analysis, the correlation found in this study indicated that the cracking tests and associated indices could be used interchangeably to evaluate the cracking potential of asphalt mixtures.

Table 8. Ranking of Cracking Susceptibility

Index	**Ranking**					
	Most resistant			**to**		**Most susceptible**
CT_{index}	D	F	A	C	B	E
N_{flex}	D	F	C	A	B	E
FI[a]	F	B	A	C	E	

[a] FI data for Mixture D were not available.

Correlation With the G-Rm Parameter

The correlations between the cracking indices and the G-Rm parameter were evaluated. Figure 15 indicates that a moderate relationship existed among the indices and the G-Rm parameter. The FI showed the highest correlation with the G-Rm parameter followed by the CT_{index} and N_{flex}. The scatter in the data points and the differences in performance rankings of the indices with respect to the G-Rm parameter may be attributed to the differences in the material response measured in the linear (G-Rm) and nonlinear viscoelastic (cracking indices) ranges. Zhang et al. (2020) suggested that the cracking susceptibility of asphalt mixtures evaluated by the G-Rm parameter may indicate the potential for cracking initiation in the early stages of a pavement's service life whereas the cracking indices may indicate the performance of asphalt mixtures in the middle or later stages of pavement service life as additional cracking initiates and propagates.

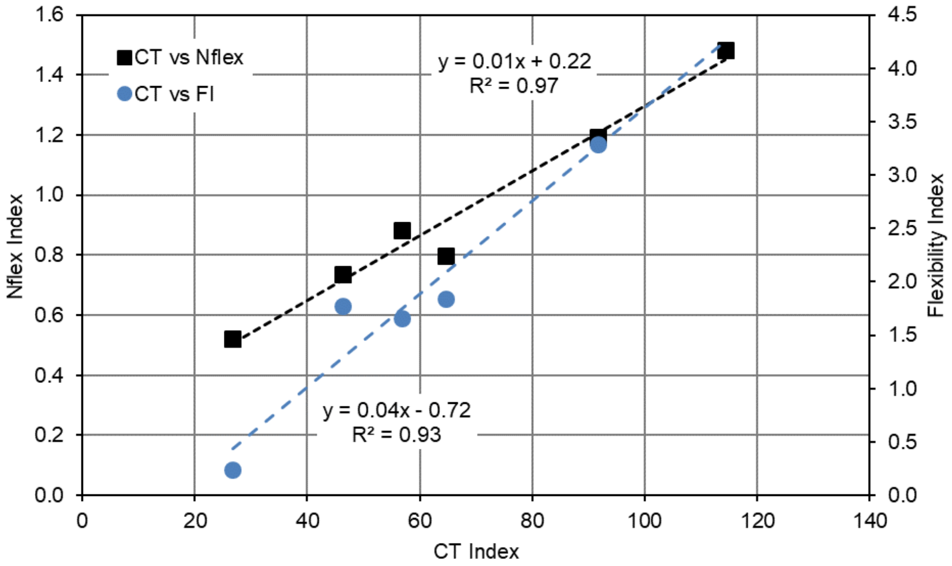


Figure 14. Correlation Among the Evaluated Cracking Indices

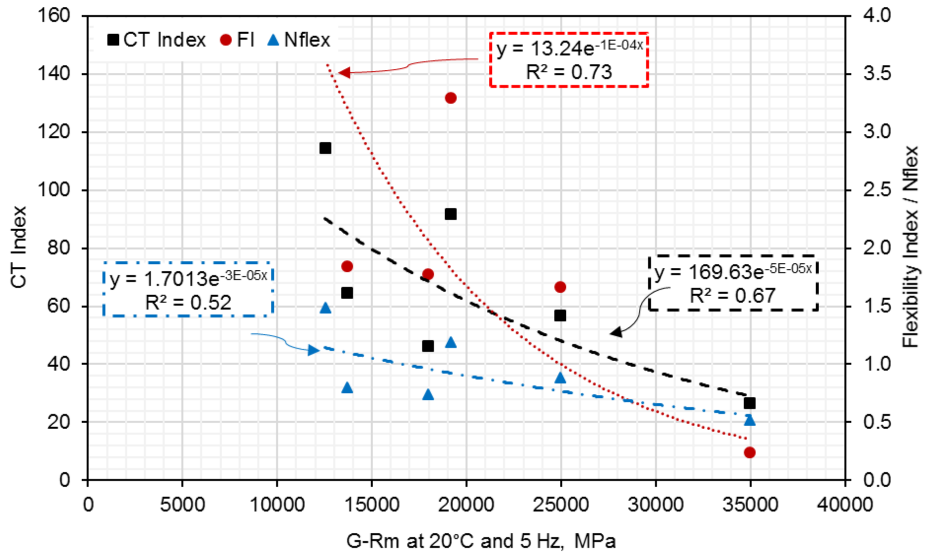


Figure 15. Relationships Showing Correlations Between G-Rm Parameter and CT_{index}, FI, and N_{flex}

As with the APA test, the need remains for the index cracking tests to be evaluated with respect to fundamental cracking tests such as the BBF test and cracking obtained from mechanistic-empirical pavement design simulations and field performance. This will ensure that the most appropriate cracking test and threshold value(s) are selected for implementation of the BMD concept.

Table 9 summarizes the factors evaluated in the consideration of the cracking indices. The evaluations of the indices and desired characteristics of each parameter in Table 9 were made based solely on relative comparisons of the results obtained in this study. For each evaluation parameter, the index satisfying the desired characteristic is shown in bold italic test. As shown in Table 9, each index met the desired characteristic for a parameter twice. Further evaluation of the parameters indicated that the CT_{index} was ranked as the second index after N_{flex} for the variability parameter and after FI for the correlation with the G-Rm parameter. Based on these findings and the considerations of the ease of specimen preparation, speed of testing, and minimal cost of equipment, the IDT-CT test and CT_{index} show promise for evaluating the cracking potential of asphalt mixtures. However, as recommended earlier, further evaluation of the cracking test needs to be done through mechanistic-empiric analysis and field performance to validate or refine these findings.

Table 9. Overall Evaluation of Considered Cracking Indices

Parameter	CT_{index}	N_{flex}	FI	Desired Characteristic
Variability	Moderate	***Low***	High	Low
Discrimination Potential	***High***	Low	Moderate	High
Performance Ranking	Similar	Similar	Similar	N/A
Correlation Between Indices	***High***	***High***	***High***	High
Correlation With the G-Rm Parameter	Moderate	Low	***High***	High

FI = flexibility index; N/A = not applicable.
Bold italic text indicates the test meets the desired characteristic.

Validation of BMD Performance Thresholds

Thirteen mixtures (A through M) were sampled and used to evaluate the performance thresholds proposed for the Cantabro, IDT-CT, and APA tests. The volumetric properties and gradations for Mixtures A through M were presented in Table 5. Testing for the validation effort was conducted on several specimen types for each mixture, as previously discussed. LCNR, LCR, and FC specimens were all available for Mixtures A through F, whereas LCNR-P specimens were available only for Mixtures B, D, and E. For Mixtures G through M, only LCNR-P and LCR specimens were available.

