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

New Jersey Department of Transportation (NJDOT)

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LIST OF ABBREVIATIONS AND SYMBOLS

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
BDWSC	Bridge Deck Waterproofing Surface Course
BMD	Balanced Mix Design
BRIC	Binder Rich Intermediate Course
BRBC	Binder Rich Base Course
COV	coefficient of variation
ESAL	equivalent (80kN) single-axle load
FBF	Flexural Bending Fatigue
FHWA	Federal Highway Administration
HPTO	High-Performance Thin Overlay
HRAP	Hot Mix Asphalt High RAP
IDT	Indirect Tensile
ILS	interlaboratory study
JMF	job mix formula
L	low design compaction level
LTPP	Long-Term Pavement Performance
M	medium design compaction level
MP	mile post
NCHRP	National Cooperative Highway Research Program
NJDOT	New Jersey DOT
NY	New York
NMAS	nominal maximum aggregate size
NYSDOT	New York State Department of Transportation
OBC	optimum asphalt binder content
OT	Overlay Tester
PBS	performance based specification
PCC	Portland cement concrete
PEP	Performance Engineered Pavements
PG	performance grade
PMS	pavement management system
PSP	Pavement Support Program
RAP	reclaimed asphalt pavement
SDI	Surface Distress Index
SHA	state highway agency
SMA	stone matrix asphalt
SP&R	State Planning and Research
SPS	Special Pavement Study

SST	Superpave Shear Tester
TSR	tensile strength ratio
TxDOT	Texas DOT
U.S.	United States
VFA	voids filled with asphalt
VMA	voids in mineral aggregate

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 determined in accordance with AASHTO R35 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. New Jersey Department of Transportation (NJDOT) 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 NJDOT virtual site visit.

GENERAL INFORMATION SPECIFIC TO NJDOT

In mid 1990s, NJDOT initiated the implementation of 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 optimum asphalt binder content (OBC). The early implementation of Superpave resulted in dense-graded asphalt mixtures that had coarser aggregate blend gradations, low asphalt binder contents, and were harder to place and compact. These asphalt mixtures were prone to poor longitudinal joint construction (generally lower in density) and to quicker failures due to durability and cracking related distresses. Furthermore, pavements under the jurisdiction of NJDOT are ~65% composite pavements; which made them prone to reflection cracking. Accordingly, NJDOT attempted to address the observed poor performance by decreasing the compaction effort to 100 gyrations from the initially selected design gyrations of 125; a gyration number that is used for a 20-year design traffic of more than 30 million equivalent (80 kN) single-axle loads (ESALs). To improve durability and cracking performance of asphalt mixtures, the number of design gyrations were further reduced (around 2014) in an effort to increase the OBC. Since then, the NJDOT specify the following compaction efforts for dense-grade asphalt mixtures:

- A low design compaction level (L) of 50 gyrations for design traffic less than 0.3 million ESALs.
- A medium design compaction level (M) of 75 gyrations for design traffic greater than or equal to 0.3 million ESALs.

While, in general, reducing the number of gyrations had shown improvements in the performance of asphalt mixtures throughout the state, it did not completely address all observed field performance issues. In several instances, NJDOT had to use proprietary asphalt mixtures for special applications. This prompted NJDOT to explore different ways for designing asphalt mixtures by supplementing volumetric-based methods with performance testing.

Accordingly, NJDOT and in collaboration with the Center for Advanced Infrastructure and Transportation at Rutgers University took steps to address the ongoing concerns with pavement durability and cracking by reverse engineering the performance of specialty asphalt mixtures. The purpose of this initiative was to increase competition (availability) and reduce cost by moving away from proprietary mixtures. This consisted of reverse engineering satisfactory performance of particular specialty mixtures using performance tests specifically selected by the state. These performance tests included the Asphalt Pavement Analyzer (APA), the Overlay Tester (OT), and the Flexural Bending Fatigue (FBF). This overall effort was in line with NJDOT's goal to increase pavements' longevity by tying asphalt mixture design to pavement structural design and pavement performance.

Asphalt mixture performance testing was first used by Rutgers University in 2006 as a means to reverse engineer a specialty (proprietary) Bridge Deck Waterproofing Surface Course (BDWSC) mixture to be placed on the steel panels of the George Washington Bridge for the Port Authority of New York (NY) and New Jersey (NJ). The BDWSC was mainly based on reverse engineering the performance of asphalt mixtures treated with Rosphalt additive (concentrated thermoplastic virgin polymeric materials). In 2007, the performance-based specification (PBS) for the BDWSC was then slightly modified for NJDOT to meet their requirements for use on concrete bridge decks. The BDWSC performance specification included requirements for the APA rut depth and the FBF cycles to failure.

In the same year, a High-Performance Thin Overlay (HPTO) specification for pavement preservation/resurfacing was developed. The HPTO was based on a 6.3 mm fine mixture from the New York State Department of Transportation (NYSDOT) with the addition of the APA test due to concerns with potential rutting. Originally, a cracking performance test was not considered in the HPTO specification. The OT was added at a later time based on feedback from observed field performance.

In 2009, PBS for a Binder Rich Intermediate Course (BRIC) and a Binder Rich Base Course (BRBC) were developed. The BRIC was based on reverse engineering the Strata® reflective crack relief system in order to achieve the desired performance. It is placed between an old cracked rigid pavement and the new asphalt concrete (AC) overlay—typically the stone matrix asphalt (SMA)—to reduce reflection cracking. On the other hand, the BRBC was developed as part of an alternative design for a deteriorated 35 year old Portland cement concrete (PCC) pavement. Given the limited available funds at that time, along with the high traffic volume that must be maintained during reconstruction, traditional solutions such as patching and overlaying or replacing broken slabs were either impractical, not cost-effective, or too slow and costly. Thus, The BRBC was then developed as an engineered asphalt mixture base course to be placed on top of the rubblized PCC to reduce total AC overlay thickness as part of a perpetual pavement design.

The PBS of BRIC and BRBC included a requirement for the APA rut depth. In the case of cracking, the BRIC and BRBC included a performance requirement for the OT number of cycles until failure and the FBF cycles to failures, respectively. The BRBC fatigue criteria is pavement structure specific. The resultant tensile strains at the bottom of the AC layer are determined using linear elastic theory for different seasonal moduli. The maximum tensile strain determined is used as the "Endurance Limit" strain. The methodology developed in NCHRP Project 09-39 is followed to evaluate the Endurance Limit of the BRBC. Modifications of the BRBC mixture must be made until it passes the Endurance Limit and rutting resistance requirements.

Around this same time, accumulation of reclaimed asphalt pavement (RAP) was becoming a real issue in NJ and industry was asking for the ability to use higher amounts of RAP in asphalt mixtures. It should be noted that most of rehabilitation projects in the state have been mill and overlay (typically 2 inches) with up to 15% RAP being allowed in the surface course. Since 2008, NJDOT had started to look at the performance of high RAP mixes by building a database of performance test results for both virgin asphalt mixtures (i.e., 0% RAP) and mixtures with varying percentages of RAP.

In 2010, and at the request of industry, NJDOT allowed the use of 25% RAP in the surface course of 5 different projects with no changes or modifications to the asphalt mixture design criteria. All except one project reported issues with production or construction of the high RAP asphalt mixtures. Thus, in 2011, NJDOT went back in maintaining their current specifications of maximum 15% RAP in the surface course and maximum 25% RAP in the intermediate or base course. Then, Rutgers University made use of the developed database of performance test results to address the potential cracking and durability issues observed with high RAP asphalt mixtures.

In 2012, a PBS for a Hot Mix Asphalt High RAP (HRAP) was then developed by NJDOT in collaboration with Rutgers University. The HRAP specification is unique in a way that a minimum percentage of RAP is specified with no required maximum percentage; minimum of 20% RAP for surface course and 30% RAP for base or intermediate course. The specification included requirements for both the APA rut depth and OT number of cycles until failure. The HRAP mixtures were required to have at a minimum a performance similar to that of virgin asphalt mixtures. In other words the performance test criteria for the APA and OT were selected for HRAP using performance test results for typical virgin asphalt mixtures used in the state.

NJDOT uses as much as 2 million tons of asphalt mixtures per year throughout the state. Between 2015 and 2019, all specialty asphalt mixtures comprised on average about 10% of the total asphalt tonnage placed in the state (figure 1). The use of specialty asphalt mixtures steadily increased from 5.1% in 2015 to as much as 16.8% in 2018. In 2019, specialty asphalt mixtures comprised 8.3% of the total asphalt tonnage placed. The observed drop in the percent use of specialty asphalt mixtures last year is mainly attributable to project prioritization and selection process (resurfacing projects not continuously ranking high in the process) in conjunction with delays in the procurement process (complexity of requirements stipulated in the procurement rules pushed back some of the projects until next year). Among all five specialty asphalt mixtures, HPTO has been used the most.

