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

Texas Department of Transportation (TxDOT)

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ALF	Accelerated Load Facility
AMPT	Asphalt Mixture Performance Tester
APT	Accelerated Pavement Testing
ASTM	American Society for Testing and Materials
CT	cracking tolerance
DOT	Department of Transportation
BMD	Balanced Mix Design
CAM	crack attenuating mixture
COV	coefficient of variation
CTIS	Center for Transportation Infrastructure Systems
CTR	Center for Transportation Research
DG	dense-graded
FHWA	Federal Highway Administration
HMA	hot-mix asphalt
HMAC	Hot Mix Asphalt Center
HWT	Hamburg Wheel test
IAC	Interagency Cooperation Contract
IDT	indirect tensile strength
ILS	interlaboratory study
JMF	job mix formula
LTRC	Louisiana Transportation Research Center
MPL	material producer list
MTD	Materials and Tests Division
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	nominal maximum aggregate size
OBC	optimum asphalt binder content
OT	Overlay test
PEP	Performance Engineered Pavements
PFC	permeable friction course
PG	performance grade
RAP	reclaimed asphalt pavement
RAS	reclaimed asphalt shingles
SHA	state highway agency
RRT	rapid rutting test
SMA	stone-matrix asphalt
SP	Superpave
SS	special specification
TBFC	thin bonded friction courses
TOM	thin overlay mixtures
TTI	Texas A&M Transportation Institute,

TXAPA	Texas Asphalt Pavement Association
TxDOT	Texas DOT
U.S.	United States
UTA	University of Texas at Austin
UTEP	University of Texas at El Paso
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 provisional AASHTO Standard Practice PP 105-20 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***. This approach starts with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) for determining an optimum asphalt binder content (OBC). The mixture is then tested with selected performance tests to assess its resistance to rutting, cracking, and moisture damage at the OBC. If the mix design meets the performance test criteria, the job mix formula (JMF) is established and production begins; otherwise, the entire mix design is repeated using different materials (e.g., aggregates, asphalt binders, recycled materials, and additives) or mix proportions until all of the volumetric criteria are satisfied.

- ***Approach B—Volumetric Design with Performance Optimization***. This approach is an expanded version of Approach A. It also starts with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) for determining a preliminary OBC. Mixture performance tests are then conducted on the mix design at the preliminary OBC and two or more additional contents. The asphalt binder content that satisfies all of the cracking, rutting, and moisture damage criteria is finally identified as the OBC. In cases where a single binder content does not exist, the entire mix design process needs to be repeated using different materials (e.g., aggregates, asphalt binders, recycled materials, and additives) or mix proportions until all of the performance criteria are satisfied.

- ***Approach C—Performance-Modified Volumetric Design***. This approach begins with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) to establish initial component material properties, proportions, and binder content. The performance test results are then used to adjust either the initial binder content or mix component properties or proportions (e.g., aggregates, asphalt binders, recycled materials, and additives) until the performance criteria are satisfied. For this approach, the final design is primarily focused on meeting performance test criteria and may not have to meet all of the Superpave volumetric criteria.

- ***Approach D—Performance Design***. This approach establishes and adjusts mixture components and proportions 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 laboratory test results meet the performance criteria, the mixture volumetrics 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. Texas Department of Transportation (TxDOT) 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 TxDOT virtual site visit.

GENERAL INFORMATION SPECIFIC TO TxDOT

TxDOT is currently responsible for maintaining approximately 197,000 lane-miles of highway infrastructure. In fiscal year 2019, TxDOT placed about 16 million tons of asphalt mixture. The TxDOT standard asphalt mixtures are specified in standard specifications Item 341 Dense-Graded Hot-Mix Asphalt (DG HMA) and Item 344 Superpave Mixtures (SP). Item 341 and Item 344 are used for approximately 35% and 45% of the asphalt mixtures placed by TxDOT, respectively. The primary differences in the specifications are Item 341 has historically relied on Texas Gyratory Compaction and Item 344 requires Superpave Gyratory Compaction, as well as has higher voids in mineral aggregate (VMA) requirements leading to higher typical asphalt binder contents than Item 341.

Specialty asphalt mixtures account for the remainder 20% of the asphalt mixtures placed by TxDOT and have been used for more than 15 years. Specialty asphalt mixtures are specified in standard specifications Item 342 Permeable Friction Course (PFC), Item 346 Stone-Matrix Asphalt (SMA), Item 347 Thin Overlay Mixtures (TOM), and Item 348 Thin Bonded Friction Courses (TBFC). TxDOT has a special specification (SS) for the crack attenuating mixture (CAM) that is designed to reduce reflective cracking in asphalt mixture overlays (SS 3000). A summary of the standard and specialty asphalt mixtures along with their applications is shown in table 1.

TxDOT specifications for DG HMA and SP mixtures currently require the Hamburg Wheel test (HWT) for rutting performance evaluation. On the other hand, TxDOT specifications for specialty asphalt mixtures require, in addition to the HWT, the overlay test (OT) for cracking performance evaluation.

Table 1. Asphalt Mixture Types Used by TxDOT.

Specifications	Specialty Asphalt Mixture	Typical Applications
Item 341 Dense-Graded Hot-Mix Asphalt (DG HMA)		• Used in base, intermediate, or surface layers. • High to low volume (demand) roadways. • New and rehabilitation construction.
Item 342 Permeable Friction Course (PFC)	X	• Used as surface layer. • High speed roadway (posted speed limit ≥ 45 mph). • Optimize safety and comfort characteristics of the roadway. • New and rehabilitation construction.
Item 344 Superpave Mixtures (SP)		• Used in base, intermediate, or surface layers. • Medium to high volume (demand) roadways. • New and rehabilitation construction.
Item 346 Stone-Matrix Asphalt (SMA)	X	• Used in intermediate or surface layers. • High volume (or high demand) roadways • New and rehabilitation construction.
Item 347 Thin Overlay Mixtures (TOM)	X	• Used as surface layer for preservation of existing pavements. • High to low volume roadways. • High performance overlay.
Item 348 Thin Bonded Friction Courses (TBFC)	X	• Used as surface layer. • High speed roadway (posted speed limit ≥ 45 mph). • Optimize safety and comfort characteristics of the roadway. • New and rehabilitation construction.
SS 3000 Crack Attenuating Mixture (CAM)	X	• Used as an interlayer. • High to low volume (demand) roadways. • Rehabilitation construction.
SS 3074 Superpave Mixtures – Balanced Mix Design (SP – BMD)		• Used as surface layer. • High to low volume roadways. • New construction and overlays.

In 2015, as part of TxDOT Project 0-672 *Performance Tests for Thin Asphalt Layers*, guidelines for project selection, design, and construction of thin overlays were developed and published. The thin asphalt overlays are laid at 1.0 to 0.5 inches thick and include the fine PFC Type F (PFC-F), fine SMA Type F (SMA-F), TOM, and CAM.

Reclaimed asphalt pavement (RAP) is widely used and reclaimed asphalt shingles (RAS) is sometimes used in asphalt mixtures in Texas. With the increase use of such materials, SP mixtures started to experience premature failure or did not perform as originally intended. Accordingly, TxDOT started, and in coordination with the industry, to examine the use of performance tests and the BMD on SP surface mixtures. A new TxDOT SS 3074 Superpave Mixtures – Balanced Mix Design was developed to produce asphalt mixtures with satisfactory volumetric and mechanical performance. The SS 3074 aims at improving asphalt pavement performance through a responsible use of recycled materials in asphalt mixtures. The HWT and OT results are implemented in the SS 3074 to assess the stability and durability of asphalt mixtures during the design process.

Recently, TxDOT initiated a large effort in partnership with industry and academia to revise and further develop the SS 3074 for SP surface mixtures with RAP. This involves the placement of ~12 test projects between 2019 and 2021 by contractors of the Texas Asphalt Pavement Association (TxAPA) around the state. Each test project will have 3 to 4 test sections; a control section and 2-3 test sections with BMDs focusing on key variables such as rejuvenators, aggregate gradation, and asphalt binder source and grade. Accordingly, TxDOT established Interagency Cooperation Contracts (IACs) with the Texas A&M University—Texas A&M Transportation Institute (TTI), University of Texas at Austin—Center for Transportation Research (CTR), and University of Texas at El Paso—Center for Transportation Infrastructure Systems (CTIS). The three universities are providing and supporting TxDOT with asphalt mixture designs and laboratory testing and analysis. The outcome of this effort is a specification and related test methods for design and quality acceptance, and performance thresholds to produce a practical method to engineer each unique materials combination to realize substantial economic and environmental benefits without forfeiting a balanced engineering performance.

BMD APPROACH

TxDOT developed a special specification for BMD of surface asphalt mixtures: "Special Specification 3074 for Superpave Mixtures – Balanced Mix Design." Figure 1 shows a flowchart of the overall BMD that highlights the major steps for undertaking an SP – BMD according to TxDOT specifications. The requirements for volumetric design and performance testing for specialty asphalt mixtures and SP – BMD are summarized in table 2 and table 3. Performance testing requirements are provided as a function of the high temperature asphalt binder performance grade (PG); thus taking into consideration both climate and traffic conditions.

The TxDOT's BMD for designing asphalt mixtures and approving job mix formulas (JMFs) follows Approach A *Volumetric Design with Performance Verification*. At this time, there are a couple of goals: 1) use the BMD approach on 80% of the mixtures, and 2) use approach C or D. Starting with Approach A on pilot projects is the first step. The SP – BMD asphalt mixture is designed at 50 gyrations (N_{design}) to a target laboratory-molded density of 96.0%. However, adjustments can be made to the N_{design} value when shown on the plans, specification, or mutually agreed between TxDOT and the contractor. The N_{design} level may be reduced to no less than 35 gyrations at the contractor's discretion (a range of 35–100 gyrations).

