Case Studies on the Implementation of Balanced Mix Design and Performance Tests for Asphalt Mixtures:

Virginia Department of Transportation (VDOT)

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
AMPT	Asphalt Mixture Performance Tester
APA	Asphalt Pavement Analyzer
ASTM	American Society for Testing and Materials
DOT	Department of Transportation
BMD	Balanced Mix Design
COV	coefficient of variation
FBF	Flexural Bending Fatigue
FHWA	Federal Highway Administration
HVS	heavy vehicle simulator
IDT	Indirect Tensile
ILS	interlaboratory study
JMF	job mix formula
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NJ	New Jersey
NMAS	nominal maximum aggregate size
OBC	optimum asphalt binder content
OT	Overlay Tester
PBS	performance based specification
PCC	Portland cement concrete
PEP	Performance Engineered Pavements
PMD	Performance Mixture Design
PG	performance grade
ME	mechanistic-empirical
RA	recycling agent
RAP	reclaimed asphalt pavement
SHA	state highway agency
SMA	stone matrix asphalt
SSR	stress sweep rutting
STIC	State Transportation Innovation Councils
TSR	tensile strength ratio
TxDOT	Texas DOT
U.S.	United States
VAA	Virginia Asphalt Association
VDOT	Virginia DOT
VECAT	Virginia Education Center for Asphalt Technology
VFA	voids filled with asphalt
VMA	voids in mineral aggregate
VTM	Virginia Test Method
VTRC	Virginia Transportation Research Council

VTTI	Virginia Tech Transportation Institute

BACKGROUND

Balanced mix design (BMD) is one of the programs that supports the Performance Engineered Pavements (PEP) vision of the Federal Highway Administration (FHWA) that unifies several existing performance focused programs. This vision incorporates the goal of long-term performance into structural pavement design, mixture design, construction, and materials acceptance. In November 2019, FHWA published FHWA-HIF-20-005 Technical Brief, *Performance Engineered Pavements*. It provides an overview of the several initiatives that encompass the concept of PEP.

The BMD combines binder, aggregate, and mixture proportions that will meet performance criteria for a diverse number of pavement distresses for given traffic, climate, and existing pavement conditions. In December 2019, FHWA published FHWA-HIF-19-103, *Index-Based Tests for Performance Engineered Mixture Designs for Asphalt Pavements*. This informational brief provides practitioners with information about index-based performance tests that can be implemented within a BMD process.

In August 2018, the National Cooperative Highway Research Program (NCHRP) Project 20-07/Task 406, *Development of a Framework for Balanced Mix Design*, included a draft American Association of State Highway and Transportation Officials (AASHTO) Standard Practice for Balanced Design of Asphalt Mixtures with a nine step process for evaluating and fully-implementing a performance test into routine practice. The AASHTO Standard Practice describes four approaches (A through D) for a BMD process. The following is a brief description of the four approaches:

- ***Approach A, Volumetric Design with Performance Verification***. The Superpave asphalt mixture design at the optimum asphalt binder content (OBC) determined in accordance with AASHTO R 35 should meet the additional performance test criteria.

- ***Approach B, Volumetric Design with Performance Optimization***. Adjustments by up to plus or minus 0.5% for the preliminary asphalt binder content may be determined in accordance with AASHTO R 35 to meet the target performance test criteria.

- ***Approach C, Performance-Modified Volumetric Design***. AASHTO R 35 is used through the evaluation of trial blends to establish a preliminary aggregate structure and asphalt binder content. Performance testing is then used to adjust either the preliminary binder content or mixture component properties or proportions in order to meet the target performance test criteria. In this approach, the final asphalt mixture design is primarily focused on meeting performance test criteria and may not have to meet all Superpave volumetric criteria.

- ***Approach D, Performance Design***. Asphalt mixture components and proportions are established and adjusted based on performance analysis with limited or no requirements for volumetric properties. Minimum requirements may be set for asphalt binder and aggregate properties. Once the asphalt mixture properties measured using laboratory performance tests meet the performance criteria, the asphalt mixture volumetric properties may be checked for use in production.

The process identified in NCHRP Project 20-07/Task 406 involves nine essential steps for moving a performance test from concept to full implementation:

(1) Draft test method and prototype equipment.
(2) Sensitivity to materials and relationship to other laboratory properties.
(3) Preliminary field performance relationship.
(4) Ruggedness experiment.
(5) Commercial equipment specification and pooled fund purchasing.
(6) Interlaboratory study (ILS) to establish precision and bias information.
(7) Robust validation of the test to set criteria for specifications.
(8) Training and certification.
(9) Implementation into engineering practice.

While some of these nine steps can be adopted directly by a state highway agency (SHA) based on the level of effort completed regionally or nationally (e.g., steps 1, 4, and 5), others would need to be checked, expanded or redone using available (local) materials (e.g., steps 2, 3, 6, and 7). Steps 8 and 9 would need to be done by each SHA as part of its full implementation effort.

There is widespread recognition and desire by SHAs and the asphalt paving industry to use performance testing to complement volumetric properties to help ensure satisfactory pavement performance. Some SHAs have used the BMD process as part of mixture design and acceptance on select demonstration projects or have well developed BMD specifications, performance test methods and practices in place. These SHAs have valuable experiences and lessons learned that can facilitate the implementation of a BMD process or a performance test of asphalt mixtures into practice to improve long-term pavement performance.

OBJECTIVE

The primary objective of this overall effort was to identify and put forth positive practices used by SHAs when implementing BMD and performance testing of asphalt mixtures. To accomplish this objective, information was collected through site visits and other means with seven key agencies. Virginia Department of Transportation (VDOT) graciously agreed to host a virtual site visit.

SCOPE AND OUTCOMES

The scope of each virtual site visit included: a pre-visit kickoff web conference and review of agency documents (policy, specifications, research reports, etc.); and a two to four-day virtual site visit to obtain detailed understanding of agency best practices and lessons learned for BMD and performance testing of asphalt mixtures that can facilitate the implementation of a BMD process into practice at other SHAs. The outcomes of each virtual site visit were to include:

1. A brief report to each FHWA Division Office and SHA visited on the observations and any recommendations identified.
2. A summary document of positive practices compiled from specific reviews in all of the SHAs visited.
3. A short, informational brief with the key highlights.

4. An accompanying PowerPoint presentation.
5. Depending on observations, research need statements may be developed for consideration.

This document is the brief report on the observations and recommendations identified through the VDOT virtual site visit.

GENERAL INFORMATION SPECIFIC TO VDOT

Virginia has been a leader in successfully recycling asphalt pavements for more than 40 years. After couple successful initial experimental projects, the use of reclaimed asphalt pavement (RAP) in VDOT asphalt mixtures (ranged between 10 and 50% RAP) became common practice throughout Virginia since the early 80's. For asphalt mixtures with less than 20% RAP no asphalt binder grade change was required. However, an asphalt binder grade change was required for asphalt mixtures with 20-30% RAP content. It should be noted that RAP in Virginia is owned by asphalt producers. In 2019, the Asphalt Institute estimated that 10 million tons of RAP materials were stockpiled; 2019 usage figures were not yet available during our virtual site visit, but in 2018 the NAPA IS-138 report indicated 11 million tons of asphalt mixes with RAP were produced in Virginia and 3.9 million tons of RAP remained in stockpiles statewide.

In mid to late 1990s, VDOT adopted the Superpave method as specified in the AASHTO M 323, "Standard Specification for Superpave Volumetric Mix Design" and AASHTO R 35, "Standard Practice for Superpave Volumetric Design for Asphalt Mixtures" to identify the optimal aggregate blend and its corresponding OBC. This included the implementation of the Superpave performance grade (PG) asphalt binder system. Accordingly, VDOT reduced the allowable RAP percentages as the asphalt binder suppliers switched over to the new PG system. This stemmed from the fact that no guidance for the use of RAP in asphalt mixtures was originally provided by the Superpave design method, and because the effects of aged reclaimed asphalt binders on the PG of virgin asphalt binders were not known. Thus, VDOT adjusted its requirements to specify no more than 20% RAP in surface and intermediate asphalt mixtures (designated as SM and IM, respectively).

The implementation of Superpave resulted in dense-graded asphalt mixtures that had coarser aggregate blend gradations and low asphalt binder contents that did not perform well (durability and cracking issues). Thus VDOT made adjustments to their Superpave criteria to replicate the finer and higher asphalt binder content mixtures that were produced prior to adopting Superpave. Nonetheless, VDOT continued to allow up to a maximum of 20% RAP in asphalt mixtures.

This RAP limit stayed in place for VDOT surface asphalt mixtures until 2007, when VDOT explored the possibility of increasing RAP content to 30% and 35% without the requirement to use softer virgin asphalt binders (i.e., PG bump down) not common in the Virginia market. Field projects using more than 20% RAP were conducted (total of 129,277 tons of asphalt mixture placed containing 21% to 30% RAP). Asphalt mixtures containing less than 20% RAP were sampled and tested by the Virginia Transportation Research Council (VTRC) for comparison purposes. No significant differences were found between the higher RAP asphalt mixtures (i.e., up to 30% RAP) and the control asphalt mixtures (i.e., up to 20% RAP) when evaluated using the Flexural Bending Fatigue (FBF) test for fatigue cracking (AASHTO T 321), the Asphalt Pavement Analyzer (APA) test for rutting (Virginia Test Method [VTM] 110), and the Indirect

Tensile Strength Ratio (TSR) test for moisture damage (AASHTO T 283). Furthermore, no construction issues attributed to the use of the higher RAP asphalt mixtures were observed. The findings from this study led in 2009 to changes in the VDOT specifications. Since then up to 30% RAP has been allowed in surface and intermediate asphalt mixtures (designated as SM and IM, respectively) with PG change, and up to 35% RAP in base asphalt mixtures (BM) with softer PG.