Cantabro Mass Loss

Figure 16 shows the Cantabro mass loss of LCR, LCNR, and LCNR-P specimens from all mixtures. The average mass loss of all tested specimens was 6.3% with an average standard deviation of 0.7%. The maximum and minimum values for mass loss were 12.8% (Mixture E) and 4.6% (Mixture H), respectively, for LCR specimens; 7.7% (Mixture A) and 3.6% (Mixture D), respectively, for LCNR specimens; and 11.0% (Mixture L) and 3.8% (Mixture B), respectively, for LCNR-P specimens. The variability of the Cantabro test for repetitive measurements for the same specimen type, quantified in terms of COV and shown in Figure 17, was less than 20% except for F-LCR specimens. The mean COVs calculated from testing replicates of LCR, LCNR, and LCNR-P mixtures were 11.7%, 10.9%, and 10.0%, respectively, with a standard deviation of 6.6%, 5.0%, and 5.1%, respectively. The results indicated acceptable repeatability for the Cantabro test.

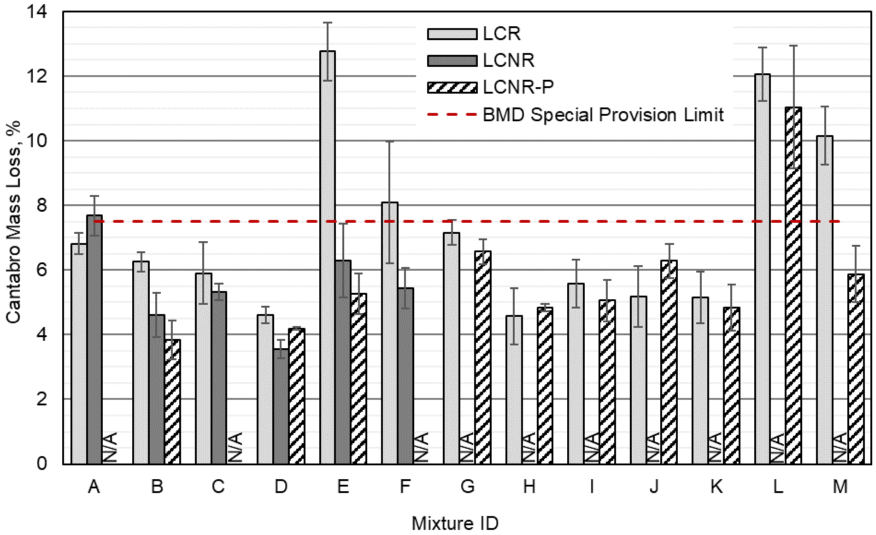


Figure 16. Cantabro Mass Loss Results. Values are the average of three replicates. I-bars indicate ±1 standard deviation.

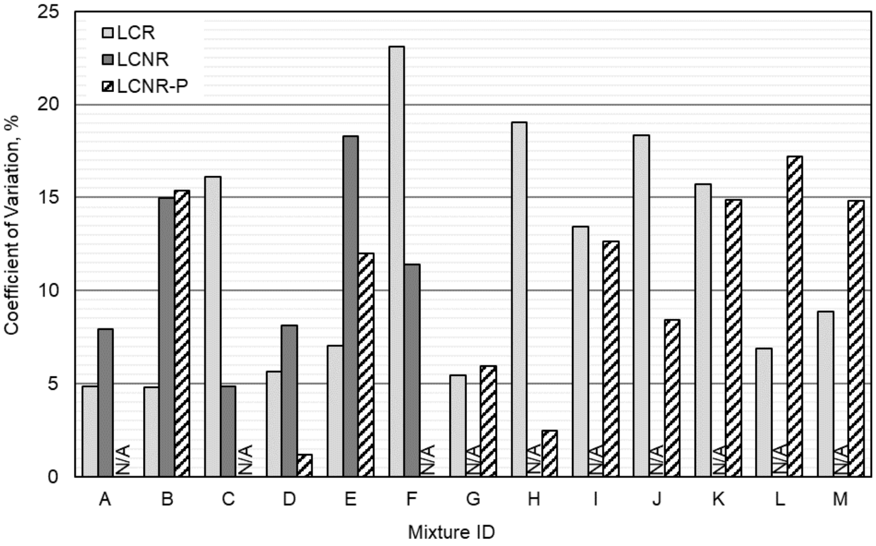


Figure 17. Variability of Mass Loss Measurements by Specimen Type

Figure 18 shows the Cantabro mass loss and air voids of LCR specimens. The dashed line in red shows the current BMD requirement for Cantabro mass loss, a maximum value of 7.5%. It can be seen from Figure 18 that Mixtures E, F, L, and M significantly exceeded the 7.5% mass loss criterion. Mixtures E and L were statistically similar, as were Mixtures F and M, although the two pairs were significantly different. In addition, the average mass loss plus 1 standard deviation for the LCR specimens, shown as the dashed double-dotted blue line, was above 7.5%.