The contractor can provide with the mixture design the HWT results performed by an approved laboratory from the TxDOT's material producer list (MPL), or can request TxDOT to perform the HWT by providing the laboratory mixture. The contractor will also provide laboratory mixture to TxDOT to perform OT. The HWT and OT results on the laboratory mixture design will be provided to the contractor within 10 working days.

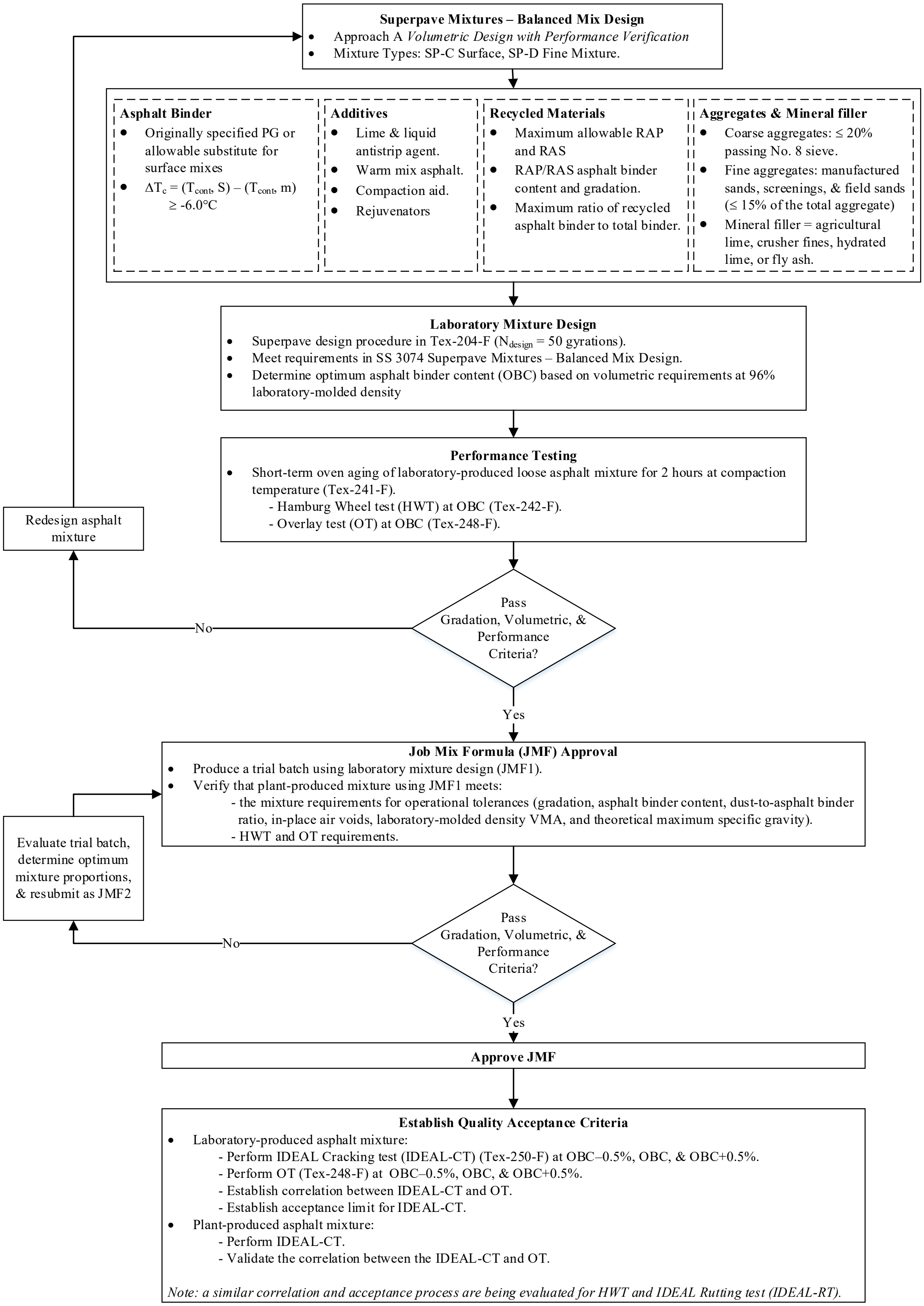

Figure 1. Chart. Overview of TxDOT's BMD approach for SP – BMD of surface mixtures.

Table 2. Mix Design Volumetric Requirements.

Mixture Type		Asphalt Binder Content (%)	Target Lab-Molded Density (%)	VMA (Minimum %)[$] Nominal Maximum Aggregate Size (NMAS) (mm)						Dust-to-Asphalt Binder Ratio[#]	Drain-down (%)
				37.5	25	19	12.5	9.5	4.75		
DG HMA	A, B, C, D, or F	–	96.5*	12.0	13.0	14.0	15.0	16.0	–	–	–
SP Mixtures	SP-A, SP-B, SP-C, or SP-D	–	96.0	13.0	14.0	15.0	16.0	–	–	0.6–1.6	
PFC	Fine (PFC-F)	6.0–7.0	≤ 78.0	–	–	–	–	–	–	–	≤0.1%
	Coarse (PFC-C)	6.0–7.0	≤ 82.0	–	–	–	–	–	–	–	≤0.1%
	Fine (PFCR-F)	8.0–10.0	≤ 82.0	–	–	–	–	–	–	–	≤0.1%
	Coarse (PFCR-C)	7.0–9.0	≤ 82.0	–	–	–	–	–	–	–	≤0.1%
SMA	SMA Mixtures	6.0–7.0	96.0	–	–	–	17.5	17.5	–	–	≤0.1%
	SMAR Mixtures	7.0–10.0	96.0	–	–	–	19.0	19.0	–	–	≤0.1%
TOM	Coarse (TOM-C)	≥ 6.0	97.5*	–	–	–	–	16.0	–	–	≤0.2%
	Fine (TOM-F)	≥ 6.5	97.5*	–	–	–	–	16.5	–	–	≤0.2%
TBFC	Fine (PFC-F)	6.0–7.0	≤ 78.0	–	–	–	–	–	–	–	≤0.1%
	Coarse (PFC-C)	6.0–7.0	≤ 82.0	–	–	–	–	–	–	–	≤0.1%
	Coarse (PFCR-C)	7.0–9.0	≤ 82.0	–	–	–	–	–	–	–	≤0.1%
	TBWC-Type A	5.0–5.8	≤ 92.0	–	–	–	–	–	–	–	≤0.1%
	TBWC-Type B	4.8–5.6	≤ 92.0	–	–	–	–	–	–	–	≤0.1%
	TBWC-Type C	4.8–5.6	≤ 92.0	–	–	–	–	–	–	–	≤0.1%
CAM	Fine Mixture	≥ 7.0	98.0	–	–	–	–	–	17.0	≤ 1.4	–
SP – BMD	SP-C Surface	–	96.0	–	–	15.0	–	–	–	0.6–1.6	–
	SP-D Fine Mixture	–	96.0	–	–	–	16.0	–	–	0.6–1.6	–

–Not applicable.
[$]Uses effective specific gravity of the aggregate (Gse) and not bulk specific gravity of the aggregate (Gsb).
[#]Defined as percent passing No. 200 sieve divided by asphalt binder content.
*Texas gyratory compactor.

TxDOT will verify and approve all mixture designs (JMF1) before the contractor can begin production. JMF1 is the original laboratory mixture design used to produce the trial batch. The JMF1 is verified based on plant-produced asphalt mixture from the trial batch. If the asphalt mixture produced using the JMF1 meets the volumetric and performance requirements (HWT and OT) for the SP – BMD, a correlation between the OT and IDEAL Cracking Tolerance test (IDEAL-CT) (Tex-250-F) will then be established. If the plant-produced asphalt mixture (JMF1) fails any of the criteria, the contractor has to redesign and resubmit the asphalt mixture for JMF approval following the same process.

To perform a correlation between the OT and the IDEAL-CT, laboratory asphalt mixture is provided to TxDOT at the OBC submitted for JMF1 and at asphalt binder contents 0.5% above and below the OBC. The performance tests will be conducted by TxDOT or by an approved laboratory from the TxDOT's MPL to establish an acceptable limit for IDEAL-CT. The IDEAL-CT test is also performed on the trial batch mixture (i.e., plant-produced asphalt mixture) to validate the correlation between the OT and IDEAL-CT. The correlation is expected to be established for each project and on a mixture by mixture basis. TxDOT is allowed 10 working days to provide the contractor with HWT, OT, and IDEAL-CT results on the trial batch.

Table 3. Mixture Design Performance Testing Requirements.