Late fall of 2017, Benchmarking of Asphalt Mixtures for Support of Higher-RAP Pilot Projects (VDOT UPC #112606) was initiated as a response to the VDOT Chief Engineer's charge to develop specifications for using surface asphalt mixtures with higher RAP contents (more than the 30% allowed per standard specification) during the 2018-2019 paving season. This effort followed field trial projects in 2013-2014 with 40-45% RAP content and continuous discussions with industry about high RAP content pilot projects. The Benchmarking study involved testing by VTRC of several asphalt mixtures from the 2015 paving season which were not yet typical in 2015, but represented what became typical mixtures by 2017; these were all either Type A or Type D mixes with nominal maximum aggregate size (NMAS) of 9.5mm or 12.5mm. These asphalt mixtures, from which baseline performance was developed, were used in a major study in 2015 to evaluate changes in laboratory performance of asphalt mixtures designed using 65 gyrations versus a trial specification requiring them to be designed at 50 gyrations. All testing was conducted on reheated laboratory compacted specimens. Note that as of 2016, VDOT requires that all dense-graded asphalt mixtures (SM, IM, and BM) be designed at 50 gyrations.

Since cracking is a main concern with high RAP asphalt mixtures, the Benchmarking study evaluated several cracking tests in order to determine which available test provided rational results, and would be implementable. The following tests were initially evaluated: Cantabro test for durability (AASHTO TP 108); APA test for rutting (VTM-110); Overlay Tester (OT) for resistance to general and reflective cracking (Tex-248-F); Illinois Flexibility Index (I-FIT) for cracking resistance (AASHTO TP 124); N_{flex} factor for cracking resistance, draft AASHTO standard method for *Determining the Indirect Tensile Nflex Factor to Assess the Cracking Resistance of Asphalt Mixtures*; and Indirect Tensile (IDT) Cracking Test (formerly known as IDEAL-CT) for cracking resistance (ASTM D8225). As a result, the Benchmarking study recommended the use of Cantabro, APA, and IDT cracking tests in both the high RAP and regular dense-graded asphalt mixture design specifications. This also included recommendations for initial performance test criteria.

The recommendations of the Benchmarking study were implemented by VTRC through project Performance Mixture Design for Asphalt Mixtures: Phase I, Roadmap and Specification Development (VDOT UPC #112037) that was initiated in 2018 to further validate the initially established performance test criteria using currently produced typical dense-graded surface asphalt mixtures (designed to 50 gyrations). The recommendations were applied in the development of a special provision for "High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria" that can be utilized in field trials.

Concurrently with the development of the BMD special provision for high RAP content surface mixtures, VDOT also developed a BMD special provision for "Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria." This special provision does not change the standard specification limit of maximum 30% RAP.

During the PMD–Phase I study, typical (not high-RAP) asphalt mixtures from on-going field projects were sampled and tested by VTRC in order to add and expand the original Benchmarking data set (this effort is still continuing). Thirteen plant-produced mixtures were collected from various plants in Virginia. The sampled mixtures were dense-graded SM having a NMAS of 9.5 mm and 12.5 mm and commonly used in Virginia. These mixtures were evaluated in the laboratory for durability using Cantabro mass loss test, resistance to rutting using APA test, and resistance to cracking using IDT cracking test. These tests were conducted on reheated laboratory-compacted specimens. Reheating was accomplished by heating the cooled mixture (collected on site and returned to the VTRC laboratory in boxes) to the compaction temperature prescribed from the mix design, and then compacting it. Fewer of these tests were conducted on non-reheated specimens compacted by the VTRC crew on site in the producer's laboratory. Moreover, some of these tests were also conducted on non-reheated specimens compacted by the producer's crew on site in the producer's laboratory. Finally, some of these tests were conducted on field compacted specimens (i.e., cores) taken at the job site after paving and returned to the VTRC laboratory for testing. There was also a plan to sample asphalt mixtures on shadow projects during the design process with producer cooperation to look at how different changes in volumetric properties influence performance test results; however, that portion of the work plan did not happen. Another part of this effort was also to assess the influence of reheating asphalt mixtures on performance test results.

During the PMD–Phase I study it was found that making gyratory pills on site could be challenging. VTRC had its laboratory technicians make gyratory pills during production in the contractors' laboratories (at that time only VTRC had been making the IDT strength and APA specimens regularly) to support and save asphalt mixture producers some effort. Unless the asphalt mixture producer made at least one trial gyratory pill prior to VTRC arrival, determining the correct asphalt mixture mass to achieve target air void levels was very difficult when using only the mass/volume relationship. In some instances none of the site prepared specimens met the target air void tolerances. Nonetheless, fabricated specimens were tested by VTRC and collected data were used to evaluate how void content affected performance test results.

The Balanced Mix Design for Asphalt Mixtures: High RAP Field Trials (VDOT UPC #115763) study started in June 2019 to evaluate field projects being constructed under the VDOT BMD special provision for high RAP content surface mixtures. The BMD special provision covers the requirements and materials used to produce asphalt mixtures containing 40% RAP and higher. Two field trials were constructed during the 2019 paving season and performance testing is still ongoing on some of the reheated specimens. One of the trials used the high RAP specification (40% RAP), while the other was constructed under the non-high-RAP version of the specification and used recycling agents (RAs) to improve asphalt mixtures with standard RAP content (26% RAP). Additional trial projects across the state are anticipated during the 2020 paving season.

Figure 1 shows VDOT's overall timeline for a statewide implementation of BMD It should be noted that VDOT maintains a total of 128,770 lane miles in interstate, primary, and secondary systems; it is anticipated that initially the majority of BMD mixes will be placed on non-interstate systems, as BMD is currently limited to standard dense-graded mixes, and interstates in Virginia are most commonly paved with polymer-modified mixes and/or stone matrix asphalt (SMA). The timeline involves development of performance test criteria for cracking and rutting, construction and evaluation of pilot projects, VDOT acquisition of laboratory equipment, development and execution of training materials, as well refinement of specification requirements as suggested by the pilot projects. VTRC is responsible for all of the related research studies and activities necessary for BMD implementation.

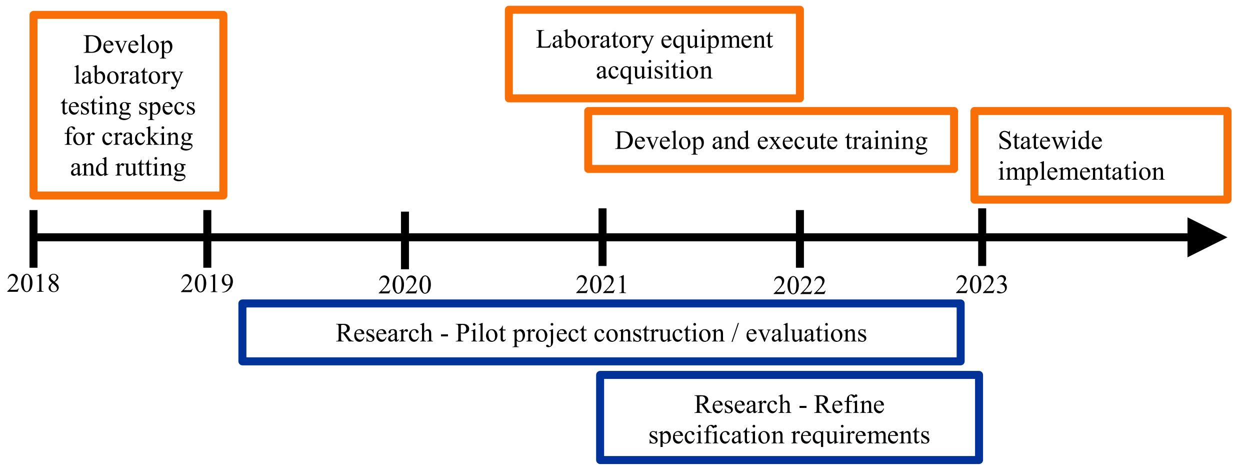


Figure 1. Chart. VDOT timeline for statewide implementation of BMD.

VDOT/VTRC acknowledges that the current timeline schedule is aggressive and the statewide implementation might be phased in based on available resources (e.g., equipment, laboratory space, and staff). Additionally, VDOT/VTRC has not yet defined how "implementation" will ultimately be defined (i.e.: BMD for all mixtures/ routes/traffic levels, or only a portion; performance testing for design only, or also for production and acceptance; or some other definition. Staff are mindful that the definition of implementation will significantly affect the extent to which the time line can be aggressive. To support a smooth implementation of performance tests as part of asphalt mixture design and acceptance, VDOT established a "BMD Advisory Committee" and a "BMD Technical Subcommittee" to assure proper communication and continuous dialogue with stakeholders and to provide timely and constructive technical inputs.

BMD APPROACH

VDOT developed two special provisions for BMD of surface asphalt mixtures:

- Special Provision for Balanced Mix Design (BMD) Surface Mixtures Designed Using Performance Criteria: RAP percentage is not addressed in this specification; the standard specification governs (a maximum of 30% RAP).
- Special Provision for High Reclaimed Asphalt Pavement (RAP) Content Surface Mixtures Designed Using Performance Criteria: This specification defines "high RAP" as a minimum of 40%, but no maximum is specified.