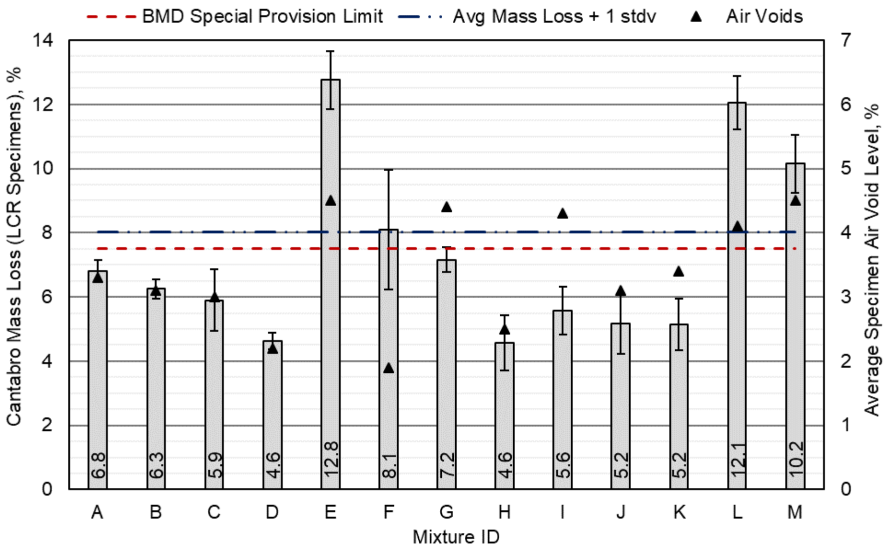


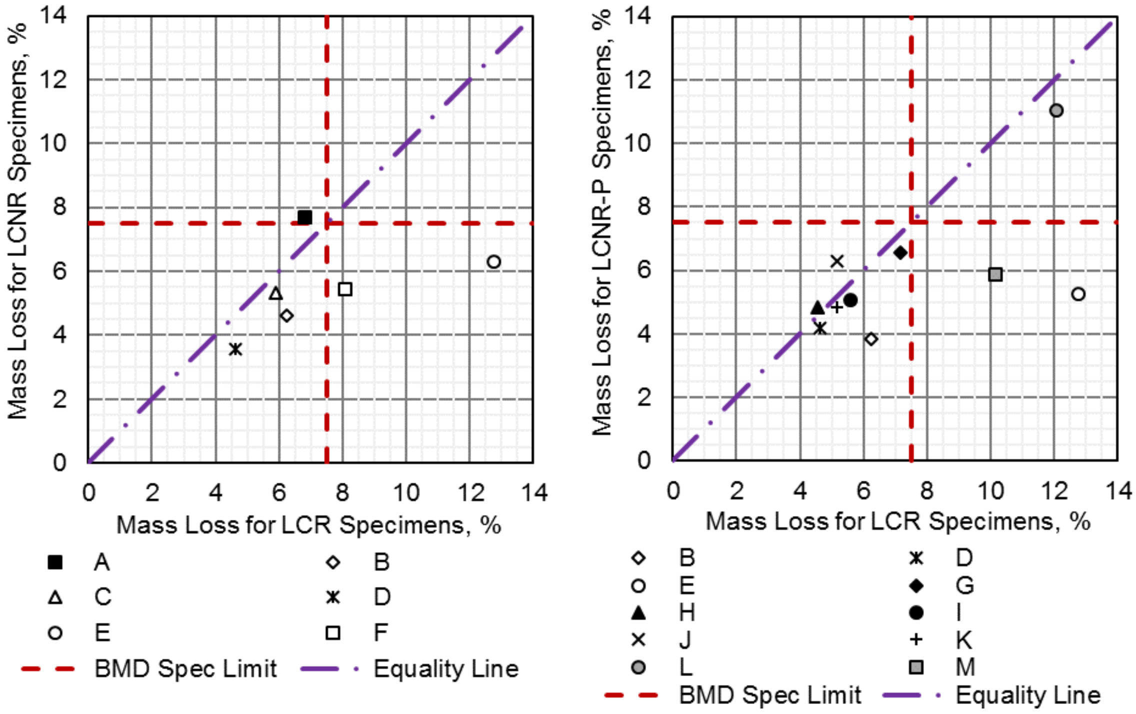
Figure 18. Average Cantabro Mass Loss and Air Voids for LCR Specimens. Average mass loss values are shown at the bottom of each column. I-bars indicate ±1 standard deviation.

Figure 19 shows the effect of reheating loose mixture to fabricate specimens. The mass loss of LCR specimens are compared to those of LCNR and LCNR-P specimens. Figure 19(a) compares LCR and LCNR specimens and shows that 5 of the 6 evaluated mixtures (B, C, D, E, and F) had increased mass loss values for reheated specimens, for which all differences but one were statistically significant; 2 of these 5 mixtures (E and F) did not meet the 7.5% mass loss criterion when reheated. Figure 19(b) indicates that 8 of the 10 evaluated mixtures had LCR specimen mass losses greater than those of the LCNR-P specimens, although only one-half of those differences were statistically significant; of those, Mixtures E and M had very large increases in mass loss after reheating, to double and nearly double the non-reheated specimen mass losses. Overall, it was shown that reheating prior to compaction generally leads to an increase in the mass loss.

Figure 20 compares the mass loss of non-reheated mixtures compacted in the producers' laboratories by VTRC staff and by producer staff (LCNR vs. LCNR-P) to evaluate multi-operator effects on specimen fabrication. No significant difference was found between the sets of results for each of the three evaluated mixtures. Differences between the multi-operator averages of 16.7%, 17.7%, and 16.4% were found for Mixtures B, D, and E, respectively, resulting in an average variation of 16.9% among operators, with a standard deviation of 0.7%.

APA Test

Figure 21 shows average measured rut depths of LCR, LCNR, and LCNR-P specimen sets from each mixture. The average values were determined from the measurements of each of the two specimens comprising each of the two replicate tests. The maximum and minimum values for APA rut depth were 8.2 mm (Mixture D) and 2.8 mm (Mixture E), respectively, for LCR specimens; 8.7 mm (Mixture A) and 4.9 mm (Mixture E), respectively, for LCNR specimens; and 6.9 mm (Mixture J) and 3.2 mm (Mixture I), respectively, for LCNR-P specimens.



(a) (b)

Figure 19. Effect of Reheating on Mass Loss: (a) LCR vs. LCNR Specimens; (b) LCR vs. LCNR-P Specimens

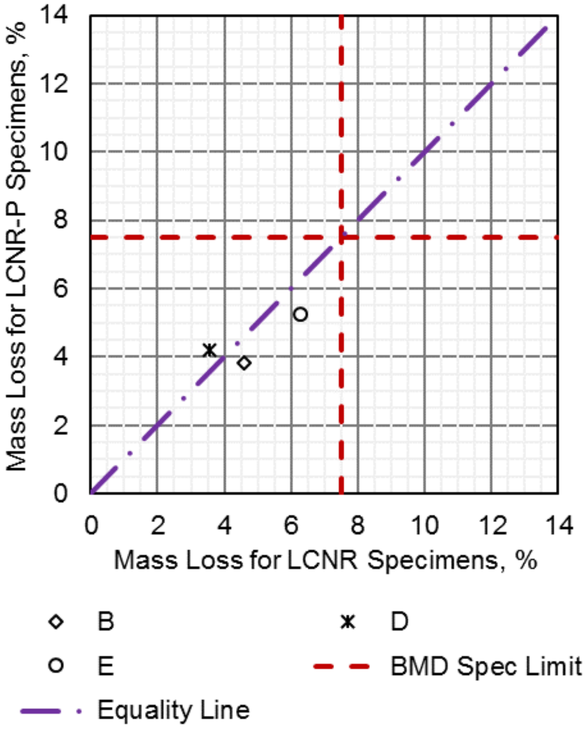


Figure 20. Effect of Multiple Operators Performing Specimen Fabrication on Mass Loss for LCNR vs. LCNR-P Specimens

In general, the expected trend for rut testing is that reheated specimens should have lower rut depths than non-reheated specimens because of the anticipation of increased mixture stiffness from reheating. However, Figure 21 indicates that the impact of reheating on rut depths may be mixture specific, as 6 of the 13 mixtures had reheated-specimen rut depths greater than or equal to those for non-reheated specimens.

The variability of the APA test for replicate measurements is shown in Figure 22. The variability was quantified in terms of COV and was less than 20% for 19 of 28 specimen sets. The mean COVs calculated from testing replicates of LCR, LCNR, and LCNR-P mixtures were 12.2%, 15.5%, and 11.7%, with standard deviations of 8.3%, 6.6%, and 13.6%, respectively. The results indicated acceptable repeatability for the APA test.

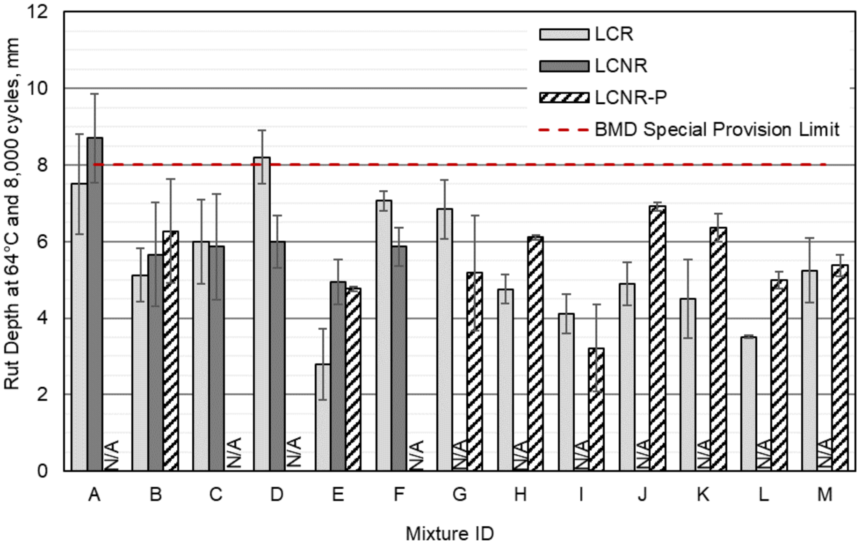


Figure 21. APA Rut Depths. Averages were computed from individual specimens tested in pairs. I-bars indicate ±1 standard deviation.