Mixture Type		High-Temperature Asphalt Binder PG	HWT at 50°C		OT$			IDT (dry), psi$
			Passes at 12.5 mm Rut Depth	Rut Depth at 20,000 passes	Number of Cycles	CFE, inch-psi	CPR	
DG HMA (Item 341)	A (Coarse Base), B (Fine Base), C (Coarse Surface), D (Fine Surface), F (Fine Mixture)	PG 64 or lower	≥ 10,000	–	–*	–	–	85–200
		PG 70	≥ 15,000	–	–*	–	–	85–200
		PG 76 or higher	≥ 20,000	–	–*	–	–	85–200
SP Mixtures (Item 344)	SP-B (Intermediate), SP-C (Surface), or SP-D (Fine Mixture)	PG 64 or lower	≥ 10,000	–	–*	–	–	85–200
		PG 70	≥ 15,000	–	–*	–	–	85–200
		PG 76 or higher	≥ 20,000	–	–*	–	–	85–200
PFC (Item 342)	Fine (PFC-F)	PG 76	≥ 10,000	–	≥ 200	–	–	–
	Coarse (PFC-C)	PG 76	Report only	–	Report only	–	–	–
	Fine (PFCR-F)	A-R	Report only	–	Report only	–	–	–
	Coarse (PFCR-C)	A-R	Report only	–	Report only	–	–	–
SMA (Item 346)	SMA	–	–	≤ 12.5 mm	≥ 200	–	–	–
	SMAR	–	–	≤ 12.5 mm	≥ 200	–	–	–
TOM (Item 347)	Coarse (TOM-C) or Fine (TOM-F)	PG 70	≥ 15,000	–	≥ 300	–	–	≤ 200
		PG 76	≥ 20,000	–	≥ 300	–	–	≤ 200
TBFC (Item 348)	Fine (PFC-F)	PG 76	≥ 10,000	–	≥ 200	–	–	–
	Coarse (PFC-C)	PG 76	Report only	–	Report only	–	–	–
	Coarse (PFCR-C)	A-R	Report only	–	Report only	–	–	–
	Thin Bonded Wearing Course (TBWC)	Type A	Report only	–	Report only	–	–	–
		Type B	Report only	–	Report only	–	–	–
		Type C	Report only	–	Report only	–	–	–
CAM (SS 3000)	Fine Mixture	PG 64 or lower	≥ 10,000	–	≥ 750	–	–	85–200
		PG 70	≥ 15,000	–	≥ 750	–	–	85–200
		PG 76 or higher	≥ 20,000	–	≥ 750	–	–	85–200
SP – BMD (SS 3074) #	SP-C (Surface) or SP-D (Fine Mixture)	PG 64 or lower	≥ 10,000	–	–	≥ 1.0	≤ 0.45	85–200
		PG 70	≥ 15,000	–	–	≥ 1.0	≤ 0.45	85–200
		PG 76 or higher	≥ 20,000	–	–	≥ 1.0	≤ 0.45	85–200

–Not applicable.
$CFE= Critical Fracture Energy; CPR=Crack Progression Rate, IDT=Indirect Tensile Strength (Tex-226-F).
*For informational only when requested or shown in the plans during the first week of production.
#When HWT and OT meet the requirements, a correlation is established between OT and IDEAL-CT (Tex-250-F).

In comparison to AASHTO M 323, "Standard Specification for Superpave Volumetric Mix Design" and AASHTO R 35, "Standard Practice for Superpave Volumetric Design for Asphalt Mixtures," the following key modifications are implemented by TxDOT to their volumetric design criteria (table 2 and table 4):

- Specified 50 gyrations for design and acceptance of all asphalt mixtures including the standard and specialty mixtures.
- Specified a minimum or a range of asphalt binder content for specialty asphalt mixtures (i.e., PFC, SMA, TOM, TBFC, and CAM). In order to avoid bleeding of the asphalt mixture, and with the exception of CAM, a draindown requirement was also specified (Tex-235-F).

- For the virgin asphalt binder, the difference in critical temperatures for low temperature testing (ΔTc) based on creep stiffness (Tcont, S) and m-value (Tcont, m), calculated as ΔTc = (Tcont, S) – (Tcont, m), must be greater than or equal to -6.0°C. The critical temperature is defined as the temperature at which the test parameter is equal to the specification limit.
- Increased the voids in mineral aggregate (VMA) requirement by 1–4% for DG HMA, SP Mixtures, SMA, TOM, CAM, and SP – BMD. However, VMA is calculated using the effective specific gravity of the aggregate (Gse).
- Reduced the design VMA by 0.5% for plant-produced asphalt mixtures (in comparison to laboratory-produced asphalt mixtures).
- Excluded the requirement for voids filled with asphalt (VFA) for all asphalt mixtures.
- Excluded the dust-to-asphalt binder ratio requirement; except in the case of CAM and SP – BMD for which the upper limit was increased by 0.2% and 0.4%, respectively. It should be note that the dust-to-asphalt binder ratio is defined as percent passing No. 200 sieve divided by total asphalt binder content.
- Increased the maximum allowable fractured RAP in surface mixtures from 20% (DG HMA and SP) to 35% (SP – BMD).

Table 4. Modifications to AASHTO Standard Volumetric Design Criteria.

Requirements	**Mixture Type**					
	PFC	**SMA**	**TOM**	**TBFC**	**CAM**	**SP – BMD**
Number of Design Gyrations (N_{des})	↓	↓	↓	↓	↓	↓
Density at N_{des}	↓	↔	↑	↓	↑	↔
Density at Maximum Number of Gyrations (N_{max})	–	–	–	–	–	–
Design Asphalt Binder Content	Range	Range	Min	Range	Min	–
Voids in Mineral Aggregate (VMA)*	–	↑	↑	–	↑	↑
Voids Filled with Asphalt (VFA)	–	–	–	–	–	–
Dust-to-asphalt binder ratio	–	–	–	–	↑ UL	↑ UL
Draindown (%)	Min	Min	Min	Min	–	–
HWT Passes at 12.5 mm Rut Depth	Min/R	–	Min	Min/R	Min	Min
HWT Rut Depth at 20,000 Passes	–	Max	–	–	–	–
OT Number of Cycles	Min/R	Min	Min	Min/R	Min	–
OT CFE	–	–	–	–	–	Min
OT CPR	–	–	–	–	–	Max

–Not applicable or not specified; Min=minimum; Max=maximum; R=report only; ↔=no change to requirement; ↓=decreased; ↑=increased; ↑ UL=increased upper limit
*Uses Gse and not Gsb.

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 allowing 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).

SELECTION OF PERFORMANCE TESTS

Table 5 summarizes the performance tests currently used by TxDOT for their BMDs of specialty and SP – BMD mixtures. TxDOT is currently evaluating the feasibility of using the rapid rutting test (RRT), known as ideal shear rutting test (IDEAL-RT), at high temperature to evaluate the rutting performance of asphalt mixtures (ASTM WK71466). The IDEAL-RT is being evaluated for potential use during production as a surrogate test for acceptance.

Table 5. Summary of Performance Tests Considered by TxDOT for BMD.

Elements	Stability/Rutting	Durability/Cracking	Moisture Damage/Stripping
Test Name	Hamburg Wheel test (HWT)	Overlay test (OT) IDEAL Cracking Tolerance test (IDEAL-CT)	Indirect Tensile Strength (IDT)–dry Boil test Hamburg Wheel test (HWT)
Test Method	Tex-242-F	Tex-248-F Tex-250-F	Tex-226-F Tex-530-C Tex-242-F
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 for 2 hours at compaction temperature (Tex-241-F). Plant-produced mixtures: Minimize any cooling of and reheat specimens at the compaction temperature and compact within 2 hours.	Lab-produced mixtures: Short-term conditioning of loose mixture for 2 hours at compaction temperature (Tex-241-F). Plant-produced mixtures: Minimize any cooling of and reheat specimens at the compaction temperature and compact within 2 hours.	
Notes/Comments	TxDOT is investigating the use of ideal shear rutting test (IDEAL-RT) for acceptance. A correlation between the HWT and IDEAL-RT is being investigated.	A correlation on a mixture by mixture basis is established between the OT and the IDEAL-CT for acceptance. TxDOT is looking into extended aging as a side study in the test projects to potentially require an extended aging protocol in the future.	

TxDOT has a long history of using the HWT and OT for evaluating and screening asphalt mixtures with good and poor rutting and cracking resistance, respectively. TxDOT has successfully used the HWT in their mixture design selection for several years, and the test has been included in their standard specifications since 2004. All HWT results are properly stored in a database that is maintained by TxDOT. A similar database exists for OT results of asphalt mixtures from TX. The OT has been implemented in the standard specifications since 2014. Prior to that, the OT was used by TxDOT in SS for specialty asphalt mixtures (e.g., SMA).

The OT was first introduced to control the cracking performance of asphalt mixtures during the design process in the laboratory as TxDOT districts started to use more of their recycled materials into their asphalt mixtures. Asphalt mixtures in TX were designed using the HWT to improve their rutting potential that might have impacted their cracking resistance and flexibility. The TxDOT's adaption of higher high-temperature asphalt binder PG and the HWT raised concerns that asphalt mixtures are drier and more susceptible to premature cracking.

The variability of the number of cycles to failure that is used as the OT performance index was a main concern for TxDOT in using the test for mixture design verification and acceptance. Thus, in 2014 TxDOT initiated a study to investigate an alternative cracking methodology and improved testing specifications for the OT with less technical complications and uncertainties in the results. The study developed two new performance indices, the critical fracture energy (CFE) and the crack progression rate (CPR). The repeatability of the CFE and CPR were found to be better than the acceptable repeatability level defined as a coefficient of variation (COV) of less than 20%. The new cracking methodology and performance indices (i.e., CFE and CPR) were later implemented in the SS 3074.

The top three factors for TxDOT in selecting a performance test are: sample preparation, specimen conditioning and testing time, and repeatability. 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 TxDOT in the development of test criteria and the implementation of performance tests into the specifications. This is tied to the ability of testing aged specimens that are representative of a future critical pavement condition for cracking while keeping in mind the need for a quick turnaround time for test results. 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.

Other important factors for TxDOT 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 TxDOT's motivations for implementation of performance tests. In the selection process, consideration was also given to the capability of the performance test to provide consistent results that follow common sense trends and rankings of the tested asphalt mixtures (based on historical field performance of asphalt mixtures). The test results of local asphalt mixtures should not contradict known and observed field pavement performance.

TxDOT recognizes that simple performance tests for acceptance (surrogates) may require correlation/calibration with more fundamental/truth tests depending on observed distresses; for instance, the IDEAL-CT is correlated to the OT in the case of cracking and the IDEAL-RT is correlated to the HWT in the case of rutting. Nonetheless, TxDOT recognizes that such correlations will likely to be project specific and on a mixture by mixture basis.

The TxDOT Materials and Tests Division (MTD) central laboratory in Austin owns one Asphalt Mixture Performance Testers (AMPT). The AMPT has been primarily used to conduct dynamic modulus and flow number (AASHTO T 378) tests on asphalt mixtures from around the state for pavement design purposes (AASHTOWare® Pavement ME).