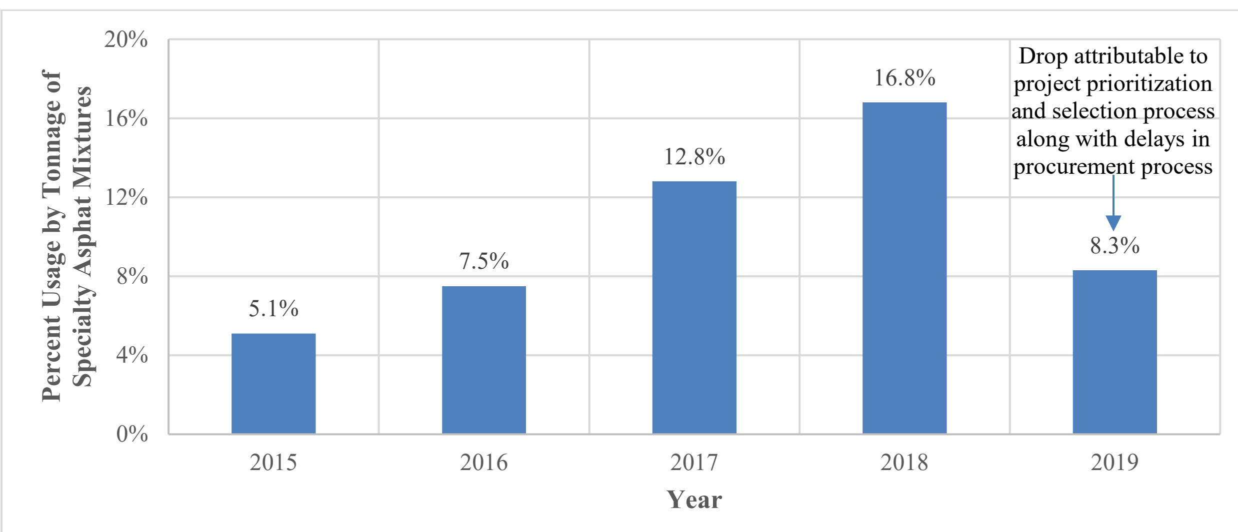

Figure 1. Chart. NJDOT annual usage for specialty mixes.

Recently, NJDOT, in collaboration with Rutgers University, started to explore the use of the high-temperature Indirect Tensile (IDT) strength and the intermediate-temperature IDT Cracking test (formerly known as IDEAL-CT) as a surrogate test during production. Based on test results of asphalt mixtures from Rutgers University, the IDT strength and IDT Cracking were found to correlate well with the APA rut depth and OT number of cycles until failure, respectively. These correlations are in the process of being verified by NJDOT. This effort mainly stemmed from the need to reduce the workload of the NJDOT staff, to accelerate the turnaround time for performance test results during production, and to provide a performance test that could be conducted by the asphalt plants quality control laboratories with minimum financial investment and required training. The two IDT-based index-based performance test methods involve a reduced time for specimen fabrication, preparation (including reduced number of specimens needed), testing, and data analysis. Thus, making them viable for routine use in a BMD process and acceptance.

In summary, the deteriorating transportation infrastructure, the continuous need to increase performance life of asphalt pavements to stretch the budget, and the increase in traffic volumes, led NJDOT to implement performance-based specialty asphalt mixtures. These mixtures are selected based on the extreme needs of the pavement structure in question (composite pavement, bridge deck overlay, etc.). Each of these performance-based mixtures is required to undergo performance testing during the mixture design, test strip, and project construction phase to ensure the final asphalt mixture achieves the desired performance to the specific pavement structure.

BMD APPROACH

NJDOT developed and implemented PBS for five specialty asphalt mixtures: BDWSC, HPTO, BRIC, BRBC, HRAP. Figure 2 shows a flowchart of the overall BMD for all five specialty asphalt mixtures. The flowchart highlights the major steps for undertaking an asphalt mixture design according to NJDOT specifications and identifies the activities that fall under the responsibility of the contractor or agency. The requirements for volumetric design, gyratory compaction efforts, and performance testing are summarized in table 1 through table 3.

In general, the NJDOT's BMD for designing asphalt mixtures and approving job mix formulas (JMFs) follows a combination of Approach A *Volumetric Design with Performance Verification* and Approach B *Volumetric Design with Performance Optimization*. During approval, the asphalt mixture has first to pass all gradation and volumetric property requirements before being evaluated in the designated performance tests. However, it should be noted that most of the volumetrics for the performance-related specifications are modified from conventional asphalt mixture design. Subsequently, the asphalt mixture needs to pass the performance criteria for both rutting and cracking. If the asphalt mixture fails any of the criteria, the contractor has to redesign the asphalt mixture and resubmit all necessary materials for JMF approval following the same process. This same methodology is conducted during three different phases; 1) mix design, 2) test strip, and 3) production.

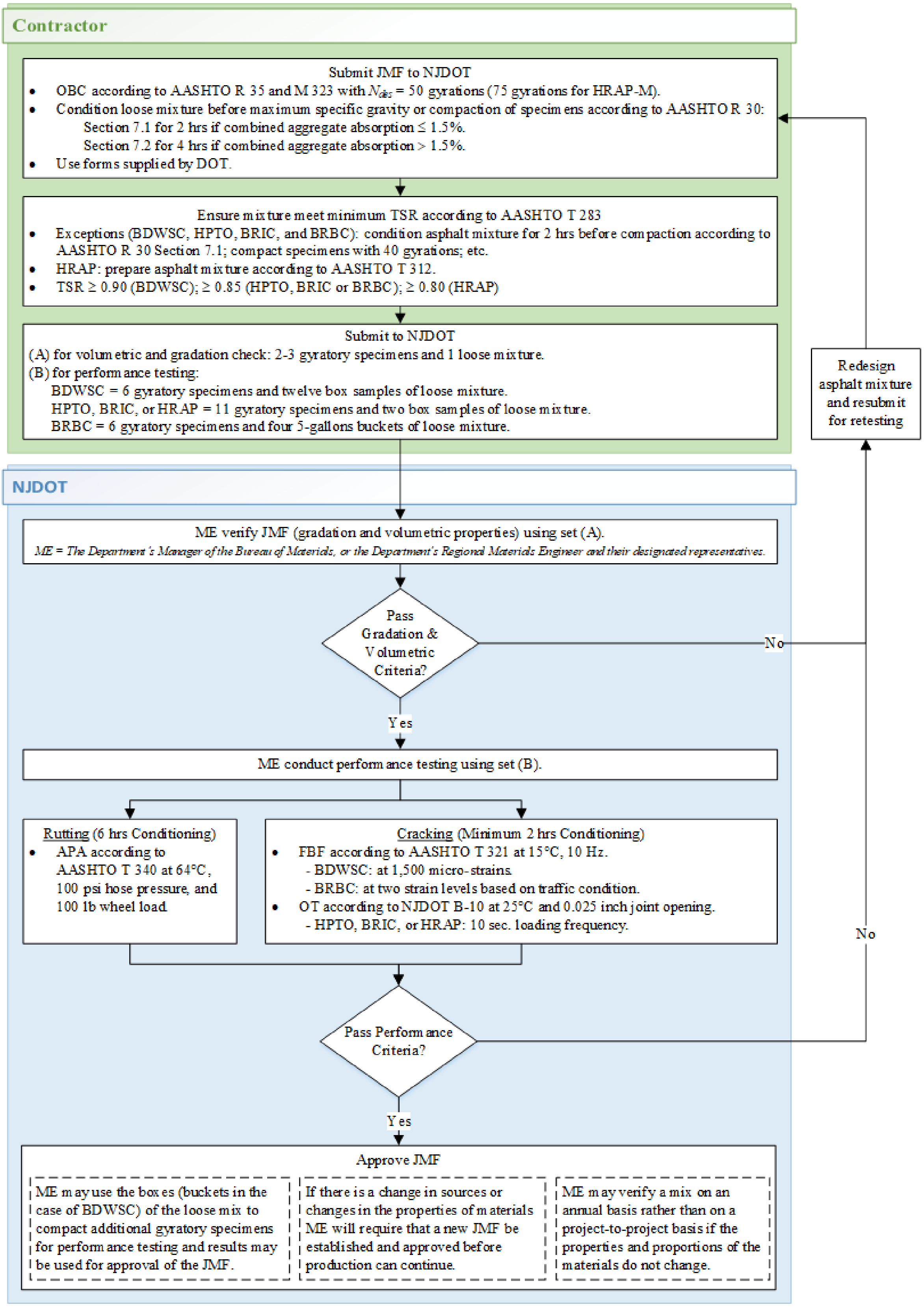

Figure 2. Chart. Overview of NJDOT BMD approach for specialty mixes.