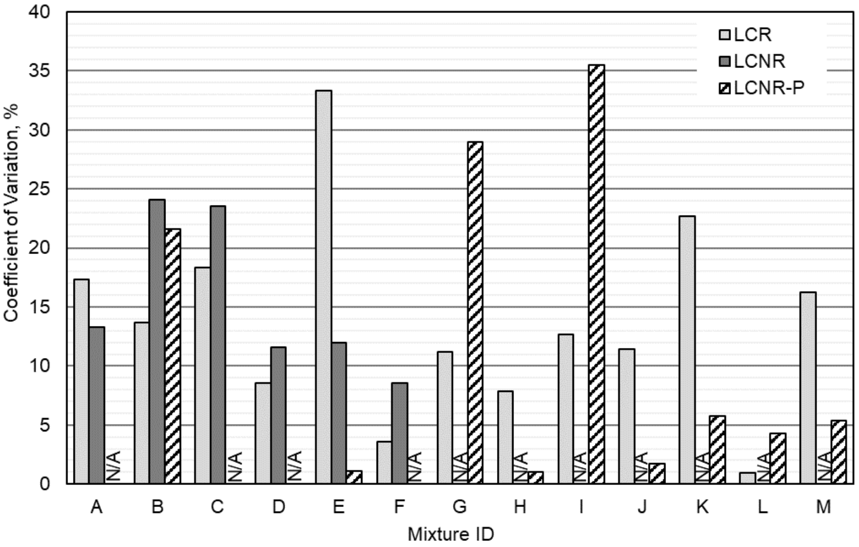


Figure 22. Variability of Rut Depths by Specimen Type

Figure 23 presents the APA rut depths and air voids of LCR-tested specimens. The dashed red line indicates the APA rut depth criterion (8.0 mm maximum), and the blue-dotted dashed line indicates the average rut depth for the LCR specimens. It can be seen that all mixtures except Mixture D had a rut depth less than 8.0 mm.

Figure 24 compares the APA rut depths for LCR specimens and those of LCNR and LCNR-P specimens to evaluate the effect of reheating loose mixture to fabricate specimens. Figure 24(a) shows that for two of the six mixtures, D and F, rut depths increased for reheated specimens; one mixture, C, had similar rut depths for reheated and non-reheated specimens; and for three mixtures (A, B, and E), rut depths decreased for reheated specimens. Figure 24(b) indicates that two of the nine mixtures (G and I) had increased rut depths for reheated specimens; Mixture M had similar rut depths for reheated and non-reheated specimens; and, for the remaining six mixtures, rut depths of reheated specimens decreased. Overall, the results indicated that reheating loose mixture to fabricate APA specimens may cause an increase in specimen stiffness, resulting in decreased rut depths as compared to those for non-reheated specimens.

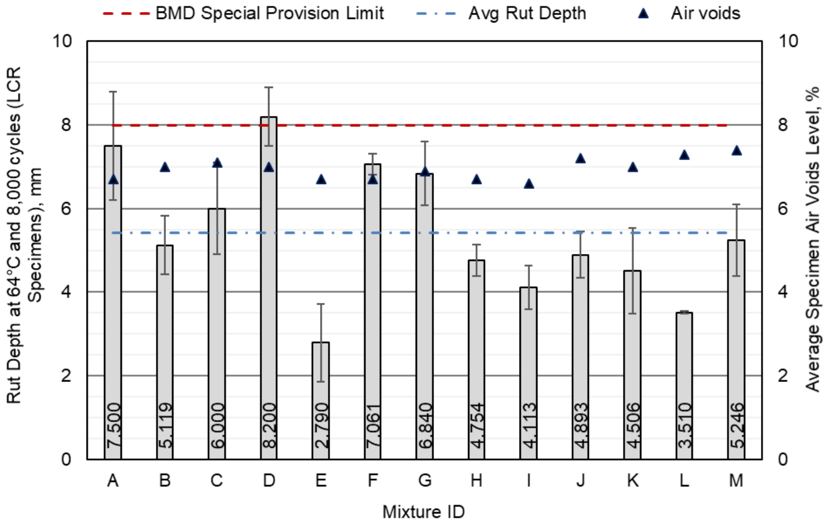
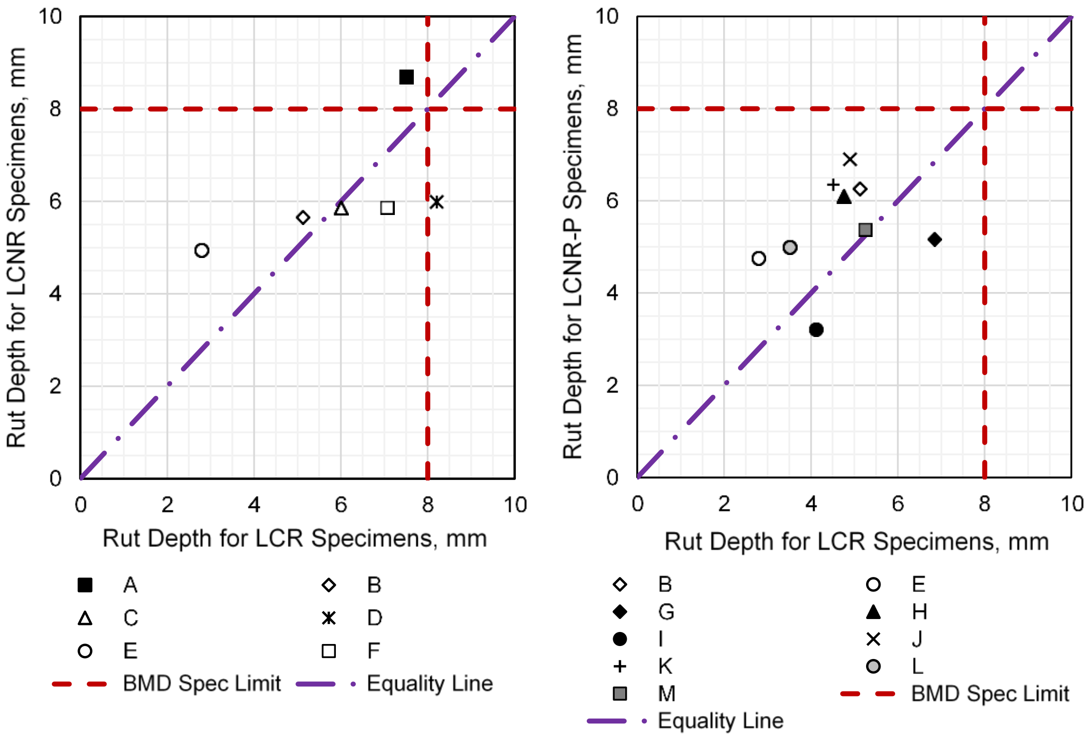


Figure 23. Average APA Rut Depths and Air Voids for LCR Specimens. Average rut depths are shown at the bottom of each column and were calculated from individual specimens tested in pairs. I-bars indicate ±1 standard deviation.