PERFORMANCE TESTS DEVELOPMENT TO IMPLEMENTATION

The following section summarizes TxDOT'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 TX test procedures available supported efficient implementation of performance tests for asphalt mixtures. TxDOT has used its own test method for HWT (Tex-242-F) since the early 2000s, before the AASHTO T 324 test method was available, and the OT (Tex-248-F) since 2007. In the Tex-242-F, the density of test specimens must be 93±1%, except for PFC mixtures (test specimens molded to 50 gyrations) and CAM mixtures (test specimens molded to 95±1%).

The ASTM test method for the IDEAL-CT (ASTM D8225) originated form the Tex-250-F test procedure. Work is currently undergoing to develop a standard procedure for IDEAL-RT. A test method has been drafted as an ASTM Standard and is under considerations for adoption (ASTM WK71466).

TxDOT constantly revises and updates the test methods as deemed necessary based on new findings and through continuous communication and coordination with researchers, industry, vendors, etc. In the case of the OT, TxDOT invested in and supported the development of the OT equipment. In 2005, and as result of the TxDOT Project 0-4467, new OT equipment was manufactured and delivered to TxDOT's MTD at the Cedar Park office in Austin, Texas. The new upgraded equipment was made practical for incorporation into asphalt mixture designs to complement the HWT.

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), volumetric parameters (e.g., air voids, VMA), and aging is an important factor for TxDOT. Contractors need to be able to make informed decisions on what changes can be made to the asphalt mixture composition and proportions in order to improve performance and meet applicable specification limits. TxDOT funded several research studies to evaluate the sensitivity of performance tests to material properties using asphalt mixtures typically used in Texas. This allowed TxDOT to build a large database of performance test results over the years, including the more than 200 aggregate sources throughout the state that can be used in asphalt mixtures. The database has been used to establish initial performance test criteria and continues to be used to refine and revise the performance test methods and their associated criteria. As an example, the following summarizes the findings from four select studies that evaluated the sensitivity of the performance tests to asphalt mixture design variables.

In 2005, TxDOT Project 0-4467 completed a study that evaluated the influence of modified asphalt binder (9 different asphalt binders) and aggregate (three different limestone aggregates) on reflection cracking resistance using the OT. It was found that aggregate absorption has a substantial impact on the reflection cracking resistance of asphalt mixtures as demonstrated with the measured OT number of cycles to failure.

In 2007, TxDOT Project 0-1707 evaluated the influence of aggregate type (e.g., gravel, igneous, limestone-dolomite), asphalt binder grade (e.g., PG 70-22, PG 76-22), asphalt mixture type, and additive (hydrated lime and liquid anti-strip) on HWT results. The HWT parameters investigated included rutting, slope of the rutting curve, and the area beneath the rutting curve at specific cycles. Based on the results of the analysis, the additive type and PG of the asphalt binder were the two factors that mainly influenced the performance of the asphalt mixtures in the HWT. This study also suggested that the influence of aggregate type on HWT results can be related to the interaction between the aggregate and the asphalt binder in the mixture.

In 2020, TxDOT Project 0-6923 evaluated the influence of asphalt binder type and source, and recycled material type and content on the HWT, OT, and IDEAL-CT results. The following summarizes the findings from this study:

- The mechanical properties of asphalt mixtures were found to be very sensitive to the source of the asphalt binder, especially for modified asphalt binders. Asphalt mixtures using asphalt binders with the same PG can have considerable variation in their mechanical properties.
- Changing the PG of the asphalt binder mainly influenced the stiffness and stability of an asphalt mixture. Thus, modifying the PG of the asphalt binder during the mixture design process can help asphalt mixtures with poor rutting performance.
- The inclusion of recycled materials, either RAP or RAS, must be limited to avoid crack-susceptible asphalt mixtures. The OBC of an asphalt mixture containing high contents of recycled material must be adjusted to minimize cracking.

As part of TxDOT Project 0-6815 to improve the OT analysis methodology for cracking resistance of asphalt mixtures, the impacts of aggregate type and gradation, asphalt binder source and PG, asphalt binder content, recycled material content, and additives on the OT parameters (CFE and CPR) were evaluated. The following summarizes the findings from this study:

- SP mixtures exhibited better cracking performance than DG HMA mixtures based on the CPR parameter. A definite trend was not observed for the CFE values between the comparable SP and DG HMA mixtures.
- The PG of the asphalt binders influenced significantly the CFE parameter but did not impact noticeably the CPR parameter.
- The CFE parameter did not show a definite trend when altering the aggregate gradation, but the CPR parameter changed systematically with the aggregate gradation. The CPR value increased as the aggregate gradation became finer (may be attributed to the

reduction in the asphalt binder content due to the incorporation of finer aggregates into the asphalt mixture).

- Regardless of the aggregate gradation, the asphalt binder content significantly influenced the CPR parameter from the OT (an increase in asphalt binder content resulted in a decrease in CPR). A definite trend was not observed for the CFE parameter.
- The source of an asphalt binder influenced both CFE and CPR parameters.
- The asphalt binder source influenced the CFE parameter of TOM mixtures significantly and the CPR parameter marginally.

The sensitivity of performance tests to material properties will continue to be evaluated with the asphalt mixtures sampled from the 2019–2021 test projects and other future projects. TxDOT will continue to populate performance test results into its database, which will help in refining specifications and guidelines to design asphalt mixtures with satisfactory cracking resistance. The buildup of the database with the new OT parameters/ performance indices (i.e., CFE and CPR) is being conducted while maintaining a continuous communication and discussion with the industry.

Step 3. Preliminary field performance relationship.

TxDOT development of the initial performance test criteria is based on historical database of HWT and OT results for an array of asphalt mixture types from various geographical regions of the state. Over the years, TxDOT supported and funded several research projects that analyzed and evaluated the HWT and OT results in relation to field pavement performance. The asphalt mixture database of performance test results for plant-produced asphalt mixtures has been used to improve the test analysis methodologies and to update test criteria. Having a large database of test results for typical asphalt mixtures from TX along with their respective history of field pavement performance were key for TxDOT's implementation efforts of BMD. The following describes a few selected studies that were supported by TxDOT throughout the years.

In the late 1990s, TxDOT evaluated the HWT very extensively by investigating the effect of temperature and different antistripping agents on the results. The tests were conducted on asphalt mixtures with aggregate from various sources throughout the state. The overall goal was to establish a reliable test method for TxDOT.

In 2001, TxDOT initiated a 5-year study to determine a correlation between field pavement performance and HWT results (TxDOT Project 0-4185). Different asphalt mixture types and aggregate sources were used in the study. Test sections were constructed to observe the performance of the asphalt mixture overlays under actual traffic and climatic conditions. Field pavement performance was monitored through visual pavement condition surveys and nondestructive tests for 4 years. Similar types of deformation patterns were assumed for both the laboratory specimens and field test sections (no stripping problems were observed in the field and laboratory specimens). At the end of this study, the HWT results of the evaluated asphalt mixtures were correlated to their field pavement performance (an average ratio of 37 was found between the HWT wheel pass and the equivalent single axle loads).

In a recent study (TxDOT Project 5-6815), a database that contained more than 1,000 OT results collected over an 8-year period for 8 different asphalt mixtures typically used by TxDOT was examined and evaluated (table 6). The median, average, standard deviation, and COV for the CFE and CPR were computed from the three OT results for each asphalt mixture. The COVs for the OT number of cycles to failure were also calculated and documented for comparison purposes.

Table 6. Summary of TxDOT Database for OT.

Asphalt Mixture Type	Number of Mixture Designs	Sample Size*
TOM	107	285
CAM	27	79
SMA-C	11	32
SMA-D	62	174
SP-C	63	177
SP-D	34	97
DG-C	31	88
DG-D	45	133
Total	*380*	*1,065*

*Triplicate specimens were tested for each mixture design with some exceptions when the data files were not saved properly.

Garcia et al. (2017) initially proposed a CPR of 0.5 or less to discriminate between a good and poor performing asphalt mixture. This threshold value corresponded to 300 cycles in OT to reach the 93% load reduction criterion. A CFE limit of minimum 1.0 inch–psi was also proposed. The initial performance test criteria were re-evaluated using the OT results for the asphalt mixtures shown in table 6.

The cumulative frequency distributions for the CFE and CPR parameters were compared with the preliminary established acceptance limits. The percentage of the asphalt mixtures in the database that met the preliminary acceptance limits varied between 85–100% for CFE and 30–95% for CPR. Most asphalt mixtures met the preliminary minimum specified CFE of 1.0 inch–psi (at the most, 15% of the SMA-D asphalt mixtures did not meet the proposed CFE limit). This high rate of passing was attributed to the fact that all asphalt mixtures must exhibit a minimum indirect tensile strength of 85 psi that corresponded to a CFE value greater than 1 inch–psi. On the other hand, most OT results for CAM, TOM, SMA-C and SMA-D met the preliminary acceptance limit of 0.5 for the CPR. In the contrary, the typical SP and DG HMA mixtures showed percent passing rates ranging between 60 and 30%.

It should be noted that the preliminary acceptance limits for CFE and CPR were uniformly applied for all asphalt mixture types. However, different asphalt mixtures are used for different applications. Thus, it was decided that acceptance criteria should be established based on the function and role of each asphalt mixture type (i.e., tied to the critical strains and stresses that each layer is expected to experience during pavement design). Specification limits were selected based on a passing rate of 80% (table 7), thus assuming in general that 80% of current asphalt mixture designs from TxDOT have exhibited acceptable pavement performance. The following justifies the selection of the new specification limits for the various asphalt mixture types in comparison to the preliminary established values of CFE ≥ 1.0 inch–psi and CPR ≤ 0.50:

- Since TOM and CAM mixtures are typically used to minimize cracking, the minimum CFE specification limit can be increased to 1.5 inch–psi and 2.0 inch–psi, respectively, to ensure high crack initiation resistance. The maximum CPR specification limit can be decreased to 0.40 to ensure satisfactory attenuation of crack propagation.
- Since SMA mixtures are intended to maximize the rutting resistance, the minimum CFE specification limit of 1.0 inch–psi can be maintained. A maximum CPR specification limit of 0.45 can be used to retard crack propagation with the higher asphalt binder content.
- DG HMA and SP mixtures can be used in a variety of applications, pavement layers, and traffic conditions. The CFE and CPR specification limits can be maintained as 1.0 inch–psi and 0.50 for intermediate and base asphalt mixture layers. Surface mixtures should still meet a minimum CFE limit of 1.0 inch–psi but should also meet a minimum CPR limit of 0.45.