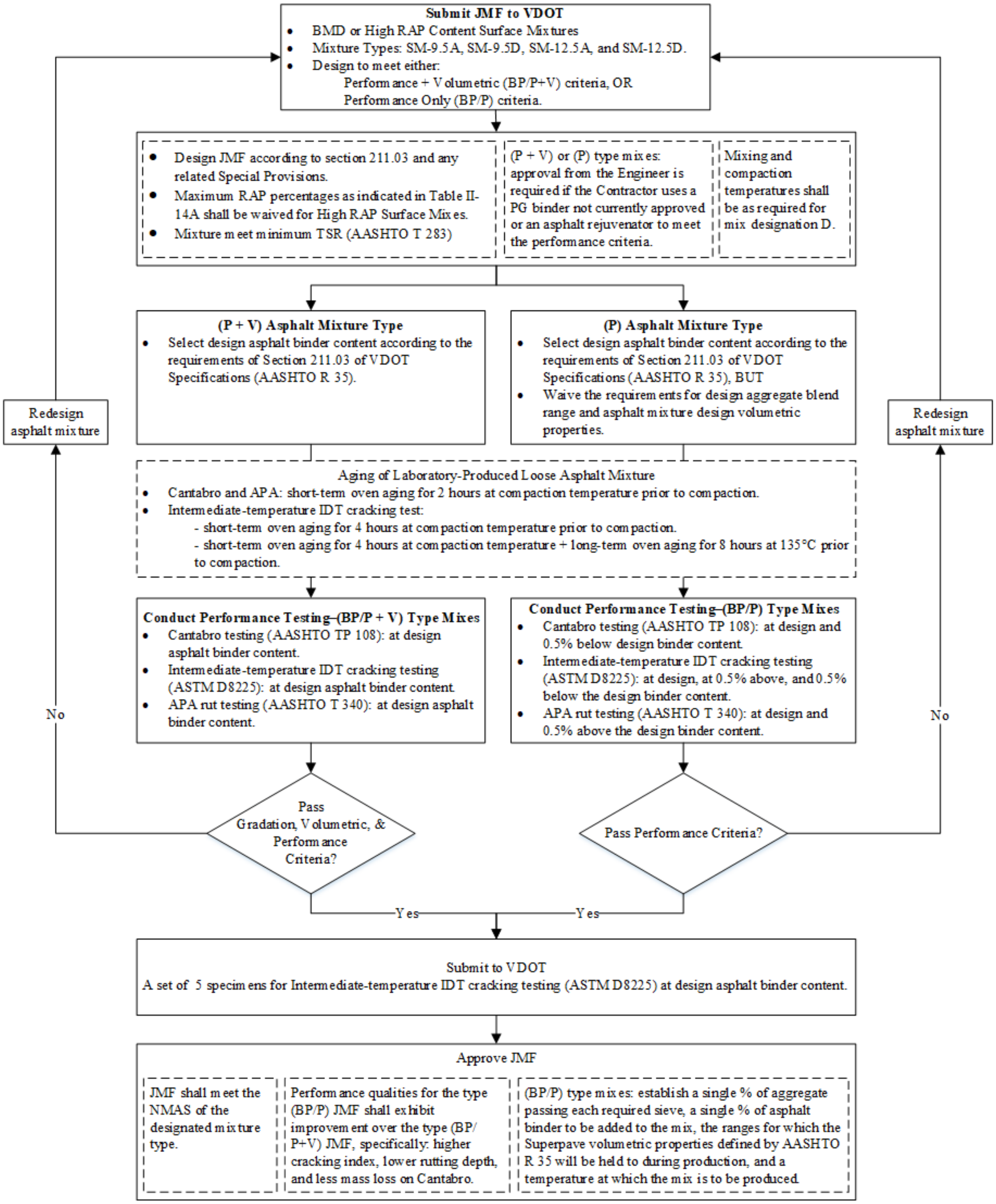
Figure 2 shows a flowchart of the overall BMD for the two special provisions for surface mixtures. The flowchart highlights the major steps for undertaking an asphalt mixture design according to VDOT specifications. The requirements for volumetric design, gyratory compaction efforts, and performance testing are summarized in table 1 and table 2.

The VDOT's BMD for designing asphalt mixtures and approving job mix formulas (JMFs) allows for using Approach A *Volumetric Design with Performance Verification* that is referred to by performance + volumetric (BP/P + V), and/or Approach D *Performance Design* that is referred to by performance (BP/P).

In approach A (i.e., VDOT BP/P + V), the asphalt mixture has first to pass all gradation and volumetric property requirements before being evaluated in the designated performance tests. Subsequently, the asphalt mixture at the design asphalt binder content needs to pass the performance criteria for durability, cracking, and rutting. If the asphalt mixture fails any of the criteria, the contractor has to redesign and resubmit the asphalt mixture for JMF approval following the same process.

In approach D (i.e., VDOT BP/P), the design aggregate blend range and volumetric property requirements are waived; however, NMAS requirements are still in place. The asphalt mixture at the design asphalt binder content needs to pass the performance criteria for durability, cracking, and rutting. Performance testing results have to be reported at design asphalt binder content along with those at 0.5% above and/or below the design asphalt binder content.

In the case of BMD surface asphalt mixtures, i.e., (BP + V) or (BP) type mixes, a PG of the asphalt binder is recommended depending on RAP content (Table 3). On the other hand, a PG is not specified for the high RAP surface asphalt mixtures; it is determined by the asphalt mixture design and performance testing. However, approval from VDOT is required if the contractor uses an asphalt binder that is not currently approved or an asphalt rejuvenator to meet the performance test criteria.



Note: TSR is part of asphalt mixture design approval during production.

Figure 2. Chart. Overview of VDOT's BMD approach for BMD and high RAP content surface mixtures.

Table 1. Mix Design Volumetric Requirements and Gyratory Compaction Effort for (P+V) Type Surface Mix.

Mixture Type	Required Density (% of Theoretical Max. Specific Gravity)	VMA (Minimum %)					VFA (%)	Dust-to-Binder Ratio	N_{des}
	N_{design}	NMAS (mm)							
		25	19	12.5	9.5	4.75			
SM-9.5A	96.0	–	–	–	16.0	–	75–80	0.7–1.3	50
SM-9.5D	96.0	–	–	–	16.0	–	75–80	0.7–1.3	50
SM-12.5A	96.0	–	–	15.0	–	–	73–79	0.7–1.3	50
SM-12.5D	96.0	–	–	15.0	–	–	73–79	0.7–1.3	50

–Not applicable.

Table 2. Mix Design Performance Testing Requirements for (P+V) and (P) Type Surface Mixes.

Index Parameter	Test	Criteria
Cantabro mass loss	AASHTO TP 108	≤ 7.5%
Cracking tolerance index	ASTM D8225	≥ 70 at 25°C
APA rut depth	AASHTO T 340	≤ 8.0 mm after 8,000 passes at 64°C
TSR	AASHTO T 283	≥ 0.80 at 25°C

Table 3. Recommended PG of Asphalt Binder for (BP+V) and (BP) Type Surface Mixes.

Mixture Type	% RAP ≤ 25.0%	25% < % RAP ≤ 30%
SM-9.5A, SM-12.5A	PG 64S-22	PG 64S-22
SM-9.5D, SM-12.5D	PG 64H-22	PG 64S-22

An antistripping additive is required in all asphalt mixtures (hydrated lime, an approved chemical additive, or a combination of both). Hydrated lime is to be added at a rate of minimum 1% by weight of the total dry aggregate. The chemical additive is to be added at a rate of minimum 0.30% by weight of the total asphalt binder content of the mixture. The contractor submits with the asphalt mixture design the TSR (AASHTO T 283) that has to meet a minimum of 0.80. The asphalt mixture is conditioned according to AASHTO R 30 before being compacted. VDOT checks TSR requirement for the first 500 tons of production on plant-produced asphalt mixtures.

In comparison to AASHTO M 323 and AASHTO R 35, due to ongoing concerns about mixture durability, in 2016 VDOT implemented the following key modifications to their volumetric design criteria (table 1):

- Specified 50 gyrations for design and acceptance of BMD or high RAP surface mixtures.
- Increased the voids in mineral aggregate (VMA) requirement by 1% for both NMAS of 9.5 and 12.5 mm.
- In general, increased the lower and upper limits of voids filled with asphalt (VFA).
- Increased the lower and upper limit of the dust-to-binder ratio by 0.1.

The above changes to AASHTO M 323 and AASHTO R 35 are aimed at increasing the durability and cracking resistance of an asphalt mixture by letting more asphalt binder into the mixture without jeopardizing its resistance to rutting (the higher the VMA, the higher the asphalt binder content for a given air void level). Similar changes were introduced for intermediate course mixtures and base course mixtures in 2019. The interest in BMD has been a continuation of efforts to improve asphalt mixture durability.

The high RAP surface mix specification is unique for the following two reasons:

- The specification calls for a minimum (not a maximum) of 40% RAP to be added to the asphalt mixture.
- The specification does not prescribe a specific PG of the asphalt binder. Any PG is allowed provided that the asphalt mixture meets all of the required volumetric property and/or performance testing requirements.

SELECTION OF PERFORMANCE TESTS

Table 4 summarizes the asphalt mixture performance tests currently used by VDOT for their BMD approach. VTRC is currently evaluating the feasibility of using monotonic loading-based tests at high temperature to evaluate the rutting performance of asphalt mixtures. These tests include but are not limited to high-temperature IDT strength, ideal shear rutting test (IDEAL-RT), and Marshall Stability. These tests are being evaluated for potential use during production for acceptance. The research efforts are still ongoing; a final selection has not been made.

Table 4. Summary of Performance Tests Considered by VDOT for BMD.

