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

California Department of Transportation (Caltrans)

Elie Y. Hajj
University of Nevada, Reno

Timothy B. Aschenbrener
Federal Highway Administration

Derek Nener-Plante
Federal Highway Administration

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PES Program
University of Nevada Reno
1664, N. Virginia Street, MS 258,
Reno, NV 89557.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
AMPT	Asphalt Mixture Performance Tester
APT	accelerated pavement testing
ASTM	American Society for Testing and Materials
BMD	Balanced Mix Design
CalME	California Mechanistic-Empirical Analysis and Design
Caltrans	California Department of Transportation
CFR	Code of Federal Regulations
DOT	Department of Transportation
CalAPA	California Asphalt Pavement Association
COV	coefficient of variation
ESAL	equivalent single axle load
FBF	flexural beam fatigue
FHWA	Federal Highway Administration
FI	flexibility index
HMA	hot-mix asphalt
HOV	High Occupancy Vehicle
HWTT	Hamburg Wheel-Track test
HVS	Heavy Vehicle Simulator
I-5	Interstate 5
I-80	Interstate 80
I-FIT	Illinois Flexibility Index test
IA	Independent Assurance
ILS	interlaboratory study
JTCP	joint training and certification program
JMF	job mix formula
LL	long life
LLAP	long-life asphalt pavement
ME	mechanistic-empirical
METS	Materials Engineering and Testing Services
NCHRP	National Cooperative Highway Research Program
NDT	non-destructive testing
NMAS	nominal maximum aggregate size
OBC	optimum asphalt binder content
PBS	performance-based specifications
PCC	Portland cement concrete
PEP	Performance Engineered Pavements
PG	performance grade
PMPC	Pavement and Materials Partnering Committee
PRS	performance-related specifications
QA	quality assurance

QC	quality control
RAP	reclaimed asphalt pavement
RAS	reclaimed asphalt shingles
RLT	repeated load triaxial
ROI	return on investment
RSST	repeated simple shear test
RWC	rolling wheel compaction
SGC	Superpave gyratory-compacted
SHA	state highway agency
SIAD	Statewide Independent Assurance Database
SML	Standard Materials Library
TS	tensile strength
TSR	TS ratio
U.S.	United States
UCPRC	University of California Pavement Research Center
VFA	voids filled with asphalt binder
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. California Department of Transportation (Caltrans) 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 Caltrans virtual site visit.

GENERAL INFORMATION SPECIFIC TO CALTRANS

In the late 1990s the asphalt pavement industry was faced with the challenge of building long-life asphalt pavements (LLAPs) that can last more than 30 years using performance-related specifications (PRS) that are based on mechanistic-empirical (ME) design. In 2003, Caltrans launched a collaborative effort with the asphalt pavement industry and the University of California Pavement Research Center (UCPRC) to test LLAP strategies on a rehabilitation project on the 710 Freeway in Southern California (District 7). The project included both full-depth asphalt concrete (AC) sections and AC overlays on cracked-and-seated Portland cement concrete (PCC) that were designed to last more than 30 years with minimal maintenance. The design traffic consisted of more than 200 million equivalent single axle loads (ESALs). The 710 Freeway rehabilitation project involved eight 55-hour weekend closures for the construction of LLAPs using fast-track construction to minimize traffic delays and inconvenience to the traveling public. Since then, Caltrans, industry, and academia continued to work together with the goal of developing additional LLAP projects in California. However, the next LLAP rehabilitation project did not occur until 2012 (9 years after the first project), in part due to the Great Recession that started in December 2007.

Between 2012 and 2014 Caltrans designed and built three additional LLAP rehabilitation projects. Two projects were in District 2 on Interstate 5 (I-5)—one just north of the city of Red Bluff and the other on the interstate running through and north of the city of Weed—and one in District 4 on Interstate 80 (I-80) in Solano County between the cities of Dixon and Vacaville. All projects had design goals of at least 40-year fatigue (bottom-up or reflective) and rutting (asphalt and unbound layers) service lives. Each project involved new and different contractors with no or limited experience in building LLAPs. For the first time, Caltrans used 25% reclaimed asphalt pavement (RAP) in the AC layers below the surface layer on these projects. This was a significant increase over the previous maximum of 15% RAP. Figure 1 shows a geographical map of the 12 Caltrans districts.

Figure 1. Map. Caltrans districts (https://dot.ca.gov/caltrans-near-me).