IDT-CT Test

Figure 25 shows average measured CT_{index} values of LCR, LCNR, and LCNR-P specimen sets from each mixture. The average CT_{index} value of all tested specimens was 79, with an average standard deviation of 14. The maximum and minimum CT_{index} values were 117 (Mixture H) and 27 (Mixture E), respectively, for LCR specimens; 165 (Mixture D) and 44 (Mixture A), respectively, for LCNR specimens; and 208 (Mixture K) and 33 (Mixtures J and G), respectively, for LCNR-P specimens. The variability of the IDT-CT test for repeatability of measurements for the same specimen type, quantified in terms of COV and shown in Figure 26, was less than 30% except for C-LCR and B-LCNR-P specimens. The mean COV calculated from testing replicates of LCR, LCNR, and LCNR-P mixtures was 17.4%, 17.7%, and 17.9%, with standard deviations of 8.6%, 11.7%, and 9.0%, respectively. The results indicated acceptable repeatability for the IDT test.



(a) (b)

Figure 24. Effect of Reheating on Rut Depth Measurements: (a) LCR vs. LCNR specimens; (b) LCR vs. LCNR-P specimens

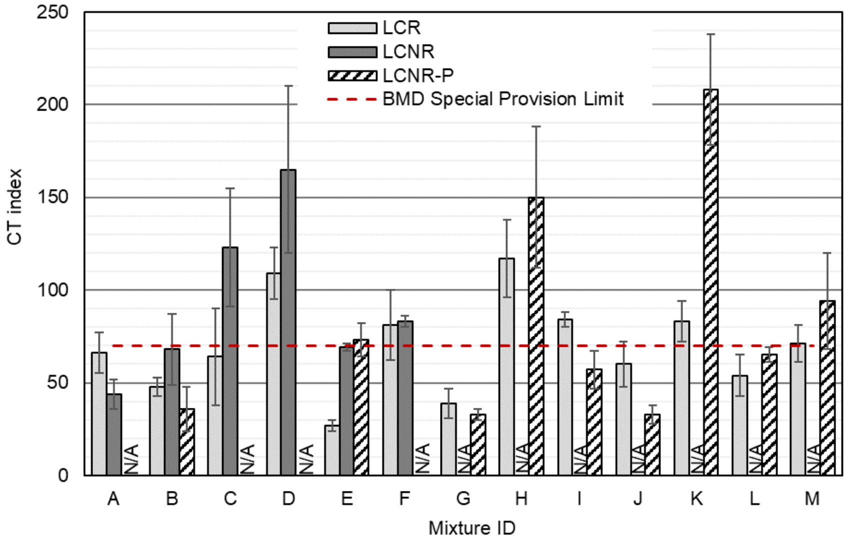


Figure 25. CT$_{index}$ Results. Averages were computed from a minimum of three replicate specimens. I-bars indicate ±1 standard deviation.

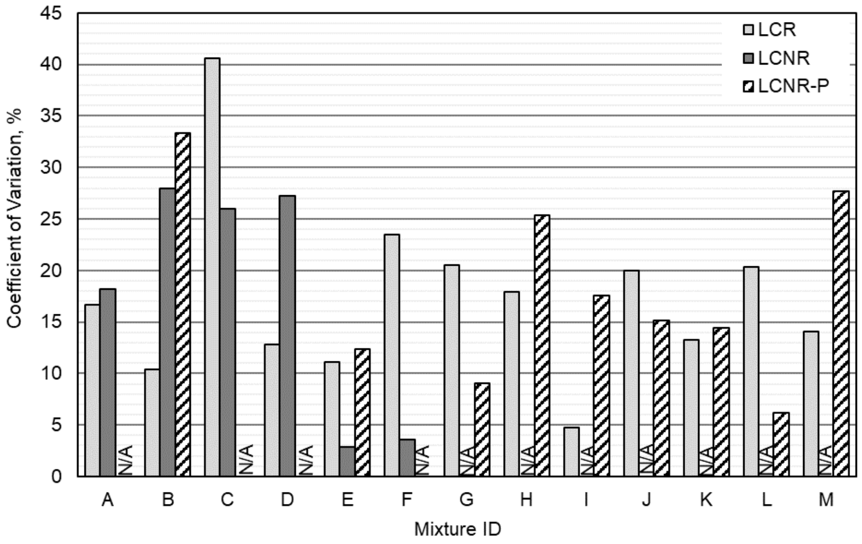


Figure 26. Variability of CT_{index} Measurements by Specimen Type

Figure 27 presents the average CT_{index} values and air voids of LCR-tested specimens for each mixture. The dashed red line shows the current BMD requirement for CT_{index}, an average minimum value of 70, and the blue dashed double-dotted line shows the average CTindex minus 1 standard deviation determined from all tested mixtures. Figure 27 shows that only Mixtures D, F, H, I, J, and M met the CT_{index} requirement. In addition, the average CT_{index} minus 1 standard deviation value was below 70 for LCR specimens, indicating that the majority of the evaluated mixtures may be susceptible to premature cracking.