Table 1. Volumetric Design Requirements.

Mixture Type	Asphalt Binder Content (%)*	Required Density (% of Theoretical Max. Specific Gravity)		VMA (Minimum %)					VFA (%)	Dust-to-Binder Ratio	Drain-down# (%)
		N_{design}	N_{max}	NMAS (mm)							
				25	19	12.5	9.5	4.75			
BDWSC	≥7.0	99.0	–	–	–	18.0	18.0	–	90–100	0.3–0.9	≤0.1%
HPTO	≥7.0	96.5	≤99.0	–	–	–	18.0	–	–	0.6–1.2	≤0.1%
BRIC	≥7.4	97.5	≤99.0	–	–	–	–	18.0	–	0.6–1.2	≤0.1%
BRBC	≥5.0	96.5	–	–	13.5	–	–	–	70–80	0.6–1.2	≤0.1%
HRAP											
L	–	96.0	≤98.0	13.0	14.0	15.0	16.0	17.0	70–85	0.6–1.2	–
M	–	96.0	≤98.0	13.0	14.0	15.0	16.0	17.0	65–85	0.6–1.2	–

–Not applicable; *asphalt binder content by ignition oven; #AAHTO T 305; minimum of 20% RAP for HRAP surface course and 30% RAP for HRAP base or intermediate course.

Table 2. Mix Design Gyratory Compaction Effort.

Mixture Type	Compaction Level	ESALs (millions)*	N_{des}	N_{max}
BDWSC	–	–	50	–
HPTO	–	–	50	100
BRIC	–	–	50	100
BRBC	–	–	50	–
HRAP	L	<0.3	50	75
	M	≥0.3	75	115

–Not applicable; *Design ESALs (Equivalent (80kN) Single-Axle Loads) refer to the anticipated traffic level expected on the design lane over a 20 year period.

Table 3. Mix Design Performance Testing Requirements.

Mixture Type	PG (AASHTO R 29)	Spec. Air Voids	TSR (AASHTO T 283)	APA @ 8,000 Loading Cycles, 64°C (AASHTO T 340)*	OT (NJDOT B-10)	FBF Life @ 15°C (AASHTO T 321)
BDWSC	–#	≤3%	≥90%	≤3 mm	–	>100,000 cycles @ 1,500 micro-strain
HPTO	–#	5.0±0.5%	≥85%	≤4 mm	≥600 cycles	–
BRIC	–#	3.5±0.5%	≥85%	≤6 mm	≥700 cycles	–
BRBC	–#	5.5±0.5%	≥85%	<5 mm	–	>100,000,000 cycles @ 100 micro-strain
HRAP						
Surface Course	64-22#	6.5±0.5%	≥80%	≤7 mm	≥200 cycles	–
	64E-22#	6.5±0.5%	≥80%	≤4 mm	≥275 cycles	–
Intermediate and Base Course	64-22#	6.5±0.5%	≥80%	≤7 mm	≥100 cycles	–
	64E-22#	6.5±0.5%	≥80%	≤4 mm	≥150 cycles	–

–Not applicable; *100 psi hose pressure and 100 lb per wheel load; #PG of asphalt binder is not specified and is determined by the mix design and mix performance testing however a certificate of analysis showing the PG continuous grading for the asphalt binder used in the mix design has to be submitted to ensure asphalt binder consistency throughout the production process.

An asphalt binder performance grade (PG) is not specified for any of the five specialty asphalt mixtures. The PG is determined by the asphalt mixture design and performance testing. However, a certificate of analysis showing the PG continuous grading (AASHTO R 29) for the asphalt binder used in the asphalt mixture design has to be submitted to ensure asphalt binder consistency throughout the production process.

The contractor submits with the asphalt mixture design the tensile strength ratio (TSR) results (AASHTO T283). The asphalt mixture is conditioned for 2 hours according to AASHTO R 30 Section 7.1 before being compacted to 40 gyrations (BDWSC, HPTO, BRIC, and BRBC). In the case of HRAP, the asphalt mixture is prepared according to AASHTO T 312 and tested according to AASHTO T 283. The asphalt mixture needs to meet the minimum TSR specified in table 3.

In comparison to AASHTO M 323 and AASHTO R 35, NJDOT implemented the following key modifications to their volumetric design criteria (table 1):

- Specified 50 gyrations for design and acceptance of all five asphalt mixtures; with the exception of 75 gyrations specified for HRAP-M (design compaction level M—more than 0.3 million ESALS) (table 2).
- Specified a minimum asphalt binder content of 7% for BDWSC and HPTO, 7.4% for BRIC, and 5% for BRBC. In order to avoid bleeding of the asphalt mixture, a draindown requirement was also specified (AASHTO T 305).
- Increased the density requirement at the design number of gyrations (N_{des}) by 3% for BDWSC, 0.5% for HPTO and BRBC, and 1.5% for BRIC.
- Increased the density requirement at the maximum number of gyrations (N_{max}) by 1% for HPTO and BRIC; and omitted the requirement for BDWSC and BRBC.
- Increased the voids in mineral aggregate (VMA) requirement by: 3 and 4% for BDWSC with a nominal maximum aggregate size (NMAS) of 9.5 and 12.5 mm, respectively; 3% for HPTO; 2% for BRIC; 0.5% for BRBC; and 1% for HRAP.
- Increased the voids filled with asphalt (VFA) range by 20% for BDWSC; and the upper limit requirement by 5 to 7% for HRAP. No VFA requirements for HPTO and BRIC.
- Decreased the dust-to-binder ratio for BDWSC by 0.3%.

The above changes to AASHTO M 323 and AASHTO R 35 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).

Except for HRAP, the use of RAP is not allowed in any of the specialty asphalt mixtures. Furthermore, the fine aggregate for all four mixtures (i.e., BDWSC, HPTO, BRIC, and BRBC) has to be 100% stone sand (i.e., no natural sand). As for the HRAP, the new PBS is unique for the following three reasons:

- The specification requires a minimum (not a maximum) amount of RAP to be added: 20% minimum in the surface course and 30% minimum in the intermediate or base course.

- As noted above, 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 performance testing requirements.
- The performance test criteria specified is based on the performance test results of virgin asphalt mixtures (i.e., 0% RAP) from around the state.

For each asphalt mixture design, the contractor submits to NJDOT two sets of samples: (A) 2–3 gyratory specimens and 1 loose mixture; and (B) 6–11 gyratory specimens and 2–12 box samples (5-gallons buckets in the case of BDWSC) of loose mixture. NJDOT first tests the set (A) samples and determine if the results meet the requirements of NJDOT for gradation and volumetric properties. If acceptable, NJDOT will then use set (B) samples for performance testing of the asphalt mixture (APA, OT, or FBF). The asphalt mixture will be required to meet all applicable requirements of table 1 through table 3 for JMF approval. Asphalt mixture designs may be verified on an annual basis rather than on a project-to-project basis if the properties and proportions of the materials do not change. The contractor has to submit a new JMF for approval each time a change in material source or material properties is proposed.

SELECTION OF PERFORMANCE TESTS

Table 4 summarizes the asphalt mixture performance tests currently used by NJDOT for their BMD approach. It also includes additional tests that are currently being evaluated for potential use during production for acceptance (i.e., high-temperature IDT strength and intermediate-temperature IDT cracking). A final decision has not been made, but these tests are the ones currently under evaluation.

The APA is currently being used to evaluate the rut resistance of all five specialty mixtures. Originally, Rutgers University was running Superpave Shear Tester (SST) on asphalt mixtures for rutting evaluation. However, the associated high cost for the equipment and time to prepare test specimens led researchers to abandon the SST and switch to the APA. The APA test results were relatively easy to analyze and interpret (pass/fail rut depth criterion at certain loading cycles). Rutgers University then developed a baseline database of the APA rut depth parameter for produced asphalt mixtures that was later correlated to field pavement performance.

When this BMD effort started, limited cracking tests were available. The most common test was the FBF test that got implemented for BDWSC and BRBC. During this effort, the OT was being introduced as a pass/fail type of test which seemed to address the needs of NJDOT for a representative cracking test that is simple and quick to run. Literature available then (2007–2009) indicated excellent correlation between the OT and field cracking for both composite and flexible pavements. It also indicated the sensitivity of OT to asphalt mixture component properties or proportions (e.g., aggregates, asphalt binders, recycled materials) and air voids; which was another important aspect (NJDOT had some concerns with mixtures with high RAP and low asphalt binder content). The OT also offered the ability to run the test on lab-prepared or field core specimens.