Elements	Stability/Rutting	Durability/Cracking	Moisture Damage/Stripping
Test Name	Asphalt Pavement Analyzer (APA)	Cantabro Indirect Tensile (IDT) Cracking	Indirect Tensile Strength Ratio (TSR)
Test Method	AASHTO T 340	AASHTO TP 108 ASTM D8225	AASHTO T 283
Test Criteria	Refer to table 2.	Refer to table 2.	Refer to table 2.
Test Implemented in Asphalt Mixture Design	Yes.	Yes.	Yes.
Aging Protocol	Lab-produced mixtures: Short-term conditioning of loose mixture for 2 hours at the design compaction temperature prior to compacting. Plant-produced mixtures: Minimize any cooling of and bring specimens to the compaction temperature and compact immediately.	Lab-produced mixtures: Short-term conditioning of loose mixture for 2 hours (Cantabro) or 4 hours (IDT cracking) at the design compaction temperature prior to compacting. Long-term conditioning of loose mixture for 8 hours at 135°C. Plant-produced mixtures: Minimize any cooling of, and bring specimens to the compaction	Lab-produced mixtures: Short-term conditioning of loose mixture in accordance with AASHTO R 30 Section 7.2 for 4 hours at 135°C. Plant-produced mixtures: Minimize any cooling of and bring specimens to the compaction temperature and compact immediately.

		temperature and compact immediately.	
Notes/Comments	VDOT is investigating the use of high-temperature IDT strength, ideal shear rutting test (IDEAL-RT), or Marshall stability for acceptance.	VDOT is investigating the use of other cracking performance tests or indices for acceptance.	VDOT conduct test on plant-produced asphalt mixtures during production part of approval process.

The selection of performance test must be matched to the mode of distress of pavement in-service, otherwise it negates the purpose of relating the BMD to ultimate in-service pavement performance. The following tests were initially considered and evaluated as part of the Benchmarking study for possible use in the BMD. The original reason for the selection of each performance test is also included.

- Cantabro test for durability, AASHTO TP 108: test was selected due to the limited number of durability tests available and for its simplicity.
- APA test for rutting, VTM-110: test was selected for initial testing due to its frequency of use and familiarity in Virginia as a rutting test. The test method recommendation was updated to follow AASHTO T-340 for consistency with current practice.
- OT for resistance to general and reflective cracking, Tex-248-F: reflection cracking distress is commonly observed throughout Virginia, particularly in asphalt concrete (AC) overlaying jointed Portland cement concrete (PCC) pavement. This test has also been successfully implemented in other performance based specifications (PBS), e.g., New Jersey DOT and Texas DOT.
- I-FIT for cracking resistance, AASHTO TP 124: test was selected based on the promise it has shown in research work conducted at VTRC and elsewhere (e.g., Illinois DOT).
- N_{flex} factor for cracking resistance, Draft AASHTO standard method: This test consists of loading specimen in indirect tensile mode using a Marshall Press or similar load frame. This test was selected based on promise shown elsewhere and the ability for VDOT and/or contractor to use a gyratory specimen (N_{design}) already produced for quality control and assurance purposes.
- IDT Cracking test (formerly known as IDEAL-CT) for cracking resistance, ASTM D8225: test was selected based on simplicity (no cutting is required and many contractors already possess the necessary load frames), speed of testing, minimal cost of equipment, and promise shown by other research groups.

As a result of the Benchmarking study, the Cantabro, APA, and IDT Cracking tests were selected for further investigation and are currently included in the two special provisions for BMD and High RAP content surface mixtures.

The top four factors for VDOT in selecting a performance test are: sample preparation, specimen conditioning and testing time, repeatability, and training needs. VDOT has noted that the ability of the test to relate to in-service performance is inherent to their entire approach, but final selection was driven by the potential to implement the test. The duration needed for sample preparation, specimen conditioning and testing, and the need for more efficient quality control during production have been key considerations for VDOT in the development of test criteria and the implementation of any performance test into the specifications. This is tied to the availability and cost of equipment needed to prepare, fabricate, and test specimens. Having an acceptable repeatability (within laboratories) and reproducibility (between laboratories) of test results is key for successful implementation of specifications. Having qualified and trained technicians helps to reduce the impact this factor might have on the overall implementation effort of performance tests.

Other important factors for VDOT are field validation and material sensitivity. Field validation and correlation of performance test results with measured field performance data is the basis for any BMD approach and was one of VDOT's motivations for implementation of performance tests. In the selection process, consideration was also given to the capability of a performance test to provide consistent results that follow common sense trends and rankings of the tested asphalt mixtures. The test results of local asphalt mixtures should not contradict known and observed field pavement performance, or recognized correlations between the mode of distress under evaluation and volumetric properties.

The feasibility of using monotonic loading-based tests to evaluate the rutting performance of asphalt surface mixtures is being researched by VTRC as surrogate performance tests for the APA during production. These tests include but are not limited to high-temperature IDT strength, ideal shear rutting (IDEAL-RT), and Marshall Stability. In general, these tests are quick procedures that use currently available equipment in the laboratory with slight modifications as needed; thus requiring minimal investments from both VDOT and the industry, and therefore allowing for more tests to be completed within normal working hours. The implementation of such tests reduce the overall need for VDOT manpower and accelerates the time to test and report back the results of sampled asphalt mixtures during production to the contractor (quick turnaround time). VTRC is planning on conducting monotonic loading-based tests during production on upcoming pilot projects this paving season in order to establish a database of test results that can be correlated to APA and mechanistically-determined rut test results (Feasibility of Monotonic Loading-based Tests to Evaluate Rutting Performance of Asphalt Mixtures [VDOT UPC #117336]). The success of this effort will facilitate the potential development and implementation of a PBS for asphalt mixtures used in the state including pay factors.

In a recently approved research project, VTRC will be developing easy-to-use guides and/or specifications that outline a framework to evaluate acceptability of RAs as part of the approved product list in Virginia. The first objective of this study is to develop or identify a testing protocol to evaluate the effectiveness of RAs in alleviating the brittleness of high RAP asphalt mixtures. Moreover, the study aims at developing a performance-based parameter(s) with its threshold limits to accept or reject RAs. Both objectives of the study aim at facilitating the incorporation of innovative materials as part of the BMD approach. The scope of work includes procuring representative asphalt binders, RAP material, and RAs from various sources and suppliers. Binders, mortar blends, and high RAP asphalt mixtures, all containing RAs, will be produced in the laboratory and will be subjected to a suite of rheology, chemistry, empirical, and mechanistic-based tests. The performance of such materials under various aging conditions will be compared to the performance of those produced using softer asphalt binders (No RAs). The performance of field trial sections previously constructed in the past two-to-four years using high RAP mixtures with RAs or softer asphalt binders will be assessed. Available data from Virginia's accelerated pavement testing (APT) program, which is expected to soon include high

RAP asphalt mixtures with RAs and softer binder, will also be considered. This effort is supported by a VTRC approved research project to evaluate RAs acceptance for Virginia: test Protocols and performance-based threshold criteria (UPC #117566 Recycling Agents' Acceptance).

The VTRC laboratory in Charlottesville owns three Asphalt Mixture Performance Testers (AMPT); a fourth located in the laboratory is on loan from the VDOT Materials Division. The AMPTs have been primarily used to conduct dynamic modulus and flow number (AASHTO T 378) tests on asphalt mixtures from around the state. VTRC continues to build and update the database of measured values for reheated plant-produced asphalt mixtures that VDOT can use as Level 1/2 inputs for the AASHTOWare® Pavement ME Design software. In addition, small specimen dynamic modulus (AASHTO TP 132), direct tension cyclic fatigue (AASHTO TP 107 and TP 133), stress sweep rutting (SSR) (AASHTO TP 134), confined flow number (NCHRP 9-30A), and Texas overlay (Tex-248-F) tests are being conducted using the AMPT on a limited basis and for research purposes.

The AMPT performance tests will be used as a reference for comparison and better selection of the index-based surrogate performance tests (part of the on-going study to assess the feasibility of using monotonic loading-based tests to evaluate rutting performance of asphalt mixtures, and part of the on-going study to evaluate the acceptance of RAs in Virginia). The AMPT test results will be utilized to evaluate the rutting and cracking performance of asphalt mixtures using mechanistic analyses and simulations (AASHTOWare® Pavement ME and FlexPAVE™). This includes analyzing the AMPT SSR and direct tension cyclic fatigue test results to provide permanent deformation and fatigue cracking model coefficients to FlexPAVE™ for mechanistic evaluation. This will provide information on the preliminary traffic-related rutting performance thresholds for the monotonic loading based rut test. This effort will also help verifying that the addition of RAs to high RAP mixtures will not jeopardize rutting while guaranteeing a good cracking performance.

PERFORMANCE TESTS DEVELOPMENT TO IMPLEMENTATION

The following section summarizes VDOT's experience with performance test implementation in terms of the nine essential steps identified in NCHRP Project 20-07/Task 406.

Step 1. Draft test method and prototype equipment.

Having existing standard test methods available supported efficient implementation of performance tests for asphalt mixtures within VDOT. AASHTO or ASTM standard test methods are available for Cantabro, APA, and IDT Cracking tests, and VDOT incorporated the methods for Cantabro and IDT cracking into the BMD approach. However, VDOT has used its own test method for APA (VTM-110) since the early 2000s, before the AASHTO T340 test method was available. VTM-110 differs from AASHTO T340 as it specifies a target air void level of 8% for compacted specimens (compared to 7% in AASHTO T 340), a hose pressure of 120 psi (compared to 100 psi in AASHTO T 340), a wheel load of 120 lb (compared to 100 lb in AASHTO T 340), and a standard test temperature of 49°C.

Instead of continuing the use of VTM-110 for the APA test, during initial work for VDOT's BMD effort, AASHTO T 340 was used to establish a performance test criterion for APA rut depth in order to bring VDOT practice into agreement with national methods. AASHTO T-340 requires the use of 7% air voids for compacted specimens, 100 psi hose pressure, and 100 lb wheel load. In addition, the test temperature as part of the BMD effort was set to 64°C. This created discrepancies between the collected data and the existing database of past APA test results. Nonetheless, this was thought to be acceptable since the VDOT BMD effort started around the same time when major changes in specifications were implemented on all VDOT dense-graded asphalt mixtures. The change in specifications necessitates the monitoring of field pavement performance of asphalt mixtures designed according to latest specifications for another 3-4 years before fully validating the initially established APA rut depth criterion. The historical database of APA test results can still be used after correlating the results obtained from the two standard test methods (i.e., AASHTO T 340 and VTM-110), which can done by comparing test results from both test methods for the same asphalt mixtures (a currently ongoing effort).