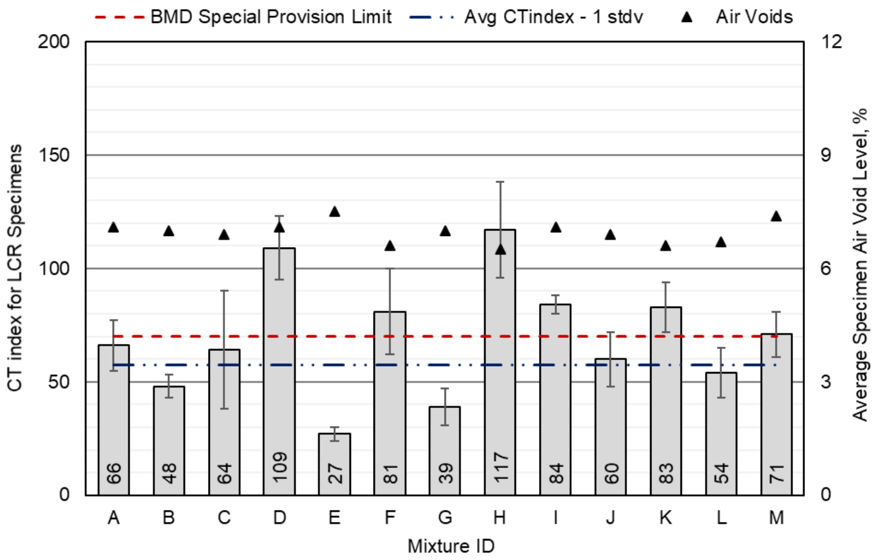
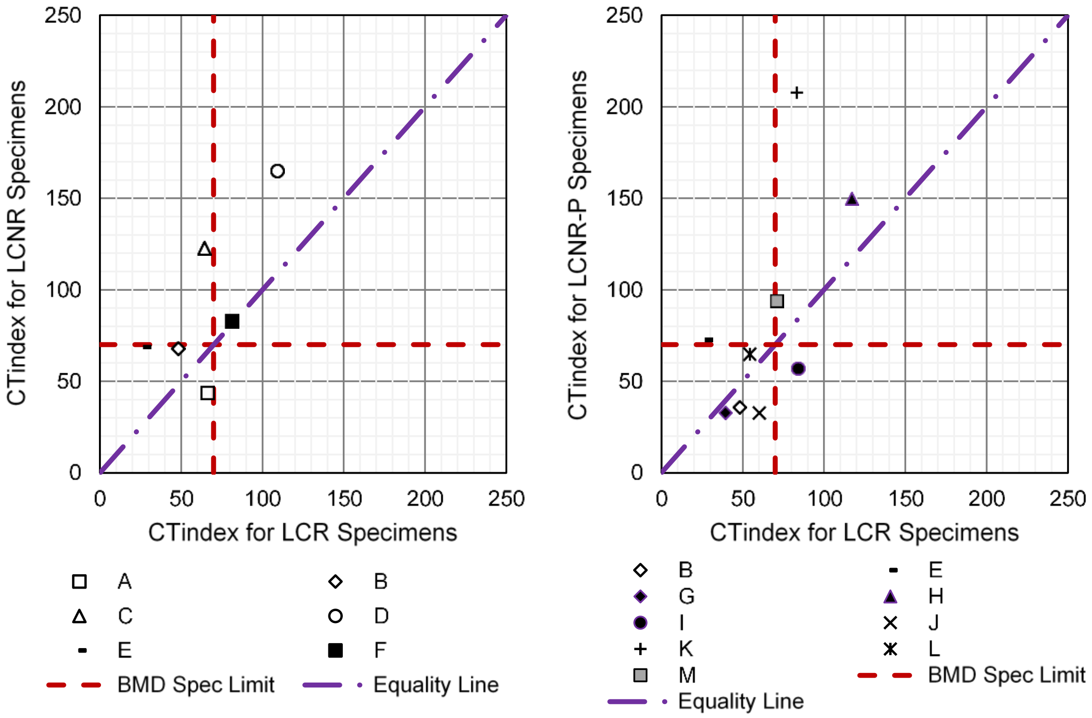


Figure 27. Average CT_{index} and Air Voids for LCR Specimens. Average CT_{index} values are shown at the bottom of each column. I-bars indicate ±1 standard deviation.

Figure 28 compares the CT$_{index}$ of LCR specimens with those of LCNR and LCNR-P specimens. Figure 28(a) shows that only Mixtures A and F had similar or higher CT$_{index}$ values after reheating; the remaining four mixtures (B, C, D, and E) had considerable decreases in CT$_{index}$ after reheating. Figure 28(b) indicates that five of the nine evaluated mixtures (E, H, K, L, and M) had decreased CT$_{index}$ values for reheated specimens; Mixture G showed similar CT$_{index}$ values for reheated and non-reheated specimens; and all remaining mixtures (B, J, and I) showed an increase in the CT$_{index}$ for reheated specimens. Overall, it was shown that reheating prior to compaction may lead to an increase in the brittleness of the evaluated specimen, leading to a decrease in the CT$_{index}$ values and greater cracking susceptibility.



(a) (b)

Figure 28. Effect of Reheating on CT$_{index}$ Values: (a) LCR vs. LCNR specimens; (b) LCR vs. LCNR-P specimens

Evaluation of Field Cores

Field core samples were collected immediately after Mixtures A through F were paved. Once trimmed, the core samples were measured to determine the in-place layer thicknesses and air voids, shown in Table 10, and the mixtures' resistance to rutting and cracking using the APA and IDT-CT tests, respectively. An initial effort was made to determine the Cantabro loss for field cores. However, field cores were too thin for testing, so no Cantabro data are available.

Table 10. Average Layer Thicknesses and Air-Void Contents for Trimmed Field Cores

Mixture	Layer Thickness, mm		Air Voids, %	
	Average	**Std. Dev.**	**Average**	**Std. Dev.**
A	35.4	3.0	7.4	1.5
B	46.9	4.7	6.5	0.8
C	44.0	4.1	6.8	2.8
D	53.6	6.3	5.7	1.2
E	38.2	3.5	5.1	1.2
F	51.4	2.9	4.7	0.9

Figure 29 also presents the CT_{index} results for the FC specimens. The field cores were thinner than the 62-mm specimen height recommended for the test, ranging from 35.4 mm to 53.6 mm. However, corrections for height are embedded in the equation used to compute and normalize the CT_{index}. However, there has been very little experience evaluating the CT_{index} for field cores or other thin specimens, as evidenced by a lack of literature addressing the topic. As a result, there is a need to evaluate further the effectiveness of the height correction factor and determine how results from field cores relate to those from laboratory-compacted specimens.

As shown in Figure 29, the mean CT_{index} value for each of the six evaluated mixtures was greater than 70, with D-FC and E-FC specimens showing the highest and lowest CT_{index} values, respectively. Except for Mixture A, the mixtures generally ranked similarly in terms of FC vs. LCNR and LCNR-P specimens, although FC specimens showed a higher magnitude of CT_{index}.

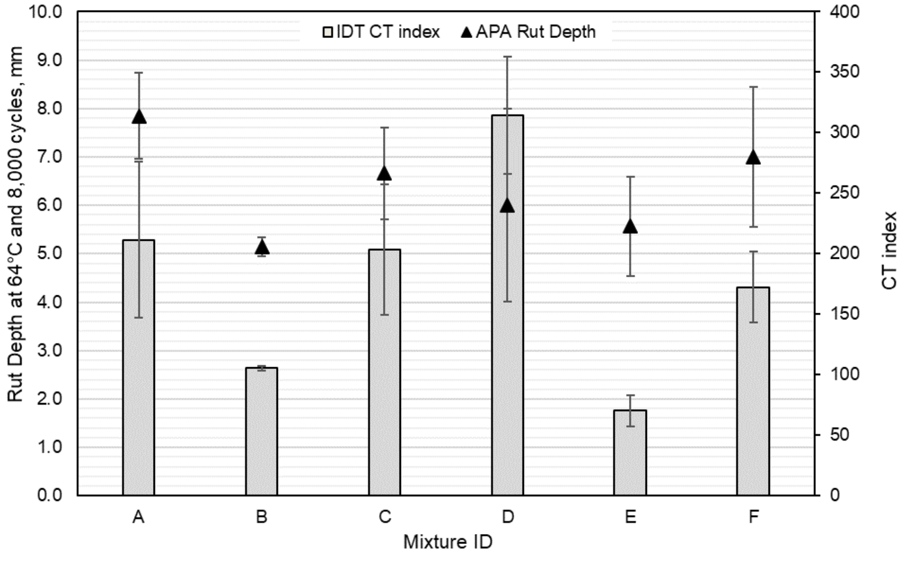


Figure 29. Average Rut Depth and CT_{index} Results for FC Specimens. I-bars indicate ±1 standard deviation.

Summary of Findings

Roadmap for BMD Implementation

- A comprehensive roadmap for BMD was developed. The roadmap is intended to be a living and evolving resource for outlining the agenda of activities necessary for implementation of BMD and will require further refinement from stakeholders to provide robust and effective guidance in support of BMD implementation.