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

Elements	Stability/Rutting	Durability/Cracking	Moisture Damage/Stripping
Test Name	Asphalt Pavement Analyzer (APA)	Overlay Tester (OT) Flexural Beam Fatigue (FBF)	Indirect Tensile Strength Ratio (TSR)
Test Method	AASHTO T 340	NJDOT B-10 AASHTO T 321	AASHTO T 283
Test Criteria	Refer to table 3.	Refer to table 3.	Refer to table 3.
Test Implemented in Asphalt Mixture Design	Yes.	Yes.	Yes.
Aging Protocol	Lab-produced mixtures: Short-term conditioning of loose mixture in accordance with AASHTO R 30: • Section 7.1 for 2 hours at 135°C if combined aggregate absorption ≤ 1.5%. • Section 7.2 for 4 hours at 135°C if combined aggregate absorption > 1.5%. Compacted specimens: Condition for 6 hours at 64°C.	Lab-produced mixtures: Short-term conditioning of loose mixture in accordance with AASHTO R 30: • Section 7.1 for 2 hours at 135°C if combined aggregate absorption ≤ 1.5%. • Section 7.2 for 4 hours at 135°C if combined aggregate absorption > 1.5%. Compacted specimens: Condition for 2 hours at 25°C (OT) or 15°C (FBF).	Lab-produced mixtures: Short-term conditioning of loose mixture in accordance with AASHTO R 30: • Section 7.1 for 2 hours at 135°C. Compacted specimens: Condition for 2 hours at 25°C.
Notes/Comments	NJDOT is investigating the use of high-temperature IDT strength for acceptance.	NJDOT is investigating the use of Indirect Tensile Cracking ASTM D8225-19 for acceptance. NJDOT is currently reviewing the findings from a recent study that established aging protocols for OT and IDT cracking tests.	–

– indicates not available.

Nonetheless, conflicting information, in particular, pertaining to the fatigue cracking performance of recycled asphalt mixtures were illustrated in the literature (while several studies described good correlations between OT results and field pavement performance of recycled asphalt mixtures others were reporting totally opposite results). This steered Rutgers University to further assess the ability of the OT results to predict field pavement performance. Accordingly, materials were evaluated from test sections at the NJ's Long-Term Pavement Performance (LTPP) Special Pavement Study (SPS) -5: Rehabilitation of Asphalt Concrete Pavements. The SPS-5 included sections with different AC overlay thickness (2 and 5 inches), milling surface (with and without milling), and RAP content (0 and 30%). Cores taken prior to rehabilitation as well as retained loose asphalt mixtures from 1994 construction were evaluated in the OT; and test results were then compared to field pavement performance (1994–2009).

While field cracks appeared at about the same time for both virgin and 30% RAP sections, the cracking progressed faster in RAP sections. Thus, resulting in rankings of field performance based on crack initiation that differ from rankings based on crack propagation; leading to different correlations with the OT results of respective asphalt mixtures. In conclusion, the OT appeared to be sensitive to the cracking performance differences (based on propagation definition) between the virgin and 30% RAP mixtures; thus, supporting the OT selection for implementation as part of the BMD approach.

Similar to the APA effort, Rutgers University then developed a baseline database of the OT number of cycles until failure for produced asphalt mixtures. The OT results were later correlated to field pavement performance and test criteria were established

The high-temperature IDT strength and the intermediate-temperature IDT cracking test (ASTM D8225) are being researched by Rutgers University as surrogate performance tests during production. In general, the IDT tests are quick procedures that use currently available equipment in the laboratory with slight modifications as needed; thus requiring minimal investments from both NJDOT and the industry. These tests entail less number of specimens that are much simpler to fabricate and prepare (no cutting or gluing involved) and faster to test; thus allowing for more tests to be completed within normal working hours. The implementation of such tests reduces the overall need for manpower and accelerates the time to test and report back the results of sampled asphalt mixtures during production to the contractor (quick turnaround time). NJDOT is planning on conducting IDT testing during production on upcoming pilot projects this construction season in order to establish a database of test results and validate the IDT tests criteria developed by Rutgers University. The success of this effort will facilitate the potential development and implementation of a PBS for dense-graded asphalt mixtures used in the state.

NJDOT owns an Asphalt Mixture Performance Tester (AMPT) that has been mainly used to test asphalt mixtures for reflective cracking in accordance with NJDOT B-10 (using an overlay test jig). The OT testing in the AMPT started around the same time when NJDOT increased the frequency of production performance testing on HPTO; and after having equipment issues with their separate OT testing equipment. Rutgers University also owns an AMPT that has been primarily used to conduct dynamic modulus and flow number (AASHTO T 378) tests on asphalt mixtures from around the state. Rutgers University continues to build and update the database of measured values for reheated plant-produced asphalt mixtures that NJDOT can use as Level 1/2 inputs for the AASHTOWare Pavement ME Design software. Direct tension cyclic fatigue tests (AASHTO TP 107) were conducted using the AMPT on a limited basis.

At first, the top three factors for NJDOT in selecting a performance test were: field validation, repeatability, and specimen conditioning and testing time. Field validation and correlation of performance test results with measured field performance data is the basis for any BMD approach and was one of NJDOT's motivations for implementation of performance tests. For NJDOT, 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 help to reduce the impact this factor might have on the overall implementation effort of performance tests. The duration needed for specimen conditioning and testing has been a key consideration in the development of test criteria and the implementation of any performance test into the specifications. Other important factors are sample preparation, material sensitivity, equipment cost, etc.

At the current phase of the implementation, NJDOT is particularly interested in effective and practical performance test methods for routine usage during production; so that test results can be tied to a pay factor for asphalt pavements. Thus sample preparation, specimen conditioning and testing time, as well as equipment cost are currently the top three factors for NJDOT in selecting a performance test for asphalt mixture acceptance. Accordingly, the high-temperature IDT and the IDT cracking tests are currently being evaluated to assure that plant-produced asphalt mixtures meet the minimum performance requirements during production.

PERFORMANCE TESTS DEVELOPMENT TO IMPLEMENTATION

The following section summarizes NJDOT'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 an existing standard test method supported efficient implementation of performance tests for asphalt mixtures in NJDOT. While AASHTO standard test methods are available for APA and FBF, NJDOT had at first to rely on Texas DOT (TxDOT) test method for OT. Afterwards, in order to maintain uniformity in the test procedure over the years, NJDOT developed its own standard test method (NJDOT B-10) to determine the susceptibility of asphalt mixture specimens to fatigue or reflective cracking using the OT.

Some changes to the OT test method occurred during the effort of establishing a database of test results. While some of the changes led to reduction in the test variability, they negatively influenced the sensitivity of the OT to key asphalt mixture parameters. Accordingly, it was decided to maintain some of the initial test method instructions and reduce test variability by eliminating the high and low OT results and averaging and reporting the middle three test results.

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

The sensitivity of a 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 NJDOT. 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.

A formal study to assess, in particular, the influence of changes in volumetric and other properties and their relationship to the performance of the asphalt mixtures was not conducted. However, Rutgers University established a large database of performance test results on an array of asphalt mixtures used throughout the state. These asphalt mixtures included different aggregate blend gradations, NMAS, PG of asphalt binder, asphalt mixture type (e.g., dense-graded, SMA, etc.), asphalt binder content, production temperatures, silo storage time, etc. This database was used as needed to validate the performance test results of other types of asphalt mixtures. Continuous communication and knowledge sharing with NJDOT allowed adjustments to be made during the performance testing period.

While this effort is significant, testing asphalt mixtures in an incremental manner helped in undertaking this task in an efficient and productive means. Performance testing of local materials was highly important for NJDOT as it helped identifying underperforming asphalt mixtures.

Similarly, a database of high-temperature IDT strength and intermediate-temperature IDT cracking is being developed by Rutgers University. A test criteria for IDT tests was developed that correlates with the APA and OT test results and criteria. NJDOT is planning on testing asphalt mixtures this paving season and validate the test criteria. Some contractors have also started the development of a baseline database of the cracking tolerance index parameter using IDT cracking test for their typically produced asphalt mixtures.

Step 3. Preliminary field performance relationship.

The APA, OT, and FBF test criteria were based on field pavement performance and testing of asphalt mixtures locally available in the state. NJDOT, and in partnership with Rutgers University, built-up a database of performance test results on asphalt mixtures that was used for establishing a state-specific relationship between test results and field performance in NJ. The initial test criteria were based on the observed performance of the conventional and proprietary asphalt mixtures.