The newly established CFE and CPR limits for SP surface mixtures have been implemented in the SS 3074. The established limits for the remaining asphalt mixtures have been incorporated into revised specifications and are currently being reviewed and commented by industry.

Table 7. Summary of Acceptance Limits Based on 80% Passing Rate for OT Results.

Asphalt Mixture Type	CFE, inch–psi		CPR	
	Median (Database)	Minimum Limit at 80% Passing Rate	Median (Database)	Maximum Limit at 80% Passing Rate
TOM	2.3	2.0	0.29	0.40
CAM	2.0	1.5	0.31	0.40
SMA-C	1.6	1.2	0.39	0.45
SMA-D	1.5	1.0	0.36	0.45
SP-C	1.9	1.5	0.46	0.45*
SP-D	2.0	1.5	0.63	0.45*
DG-C	1.3	1.0	0.59	0.45*
DG-D	1.7	1.5	0.57	0.45*

*The maximum CPR limit should be 0.50 to minimize crack susceptible mixtures on base layers.

Step 4. Ruggedness experiment.

TxDOT did not conduct or participate in any formal ruggedness testing yet. Some ruggedness studies have been completed by Texas university researchers for select performance tests. In particular, researchers from TTI are leading NCHRP project 09-57A Ruggedness of Laboratory Tests to Assess Cracking Resistance of Asphalt Mixtures (https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4471). The ruggedness testing for the OT and IDEAL-CT have been completed and the recommendations will be shared with TxDOT for consideration. The following seven factors were considered for each test in the ruggedness experiments:

- OT: specimen height, specimen width, air voids, crack opening displacement, loading period (frequency), block weight, and test temperature.
- IDEAL-CT: specimen thickness, specimen center location, air voids, loading rate, contact load, test temperature, and conditioning method.

While four factors were identified significant for the OT (specimen height, air voids, crack opening displacement, and test temperature), only one factor was identified significant for IDEAL-CT (air voids). Recommended tolerances were provided for all seven factors for each of the OT and IDEAL-CT.

Step 5. Commercial equipment specification and pooled fund purchasing.

TxDOT MTD central laboratory is very well equipped to run and analyze all performance tests implemented or being evaluated for the BMD approach. This includes all necessary equipment for sample preparation, fabrication, and conditioning of asphalt mixture specimens. TxDOT MTD laboratories currently have 5 HWT devices, 4 OT devices, and 1 IDEAL-CT test device. TxDOT is currently in the process of acquiring a sixth HWT device. The HWT devices are from two different manufacturers. Eight out of the 25 TxDOT district laboratories each own an HWT device. While none of the district laboratories have an OT device, at least two districts have a plan to acquire an OT device. Some districts have converted/upgraded their existing press machines to be able to run IDEAL-CT. Contractors also started to invest in and acquire IDEAL-CT devices. In general, funding and space resources for acquiring and installing new equipment in laboratories have not been a major issue for TxDOT.

The current TxDOT technician manpower and equipment capabilities have been acceptable. Maintaining an active MPL for laboratories approved to perform HWT (Tex-242-F) helped TxDOT in maintaining an acceptable workload level (http://ftp.dot.state.tx.us/pub/txdot-info/cmd/mpl/hamburgs.pdf). The current MPL includes ~40 laboratories from consultants and contractors.

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.

TxDOT maintains an up-to-date MPL for all laboratories approved to perform HWT (Tex-242-F). The approval process requires an initial split sample testing with the MTD central laboratory. Laboratories must also participate in the Annual State-wide Hamburg Wheel Tracking Test proficiency program. There is a plan for TxDOT to create a similar MPL for all laboratories approved to perform OT (Tex-248-F).

Historically, a COV of ~30% has been observed with the HWT number of passes. Throughout the years, research studies were undertaken to study and improve the variability of the HWT. In the late 1990s, TxDOT evaluated the repeatability of the HWT and other similar devices among seven agencies (TxDOT, Utah DOT, Colorado DOT, FHWA, Koch Materials, Superfos Construction, and University of Arkansas).

The COV for the OT number of cycles to failure has been as high as ~40%. The refinement of the sample preparation procedure along with the implementation of a new OT cracking analysis methodology to calculate CFE and CPR resulted in a significant reduction in the variability of the test results (TxDOT Project 0-6815). Based on more than 1,000 OT test results from more than 380 different asphalt mixture designs and 8 mixture types, the COV of the CFE and CPR ranged between 5–15%.

Under the current IAC, a round-robin study is planned among CTIS, CTR, TTI, and other laboratories to establish test results variability within each laboratory and between laboratories for the HWT, OT, and IDEAL-CT. The samples required for each test are to be prepared by CTIS to maximize the consistency among samples. The following summarizes the round robin experiment:

- At least three typical asphalt mixture designs are to be used.
- A minimum of 5 samples for each the OT and IDEAL-CT will be tested by each participating laboratory.
- A minimum of 10 samples for the HWT will be tested by each participating laboratory.
- A minimum of 10 laboratories will be participating in the between laboratory variability assessment for HWT and OT.
- A minimum of 5 laboratories will be participating in the between laboratory variability assessment for IDEAL-CT.

As a result, a precision and bias statement will be developed for each of the HWT, OT, and IDEAL-CT. The results from the round robin will also be combined with the data collected from the 2019–2021 test projects to conduct the correlation analyses for the performance indices from the selected test methods.

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

TxDOT continues to validate the HWT and OT criteria by sampling and testing of asphalt mixtures, monitoring field pavement performance, and comparing the results.

TxDOT Project 0-6132 (2008–2012) evaluated the BMD approach in an Accelerated Pavement Testing (APT) study conducted in cooperation with the Louisiana Transportation Research Center (LTRC) at their Accelerated Load Facility (ALF) in Baton Rouge. Performance data from this study confirmed the laboratory HWT relationship to field rutting and the OT relationship to reflection cracking.

TxDOT Project 0-6815 (2017–2020) compared the cracking performance of field pavement sections to their predicted performance from OT. The OT reasonably predicted the cracking performance of asphalt mixtures placed on different pavement test sections. The comparison between laboratory-produced asphalt mixtures and field cores from 17 field pavement sections revealed that asphalt mixtures that initially exhibited poor performance in the OT yielded worse OT results from the field cores extracted after around 4 years. The pavement sections were subjected to different truck volumes and included different types of asphalt mixtures (e.g., SMA-D, TOM), asphalt binder PG, and RAP content (0–23%). The cracking resistance of 10 asphalt mixtures used to build ten lanes at the FHWA ALF was also evaluated with the OT. A strong correlation was found between the OT results and the pavement performance data from the accelerated testing.

In 2018, TxDOT sponsored two sections on the National Center for Asphalt Technology (NCAT) Test Track to compare the field performance of asphalt mixtures designed using SS 3074 to the Superpave volumetric approach under accelerated loading conditions (sections are loaded for 2 years). The NCAT Test Track results provided TxDOT with an additional robust validation of their BMD approach, thus providing TxDOT with initial confidence to move forward with low risk field projects.

Further validation and refinements to the performance test criteria are anticipated with the 12 test projects that are being placed between 2019 and 2021 around the state (estimated to have 35 to 45 test sections). The robust effort is anticipated to result in a revised specification and related test methods for design and quality assurance, and performance thresholds to provide a practical method to engineer each unique material combination.

Step 8. Training and certification.

Training technicians on the procedures and analysis of test results is necessary. TxDOT requires all technicians to be certified through the Hot Mix Asphalt Center (HMAC). The purpose of the certification program is to develop and maintain a pool of well-trained asphalt specialists for the state and contractors to design, test, and manage asphalt pavements.

The HMAC is managed and operated by the Texas Asphalt Pavement Association (TXAPA). A joint TxDOT and TXAPA Steering Committee carries out oversight of the operation to ensure the integrity of the program meets the high standards originally stipulated.

The HMAC provides four levels of certification in testing and evaluating asphalt mixtures and aggregates. These levels include field laboratory testing (Level 1A), roadway testing (Level 1B), quality management and mixture design (Level 2), and aggregates specialist (AGG101). The original certification is valid for three years. At the end of the three-year period, specialists are required to complete re-certification courses. The four certification levels are briefly described below (https://www.txhmac.org/certifications/):

- Level 1A is a one-day certification course that certifies an individual’s ability to test asphalt mixture produced at the plant in accordance with TxDOT Test Procedures and Specifications. Individuals must pass both a written and a practical examination.
- Level 1B is a one-day certification course that certifies an individual’s ability to properly monitor and conduct quality control/quality assurance testing for the placement of asphaltic mixes on the roadway in accordance with TxDOT Test Procedures and Specifications. Individuals must pass both a written and a practical examination.
- Level 2 Mix Design Specialist certification is a three-day certification course that certifies an individual’s ability to properly design and mix asphalt mixtures. This course takes an individual through the processes needed to sample and test the individual components of materials that go into an asphalt mixture design, blend the design in a laboratory, then test the completed design in accordance with TxDOT test procedures to assure the design meets the required specifications.
- AGG101 is a one-day certification course that certifies an individual’s ability to sample and test aggregates according to TxDOT Test Procedures and Specifications. Individuals

must pass both a written and a practical examination. This certification level is a pre-requisite for Level 2.