Validation of BMD Performance Test Selection

- Binder testing performed on the extracted and recovered binders from six mixtures indicated that the binders met or exceeded VDOT specification criteria for binder properties.

- Analysis of the critical cracking parameter, ΔT_c, showed that the cracking warning limit of -2.5°C was exceeded by four mixtures (A, C, D, and F). The ΔT_c values of the remaining two mixtures (B and E) exceeded the cracking limit of -5.0°C, indicating a high susceptibility to non-load related cracking.

Dynamic Modulus Test

- The visual inspection of dynamic modulus mastercurves showed that Mixtures A and D had lower $|E^*|$ values (lower stiffness) and Mixture E had higher $|E^*|$ values (higher stiffness) across the loading spectrum. From the phase angle mastercurves, Mixture D had higher δ values and Mixture E had lower δ values (lower relaxation capability), indicating a higher cracking potential for Mixture E among the six mixtures.

- When $|E^*|$ values at 38°C and 0.1 Hz were plotted to quantify the rutting potential, Mixture E ranked as the most rut-resistant mixture, and Mixture D was potentially the most susceptible to rutting.

- The G-Rm parameter values calculated for the reheated mixtures were more comparable to the recommended threshold value (19,000 MPa) for long-term oven-aged laboratory-made mixtures than that for short-term oven-aged laboratory-produced mixtures (8,000 MPa), although neither threshold is directly applicable to the mixtures. A relative comparison among the G-Rm parameters indicated that Mixtures E and D ranked as the most and least crack-susceptible mixtures, respectively.

APA Test

- The APA rut depth was highly correlated ($R^2 = 0.89$) with the $|E^*|$ rutting parameter; in addition, the correlation trend was in the right direction (i.e., the higher the stiffness, the lower the rutting potential).

- The APA rut depth was moderately correlated with the binder parameters $|G^*|/\sin \delta$ (R^2 = 0.50) and $J_{nr,3.2kPa}$ (R^2 = 0.59); when an apparent outlying data point was removed, the correlations significantly increased (R^2 = 0.95 and R^2 = 0.97, respectively).

Cracking Tests

- Evaluation of the CT_{index}, FI, and N_{flex} factor variability using the COV parameter showed that the N_{flex} factor had the lowest variability followed by the CT_{index} and the FI had the highest variability.

- The assessment of the cracking indices for performance discrimination potential showed that the CT_{index} was the most sensitive index among those considered in this study. Pairwise statistical comparisons of the CT_{index} resulted in three groupings whereas those of the FI resulted in two groupings among the mixtures evaluated in this study. The N_{flex} index did not statistically discriminate the cracking performance of the mixtures.

- Ranking of the mixtures by performance indices showed that Mixture E was the most susceptible to cracking. The CT_{index} and N_{flex} ranked Mixture D as the most resistant to cracking. The FI ranked Mixture F as the most resistant to cracking in the absence of Mixture D data. The order of the ranking for the FI differed slightly from that of the CT_{index} and N_{flex} index, but the difference was deemed insignificant, as the order of ranking was not statistically and practically different when evaluated with respect to the discrimination potential.

- A very strong linear relationship was found among the indices. In combination with the performance ranking analysis, the correlation found in this study indicated that the cracking tests and associated indices could be used interchangeably to evaluate the cracking potential of asphalt mixtures.

- Moderate relationships were found between the indices and the G-Rm parameter. The FI showed the highest correlation to the G-Rm parameter, followed by the CT_{index} and N_{flex}.

Validation of BMD Performance Thresholds

Thirteen mixtures (A through M) were sampled and used to evaluate the performance thresholds proposed for the Cantabro, IDT-CT, and APA tests. Testing for the validation effort was conducted on several specimen types for each mixture to evaluate the differences among non-reheated specimens, reheated specimens, and field cores.

Cantabro Test

- The mean COVs for the Cantabro test calculated from testing replicates of LCR, LCNR, and LCNR-P mixtures were 11.7%, 10.9%, and 10.0%, respectively, with standard deviations of 6.6%, 5.0%, and 5.1%, respectively. The results indicated acceptable repeatability for the Cantabro mass loss test.

- Five of 6 evaluated mixtures had increased mass loss values when reheated specimens were compared with LCNR specimens; all differences but one were statistically significant. Two of those mixtures no longer met the 7.5% mass loss criterion when reheated.

- Eight of the 10 evaluated mixtures had LCR specimen mass losses greater than those of LCNR-P specimens, although only one-half of the differences were statistically significant. Reheated specimens for 2 mixtures showed very large increases in mass loss, to double and nearly double the LCNR-P specimen mass losses. Overall, it was found that reheating prior to compaction generally leads to an increase in mass loss.

- Comparisons of the mass loss values for 3 non-reheated mixtures compacted in the producers' laboratories by VTRC staff and by producer staff (LCNR vs. LCNR-P) to evaluate multi-operator effects on specimen fabrication showed no significant difference between the operator results for each mixture. Differences of 16.7%, 17.7%, and 16.4% between the operator averages were observed for the 3 mixtures; the average variation among operators was 16.9%, with a standard deviation of 0.7%.

APA Test

- The APA rut depth had a COV less than 20% for 19 of 28 specimen sets. The mean COVs calculated from testing replicates of LCR, LCNR, and LCNR-P mixtures were 12.2%, 15.5%, and 11.7%, with standard deviations of 8.3%, 6.6%, and 13.6%, respectively. The results indicated acceptable repeatability for the APA test.

- Based on LCR specimens, all but 1 mixture had a rut depth less than the 8.0 mm criterion. This was not surprising, despite the fact that these mixtures were not designed using the BMD method, as rutting has not been a major problem for VDOT since the adoption of Superpave.

- Comparisons of APA rut depths for reheated and non-reheated specimens indicated that reheating loose mixture to fabricate APA specimens may or may not cause an increase in specimen stiffness, resulting in decreases in the measured APA rut depth as compared to that of non-reheated specimens. Six of the 13 mixtures evaluated had reheated-specimen rut depths that were greater than or equal to those for non-reheated specimens. The comparisons of LCR and LCNR specimens from 6 mixtures resulted in 2 mixtures having increased rut depths for reheated specimens; 1 mixture having similar rut depths for reheated and non-reheated specimens; and 3 mixtures having a decrease in rut depths for reheated specimens. Similar results were found in the comparisons of LCR and LCNR-P specimens from 9 mixtures as 2 mixtures had increased rut depths for reheated specimens; 1 mixture had similar rut depths for reheated and non-reheated specimens; and the remaining 6 mixtures had decreased rut depths for reheated specimens.

IDT-CT Test

- The variability of the IDT-CT test for repeatability of measurements for the same specimen type in terms of COV was less than 30% except for two specimen sets. The mean COV calculated from testing replicates of LCR, LCNR, and LCNR-P mixtures was 17.4%, 17.7%, and 17.9%, with standard deviations of 8.6%, 11.7%, and 9.0%, respectively. The results were judged to indicate acceptable repeatability for the IDT test.

- The average CT_{index} values of LCR specimens from each mixture were compared to the current CT_{index} requirement, a minimum value of 70; only 6 of the 13 mixtures met the requirement. This was not surprising, as these mixtures were not designed using the BMD method.