NJDOT has a history of good and poor performing asphalt mixtures. The Pavement Management System (PMS) data provided useful means for comparing field pavement performance to laboratory test results. However, comparisons can also be as simple as general field observations and acknowledging when a field pavement section has or has not performed well.

It is critical to properly identify the cracking type and mechanism that a performance test is intended to address. For example, the FBF test is better at capturing the resistance of an asphalt mixture to crack initiation while the OT is mainly aimed at capturing the mixture's resistance to crack propagation. This should also be complemented with proper identification of field crack distresses and their associated modes of failure (e.g., fatigue cracking versus block cracking) along with adequate duration for in-service performance (e.g., longer in-service time is needed to capture differences in the resistance of asphalt mixtures to crack propagation).

Adjustments were made to performance test criteria based on the asphalt mixture location in the pavement structure and applied traffic level. Accordingly, air void levels representative of field density were selected for test specimens. The use and enclosure of additional performance tests also evolved over time. For example, the HPTO had initially an APA rut depth criterion due to concerns with potential rutting. Then, the HPTO PBS was revised to include an OT cracking performance test and a number of cycles until failure criterion.

Step 4. Ruggedness experiment.

NJDOT did not conduct or participate in any formal ruggedness testing yet. However, a study was completed in 2001 that evaluated the effect of asphalt mixture gradations, compaction methods, sample geometries, and testing configurations on rutting potential of asphalt mixtures in the APA. The testing matrix consisted of 143 samples with air voids of 7±1%. Four aggregate gradations were studied. For each aggregate blend, two compaction methods were used: vibratory (bricks and pills), and Superpave gyratory (pills). The pill samples were tested both in traditional two-sample molds, as well as in center-cut one sample molds built specifically for this study. APA rut tests were conducted at both 64°C and 60°C. The following summarizes the key findings from this study:

- Asphalt mixture gradation, compaction method, testing configuration, and temperature all have reasonably significant impacts on APA rut depts.
- Specimens compacted by the Superpave Gyratory Compactor showed less rutting than samples compacted in the Asphalt Vibratory Compactor.
- The increase of 4°C in testing temperature led to a significant increase in APA rut depth.
- Variations in sample characteristics and/or testing conditions can have significant impact on observed test results. Thus, caution should be observed whenever comparing any testing results.
- The development of APA test failure criteria for NJDOT should use materials locally available and be developed utilizing pavements with known field performance.

Step 5. Commercial equipment specification and pooled fund purchasing.

NJDOT invested in new equipment and accessories in order to undertake performance testing. This involved additional resources to create new areas in the laboratories to accommodate equipment. All performance testing equipment are currently located in the central laboratory (Bureau of Materials– Bituminous Labs, Trenton, NJ) including an APA, FBF equipment with its own environmental chamber, standalone OT equipment, Marshall load frame on wheels utilized with an IDT jig, a compression machine (in the process to be retrofitted for IDT tests), and an AMPT utilized with OT jig.

The challenge is to be able to find the resources to acquire equipment. Even when funds are available, procurement of the proper equipment requires time. Once the equipment manufacturer is identified, the procurement process can also be delayed due to capital equipment justification that is needed to compare the costs, benefits, and capabilities of different equipment (especially if the agency decided not to go with the least offered price). In some instances, NJDOT had to acquire equipment through research funds.

In 2015, a mini round robin study was conducted to compare test results of a newly acquired OT equipment from another manufacturer to those from the original device. A statistical analysis comparing the test data from the two pieces of equipment was conducted. It should be noted that the new OT equipment was one of the first units built by the manufacturer, which created some challenges and issues with the equipment.

A total of three sub round robin studies were conducted using a single operator. The first sub round robin study was stopped mid-way through testing due to extremely poor test results. The results of the sub round robin 2 indicated that there were statistically significant differences between the average values from the two devices as well as differences in the resultant variability when testing a set of mixtures. After redesigning the environmental chamber and improving the cooling fan system, the test results generated from the sub round robin 3 showed that both machines were resulting in statistically equal average values and in very similar variances when testing the same mixture.

The study concluded that the new equipment can be used to determine the number of cycles until failure in accordance with the NJDOT B-10 test procedure. After the evaluation, the new unit was delivered to the NJDOT, and a two-day training course was held to familiarize the NJDOT engineers with the sample fabrication, preparation, testing, and data analysis.

Additional costs are also involved in equipment necessary for sample fabrication and preparation (e.g., saw, compactor). Depending on equipment needed the cost can be significant (e.g., vibratory compactor for preparation of FBF specimens). Furthermore, NJDOT had to budget for equipment verification, calibration and maintenance services. These recurring costs can be significant and have to be covered by NJDOT (such costs cannot be built into a project contract).

With the purchase of several performance tests and associated sample fabrication equipment, laboratory space becomes a challenge. For instance, NJDOT is in the process of reorganizing a laundry room for washing and drying dirty rags to fit the equipment for IDT testing. In another instance, a janitor closet was re-purposed for housing tack coat samples from field projects.

Contractors also had to invest in certain equipment and associated training efforts. Having continuity and uniform performance testing methods across the state helps to reduce overall cost and accelerate implementation. NJDOT has to take into consideration the contractors' learning curve and minimize frequent changes to test procedures and equipment.

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. Thus, creating a potential issue if two separate laboratories achieve different test results for the same asphalt mixture. Accordingly, NJDOT pursued a round robin study for each of the APA, OT, FBF, and IDT to determine single and multiple operator repeatability. Overall this effort was a major undertaking.

- Round robin 1 (2016): Asphalt mixtures were tested in accordance with AASHTO T 340 in six different laboratories. Three of the laboratories utilized two-loaded wheel machines, while the remaining three laboratories utilized three-loaded wheel machines. Each laboratory was provided with four sets of asphalt mixtures that had different levels of rutting performance. For one of the mixture sets, the laboratories were provided three different subsets to address the interlaboratory variability of the APA test method. The testing results indicated a single and multiple laboratory coefficient of variation (COV) of 10% and 20%, respectively. A comparison between two- and three-loaded wheel APA machines showed that both machines provide very similar test results. However, a lower variability was achieved with the three-wheel loaded machines (utilize 6 test specimens) when compared to the two-wheel loaded machines (utilize 4 test specimens).
- Round robin 2 (2017): asphalt mixtures were tested in accordance with NJDOT B-10 in five different research laboratories (four different equipment manufacturer types). Each laboratory was provided with three sets of asphalt mixtures that had different levels of cracking performance. For one of the mixture sets, the laboratories were provided three

different subsets to address the interlaboratory variability of the OT test method. The testing results indicated a single and multiple laboratory COV of 24% and 30%, respectively. The study also determined the multiple laboratory COV for three different ranges of OT number of cycles until failure (i.e., COV of 18% for 300–600 cycles; COV of 42% for 800–1,900 cycles; and COV of 26% for cycles >2,000). It should be noted that all findings are based on testing five specimens for each asphalt mixture, eliminating the high and low value, and averaging the middle three results for reporting. Due to the observed variability in OT test results, the round robin revealed that an asphalt mixture designed for low level traffic would actually perform the same as for a higher traffic level. Accordingly, the HRAP OT requirements were revised to account for the test method repeatability and to differentiate between different levels of performance with no statistically equivalent overlap in test results.

- Round robin 3 (2018): a similar round robin study was completed for AASHTO T 321. An acceptable COV (~30%) was determined with BDWSC asphalt mixtures. All asphalt mixture samples were compacted by Rutgers University and shipped to the participating laboratories that were responsible for cutting and testing the specimens.
- Round Robin 4 (2019): asphalt mixtures were tested for high-temperature IDT strength and intermediate-temperature IDT cracking (ASTM D8225) by various asphalt plant quality control laboratories in New Jersey (9 different laboratories). Contrary to the prior three studies, the IDT round robin study prompted a much higher number of interested participants from the industry. Due to limitation in funds, the study selected 7 out 13 industry partners to participate in the round robin. The round robin study involved a wide range of equipment types (5 test equipment setups) and technicians with some or minimal experience regarding the test procedures. The testing results of high-temperature IDT indicated a single and multiple laboratory COV for triplet specimens of 8.2% and 11.8%, respectively. The single and multiple laboratory COV for intermediate-temperature IDT were 15.2% and 23.0%, respectively.

In all round robin studies, participating laboratories were provided clear instructions on sample handling and testing procedures. Laboratories were supplied with a Microsoft Excel reporting sheet for each of the test methods. Rutgers University analyzed and reported all test results from the different participating laboratories.