Step 2. Sensitivity to materials and relationship to other laboratory properties.

The sensitivity of performance test results to asphalt mixture component properties or proportions (e.g., aggregates, asphalt binders, recycled materials, additives), air voids, and aging is an important factor for VDOT. Contractors need to be able to make informed decisions on what changes can be made to the asphalt mixture composition in order to improve performance and meet applicable specification limits. While VDOT/VTRC relied on available relevant literature, studies were still conducted at VTRC using asphalt mixtures typically used in Virginia.

The Benchmarking study database was used to assess the ability of each performance test to distinguish among various asphalt mixtures; and to determine the ability of each performance test to relate to key asphalt mixture volumetric properties (e.g., air voids, effective asphalt binder content). As part of this study the Cantabro test, APA rut test, and four different cracking performance tests were evaluated using typical plant-produced asphalt mixtures. A performance test that does not relate to any of the volumetric properties was discarded from further evaluation. The following summarizes the findings from this study:

- Cantabro results were moderately correlated with only air voids and VFA.
- The APA rut results showed good correlations with air voids and VFA. Only moderate correlations were observed between APA rut depth and the dust-to-binder ratio, and percent passing the 12.6 and 9.5 mm sieves.
- The OT results were analyzed using three methods: an averaging method, the New Jersey (NJ) method, and the Texas DOT (TxDOT) method. The TxDOT method resulted in the lowest coefficient of variation (COV), followed by the NJ method and averaging method. Each method resulted in a different average number of cycles until failure. The averaging and NJ methods indicated that OT number of cycles until failure were positively correlated with asphalt binder content (coefficients of correlation of 0.79 and 0.80, respectively) and effective asphalt binder content (coefficients of correlation of 0.82 and 0.80, respectively); weaker correlations (0.66 and 0.61) were seen for the TXDOT method results. Thus, it was clear that the analysis method influenced the sensitivity of the OT to volumetric properties.

- In the case of the I-FIT test, minimal relationships were found between the flexibility index values and the studied properties in general. A correlation analysis found moderate relationships between the flexibility index and the asphalt mixture bulk and maximum theoretical specific gravities, and aggregate effective and bulk specific gravities.
- The N_{flex} factor values showed almost no relationship with the evaluated volumetric properties. Thus, the test was excluded from the PMD–Phase I study.
- The IDT Cracking test showed moderate correlations between the cracking tolerance index and asphalt binder content, air voids, VFA, effective asphalt binder content, and film thickness; no correlations were found with VMA or sieve sizes.

Similarly, a database of monotonic loading-based IDT surrogate tests (i.e., high-temperature IDT strength, IDT Cracking, and Marshall stability) is being developed by VTRC. VDOT is planning on testing plant-produced surface asphalt mixtures with A and D designations starting this paving season. The test results will be analyzed to assess test repeatability and ability to discriminate and rank asphalt mixtures based on their rutting performance. Correlations to APA test measurements will also be established; thus, allowing the development of performance test criteria for the IDT-based surrogate tests.

The sensitivity of the performance tests to RAs will also be examined in a newly approved research study that aims at developing a testing protocol to assess the effectiveness of RAs in alleviating the brittleness of high RAP asphalt mixtures. This study will evaluate asphalt mixtures produced in the laboratory using standard PG asphalt binder with various combinations of RAs or softer asphalt binders.

It should be noted that the majority of the studies and efforts have been based on plant-produced asphalt mixtures. A comprehensive study to assess the influence of changes in volumetric and other properties and their relationship to the performance of laboratory-produced asphalt mixtures has not been practical due to limitations in VTRC's technician manpower and workloads.

Step 3. Preliminary field performance relationship.

VDOT development of the initial specification has been based on benchmarking typical asphalt mixtures currently in use within Virginia. Plant-produced asphalt mixtures from 11 field projects were collected from various geographical regions of the state and tested (reheated samples) in VTRC laboratories. VDOT's approach for the development of test criteria is based on testing of asphalt mixtures with known history of field performance to correlate to laboratory test results. However, such performance history was not available for the 2015 typical asphalt mixtures used in the Benchmarking study. This was due to major specification changes in 2015 that comprised a reduction from 65 to 50 gyrations and an additional limitation on the No. 30 sieve for 9.5mm and 12.5mm NMAS dense-graded surface asphalt mixtures. Nonetheless, the established database of test results for the 2015 benchmarked asphalt mixtures is still being used in the BMD development efforts for comparison with field pavement performance as such data become available.

Three methods were considered to establish initial performance test criteria using the benchmarked asphalt mixtures:

- Method 1 (conservative application): Set the threshold at a value that will allow all tested asphalt mixtures to pass the criteria (i.e., a maximum value above or equal to the highest observed rutting or mass loss value; a minimum value below or equal to the lowest cracking index). This assumes that all mixtures tested will perform satisfactorily in the field as they meet the prescribed volumetric requirements.
- Method 2 (average): Use the average value of all tested mixtures for each of the performance tests.
- Method 3 (average ± standard deviation): Set the threshold at the average value plus (rutting and mass loss value) or minus (cracking index) the average standard deviation of all tested asphalt mixtures to incorporate mixture and test variability.

The analysis and scrutiny of performance test results led to the selection of:

- A maximum 7.5% for Cantabro loss based on Method 1: there was no evidence of durability concerns among the tested asphalt mixtures.
- A maximum 8 mm for APA rut depth based on Method 1: there was no evidence of rutting concerns among the tested asphalt mixtures.
- A minimum 70 for cracking tolerance index based on Method 2: even though none of the evaluated asphalt mixtures was shown to be particularly susceptible to cracking at the time of testing after 2 years in service, the cracking criteria was selected aggressively such that an emphasis was placed on cracking resistance in the BMD specification. Cracking was thought to be the biggest area of concern, especially for high RAP asphalt mixtures.

The preliminary performance test criteria are expected to be modified as more data are being collected by VTRC for 2018 (and continuing to the present) asphalt mixtures (testing of additional asphalt mixtures and monitoring field pavement performance). Moreover, additional criteria may be established specifically for high RAP asphalt mixtures with RAs. Work is also undergoing to select an IDT-based surrogate test and develop the associated preliminary test criteria to evaluate and accept asphalt mixtures designed following the BMD approach.

Step 4. Ruggedness experiment.

VDOT/VTRC did not conduct or participate in any formal ruggedness testing yet. Some ruggedness studies have been completed by other researchers for select performance tests. In 2019, VTRC completed IDT Cracking testing for plant-produced asphalt mixtures (compacted on site and reheated) and field core samples using different types of equipment/jigs (as part of the PMD–Phase I study). The testing was completed by VTRC and involved asphalt producers on a voluntary basis. A total of 13 asphalt mixtures were collected: plant-compacted, reheated, and field core specimens from 6 field projects; and plant-compacted and reheated specimens from 7 asphalt plants.

The comparison of raw data and test results from different setups helped VTRC in identifying and addressing issues that were observed with testing and equipment. Some examples are shown below:

- A ram travel safety switch on the Marshall press used to stop the loading before the peak value is reached. A solution was to override the safety switch on the Marshall press until it could be reconfigured, but that may not be a viable option.
- A Marshall press failed to meet the test method requirements for loading rate tolerance limits. The significance of this failure could not be assessed.
- For a specific jig, an incorrect zeroing of the LVDT on the jig during installation resulted in unacceptable test data. As a result the respective manufacturer issued clearer instructions on setting up the jig so that the zeroing shouldn't be a problem going forward.

The test results for the field cores were extremely variable with no strong correlation to air voids level. A total of 12 cores were sampled per field project, and testing was completed for the three cores closest to 7% air voids. Much higher cracking tolerance indices were observed for the field cores in comparison to the values for laboratory-compacted specimens of loose plant-produced asphalt mixtures. Field cores were also substantially less thick than laboratory prepared specimens, as surface lifts are typically only 1.5–2.0 inches (38–50 mm) thick.

As a result of this effort, VTRC concluded that quality test indicators for IDT Cracking need to be developed and implemented. Analyzing and reporting just the cracking tolerance index was found not to be a good practice. Raw data and measured load-deflection curves should also be examined, evaluated, and reported with test results.

Contractors started doing some of their own internal or collaborative research among themselves to gain comfort and trust with the IDT Cracking testing of their own asphalt mixtures.

Step 5. Commercial equipment specification and pooled fund purchasing.

While VTRC is very well equipped to run and analyze all performance tests recommended or being evaluated for the BMD approach, VDOT laboratories have currently none or, at best, limited performance testing equipment. VDOT will be investing in new equipment and accessories in order to be able to undertake performance testing; especially since some of the old press machines that are in existence fail to meet the IDT Cracking test requirements. The challenge is to be able to find the resources to acquire equipment. Currently, VDOT is in the process of procuring equipment for state laboratories including Cantabro, IDT Cracking, and APA through funding from VTRC; IDT Cracking equipment has already been purchased for each district laboratory. It is anticipated that two APA devices will be acquired; one for each of the Central Laboratory and the Salem District laboratory. This effort involves additional resources to create new areas in the laboratories to accommodate equipment.

Additional resources and laboratory spaces are also needed for sample preparation equipment (e.g., conditioning chambers, water baths, and aging ovens). Based on the current technician manpower and equipment capabilities, state laboratories will only be able to handle a limited number of BMD projects. The transition to the new performance tests will need to be accomplished while continuing to meet the needs for the regular workload with current manpower.