The Tex-242-F Hamburg Wheel-Tracking Test is covered under the Level 1A certification, which is a pre-requisite for Level 2 certification (current Level 1A and AGG101 certifications are required for Level 2). Several training videos are provided by HMAC including two of them that are specifically made for Tex-242-F (https://vimeopro.com/user33086364/test-procedure-videos).

Currently none of the other performance tests (i.e., OT, IDEAL-CT, and IDEAL-RT) are included in the HMAC certification program. TxDOT envisions that these performance tests will be part of the certification program. In the interim, TxDOT will continue to support and require the on-going in-house certification program on performance testing for state technicians.

TxDOT plans on having training activities related to BMD, including workshops for laboratory testing and asphalt mixture design and adjustments.

Step 9. Implementation into engineering practice.

TxDOT has been investing significantly in research over the years to support the implementation of performance tests and BMD for design and acceptance. TxDOT originally introduced the HWT into routine asphalt mixture designs in order to minimize the risk of designing mixtures that are prone to rutting and stripping. This adoption of the HWT has prompted contractors to use stiffer asphalt binder grades. The increase use of recycled materials raised additional concerns with the typical asphalt mixtures being drier and more prone to premature cracking. Thus, alternative asphalt mixture design approaches to optimize field pavement performance with respect to rutting and cracking were investigated. This led to the development of the BMD approach for selecting the OBC for all of TxDOT's asphalt mixtures based on the HWT and OT results. The following summarizes some of the major steps that were undertaken to implement BMD into engineering practice. These steps were undertaken, among other studies, as part of TxDOT Project No. 0-5123 (2004–2008), 0-6132 (2008–2012), 0-6679 (2011–2013), and 0-6923 (2016–2020).

- Researchers promoted the development and implementation of the BMD approach for selecting the OBC using HWT and OT for all of TxDOT's asphalt mixtures, including Item 341. This included the demonstration of the BMD approach concept and efforts to upgrade the OT equipment.
- Researchers used the BMD approach with asphalt mixtures from seven different Districts.
- Several full scale 1,000 ft long test sections were constructed around Texas.
- The BMD approach was also evaluated in an APT study.
- Researchers proposed the use of the OT in the newly updated TxDOT SMA specifications (Item 346), and for the new fine PFC (Item 342), and recommended to continue to be required with CAM (SS 3191) and TOM mixtures (SS 3239).
- Researchers proposed an approach to implement the BMD within Item 341, which represents the bulk of TxDOT's asphalt mixtures.

- Researchers developed a draft specification for Item 341 and made recommendations for an implementation project and that the BMD be incorporated into upcoming Item 341 projects.
- Rigorous experimental plans were carried out to investigate the main steps of the BMD process including mixture design approach, optimization of aggregate gradation, formulation of BMD mixtures, and influence of essential asphalt mixture design variables.
- Laboratory and field performance of historical and in-service pavement sections constructed with and without RAP, RAS, and additives were gathered.
- The OT (Tex-248-F), HWT (Tex-242-F), and IDT (Tex-226-F) were implemented to assess the cracking, rutting, and strength of the asphalt mixtures, respectively.
- Correlations were established between HWT and OT performance indicators and performance of pavement sections.
- The role of aggregate gradation and the influences of other variables such as asphalt binder content, asphalt binder PG and source, and the type and percent of recycled materials on the performance of BMD asphalt mixtures were investigated.
- The knowledge and experience gained from research was used to convert four traditional asphalt mixtures to BMD using locally available pavement materials.
- A new TxDOT special specification (SS 3074) was developed and proposed to produce BMD asphalt mixtures.

TxDOT has implemented SS 3074 for Superpave Mixtures – Balanced Mix Design that allows for 30% of maximum ratio of recycled asphalt binder to total binder. Most of the current effort has focused on applying performance testing to the design and acceptance of SP surface mixtures. Monotonic load-based tests including IDEAL-CT and IDEAL-RT are being evaluated for possible use as surrogate performance tests during production after being correlated to OT and HWT, respectively. The following section summarizes the major on-going efforts for full implementation of performance tests and BMD approach for surface mixtures.

IMPLEMENTATION OF PERFORMANCE TESTS ON PROJECTS

TxDOT has been leading and investing significantly in the process to develop and implement a BMD for its standard asphalt mixtures. This stems from TxDOT's successful experience with specialty asphalt mixtures and the immediate need to address premature failure of asphalt mixtures with RAP. In a major undertaking, TxDOT funded in 2019 an IAC with multiple TX universities to implement the concept of BMD for Superpave asphalt mixtures with RAP. This is a large coordinated effort between TxDOT (including districts), contractors (TXAPA is engaged in this effort), additives manufacturers and suppliers, and academia.

Several test projects will be selected from participating TxDOT districts to validate the testing requirements and design specifications for BMD. The test projects are anticipated to spread throughout the entire state. Each test project site comprises multiple test sections including a control test section. The test sections will be comprehensively investigated and monitored. Two test projects have been constructed thus far and four new test projects are scheduled to be constructed in July–September 2020. The remaining test projects are planned for summer of 2021. The factors that are being considered in the various test projects are: RAP, RAS, soft virgin asphalt binder, rejuvenator, warm mix asphalt produced at low temperature, N_{design}, gradation, and aggregate quality. It should be noted that some test sections will include RAP at different ratios of recycled asphalt binder to total binder.

The overall process for selecting and completing test projects involves significant and continuous coordination efforts among the various stakeholders. First an invitation email is sent out to all TxDOT districts exploring their interest in participating in the test projects. For interested districts, follow-up conversations are undertaken to go over the project goals, benefits, and expectations. Next district interest in the type of asphalt mixtures is identified and candidate test projects are solicited. Discussions are also carried out with involved contractors on the asphalt mixture design requirements and the potential changes to accommodate the increased use of RAP while considering their specific challenges and issues. Once the test project is selected and confirmed, additional coordination meetings are held between TxDOT district and MTD personnel, contractor, additives suppliers, and at least one representative from the universities' team to discuss the overall progress and planning activities including specifications, mixture designs, test sections layout, pre-construction evaluation, construction schedule, sampling plan, etc. This may take up to seven 20–30 minutes coordination meetings.

CTIS, CTR, and TTI will provide support to TxDOT and contractors in all three phases of pre-construction, asphalt mixture design and placement, and post-construction. This includes visual distress survey and layout of test sections, asphalt binder and blend characterization, asphalt mixture design support, trial batch validation, asphalt mixture design performance correlations, asphalt mixture design verification, production sample testing, and post-construction field core samples testing.

According to the current SS 3074 for Superpave Mixtures – Balanced Mix Design, performance testing during production is to be conducted at the frequencies shown in table 8. All performance testing is to be performed by TxDOT MTD or a designated laboratory from the MPL.

Table 8. Minimum Production Testing Frequency.

Entity	Gradation	Volumetrics[2] and In-place Air voids	Asphalt Binder Content	HWT	OT	IDEAL-CT Test
Contractor	1 per sublot	–	1 per sublot	–	–	–
TxDOT	1 per 12 sublots[1]	1 per sublot[1]	1 per lot[1]	1 per project[3]	1 per project[3]	1 per project[3]

–Not applicable.
[1]1 per day if 100 tons or more are produced. No testing is required when less than 100 tons are produced.
[2]Laboratory-molded density and bulk specific gravity, VMA, and theoretical maximum specific gravity.
[3]Testing performed by MTD or designated laboratory.

TxDOT may perform an HWT or OT at any time during production. In case of failing results, production is suspended until further HWT or OT production samples meet the specified values in table 3. In addition to testing production samples, TxDOT may obtain cores and perform HWT on any areas of the roadway where rutting is observed. Production is also suspended until further HWT meet the specified values when the core samples fail the HWT criteria in table 3.

TxDOT may require up to the entire sublot of any mixture failing the HWT to be removed and replaced at the contractor's expense.

If TxDOT's HWT results in a remove and replace condition, the contractor may request that TxDOT confirm the results by re-testing the failing material. The MTD will perform the HWT or OT and determine the final disposition of the material in question based on the test results.

The IDEAL-CT correlation with OT that was developed during the project trial batch will be used to monitor cracking performance during production. If at any time the minimum correlation limit is not met, the OT is then used to determine the compliance of the produced asphalt mixture with the performance specifications shown in table 3.

Recently, TxDOT implemented a barcode system to track and monitor asphalt binder sampling, shipping, and delivery to the MTD laboratory during construction. The implementation of a similar system for tracking asphalt mixtures would allow TxDOT to effectively plan, conduct, and report performance test results to the contactor within the allowable 10 working days in accordance with specifications.

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. Based on a contractor experience with test projects thus far, the following observations were made:

- Changes to asphalt mixtures to get acceptable performance testing values were material specific. In particular, the performance test results were found to be sensitive to the aggregate type and properties (e.g., specific gravities, absorptions, particle shapes). This required adjustments to bin percentages or the use of different aggregate sources. Aggregate suppliers' may be required to re-evaluate and adjust their aggregate production process.
- Aggregate breakdown in the plant-produced asphalt mixture can occur (depending on the aggregate source,) as demonstrated with an increase in the percent passing the No. 8 sieve. Adjustments in the aggregate bin percentages within the allowable production tolerances are needed to match the laboratory-produced asphalt mixture design.
- An increase in asphalt binder content by 0.7–0.8% was observed in order to meet the OT criteria. Meeting the HWT requirement was not an issue.
- The OT results were sensitive to conditioning and reheating of asphalt mixtures, thus resulting in out-of-specification acceptance test results. A standard protocol for conditioning and testing plant-produced asphalt mixtures is needed.
- The BMD allowed the use of up to 35% fractionated RAP when only up to 20% fractionated RAP was allowed in standard surface mixtures.
- A proper RAP stockpile management plan and process control are important for maximizing the use of RAP in an asphalt mixture. Fractionated RAP created flexibility in adjusting the composition of the RAP for the asphalt mixture design and minimized the variability of the RAP material.
- Plant trial batching was a critical and important step of the process in order to make sure that the asphalt mixture will be in compliance during production. Plant-produced asphalt

mixtures typically exhibited different performance test results than laboratory-produced asphalt mixtures during design.