In general, the round robin studies were very beneficial and helped NJDOT to further gain trust and comfort with performance tests. The round robin studies were all conducted under the NJDOT Pavement Support Program (PSP) that is funded by the State Planning and Research (SP&R) Program. Having such an established program with available resources greatly supported the overall effort to advance performance tests into practice.

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

In 2017, a resurfacing project using HPTO was completed and accepted by NJDOT on Route 295 from mile post (MP) 14.4 to 24.5. About two years later, significant rutting was observed on a portion of the project (between MP 20 and MP 24). A review of the APA test results revealed that 4 out of 10 lots failed the 5 mm rut depth criterion for plant-produced HPTO during production. It should be noted that sampling for performance testing was done at that time every 10,000 tons of asphalt mixture placed. Asphalt mixtures sampled from these four lots exhibited an average APA rut depth of 6.6 mm, 9.7 mm, 10.8 mm, and 12.4 mm. According to the NJDOT standard specifications, the lot with 12.4 mm (>12 mm) is in remove and replace category. It should be noted that sampled asphalt mixtures met the volumetric property requirements. The rutted pavement section had to be repaired. A 2 inch mill and 2 inch inlay was selected. The overall repair cost was split between NJDOT and the contractor.

At that time, the NJDOT staff in the laboratory were new to this type of performance testing due to the large amount of recent staff turnover, and did not have enough comfort and trust with the APA test. Furthermore, some of the samples delivered to NJDOT were not within the proper air voids range. Accordingly, the decision was to accept the asphalt mixture and wait and see how it performed in the field. As a result, NJDOT started research to identify the relationship between air void levels and APA or OT results.

The Route 295 offered NJDOT an independent validation of the HPTO PBS. The observed premature rutting was traced to a poor asphalt mixture design for HPTO; including the use of a highly angular fine aggregate. The fine aggregate was incorporated during the design and production to increase the VMA of the asphalt mixture to help meet the minimum asphalt binder content. Unfortunately, this resulted in the asphalt plant "chasing" asphalt binder content during production to meet air voids on plant-produced asphalt mixtures. Quality control results showed asphalt binder contents in excess of 1 to 2% higher than the design. A redesign of the HPTO (essentially taking all of the angular fine aggregate out of the mixture) after paving the northbound lanes stopped the rutting from occurring in the southbound lanes. This allowed NJDOT to gain trust with performance testing.

In 2016, a resurfacing project of a composite pavement using HPTO was completed on Route 80 from MP 0.50 to 12.80. The project consisted of a 1 inch HPTO on top of 2 inches SMA on top of an existing 9–10 inches jointed plain concrete pavement. Prior to resurfacing the Surface Distress Index (SDI) was 2.45. The SDI is a measure of the pavement's surface distress, which incorporates the various types of cracking (longitudinal, transverse, fatigue, etc.). SDI is collected on a yearly basis during network level data collection and ranges between 0 and 5 (0 being worst and 5 being the best condition). NJDOT trigger for rehabilitation is an SDI of 2.4 or less. The project performed well for two years until 2019 when high SDI values in the range of 2.79 to 4.88 were reported. The poor performance was mainly due to a high frequency of reflection cracking both transverse and longitudinal. It should be noted that prior to resurfacing a windshield survey was conducted while an automated distress survey was performed afterwards, which created inconsistencies in the reported distresses for the calculation of SDI (in general pavements are rated worse with automated distress survey than manual survey). On this project APA testing was completed by Rutgers University and only a rut depth criterion was specified, which was the practice at the time of construction of this project. The HPTO exhibited a rut depth between 4.14 and 6.45 mm. Two out of 5 sampled asphalt mixtures during production exhibited a rut depth that exceeded the NJDOT specification of 5 mm for plant production (5.37 and 6.45 mm). This project raised the need to include a cracking performance test in the HPTO specification. Efforts were then undertaken to establish an OT criterion for HPTO using the developed database of asphalt mixture test results.

These two field projects illustrate how field pavement performance served NJDOT as a great feedback and a robust validation of established performance test criteria for specifications. This feedback loop requires continuous communication and partnership between material, pavement design, and pavement management groups.

Step 8. Training and certification.

Trained technicians on the procedures and analysis of test results are necessary. Whenever needed or requested, Rutgers University hosted laboratory demonstration visits or provided training (hands-on) to familiarize the NJDOT engineers, contractors, or consultants with sample fabrication, preparation, testing, and data analysis. Nonetheless, Rutgers University was in continuous communication and maintained engaged conversations with NJDOT.

NJDOT faced a challenge with the loss of institutional knowledge due to a recent retirement of staff who had been involved in the implementation effort of PBS for asphalt mixtures. Rutgers University played a major role in assuring continuity and preserving historical knowledge.

Step 9. Implementation into engineering practice.

NJDOT has implemented the following five PBS specialty asphalt mixtures with their respective application purpose:

- ***BDWSC.*** It is utilized as a water proof surface course for bridge deck overlays. The BDWSC was developed in 2007 and was utilized on several bridge decks requiring an AC overlay. The decline in BDWSC use over the years has been driven primarily by other factors not necessarily related to its good performance (e.g., BDWSC masks deteriorated and delaminated areas in a concrete bridge deck).
- ***HPTO.*** It is utilized as a thin-lift surface course for primarily pavement preservation purposes. HPTO has also been utilized as a leveling course in some areas. The HPTO was developed around 2008 and since ~2014 it has been heavily used as a rehabilitation/pavement preservation surface course.
- ***BRIC.*** It is utilized as a reflective cracking relief interlayer material to help retard reflection cracking on composite pavements. The BRIC was developed in 2009. It is overlaid primarily with SMA (HPTO was used occasionally). The SMA overlay was found to outperform the conventional AC overlays.
- ***BRBC.*** It is utilized as the base layer in the design and construction of perpetual pavements. It was developed in 2010 for a rubblization/perpetual pavement project on Route I-295. Since this project, BRBC has been proposed for use on other rubblization/perpetual pavement projects in New Jersey.
- ***HRAP.*** It is utilized when a high percentage of RAP is used in the asphalt mixture (at least 20% RAP for surface course and 30% RAP for base or intermediate course). It was developed in 2012 and has been used since 2013. Performance tests criteria are based on database of typical virgin (i.e., 0% RAP) asphalt mixtures.

In an on-going effort, NJDOT has been working on the development of a pavement design and policy manual. NJDOT has been following the 1993 AASHTO Design Method and is in the process of transitioning to the AASHTOWare Pavement ME Design. The selection of a specialty asphalt mixture for the pavement structure in question has been generally based on the accrued experience of senior staff throughout the years. With the use of specialty asphalt mixtures being more frequent and on a regular basis, a project selection document that provides guidance to junior staff is considered critical and timely to ensure knowledge and expertise continuity within NJDOT.

NJDOT effort started on the process of developing a pavement design and policy manual in 2016. Some internal design guidance and flowcharts on mix type selection were developed over time but these were never compiled into one comprehensive manual. Early 2019, NJDOT procured proposals from consultants to assist as part of the department wide "augmentation" effort. Also in 2019, they met with FHWA as part of a national effort to update current federal policies and procedures on pavement design, at which time FHWA offered to assist with NJDOT pavement design and policy manual. This collaborative effort is between NJDOT, FHWA and their consultant.

IMPLEMENTATION OF PERFORMANCE TESTS ON PROJECTS

NJDOT and in collaboration with Rutgers University led and invested significantly in the process to develop and implement PBS for asphalt mixtures. NJDOT's selection of the specialty asphalt mixtures to be used is based on the extreme needs of the pavement structure in question (composite pavement, bridge deck overlay, etc.) and applied traffic level.

At first, few contractors were interested and there was trepidation and opposition due to contractors' lack of understanding regarding the "performance" NJDOT was looking for. Industry primarily cared about volumetric, in-place air voids, and smoothness as these are the factors that control production and pay factors. However, even when meeting these parameters, asphalt mixtures can still rut and crack. Thus, initially, there was a disconnect that needed to be bridged. Additionally, several contractors were not experienced with performance testing and expressed concerns with failing test requirements. At one point, there was a push from some members of the industry to stop the use of PBS for specialty asphalt mixtures. It took time, dialogue, education, and partnering to get the performance tests implemented on field projects. Having a champion from the NJDOT along with a trusted partner from the industry who is willing to work with the agency on improving the process, accelerated the learning curve and made implementation possible.

In general, there was no formal implementation plan. Early on, specialty asphalt mixtures were implemented on projects with no penalties being imposed for plant asphalt mixtures failing performance specifications during production. Thus, providing contractors the opportunity to gain experience and time to become familiar and comfortable with the process. Furthermore, the sampling frequency was initially low and around 10,000 tons of placed asphalt mixtures to allow for time and to gain experience with testing and the process.