Findings from the PMD–Phase I study revealed the potential need for stricter specifications for equipment for it to be used in a BMD approach. There is a need for a study to assess and develop equipment specifications for use in PBS.

Contractors are also investing in certain equipment and associated training efforts. Having simple and practical performance tests (e.g., IDT Cracking), made it easier and faster for contractors to setup their laboratories for testing.

Step 6. Interlaboratory study (ILS) to establish precision and bias information.

None of the performance tests have information regarding the precision and bias of the test method. This creates a potential issue if two separate laboratories achieve different test results for the same asphalt mixture. Accordingly, VDOT/VTRC has thus far participated in a round robin study initiated by the National Center for Asphalt Technology (NCAT), and are leading a separate round robin study for the IDT Cracking test.

The NCAT round robin study for asphalt mixture performance tests was initiated in 2018 with over 40 participating laboratories (SHAs, contractors, consulting firms, materials suppliers, etc.). The study aimed to give laboratories that are new to asphalt mixture performance tests a chance to gauge their results compared to results from other laboratories; and to establish the single and multiple laboratory COVs. Several asphalt mixture performance tests were included and each participating laboratory selected the tests that they wanted to perform. VDOT/VTRC participated in the APA and IDT Cracking round robin efforts through the following activities:

- APA: VTRC fabricated and tested specimens using the loose asphalt mixture sampled from the NCAT test track construction. VTRC reported back test results along with a copy of the raw data files to NCAT for compilation and analysis. NCAT is currently preparing an APA summary report.
- IDT Cracking: VTRC tested two sets of specimens. The first set was fabricated by VTRC using the same loose asphalt mixture sampled from the NCAT test track construction. The second set consisted of compacted specimens of the same asphalt mixture that were fabricated and shipped to VTRC by NCAT. The multiple laboratory COV was 33% for the first set of specimens and was reduced to 11.1% with the second set of specimens. This indicates that two-thirds of the overall multiple laboratory variability of the test is related to differences in sample fabrication between laboratories. This emphasizes the need for thorough hands-on training as part of implementation plans for performance tests used in PBS.

A round robin study (funded via VDOT UPC #116473) is currently undergoing by VDOT/VTRC and in collaboration with Virginia Asphalt Association (VAA) for the IDT Cracking test (ASTM D8225-19) using two different types of dense-graded asphalt surface mixtures (initiated in early 2020). A total of 40 laboratories are participating in the round robin resulting in 45 unique data sets (some laboratories have more than one piece of equipment): academia (2), consultants and commercial laboratories (11), contractors (23), SHAs (2), VDOT/VTRC (2 ─ one District laboratory and VTRC). Additional VDOT/VTRC laboratories may be able to participate in the round robin study should they acquire the new equipment in time.

Guidelines for handling and testing round robin specimens were provided to all participants. Each participant received two sets of five specimens, for a total of ten test specimens, along with clear instructions on sample handling and testing procedures. It was requested that all testing be performed within two weeks of specimen receipt.

Laboratories were supplied with a Microsoft Excel reporting sheet for the IDT Cracking test; requested information included raw test data, equipment manufacturer and model utilized, and whether the machine is screw-drive or servo-hydraulic. VTRC will be collecting and analyzing all test results from the different participating laboratories (expected to be submitted by end of May 2020). The aim is to develop a precision statement for the IDT Cracking test in accordance with ASTM E691-19e1 "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method."

Step 7. Robust validation of the test to set criteria for specifications.

The plan for validating performance test criteria comprises sampling and testing of additional asphalt mixtures. This is currently being conducted by VTRC as part of the PMD–Phase I study that was initiated in 2018. Asphalt surface mixtures were sampled and tested to expand the database of test results for typical dense-graded asphalt surface mixtures. The study also included marginally performing asphalt mixtures that can be used to evaluate the sensitivity of the performance test methods and criteria. A total of 13 asphalt mixtures were collected and comprised the following specimen types:

- 6 field projects: testing performed on plant-compacted, reheated loose mixture, and field core specimens.
- 7 projects with plant sampling only: testing performed on plant-compacted and reheated loose mixture.

The additional test results are anticipated to provide a more robust data sample for the determination and validation of appropriate performance test criteria. In the case of field projects, the actual in-service pavement performance of the tested asphalt mixtures is being monitored throughout their lives to provide information necessary to validate the initial performance test criteria.

Step 8. Training and certification.

Training technicians on the procedures and analysis of test results is necessary. Most of the VDOT/VTRC effort thus far has been focused on testing and analysis to gain trust and comfort with the performance tests. Training videos made available by certain equipment manufacturers have also been used.

While no formal training activities have been conducted by VTRC to date, instructions and guidance related to sample fabrication, preparation, testing, and data analysis were provided to contractors, consulting firms, and asphalt mixture suppliers. Towards the end of 2019, VAA conducted a hands-on training workshop for laboratory testing and asphalt mixture design and adjustments.

VDOT envisions a statewide training and certification program for agency and industry on BMD approaches. Informal discussions are currently undergoing with stakeholders at the VDOT "BMD Advisory Committee." The training program is anticipated to be developed and offered within a couple of years as part of the technicians' certification program that is currently established under the Virginia Education Center for Asphalt Technology (VECAT). VTRC submitted a proposal to help fund these goals to the State Transportation Innovation Council (STIC), since the purpose of FHWA's STIC Incentive Program is to advance innovative technologies and/or methods into statewide practices.

Step 9. Implementation into engineering practice.

VDOT has implemented pilot special provisions for non-high-RAP BMD and for high RAP content (40% or more) surface mixtures designed using performance criteria. Most of the effort has focused on applying performance testing to the design of surface asphalt mixtures. Additional efforts will need to consider the feasibility of using performance testing for asphalt mixture acceptance during production. Thus, monotonic load-based tests including high-temperature IDT, IDEAL-RT, Marshall stability, and IDT Cracking are being evaluated for possible use as a surrogate performance tests during production. In the meantime, volumetric requirements can still be used for acceptance given concerns related to timeliness and responsibility for testing, single and multiple operator variabilities in test results, and the need for additional resources.

In order to support the implementation of BMD and acceptance, VDOT established a "BMD Advisory Committee" to provide: periodic status updates for the BMD initiative for key executive stakeholders; and a periodic forum for dialogue about progress and key milestones as the effort progresses. For instance, the importance of having more than one round of BMD pilot projects was discussed so that contractors that are not ready to get involved immediately can trust that they will have more opportunities before full implementation by VDOT. Contractors will need time to gain experience and become familiar and comfortable with the process before full implementation.

Additionally a "BMD Technical Subcommittee" was established to oversee the progress of related research projects, provide technical inputs, and support the development of the BMD special provisions and guidance. VDOT is considering a phased~~-in~~ approach for the implementation of BMD for design and acceptance.

IMPLEMENTATION OF PERFORMANCE TESTS ON PROJECTS

VDOT/VTRC has been leading and investing significantly in the process to develop and implement PBS for asphalt mixtures. In general contractors were supportive of the BMD approach. Continuous communication, dialogue, and partnering with industry helped in balancing both the agency and industry needs and concerns. Having a trusted partner from the industry who is willing to work with the agency on improving the process accelerates the learning curve and support proper implementation of new specifications.

A simplistic summary of VDOT's overall method for the implementation of performance tests comprised the following steps: 1) select the BMD approach; 2) evaluate many performance tests and then make a selection; 3) refine the test procedures and equipment with ILS; 4) develop initial performance tests criteria and related specifications; 5) validate performance tests' criteria through field trials; and 6) select quality criteria for acceptance.

In 2019, the study Balanced Mix Design for Asphalt Mixtures: High RAP Field Trials (VDOT UPC # 115763) was initiated to develop field trials for the High RAP content surface asphalt mixtures designed using performance criteria. The study also involved the assessment of materials, production, and construction processes; and the efficacy of the special provision developed to support the use of BMD. VDOT currently has general guidelines for project selection of BMD in which the project includes at least 4,000 tons of placed asphalt mixture. These will be further developed in the future. The contractor participation in the field trials has been thus far voluntary.

In 2019, two projects were completed by two separate contractors. Each project involved two different roadways where the same asphalt mixture was applied (less than a 1,000 ton of asphalt mixture was placed on each of the project sections). One of the projects included three sections with 40% RAP and a combination of different PG asphalt binders and an RA. The project included two control sections with 30% RAP and different PG asphalt binders. The second project~~,~~ included only 26% RAP but involved two different types of RAs with asphalt mixtures designed in accordance with the special provision for BMD surface asphalt mixtures.

According to the special provisions for BMD and High RAP content surface mixtures, performance testing during production is to be conducted at the frequencies shown in table 5. The contractor is required to fabricate and provide VDOT with specimens for Cantabro and IDT cracking testing; and VTRC with specimens for APA testing. VDOT may require that production be stopped until corrective actions are taken by the Contractor when any performance tests fail to meet the criteria specified in table 2.

Table 5. Production Testing Frequency.[1]

Entity	Gradation/AC	Volumetrics	APA Rutting	Cantabro	IDT Cracking
Producer	500 tons	500 tons	–	500 tons	500 tons
VDOT	500 tons	1,000 tons	–	1,000 tons[2]	1,000 tons[2]
VTRC	500 tons	500 tons	500 tons[2]	500 tons (reheat)	500 tons (reheat)

–Not applicable.
[1]With a minimum of 1 sample per day, per entity, per test.
[2]Minimize any cooling of the plant-produced asphalt mixture and bring the specimens to the compaction temperature and compact immediately to the required specimen size. Specimens are fabricated and provided to VDOT by the contractor.