- The help and support of the TxDOT MTD personnel with performance tests (training on equipment and test result calculations) was essential, especially at the beginning, in order to make sure that tests are being properly conducted in the contractor laboratory.
- No issues or challenges in meeting in-place density requirements were observed or encountered.

OVERALL BENEFITS

The use of BMD on test field projects allowed contractors to utilize innovative and recycled materials (e.g., RAP, warm mix additives, rejuvenators) in order to produce asphalt mixtures that are in compliance with TxDOT specifications. Furthermore, the traditional volumetric-based mixture design did not provide optimum performance for asphalt mixtures with higher RAP content. Performance testing helped in designing asphalt mixtures with higher RAP contents; 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, mainly due to the increase in the asphalt binder content. TxDOT Project 0-6132 determined that using the BMD approach in one of the districts resulted in a savings of over $5 per ton of asphalt mixture by moving to a less expensive asphalt binder while improving the mixture's overall engineering properties. No problems were encountered with constructing any of the sections with excellent field performance reported at the time of the study.

TxDOT had about 16 million tons of asphalt mixture placed in last fiscal year. Thus, if every ton of asphalt mixture produced contained 15 to 20% RAP, TxDOT would have consumed 2.4 to 3.2 million tons of RAP. For a $5 per ton saving for using 15 to 20 percent RAP, the total annual savings for TxDOT would be about $80 million. Accordingly, TxDOT believes that the implementation of BMD should result in cost savings by providing contractors with more flexibility during the asphalt mixture design and allowing more opportunities to use recycled materials without jeopardizing asphalt pavement performance.

FUTURE DIRECTION

TxDOT has been successfully using the BMD approach for specialty asphalt mixtures, and envisions using it on all of its standard asphalt mixtures using a stepwise approach (phased-in implementation). The BMD is primarily founded on the HWT and OT, with which TxDOT has had a long history of use. The implementation of the BMD for acceptance required the use of surrogate tests that are simple and quick to run. This necessitated the development of a correlation between the surrogate tests (i.e., IDEAL-CT and IDEAL-RT) and what is considered to be the truth tests (i.e., OT and HWT). 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:

- Continue the effort with the test 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 BMD approach and the established performance test criteria.
- Verify and validate the correlation between the OT and IDEAL-CT. Establish a similar correlation between the HWT and IDEAL-RT.
- Optimize the laboratory aging conditions for asphalt mixtures to better simulate field behavior. The aging methods are anticipated to be used when the rutting and cracking resistance of asphalt mixtures are being evaluated as a part of the BMD process.
- Establish necessary precision and bias statements for utilized performance tests.
- Document the cost-benefit of the BMD specifications in comparison with other mixture design specifications such as SP mixtures, DG HMA, and SMA 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 TxDOT that can help facilitate the implementation of a performance test into practice. Positive practices are those successful efforts that were used by TxDOT that could also be considered by other SHAs. Lessons learned are those efforts that, if TxDOT had it to do over again, they would definitely reconsider. Challenges are those efforts that TxDOT is still in the process of addressing.

Positive Practices

- The motivations for implementation of BMD in Texas were primarily two-fold: 1) there was an immediate need to address the observed premature failures of asphalt pavements as a result of the use of recycled materials in asphalt mixtures; and 2) there was a desire to use higher quantities of RAP that allowed for economical and environmental-friendly asphalt mixtures.
- Partnering with and collaboration between TxDOT, industry, and academia is integral 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 is a strong commitment, support, and contribution to the development effort of BMD.
    - Externally, having strong and established relationships with academia (i.e., CTIS, CTR, and TTI) have been instrumental for carrying the various steps involved in the development of BMD. Having an established program through the state to support critical and pressing research was key in the development and implementation of performance tests and BMD.

- Externally, having industry partners that are volunteering for test projects is accelerating 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.

- TxDOT started using performance tests with their specialty asphalt mixtures, which now accounts for approximately 20% of their total asphalt mixtures. Successes in this area allowed the consideration of performance testing and BMD to evolve into the Superpave surface mixtures.
- TxDOT has been going through a rigorous process for implementing BMD into engineering practice including: initial development and continuous improvement of performance tests; field pavement test sections and APT studies; development and revision of specifications; investigation of the main steps of an BMD process including mixture design approach, optimization of aggregate gradation, formulation of BMD mixtures, and influence of essential asphalt mixture design variables; establishing correlations between performance tests indicators and field pavement performance; development of new special specifications to produce BMD for asphalt mixtures; and statewide test projects to validate and update the specifications.
- Having test procedures available supported efficient implementation of performance tests for asphalt mixtures (Step 1).
    - Continuously improving and updating test procedures and analysis methodologies improves test repeatability.
    - Maintaining consistency throughout the various documents makes it easier for users to compare and contrast different standard specifications.
    - Supporting the research effort to upgrade the OT equipment to be practical made it possible for incorporation into asphalt mixture designs to complement the HWT.
- TxDOT funded several research studies to evaluate the sensitivity of performance tests to material properties using asphalt mixtures typically used in Texas (Step 2). This allowed TxDOT to build a large database of performance test results over the years.
    - Establishing a database of test results helps in understanding the performance of typical asphalt mixtures and in establishing initial performance test criteria.
    - Having a good practice for managing the database including proper storage of raw test results allowed for refinements and improvements to be made for performance tests.
- The top factors in selecting HWT, OT, and IDEAL-CT were (Steps 3 and 7):
    - TxDOT has a long history of using the HWT (+15 years) and OT (+6 years) for evaluating and screening asphalt mixtures with good and poor rutting and cracking resistance potential, respectively. This long record of test results allowed TxDOT to tie asphalt mixture properties to their related field performance from actual TxDOT projects, the NCAT test track, and ALF experiments.
    - The OT was first introduced to control the cracking performance of asphalt mixtures as TxDOT districts started to use more of their recycled materials into their asphalt mixtures.
    - The time needed for sample preparation, specimen conditioning, and testing, as well as test repeatability, were key considerations in the development and implementation of test criteria into the specifications.

    - The tests should have acceptable repeatability (within laboratories) and reproducibility (between laboratories) of test results.
    - The ability of testing aged specimens that are representative of a future critical pavement condition for cracking with a quick turnaround time for test results is also considered.
    - Capability of a performance test to provide consistent results that follow common sense trends and rankings of the tested asphalt mixtures is important. 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.
    - Specification limits were selected based on a passing rate of 80%, thus assuming in general that 80% of current asphalt mixture designs from TxDOT have exhibited acceptable pavement performance.
    - The NCAT Test Track results provided TxDOT with an additional robust validation of their BMD approach. It provided TxDOT with initial confidence to move forward with low risk field projects.
- TxDOT is funding a round robin for HWT, OT, and IDEAL-CT to determine the single and multiple operator variability (Step 6).
    - TxDOT maintains an updated MPL for all laboratories approved to perform HWT (Tex-242-F). The approved laboratories helped reducing the TxDOT workload related to HWT.
    - TxDOT manages the Annual State-wide Hamburg Wheel Tracking Test proficiency program.
    - TxDOT plans to create a similar MPL for all laboratories approved to perform OT (Tex-248-F).
- Having a certification program in-place for testing and evaluating asphalt mixtures that is supported by both TxDOT and industry (TxAPA) facilitated the training of technicians on performance tests (Step 8).
    - Training videos are provided for HWT (Tex-242-F) and there is a plan to develop similar ones for other performance tests.
    - The certification program is envisioned to include all selected performance tests and the BMD approach.
- Keys to implementation (Step 9) included:
    - Having multiple test projects across the states so that contractors can have an opportunity to gain experience and become familiar and comfortable with the process before full implementation.
    - Consideration of a phased approach for the implementation of BMD with initially no ties to pay factors.
    - Implementation of performance tests coupled with changes to the volumetric design criteria of asphalt mixtures (e.g., increase in VMA, minimum or a range of asphalt binder content, a limit on the virgin asphalt binder ΔTc).
    - Establishing a relationship between the truth tests used during mixture design and the surrogate tests used during production of plant-produced asphalt mixtures for practical implementation of performance tests for acceptance and pay.

- TxDOT helping and supporting contractors with performance tests (training on equipment and test result calculations) to make sure that tests are being properly conducted in the contractor laboratory.
    - A plan for a better tracking system for monitoring asphalt mixture sampling, shipping, and delivery to the MTD laboratory that would allow for effective planning and reporting of performance test results to contactors within the allowable 10 working days in accordance with specifications.
- There have been benefits:
    - Asphalt mixtures designed using the BMD approach were in general easier to compact in the field and to reach target in-place density
    - The BMD allowed contractors to use innovative and recycled materials (e.g., RAP, rejuvenators) in order to produce asphalt mixtures that are in compliance with TxDOT SS 3074.
    - Using the BMD approach resulted in a savings of over $5 per ton of asphalt mixture by moving to a less expensive asphalt binder while improving the mixture's overall engineering properties.
    - For a $5 per ton saving for using 15 to 20 percent RAP, the total annual savings for TxDOT would be about $80 million.