In the latest specifications, NJDOT requires the asphalt mixture producer to sample and test for volumetric properties at the plant for each 700 tons of specialty asphalt mixture. The contractor is also required to provide NJDOT with gyratory compacted specimens and boxes of loose asphalt mixtures. The compacted specimens are used for performance testing and loose asphalt mixture is used to determine the maximum specific gravity of the asphalt mixture. While testing for volumetric properties happens in NJDOT regions (at the asphalt plant by personnel from

NJDOT districts and contractors quality control technicians), performance testing is conducted by NJDOT at the central laboratory in Trenton, New Jersey.

The first sample is taken during the construction of the test strip. Thereafter, every lot (HPTO, or HRAP), every second lot (BDWSC, or BRIC), or every fifth lot (BRBC) is sampled. Performance testing is conducted at the rate of one sample for each 1,400 tons of BDWSC, 3,500 tons of HPTO, 1,400 tons of BRIC, 3,500 tons of BRBC, and 700 tons of HRAP (rates of testing can be modified by ME). The performance testing results will be included in the first lot if the test strip was done within the project limits and the results were acceptable.

If a sample does not meet the criteria for performance testing as specified in table 3, a pay adjustment will be assessed (HPTO, or HRAP) or production may be stopped until corrective action has been taken. Removal and replacement of a lot may be required if the BRIC exceeds the respective APA criterion or if the HRAP fails to meet requirements for both APA and OT. Thus, a quick turnaround of performance test results was critical during production, in particular for HPTO and HRAP where results are tied to a pay factor. Equipment calibration and proper documentation are a must in case of any disputes by contractors.

In comparison to asphalt mixture design criteria, a slightly higher APA test criteria is implemented on plant-produced asphalt mixtures for HPTO and BRIC (HPTO: 5 mm relative to 4 mm rut depth in design; and BRIC: 7 mm relative to 6 mm rut depth in design). Similarly, the minimum OT number of cycles under failure was reduced from a minimum of 700 cycles during asphalt mixture design to a minimum of 650 cycles during plant production. These changes stemmed from the observed pavement performance, where plant-produced asphalt mixtures that slightly failed the asphalt mixture design test criteria still performed well in the field. Based on a recent study on the laboratory performance of plant-produced asphalt mixtures, the minimum OT requirements for BRIC will be increasing in 2020 for both the design and production performance testing.

Early on in the implementation process, asphalt binder contaminations were sometimes observed during production. Residual asphalt binders along with the use of a release agent to flush the pipelines system at the plant negatively impacted the performance of BDWSC, which is made with a highly polymer-modified asphalt binder. For instance, it was determined that at least 75 to 125 tons of BDWSC need to be first produced and discarded to clear up the pipelines from any remaining contaminants. Producing specialty asphalt mixtures requires a certain level of transition at the plant to assure proper production and performance.

Requiring performance testing during production and at an increased frequency of sampling required NJDOT staff to work overtime (added cost to the agency) in order to keep up with sample preparation, testing, data analysis, and test reports. Performance testing required longer working hours that involved the readiness, approval, and adjustment of the staff to the new schedule. Having extra sample molds and programmable conditioning ovens would help to speed up the process; however, that option was not viable to NJDOT because of electricity issues in the aging building where performance tests are being housed.

Another challenge that NJDOT faced during production is the breakdown of a specific performance test equipment with no access to a backup equipment or a quick repair service. In some instances, repairing a malfunctioning equipment requires issuing a purchase order that can take up to three months to be executed. Thus, there is a need to develop good relationships with equipment suppliers and ensure they can provide quick service in emergency situations. Through their existing contract, NJDOT relied on Rutgers University's support with the overflow of performance testing when NJDOT is inundated with test specimens or when an equipment is down.

Recently, the time needed to perform testing and report results prompted some contractors and asphalt mixture suppliers to ask permission to revise the approval process by combining the asphalt mixture design with a test strip that can be done during the off construction season. While NJDOT was receptive to the proposition, concerns were raised with the current extended time difference between when the asphalt mixture is approved and the actual construction/production time. Industry has also expressed interested in having IDT performance testing on pilot projects as part of the project bid.

Implementing proper performance tests within a BMD approach allowed contractors to be creative and see the benefits of the tests. However, contractors are looking for information on recommended changes to asphalt mixtures to bring them into compliance. These changes could be different than those that contractors make using traditional volumetric-based mix designs. This would require training and certification of asphalt plant technicians and operators from around the State.

OVERALL BENEFITS

A 2016 PSP study evaluated the field performance of pavement sections containing HPTO and BRIC using the NJDOT PMS. Pavement performance curves in terms of the SDI parameter as a function of time were developed. A pavement is considered deficient when the SDI is less than or equal to 2.4.

The study showed that the HPTO would last 10–13 years when placed on pavements with an existing SDI greater than 2.4. The projected life of HPTO was reduced to ~5 years when placed on pavements with an existing SDI less than 2.4. On the other hand, the use of BRIC in general improved the projected pavement life. The use of an SMA overlay with BRIC improved the projected pavement life by over 10 years in comparison to a composite pavement with a dense-graded asphalt mixture with no BRIC.

In summary, both HPTO (when placed over a pavement with SDI > 2.4) and BRIC (with SMA overlay) showed very good field performance that considerably exceeded the performance of conventional NJDOT asphalt mixtures. Thus, delaying the next rehabilitation or reconstruction activity and leading to significant life cycle cost savings in terms of both agency and user costs.

The use of PBS allowed contractors to utilize innovative and recycled materials (e.g., RAP, recycling agents, PG of asphalt binders) in order to produce asphalt mixtures that are in compliance with NJDOT specifications; including asphalt binder suppliers which had to formulate specialty asphalt binders to help with performance requirements. Furthermore, the traditional volumetric-based mixture design did not provide optimum performance for asphalt mixtures with high RAP content. Performance testing helped designing asphalt mixtures with high RAP that resulted in ultimate performance against primary modes of distress (i.e., durability/cracking and rutting); thus allowing for the production of economical and environmentally-friendly asphalt mixtures without jeopardizing performance.

FUTURE DIRECTION

NJDOT's ultimate plan is to also implement BMD approach for its dense-graded asphalt mixtures. Some preliminary steps and timeframes on how NJDOT can move to using performance tests on all of its asphalt mixtures were developed and are summarized below. The draft 5-year implementation plan is currently being evaluated and, once ready, it will be executed. It should be noted that the 5-year timeline can vary based on staffing and pandemic situation.

- ***Step 1: Establish a minimum effective asphalt binder content for dense-graded asphalt mixtures.*** The ultimate objective is to specify a minimum asphalt binder content for dense-graded asphalt mixtures based on the specific gravity of the blend aggregates that will ensure at a minimum a certain level of performance. This step would be instrumental for the development of a database of performance test results for dense-graded asphalt mixtures used throughout the state. One of the identified challenges in this step is a proper selection of the specific gravity of the aggregates, in particular when a high content of RAP is being used.
- ***Step 2: Explore the high-temperature IDT strength and IDT cracking tests for asphalt mixtures during production***. The high-temperature IDT strength was found to correlate with the APA rut depths and the IDT cracking test index was found to correlate with the OT number of cycles until failure. Both IDT tests are much quicker to run and equipment are much simpler (i.e., equipment are less likely to break down during operation and if a malfunction occurs the NJDOT staff should be able to repair). Pilot testing during production is anticipated to start this paving season to: (1) confirm the results and criteria from Rutgers University; (2) assess if IDT testing on plant-produced asphalt mixtures can be properly handled during production in a timely and efficient manner. If successful, changes to conduct testing on production samples can possibly be made by next paving season (2021).
- ***Step 3: Start using high-temperature IDT strength and IDT cracking tests on all performance-based asphalt mixtures.*** This step would be accomplished the following paving season after step 2 being successfully completed (2022). Testing is not anticipated on older projects but any new ones would need to include a new performance testing frequency during production.
- ***Step 4: Transition to all asphalt mixtures for performance testing.*** This may be the most difficult step. 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. This will involve a major culture and procedural shift on how things are currently being done and operating within the asphalt laboratories of the NJDOT Bureau of Materials and regions. One option to possibly get this accomplished is to enlist the help Rutgers University and Rowan University to research the best way for this implementation. There will be a need to acquire additional staff and space or suspend some other tests that are currently being performed (e.g., stop or reduce the frequency of verification testing for

asphalt binder content during production) in the asphalt laboratories; thus freeing up some of the staff time.