Performance test results have not been tied to any pay factors yet. An understanding of the influence of asphalt plant production variability and tolerances (e.g., asphalt binder content, gradation) on the performance test results of plant-produced asphalt mixtures is needed. Also contractors need to know what corrective changes to make in order to bring a produced asphalt mixture back into compliance. Accordingly, VTRC has an on-going study (Impact of Production Variability on Balanced Mix Design in Virginia [UPC # 116425]) to assess the influence of production variability on the performance test responses of asphalt mixtures. The study involves the reproduction of plant-produced asphalt mixtures in the laboratory according to the approved JMF as well as at the upper and lower asphalt plant tolerances for gradation and asphalt binder content. This study is an essential step in the validation of the performance test criteria, and in developing allowable tolerances for acceptance.

During the 2018 field trial projects, it was very challenging for VTRC to fabricate specimens on site (i.e., at the plant and without reheating) to meet air voids level and tolerances. To overcome this challenge, the contractor had to compact at least one trial specimen prior to VTRC arrival for sample fabrication. The trial specimen was used to estimate the proper asphalt mixture mass that would result in compacted specimens within the target air void tolerances. Throughout the 2018 and 2019 field trial projects, the following observations were found:

- It is critical to use proper sampling and splitting methods to achieve an appropriate sample size for testing. A performance test can be very sensitive to segregation or alteration in aggregate gradation when no influence is observed on traditional volumetric properties.
- Make sure to measure the maximum theoretical specific gravity on the same asphalt mixture sampled for performance testing and use it for targeting and calculating air voids for compacted specimens.
- Each laboratory will have to establish a procedure to achieve the target air void level. Depending on the technician experience and the approach used, the specimen rejection rate based on air voids for APA, Cantabro, and IDT Cracking can vary among laboratories. The rejection rate can be high initially (~50%) but will typically drop to 10% or less once the appropriate mass and compaction method were established.

In 2020, it is anticipated that at least four field trial projects will be completed under the study Balanced Mix Design for Asphalt Mixtures: High RAP Field Trials (VDOT UPC #115763). Furthermore, the study includes the heavy vehicle simulator (HVS) experiment that is currently undergoing at Virginia Tech Transportation Institute (VTTI). The HVS experiment involves six different asphalt mixtures designed using the VDOT BP approach in accordance with the special provision for BMD surface mixtures using performance criteria.

Based on contractors experience with field trial projects thus far, the following observations were made:

- In general, an increase in asphalt binder content by a couple tenths improved IDT cracking significantly without jeopardizing APA rut depths. The use of RA at the proper dose with 40% RAP also helped in improving the asphalt mixture performance. These changes were coupled with the use of different sources of manufactured sand (even sometimes had to add more sand and cut down on the No. 8 sieve) or some minor changes in aggregate blend gradation. Making the aggregate gradation coarser on the coarse side and finer on the fine side increased the VMA and allowed more room for asphalt binder in the mixture. Increasing fines in the asphalt mixture, along with the increase in asphalt binder content, increased the mastic content in the mixture and improved cracking resistance.
- Changes to asphalt mixtures to get acceptable performance testing values were material specific. For instance, the same practice that seemed to work well for a given asphalt mixture was not necessarily effective for a mixture produced using other sources of

materials. This can be challenging for asphalt mixture suppliers possessing several quarries and aggregates with different specific gravities, absorptions, and particle shapes.

- In general, performance tests, and in particular IDT Cracking, were sensitive to changes in the properties of utilized RAP material. Thus, a proper stockpile management plan and process control for RAP properties was found to be critical; thus allowing for making appropriate adjustments to the asphalt mixture during production whenever significant changes in RAP properties were detected.
- Plan ahead for enough time to conduct asphalt mixture designs following the BMD approach. The critical part of the BMD approach was to make sure the asphalt mixture passed the cracking performance test criteria first, before moving forward with the evaluations in APA and Cantabro.
- Specimen and test temperatures were found to affect Cantabro test results. For instance, a failing asphalt mixture may end up passing the Cantabro loss criteria if left to run overnight during a drop in the laboratory ambient temperature.
- Plant-produced asphalt mixtures exhibited cracking tolerance indices that were higher than those observed for laboratory-produced asphalt mixtures during design. This needs to be addressed either by adjusting the test criteria, or by applying a correction factor between the test results of laboratory- and plant-produced asphalt mixtures.
- In order to make sure that the asphalt mixture will be in compliance during production, a good practice was to have a dry run of the asphalt mixture production the day before the actual construction of the field trial project. Asphalt suppliers need to start establishing a reference database for all of their produced asphalt mixtures.

Contractors were fabricating as much as 48 compacted specimens a day that comprised 4 APA, 3 Cantabro, and 5 IDT Cracking specimens per lot for 4 sampling lots. Contractors expressed interest in and support for the IDT Cracking testing because it is a quick test and results are instantaneous; fabrication and testing was as much as 20 specimens a day. The bottleneck in the process during production was the time needed to cool down compacted specimens before bulking; specimens were put for couple hours in front of a fan to dry them faster (a small air conditioning unit was also used). This pushed back testing, in particular APA, to the next day; on future trial projects, an accelerated cooling method is needed. The very limited production (only 75 tons per lane per day) on the HVS test sections was noted; however, that was judged to not be representative of Virginia's BMD trials; that project was not set up to be a production contract (where a decision was made to incorporate a BMD trial) but rather a series of specific different trials.

Implementing proper performance tests within a BMD approach allowed contractors to be creative, use innovative materials, and see the benefits of the tests. However, a key question contractors want to have answered is what corrective changes to make in order to bring the asphalt mixture back into compliance if there were to be a failing performance test. Being able to communicate all challenges and issues with VDOT/VTRC on the trial field projects helped the contractors in overcoming these challenges and producing asphalt mixtures that met specifications.

OVERALL BENEFITS

The use of BMD on trial field projects allowed contractors to utilize innovative and recycled materials (e.g., RAP, RAs, PG of asphalt binders) in order to produce asphalt mixtures that are in compliance with VDOT specifications. Furthermore, the traditional volumetric-based mixture design did not provide optimum performance for asphalt mixtures with high RAP content. Performance testing helped in designing asphalt mixtures with high RAP contents that resulted in greater resistance against primary modes of distress (i.e., rutting, durability, and cracking); thus allowing for the production of economical and environmentally-friendly asphalt mixtures without jeopardizing performance.

The asphalt mixtures designed using the BMD approach were in general easier to compact in the field and to reach target in-place density. More consistent in-place densities were also observed in the BMD sections when compared to control sections (using traditional asphalt mixtures). For example, a BMD test section from the HVS experiment exhibited in-place densities that were on average 1.5% higher than those observed on control section; 93–94% densities in comparison to 91– 93% . This observed improvement in the in-place pavement density can lead to more than 10% increase in asphalt pavement service life.

FUTURE DIRECTION

VTRC is currently working on a framework for the full implementation of BMD for design and acceptance. This includes an overall plan describing the steps to move forward with implementation based on current status while identifying and quantifying all potential concerns and how to navigate them in order to overcome.

VDOT envisions a two part criteria for BMD, one on the initial design and one during production to guarantee that an asphalt mixture has the desired performance properties. A series of studies and activities are needed in order to ensure full implementation of BMD for design and acceptance. Some examples are provided below:

- Increase the number of pilot projects to cover the different materials throughout the state.
- Continue monitoring the field pavement performance and use information to validate and modify as needed the established initial performance test criteria.
- Select and implement surrogate performance tests as an alternative to APA that can be used during production.
- Develop RA evaluation process for acceptance to facilitate its proper use in BMD approach.
- Implement an application-based performance test criteria based on traffic level and asphalt mixture type (i.e., SM, IM, BM, or stone matrix asphalt).
- Investigate and develop a representative long-term oven aging protocol for asphalt mixtures to simulate in-service aging. The long-term aging method is anticipated to be part of the asphalt mixture design method and not acceptance.
- Establish necessary precision and bias statements for utilized performance tests.

- Understanding and quantifying the influence of asphalt plant production variability and tolerances (e.g., asphalt binder content, gradation) on the performance test results of plant-produced asphalt mixtures.

The full implementation effort needs to be supplemented with proper communication, training and education activities. Contractors will need to be educated on what changes can be made to the asphalt mixture composition or proportions in order to make informed and cost-effective decisions to improve performance and meet applicable specification limits.

POSITIVE PRACTICES, LESSONS LEARNED, AND CHALLENGES

The following is a list of positive practices, some lessons learned, and challenges from VDOT that can help facilitate the implementation of a performance test into practice. Positive practices are those successful efforts that were used by VDOT that could also be considered by other SHAs. Lessons learned are those efforts that, if VDOT had it to do over again, they would definitely reconsider. Challenges are those efforts that VDOT is still in the process of addressing.

Positive Practices

- The motivations for implementation of BMD in Virginia were primarily two-fold: 1) there was a desire to use of higher quantities of RAP that allowed for contractor innovation; and 2) there was a desire to continue to build upon the improvements to the durability and performance of asphalt mixtures after the original Superpave mixtures did not perform as well as expected.
- VDOT created an overall timeline for a statewide implementation of BMD (figure 1). It includes development of performance test criteria for cracking and rutting, construction and evaluation of pilot projects, VDOT acquisition of laboratory equipment, development and execution of training materials, as well as refinement of specification requirements as suggested by the pilot projects.
    - There were some needs identified to create more detailed work processes for each of these steps at the appropriate time.
    - VDOT currently has general guidelines for pilot project selection of BMD in which the project includes at least 4,000 tons of placed asphalt mixture. These will be further developed in the future. Data needs to be gathered in terms of the use of multiple performance tests on multiple projects (i.e., scaling).
- Collaboration and cooperation between VDOT, VTRC, industry, and academia is important for a successful and smooth implementation of performance tests as part of asphalt mixture design and acceptance. This involves good communication and continuous dialogue with the industry, knowledge transfer, and necessary education and training.
    - Internally, having a strong and established research council is supporting the development effort of BMD.
    - Establishing a “BMD Advisory Committee” to provide periodic status updates for the BMD initiative for key executive stakeholders; and a periodic forum for dialogue about progress and key milestones as the effort progresses.