- Comparisons of the CT_{index} of reheated and non-reheated specimens indicated that reheating prior to compaction may increase mixture brittleness and result in a decreased CT_{index} value, hence increased cracking susceptibility. The comparisons of LCR and LCNR specimens from 5 mixtures showed that 4 mixtures had statistically significant decreases in CT_{index} after reheating and only 3 mixtures had similar or higher CT_{index} values after reheating. The comparisons of CT_{index} for LCR and LCNR-P specimens found that 5 of the 9 evaluated mixtures had decreased values for reheated specimens; 1 mixture had similar values for reheated and non-reheated specimens; and the 3 remaining mixtures had increases for reheated specimens.

Field Cores

- Field cores collected from surface courses were too thin to conduct Cantabro testing. An attempt to perform the test resulted in destruction of the specimens, rather than an evaluation of mass loss.

- All FC specimens had an average APA rut depth less than 8 mm, meeting current rutting criteria. All FC specimens had similar or lower rut depths compared to those of the corresponding LCNR and LCNR-P specimens.

- FC specimens were thinner than the 62-mm specimen height recommended for the CT_{index} test, ranging from 35.4 mm to 53.6 mm. A specimen height correction factor is used in the computation of the CT_{index}, although there has been little experience evaluating the CTindex for field cores or other thin specimens.

- The average field core CT_{index} for each of the 6 evaluated mixtures was greater than 70. Except for 1 mixture, the mixtures generally ranked similarly in terms of FC vs. LCNR and LCNR-P specimens, although FC specimens had a larger CT_{index}, possibly because of the difference in thickness or compaction method.

CONCLUSIONS

- *A roadmap for BMD was developed and is intended to be a dynamic resource for outlining the agenda of activities necessary for implementation of BMD.*

- *The correlations between test parameters for the mixtures tested in this study validated that the APA and IDT-CT tests selected for use in the BMD method are in agreement with fundamental performance tests.*

- *Based on the evaluation of desired characteristics and the considerations of the ease of specimen preparation, speed of testing, and minimal cost of equipment, the IDT-CT test and* CT_{index} *show promise for evaluating the cracking potential of asphalt mixtures.*

- *Based on results from the mixtures tested in this study, the APA test is suitable for continued use in BMD. The current performance criterion limiting APA rut depth to a maximum of 8.0 mm is reasonable based on additional mixture testing.* However, for full assurance that APA test threshold values used for BMD implementation are appropriate, results should also be compared and correlated to test results from fundamental rut tests such as the flow number test and rut depths obtained from mechanistic-empirical pavement design simulations and field performance. In addition, there is a need to evaluate the acceptable levels of test variability and develop precision estimates and statements.

- *Based on results from the mixtures tested in this study, the impact of reheating on rut depths may be mixture specific.* Six of the 13 mixtures evaluated had reheated-specimen rut depths that were greater than or equal to the rut depths for non-reheated specimens. This is in contrast to the expected trend for rut testing in which reheated specimens are expected to show lower rut depths than non-reheated specimens because of increased mixture stiffness from reheating. There is a need to address the effects of mixture reheating on rut test results.

- *Based on results from the mixtures tested in this study, the IDT-CT test is the most suitable test for continued use in BMD. The current performance criterion requiring a minimum* CT_{index} *value of 70 is reasonable based on additional mixture testing.* The need remains for the test to be evaluated with respect to fundamental cracking tests such as the BBF test and cracking obtained from mechanistic-empirical pavement design simulations and field performance. In addition, there is a need to evaluate the acceptable levels of test variability and develop precision estimates and statements. This will ensure that the most appropriate threshold value(s) is selected for implementation of the BMD method.

- *Based on results from the mixtures tested in this study, reheating loose mixture prior to compaction may increase mixture brittleness and result in a decreased* CT_{index} *value.* Nine of the 13 mixtures evaluated had $\mathrm{CT}_{\mathrm{index}}$ values for reheated specimens that were less than those for the non-reheated specimens. There is a need to address the impact of mixture reheating on cracking test results.

- *Based on results from the mixtures tested in this study, the Cantabro test is suitable for continued use in BMD. The current performance criterion limiting mass loss to 7.5% is reasonable based on additional mixture testing. Further, reheating prior to compaction generally leads to an increase in the Cantabro mass loss.* There is a need to evaluate the acceptable levels of test variability, develop precision estimates and statements, and address the effects of mixture reheating on test results.

RECOMMENDATIONS

1. *VDOT’s Materials Division and VTRC should continue to collaborate to support the implementation of BMD, including cooperative efforts to assemble a group of stakeholders and key persons to refine the roadmap for BMD. The roadmap should provide a clear direction regarding the activities necessary for implementation and serve as a resource to evaluate progress.*

2. *VDOT’s Materials Division and VTRC should continue to use the APA, IDT-CT, and Cantabro tests for BMD.*

3. *VTRC should continue to evaluate the relationships and correlations between the results of the APA and IDT-CT tests and the results of fundamental tests, mechanistic-empirical simulations and analyses, and field performance to ensure that the most appropriate threshold criteria are applied for implementation of the BMD method.*

4. *VTRC should continue to address the differences in test results attributable to mixture reheating and to different specimen types, such as laboratory-compacted specimens and field cores.*

5. *VTRC should continue to evaluate the APA, IDT-CT, and Cantabro tests to determine the acceptable variability and establish precision estimates and statements for each test.*

IMPLEMENTATION AND BENEFITS

Implementation

Regarding Recommendation 1, VDOT’s Materials Division has committed to the implementation of BMD beginning in 2023. VTRC is dedicated to supporting this effort and will continue to collaborate and provide research support. VTRC and the Materials Division will work together to refine the roadmap for BMD so that it can serve as a guide to the activities necessary for implementation and a resource to evaluate progress. This recommendation will be implemented within the first 6 months of 2021.

Regarding Recommendation 2, no further implementation is necessary at this time. VDOT’s Materials Division and VTRC are continuing the process of BMD implementation using the three recommended tests.

Regarding Recommendations 3 and 4, VTRC is supporting and will continue to support the testing and evaluation needs of the BMD implementation effort until full implementation is achieved. Ongoing work with BMD trial and pilot projects is providing a basis for the evaluation of field performance and comparison of specimen types. Current collaborations with Virginia Tech toward the evaluation of high RAP BMD mixture performance at VDOT’s heavy vehicle simulator site in Blacksburg will be providing accelerated performance results. Project

117336, Feasibility of Using Monotonic Loading-Based Tests to Evaluate Rutting Performance of Asphalt Mixtures, is performing extensive analyses on the IDT test and will be completed in late 2022.

Regarding Recommendation 5, VTRC is in the process of addressing test variability and the need for precision estimates and statements. Project 1167473, Round Robin Testing Program for the Indirect Tensile Cracking Test at Intermediate Temperature—Phase I, has begun to address this issue for the IDT-CT test. Phase II of the effort addressing the IDT-CT test variability is expected to begin in spring 2021 to address further the IDT-CT test variability; additional efforts to develop precision estimates and statements for the APA and Cantabro tests are expected to be undertaken as part of the BMD implementation effort.

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 will provide 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 framework 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

BMD SPECIAL PROVISIONS (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.

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. Job-Mix Formula

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.