Lessons Learned

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

- Laboratory testing processes:
    - Changes to asphalt mixtures to get acceptable performance testing values were material specific. In particular, the performance test results were found to be sensitive to the aggregate type and properties (e.g., specific gravities, absorptions, particle shapes). This required adjustments to bin percentages or the use of different aggregate sources.
    - The asphalt binder source, especially for modified asphalt binders, was found to influence the performance test results of asphalt mixtures.
    - Increasing asphalt binder content by 0.7–0.8% improved the OT results significantly without jeopardizing HWT results.
    - OT results were sensitive to asphalt mixture's conditioning and reheating, which can result in out-of-specification acceptance test results. A standard protocol for conditioning and testing plant-produced asphalt mixtures is needed.
    - The BMD for surface mixtures allowed the use of 35% fractionated RAP without jeopardizing the cracking performance of the asphalt mixture.
- Plant operation processes:
    - A proper RAP stockpile management plan and process control are important for maximizing the use of RAP in asphalt mixtures. Fractionated RAP created flexibility in adjusting the composition of the RAP for the asphalt mixture design and minimized the RAP stockpile variability.
    - Plant trial batching was a critical and important step of the process in order to make sure that the asphalt mixture is in compliance during production.

    - Plant-produced asphalt mixtures typically exhibited different performance test results than laboratory-produced asphalt mixtures during design which necessitated some modifications to the JMF during the trial batch.

Challenges

- The increased use of recycled materials raised additional concerns with the typical asphalt mixtures designed using only HWT being drier and more prone to premature cracking.
- The overall process for selecting and completing test projects involves significant and continuous coordination efforts among the various stakeholders (TxDOT, contractor, academia, etc.). This involves multiple coordination meetings (approximately 7 meetings) prior to the start of each project to plan activities and work on adjusting the asphalt mixture design as needed to have acceptable performance test results.
- Aggregate breakdown in the plant-produced asphalt mixture can occur (depending on the aggregate source) as demonstrated with an increase in the percent passing the No. 8 sieve. Adjustments in the aggregate bin percentages within the allowable production tolerances are needed to match the laboratory produced asphalt mixture design.
    - The CPR parameter from OT increased as the aggregate gradation became finer (i.e., a decrease in the asphalt mixture resistance to cracking).
    - TX has over 200 aggregate sources that can be used in asphalt mixtures. Thus having performance tests that are sensitive enough to the presence of poor quality aggregates in the asphalt mixture is important.
- Correlations between the surrogate tests (IDEAL-CT, IDEAL-RT) and the truth tests (OT, HWT) are needed for implementation of performance tests as part of quality assurance.
- 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.
- Contractors faced some challenges with acquiring equipment and analysis of performance test results. Contractors sought help from TxDOT on how to properly conduct and analyze raw test data.
- TxDOT needed to acquire equipment from more than a single manufacturer in order to avoid any potential bias with the performance test results from different equipment. This involved a greater budget to cover the cost of some of the more expensive equipment.

TxDOT desires to select a surrogate 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

TxDOT suggests the following research topics:

- What changes and improvements can be made to the performance tests to reduce test variability.

- Training materials and hands-on workshops on testing, analysis, and interpretation of performance test results including the influence of changes in asphalt mixture components, composition, and proportions during design or production on performance.
- Continuous support for ruggedness studies of new and existing performance tests.
- Peer exchange with other lead states to share experiences and lessons learned.

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REFERENCES

American Association of State Highway and Transportation Officials (2019). AASHTO M 323-17, Standard Specification for Superpave Volumetric Mix Design, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2020). AASHTO MP 46-20, Standard Specification for Balanced Mix Design, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2019). *AASHTO R 29-15 (2019), Standard Practice for Grading or Verifying the Performance Grade of an Asphalt Binder*, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2019). *AASHTO R 35-17, Standard Practice for Superpave Volumetric Design for Asphalt Mixtures*, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2019). *AASHTO T 324-19, Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures*, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2018). *AASHTO T 378, Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT)*, AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (2020). *AASHTO PP 105, Standard Practice for Balanced Design of Asphalt Mixtures*, AASHTO, Washington, DC.

ASTM Standard D8225, "Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature," ASTM International, West Conshohocken, PA, 2019, DOI: 10.1520/D8225-19.

ASTM Standard E691-19e1, "Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method," ASTM International, West Conshohocken, PA, 2019, DOI: 10.1520/E0691-19E01.

ASTM WK71466, "New Test Method for Determination of Rutting Tolerance Index of Asphalt Mixture Using Rapid Rutting Test," ASTM International, West Conshohocken, PA.

Chowdhury, A., Button, J.W., and Wikander, J.P. (2004). *Variability of Hamburg Wheel Tracking Devices*, Final Report TxDOT 5-4977-01-1, TxDOT Project No. 5-4977-01, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Garcia, V., Miramontes, A., Garibay, J., Abdallah, I., and Nazarian, S. (2017). *Improved Overlay Tester for Fatigue Cracking Resistance of Asphalt Mixtures*, Final Report TxDOT 0-6815-1, TxDOT Project No. 0-6815, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Garcia, V., Castillo, E., Rocha, S., Garibay, J., Abdallah, I., and Nazarian, S. (2020). *Improved Overlay Tester for Fatigue Cracking Resistance of Asphalt Mixtures*, Final Report 5-6815-1, TxDOT Project No. 0-6815, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Garcia, V., Vieira, D., Barros, L., Abdallah, I., and Nazarian, S. (2020). *Develop Guidelines and Design Program for Hot-Mix Asphalts Containing RAP, RAS, and Other Additives through a Balanced Mix-Design Process*, Final Report 0-6923-1, TxDOT Project No. 0-6923, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Hajj, E. Y., Hand, A. J. T., Chkaiban, R., and Aschenbrener, T. B. (2019). *Index-Based Tests for Performance Engineered Mixture Designs for Asphalt Pavements*, Final Report to U.S. Department of Transportation, FHWA-HIF-19-103, Federal Highway Administration, Washington, DC.

Hot Mix Asphalt .Center (HMAC), Buda, TX 78610. https://www.txhmac.org/, last accessed August 28, 2020.

Izzo, R. P., and Tahmoressi, M. (1999). *Testing Repeatability of the Hamburg Wheel-Tracking Device and Replicating Wheel-Tracking Devices Among Different Laboratories*, Association of Asphalt Paving Technologists, Volume 68, pp. 589-608.

Lubinda, F. W., Das, G., and Tanvir, H. (2012). *New Generation HMA Mix-Design Procedures and Specifications for Texas*, TxDOT Project No. 0-6132, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Texas Department of Transportation (2014). Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges. Available online: http://ftp.dot.state.tx.us/pub/txdot-info/des/specs/specbook.pdf, last accessed August 21, 2020.

Texas Department of Transportation (2004). Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges. Available online: https://www.txdot.gov/business/resources/txdot-specifications.html, last accessed August 21, 2020.

Texas Department of Transportation (2014). Special Specifications Items 3000 – 3999 Surface Courses/Pavements. Available online: http://www.dot.state.tx.us/apps-cg/specs/ShowAll.asp?year=4&type=SS&number=3, last accessed August 21, 2020.

Technical Brief (2019). *Performance Engineered Pavements*, FHWA-HIF-20-005, Office of Infrastructure, Federal Highway Administration, Washington, DC.

Texas Department of Transportation. *Test Procedure for Design of Bituminous Mixtures*, Tex-204-F, Effective Date August 2016, Test Procedures Series, 200-F Series (ftp site) TxDOT. Available online: http://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit204.pdfhttps://www.txdot.gov/insidetxdot/division/construction/testing.html, last accessed August 24, 2020.

Texas Department of Transportation. *Test Procedure for Overlay Test*, Tex-248-F, Effective Date July 2019, Test Procedures Series, 200-F Series (ftp site) TxDOT. Available online: http://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit248.pdfhttps://www.txdot.gov/insidetxdot/division/construction/testing.html, last accessed August 24, 2020.

Texas Department of Transportation. *Test Procedure for Overlay Test*, Tex-250-F, Effective Date January 2020, Test Procedures Series, 200-F Series (ftp site) TxDOT. Available online: http://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit250.pdfhttps://www.txdot.gov/insidetxdot/division/construction/testing.html, last accessed August 24, 2020.

West, R., Rodezno, C., Leiva, F., and Yin, F. (2018). *Development of a Framework for Balanced Mix Design*, Final Report to the National Cooperative Highway Research Program (NCHRP), Project NCHRP 20-07/Task 406, Transportation Research Board of the National Academies, Washington, DC.

Williams, B. A., Willis, J. R., and Ross, C. (2019). *Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2018*, National Asphalt Pavement Association, Information Series 138 (9th edition), IS 138(9e), 46 pp.

Yildirim, Y., and Kennedy, T. W. (2001). *Correlation of Field Performance to Hamburg Wheel Tracking Device Results*, Final Report TxDOT 0-4185-1, TxDOT Project No. 0-4185, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Yildirim, Y., and Kennedy, H. S. II (2006). *Analysis of Hamburg Wheel Tracking Device Results in Relation to Field Performance*, Final Report TxDOT 0-4185-5, TxDOT Project No. 0-4185, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Yildirim, Y., Jayawickrama, P.W., Hossain, M.S., Alhabshi, A., Yildirim, C., De Fortier Smit, A. and Little, D. (2007). *Hamburg Wheel-Tracking Database Analysis*, Final Report TxDOT 0-1707-7, TxDOT Project No. 0-1707, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Zhou, F., and Scullion, T. (2005). *Developing an Upgraded Overlay Tester System to Characterize the Reflection Cracking Resistance of Asphalt Concrete*, Final Report, TxDOT Project No. 0-4467, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Zhou, F., Hu, S., Hu, X., and Scullion, T. (2008). *Developing of an Advanced Overlay Design System Incorporating Both Rutting and Reflection Cracking Requirements*, Final Report, TxDOT Project No. 0-5123, Texas Department of Transportation, Research and Technology Implementation Office, Austin, TX.

Zhou, F., Im, S., Sun, L., and Scullion, T. (2017). *Development of an IDEAL Cracking Test for Asphalt Mix Design and QC/QA*, Road Materials and Pavement Design, Vol. 18, Issue sup. 4, pp. 405-427.