    - Establishing a "BMD Technical Subcommittee" to oversee the progress of related research projects, provide technical inputs, and support the development of the BMD special provisions and guidance.
    - Externally, having trusted industry partners that volunteered for pilot projects accelerated the learning curve and practicality of the approach.
    - Communicating with contractors the impact of new specifications on the design and acceptance of their asphalt mixtures was key to facilitating implementation.
    - There is an HVS experiment that is currently undergoing at VTTI. The HVS experiment involves six different asphalt mixtures designed using the VDOT BP approach in accordance with the special provision for BMD surface mixtures using performance criteria.
- A simplistic summary of VDOT's overall approach for the implementation of performance tests comprised the following steps: 1) select the BMD approach; 2) evaluate many performance tests and then make a selection; 3) refine the test procedures and equipment with ILS; 4) develop initial performance tests criteria and related specifications; 5) validate performance tests' criteria through field trials; and 6) select quality criteria for acceptance.
    - VDOT has a creative method for selection of the BMD approach. At the time when a pilot project is proposed, the contractor may select *Approach A Volumetric Design with Performance Verification* and/or *Approach D Performance Design*; contractors are encouraged to do both, but only one is required per the special provision.
- A comprehensive study was not conducted to assess the changes of asphalt mixture properties to identify the relationship to the performance test results (Step 2) due to limitations in VTRC's technician manpower and workloads (i.e., laboratory-produced asphalt mixtures are not practical). However, this was done in an effective manner on plant-produced asphalt mixtures by testing local materials.
    - VDOT/VTRC relied on available relevant literature to assist.
    - Establishing a database of test results helps in understanding the performance of typical dense-graded asphalt surface mixtures and in establishing an initial performance test criteria.
- The top factors in selecting APA, Cantabro and IDT Cracking tests were (Steps 3 and 7):
    - The duration needed for sample preparation as well as specimen conditioning and testing were a key consideration in the development and implementation of test criteria into the specifications.
    - The availability and cost of equipment needed to prepare, fabricate, and test specimens were also considered.
    - Acceptable repeatability (within laboratories) and reproducibility (between laboratories) of test results.
    - Capability of a performance test to provide consistent results that follow common sense trends and rankings of the tested asphalt mixtures. The test results of local asphalt mixtures should not contradict known and observed field pavement performance, or recognized correlations between the mode of distress under evaluation and volumetric properties.
    - Initial performance test specification limits were established by testing "everyday" asphalt mixtures to benchmark test results.

- The process of selecting tests has not been completed.
  - Monotonic loading-based tests including high-temperature IDT strength, IDEAL-RT, and Marshall stability tests are being researched by VTRC as surrogate performance tests for the APA during production. In general, these tests are quick procedures that use currently available equipment in the laboratory with slight modifications as needed; thus, requiring minimal investments from both VDOT and the industry.
  - The AMPT performance tests will be used as a reference for comparison and better selection of the index-based surrogate performance tests (part of the on-going study to assess the feasibility of using monotonic loading-based tests to evaluate rutting performance of asphalt mixtures, and part of the ongoing study to evaluate the acceptance of RAs for Virginia). The AMPT is not practical for VDOT or industry implementation.
  - Some in industry reported that they were privileged and excited to be part of the current BMD process.
- VDOT conducted and participated in several round robins (Step 6) to gain trust and comfort with the performance tests which resulted in single and multiple operator variability. The round robins considered different equipment manufacturer types. The round robins were so successful, they are still continuing.
- VDOT envisions a statewide training and certification program for agency and industry on BMD approaches (Step 8). This will be done in collaboration between VDOT and Industry.
- Keys to implementation (Step 9) included:
  - Have more than one round of BMD pilot projects so that contractors that are not ready to get involved immediately can trust that they will have more opportunities to gain experience and become familiar and comfortable with the process before full implementation.
  - Consider a phased in approach for the implementation of BMD with initially no ties to pay factors.
  - Implementation of performance tests followed previous changes to the volumetric design criteria of asphalt mixtures (e.g., increase in VMA, increase in VFA, and increase in dust-to-binder ratio) that were intended to improve mixture durability and performance.
- There have been benefits:
  - In-place pavement density improved and was more consistent. In one of the projects, in-place pavement densities for the asphalt mixture designed using BMD were on average 1.5% higher than those observed on control section. This observed improvement in the in-place pavement density can lead to more than 10% increase in asphalt pavement service life. Thus, delaying the next rehabilitation or reconstruction activity and resulting in significant life cycle cost savings for both the agency and the public user.
  - The BMD allowed contractors to use innovative and recycled materials (e.g., RAP, RAs, PG of asphalt binders) in order to produce asphalt mixtures that are in compliance with VDOT specifications.

Lessons Learned

During the construction of the pilot projects, several lessons were learned related to the laboratory testing processes and plant operation process.

- Laboratory testing processes:
  - Use proper sampling and splitting methods to achieve an appropriate sample size for performance testing and reduce the influence on test results.
  - Measure the maximum theoretical specific gravity on the same asphalt mixture sampled for performance testing and use it for targeting and calculating air voids for compacted specimens.
  - Improve the specimen rejection rate based on air voids by establishing materials/plants specific methods for targeting air void levels.
  - A bottleneck in the process during production was the time needed to cool down compacted specimens prior to bulking.
  - Increasing asphalt binder content by a couple tenths improved IDT cracking significantly without jeopardizing APA rut depths. The use of RA at the proper dose also helped in improving the asphalt mixture performance. These changes were coupled with the use of different sources of manufactured sand or some minor changes in aggregate blend gradation.
  - Changes to asphalt mixtures to get approved designs were material specific. This can be challenging for asphalt mixture suppliers possessing several quarries and aggregates with different specific gravities, absorptions, and particle shapes.
  - Plan ahead for enough time to conduct asphalt mixture designs following the BMD approach. The critical part of the BMD approach is to make sure the asphalt mixture pass the cracking performance test criteria first, before moving forward with the evaluations in APA and Cantabro.
  - Specimen and test temperatures were found to affect Cantabro test results. For instance, a failing asphalt mixture may end up passing the Cantabro loss criteria if left to run overnight during a drop in the laboratory ambient temperature.
- Plant operation processes:
  - A proper RAP stockpile management plan and process control are important for making appropriate adjustments to the asphalt mixture during production whenever significant changes in RAP properties were detected.
  - In order to make sure that the asphalt mixture will be in compliance during production, a good practice was to have a dry run of the asphalt mixture production the day before the actual construction of the field trial project. Asphalt suppliers need to start establishing a reference database for all of their produced asphalt mixtures.
- Plant-produced asphalt mixtures exhibited cracking tolerance indices that were higher than those observed for laboratory-produced asphalt mixtures during design. This needs to be addressed either by adjusting the test criteria, or by applying a correction factor between the test results of laboratory- and plant-produced asphalt mixtures.

Challenges

- Implementation of performance testing required allocation of additional resources from VDOT/VTRC.
    - Proper planning in advance of laboratory space need for sample preparation and performance testing is necessary. This required re-organization of existing space to maximize space utilization.
    - Requiring performance testing during production resulted in increased workload for VDOT/VTRC staff.
    - Finding resources to acquire equipment necessary to conduct performance tests. Funds are also needed for purchasing equipment necessary for sample fabrication and preparation. VDOT had to procure equipment from research funds.
- Major changes in specifications that were implemented on all VDOT dense-graded asphalt mixtures shortly before the BMD efforts started resulted in lack of field pavement performance of asphalt mixtures designed according to latest specifications and a disconnect with the historical database of APA test results.
- Performance test methods lack precision and bias, thus creating a potential issue if two separate laboratories achieve different test results for the same asphalt mixture.
- Having equipment from different manufacturers resulted in differences in test results, which required additional testing and evaluation. Additional resources and time were needed to undertake this task.
- Quality test indicators for IDT Cracking are needed. Raw data and measured load-deflection curves should be examined, evaluated, and reported with all other test results.
- Balancing the requirements of a successful BMD program with financial and manpower constraints is a challenge. VDOT is considering a phased in approach for the implementation of BMD for design and acceptance.
- Fabricating specimens on site (i.e., at the plant and without reheating) to meet air voids level and tolerances was challenging for VTRC and for producers as well; however, VTRC's experience with this was documented and they noted that it impacted their data. The contractor was asked to compact at least one trial specimen prior to VTRC arrival for sample fabrication. The trial specimen was used to estimate the proper asphalt mixture mass that would result in compacted specimens within the target air void tolerances.

VDOT desires to select a performance test(s) as part of production testing. A likely result of this will be the awareness that contractors will need to improve their process control. Additionally, contractors will need results from a performance test promptly such that they can make decisions on production based on the results.

RESEARCH AND DEPLOYMENT OPPORTUNITIES

VDOT suggests the following research topics:

- What changes can be made to the asphalt mixture composition, components, and proportions to get acceptable results in performance tests (e.g., increase in asphalt binder content, decrease in fine contents, use of additives, etc.). These changes are likely to be asphalt plant and material specific as well as agency specific driven by differences in the

implemented specifications. Contractors can then make cost-benefit analysis decisions based on this information. There was a steep learning curve for Superpave volumetric mix design and it will be similar for performance testing. Findings from the study can accelerate the learning curve and facilitate the implementation of performance testing.
- Training materials and hands-on workshops on testing, analysis, and interpretation of performance test results including the influence of changes in asphalt mixture composition and components during design or production on performance.
- With the use of increased RAP, additional efforts on surface characteristics need to be examined (e.g., skid resistance, smoothness).

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