- ***Step 5: Full implementation of performance tests on all asphalt mixtures.*** Once staffing and space have been resolved, NJDOT can fully move to full performance testing on all of its asphalt mixtures produced in the state. In the interim, contractors may be asked to support with performance testing. This would require having the contractor's laboratory meet certain assessment or accreditation criteria. It also requires establishing a statewide proficiency testing program and developing a robust independent assurance program.

The full implementation effort needs to be supplemented with proper 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 NJDOT that can help facilitate the implementation of a performance test into practice. Positive practices are those successful efforts that were used by NJDOT that could also be considered by other SHAs. Lessons learned are those efforts that, if NJDOT had it to do over again, they would definitely reconsider. Challenges are those efforts that NJDOT is still in the process of addressing.

Positive Practices

- Collaboration and cooperation between NJDOT, Rutgers University, and industry 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, there was a champion. Continuous communication and partnership between materials, pavement design, and pavement management groups helped in validating and refining performance test criteria.
    - Externally, having a strong and established relationship with academia (i.e., Rutgers University) helped in developing PBS for asphalt mixtures. Having an established program through the state such as the NJDOT PSP (funded by SP&R) to support critical and pressing research was key in the development and implementation of performance-based asphalt mixtures.
    - Externally, having trusted industry partners (i.e., asphalt binder suppliers, asphalt plants, contractors) supporting the implementation of specialty asphalt mixtures accelerated the learning curve and practicality of the developed PBS.
    - Communicating with contractors the impact of new specifications on the design and acceptance of their asphalt mixtures was key to facilitating implementation.
- A formal study was not conducted to assess the changes of asphalt mixture properties to identify the relationship to the performance test results (Step 2). However, this was done efficiently and productively in an informal manner by testing local materials.

- Establishing a large database of test results helps in understanding the performance of local asphalt mixtures (underperforming mixtures were identified) and in establishing a comfortable transition from volumetric to performance tests.
    - Testing of asphalt mixtures was conducted by Rutgers University in an incremental manner to effectively manage the significant work involved with experimental testing.
- A top factor in selecting a performance test was the field validation and correlation of the performance test with field performance (Steps 3 and 7).
    - The PMS data provided useful means for comparing field performance to laboratory test results and to validate established performance test criteria for specifications (Steps 3 and 7).
    - Initially, criteria were selected based on the literature and then performance of LTPP SPS-5 sections in New Jersey (Step 3).
    - Following that, a database was prepared of performance test results that were later correlated to field performance (Step 7). This assisted in setting and modifying the test criteria.
    - Comparisons were also based on specific field observations by acknowledging when a field pavement section has or has not performed well (Step 7).
- NJDOT conducted several round robins (Step 6) to gain trust and comfort with the performance tests which resulted in positive adjustments to test procedures. As a result of round robins, single and multiple operator variability were developed. The round robins considered different equipment manufacturer types. The round robins were so successful, they are still continuing.
- NJDOT envisions some form of an accreditation program for the asphalt plant laboratory (Step 8). This will be done in collaboration between SHA and regional or national organizations.
- The selection of a performance test had many positive practices associated with it:
    - Performance tests were selected that were easy to analyze and interpret. It was also important that specimens were simpler to fabricate and prepare as well as faster to test.
    - Selection of performance tests and associated test criteria considered the intended application and type of the asphalt mixture (e.g., bridge deck overlay, pavement preservation, perpetual pavement), as well as applied traffic level. This resulted in NJDOT implementation of five different performance-based asphalt mixture designs with proper adjustments made to performance test criteria.
    - Identification of the primary asphalt pavement modes of distress and related failure mechanism was critical for the proper selection of performance tests. In the case of NJDOT, the evaluation of SPS-5 test sections revealed a very good correlation between OT results and observed field cracking propagation.
    - The OT was implemented to determine key characteristics of asphalt mixtures that can be improved to slow down observed field cracking. The OT is not being used to mimic the field expansion and contraction of an asphalt mixture placed on top of a cracked pavement or an existing joint.
- Keys to implementation (Step 9) included:
    - The implementation of performance tests is an ongoing process. A program was successfully established to test an average of 10% and up to 17% of NJDOT's

annual tonnage. A draft 5-year plan is being developed to expand the use of performance tests. This plan includes the use of even simpler and more efficient tests.
    - Implementation of performance tests was coupled with changes to the volumetric design criteria of asphalt mixtures (e.g., specification of a minimum asphalt binder content, increase in density requirement at N_{des} and N_{max}, increase in VMA, increase in VFA, decrease in dust-to-binder ratio).
    - Phasing in the implementing of specialty asphalt mixtures with initially no ties to pay factors provided NJDOT and contractors the opportunity to gain experience and time to become familiar and comfortable with the process. Starting with relatively lower sampling frequency of placed asphalt mixtures was also helpful and beneficial.
    - Implementation of performance tests as part of pay factors for HPTO and HRAP are going well so far.
- The benefits of BMD are as follows:
    - Pavement performance improved. There is documentation through the PMS regarding the increase in pavement life of HPTO and BRIC. The HPTO has lasted up to 13 years when placed on pavements with an existing SDI greater than 2.4. The BRIC with an SMA overlay improved the projected pavement life by over 10 years in comparison to a pavement with just a dense-graded asphalt mixture.
    - Delayed the next rehabilitation or reconstruction activity resulting in significant life cycle cost savings for both the agency and the public user.
    - The PBS allowed contractors to use innovative and recycled materials (e.g., RAP, recycling agents, PG of asphalt binders) in order to produce asphalt mixtures that are in compliance with NJDOT specifications.

Lessons Learned

- There is a desire to expand the use of performance testing for asphalt mixtures. There is a need to reduce the workload of the NJDOT staff and to accelerate the turnaround time for performance test results during production. As a result, the IDT strength and IDT cracking tests were found to have good correlations and are being evaluated further. NJDOT is particularly interested in effective and practical performance test methods for routine use during production, and tying these to pay factors.
- Producing specialty asphalt mixtures requires a certain level of transition at the plant to assure proper production and performance. The performance of such mixtures and their ability to meet respective performance test criteria is more likely to be negatively influenced with the presence of any asphalt binder contaminations.
    - At a minimum a certain tonnage of the specialty asphalt mixture needs to be produced and discarded to clear up the pipelines from any remaining contaminants.
- Lack of experience with the influence of air void levels of specimens on performance test results. Development of relationships between test results and air voids level ahead of time would help in making informed decisions on the acceptance or rejection of a plant-produced asphalt mixture.

- Further observations of HPTO and BRIC field pavement performance revealed good performance of some borderline plant-produced asphalt mixtures. Thus, revisions were made to include test criteria for plant-produced asphalt mixtures different from those required during mixture design.

Challenges

- Implementation of performance testing required allocation of additional resources from NJDOT.
    - Proper planning in advance of laboratory space needed for sample preparation and performance testing is necessary. This required re-organization or re-purposing of existing space to maximize space utilization. Additionally, dealing with an aging building where performance tests are being housed can cause additional challenges.
    - Requiring performance testing during production and at an increased frequency of sampling required NJDOT staff to work overtime. Thus, the need to plan for staff overtime including the approval and support of both staff and upper management.
    - Finding resources to acquire equipment necessary to conduct performance tests. Funds are also needed for purchasing equipment necessary for sample fabrication and preparation. NJDOT had to also budget for a yearly recurring cost for equipment verification, calibration and maintenance services.
- Equipment breakdowns occurred (Step 5).
    - It is important to develop good relationships with equipment suppliers/manufacturers and assure they can provide a quick service in emergency situations.
    - Having no access to a backup equipment or a quick repair service was of great challenge. In some instances, repairing a malfunctioning equipment required issuing a purchase order that took up to three months to be executed.
    - NJDOT used Rutgers as a back-up for testing samples when equipment breakdowns occurred. A back-up plan is important.
- Performance test methods that lack precision and bias, thus creating a potential issue if two separate laboratories achieve different test results for the same asphalt mixture. Performance criteria need to take into consideration the precision and bias of the test method.
- Having equipment from different manufacturers resulted in differences in test results, which required the completion of a round robin study. Additional resources and time were needed to undertake this task.

NJDOT 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

NJDOT suggests the following research topics:

- What changes can be made by contractors 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.
- Procedures and guidelines on how to implement performance testing of asphalt mixtures in the acceptance process. The study needs to look into a practical approach that takes into consideration testing turnaround time (including sample fabrication and consideration of many projects occurring simultaneously in the paving season), repeatability and reproducibility, material sensitivity, and associated risks.
- 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 and its implication on specifications. This will provide contractors with the information needed to control their produced asphalt mixture and to make the necessary changes to bring them into compliance. It will also provide SHAs with proper justification to make any necessary and reasonable changes in production tolerances.
- 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.

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