In 2019, a fifth LLAP rehabilitation project on I-5 (Sacramento) was awarded—the project is 15.1 miles long and extends from 1.1 mile south of the Elk Grove Boulevard overcrossing to the American River Bridge (https://fixsac5.com/project-overview/). The project costs $370 million and will rehabilitate pavement, construct new High Occupancy Vehicle (HOV) lanes, replace a pedestrian overcrossing, construct sound walls, install new fiber optic lines and new ramp meters, and extend various entrance and exit ramps. The project is expected to be completed by December 2022.

The overall Caltrans approach for LLAPs comprises the following three major activities (stages): (1) select a project location (including route and post mile range) and develop a conceptual asphalt pavement design; (2) obtain representative materials and establishing performance-related test specifications (criteria) for each of the asphalt mixtures in the pavement design used on the project; and (3) create the final LLAP design for the project utilizing the ME concept and measured properties for locally available materials. The flexural beam fatigue (FBF)—AASHTO T 321 and the repeated simple shear test (RSST)—AASHTO T 320 laboratory testing are implemented in the pavement designs and specifications.

The California Mechanistic-Empirical Analysis and Design (CalME) software design methodology which was first developed in 2000 is used in the process. The CalME is a flexible pavement ME design software that is based on incremental-recursive damage models and materials parameters from repeated load tests for fatigue (FBF) and rutting (RSST), and frequency sweeps for stiffness (FBF). Accelerated pavement testing (APT) using Heavy Vehicle Simulators (HVS) from different studies and some other field sections were used to calibrate the CalME. The ME design provided Caltrans with the tool to consider non-traditional material properties such as rubberized HMA, high RAP asphalt mixtures (i.e., RAP up to 40% by binder replacement) in the pavement design.

The results from the FBF and RSST are used for the design and PRS. In the most recent I-5 project (2019), the RSST was replaced with the repeated load triaxial (RLT) test (AASHTO T 378) after recent challenges in identifying consultants and research institutions with the ability to operate and run the RSST. The RLT is conducted using the Asphalt Mixture Performance Tester (AMPT). The HWTT was required in the performance-based specifications (PBS) for all LLAP projects as a consideration for moisture sensitivity. The Illinois Flexibility Index test (I-FIT) was required on the I-5 (Sacramento) project as a shadow test for its potential use as a surrogate cracking test in the future. Neither the HWTT nor the I-FIT results were used in the ME design process. Throughout the years, Caltrans funded and coordinated relevant research with the UCPRC to assure rational implementation of performance testing and PRS.

For non-PRS projects (i.e., non-LLAP or standard projects), Caltrans standard specifications (2018) for hot-mix asphalt (HMA)—Section 39 require the HWTT for rutting performance evaluation using the AASHTO T 324 (modified). The HWTT is implemented for Superpave Type A Hot-Mix Asphalt and Rubberized Hot Mix Asphalt–Gap Graded (RHMA-G) mixtures. Test criteria are established based on the asphalt mixture type and the asphalt binder performance grade (PG). The AASHTO T 283 is required for the evaluation of asphalt mixtures to moisture susceptibility. In the case of PRS or LLAP projects, performance testing requirements are specified for asphalt mixtures. A summary of the asphalt mixtures used by Caltrans along with their applications is shown in table 1. It should be noted that while an LLAP is designed to last a minimum 40 years, the HMA-LL Surface mixture is overlaid with a thin (sacrificial layer) HMA/RHMA-open graded mixture that is intended to be replaced every 12–16 years.

Table 1. Asphalt Mixture Types Used by Caltrans.

Mixture Type		Application
PRS and Non-PRS	Type A HMA	• Surface, intermediate, or bottom course.
	RHMA-G	• Surface course.
LLAP	HMA-LL Polymer Modified Mixture	• Surface course.
	HMA-LL Stiff Mixture	• Intermediate course.
	HMA-LL Rich Binder Mixture	• Bottom course.

BMD APPROACH

In 2014, Caltrans implemented the Superpave methodology for asphalt mixture design into Section 39 'Hot Mix Asphalt' of the Standard Specifications. The specification requires the use of HWTT (AASHTO T 324—Modified) and the tensile strength (TS) to identify the rutting resistance and moisture susceptibility properties of asphalt mixtures, respectively. The BMD of Type A HMA and RHMA-G for designing and approving JMFs follows Approach A *Volumetric Design with Performance Verification*.

Figure 2 shows a flowchart of the overall BMD for Type A HMA that highlights the major steps for undertaking an asphalt mixture design according to Caltrans specifications. The requirements for volumetric design and performance testing for Type A HMA and RHMA-G are summarized in table 2 and table 3. The HWT criteria is based on the asphalt binder PG; thus taking into consideration both climate and traffic conditions. The TS criteria is the same for both asphalt mixtures. Currently a cracking test is not required in the Section 39 specification.

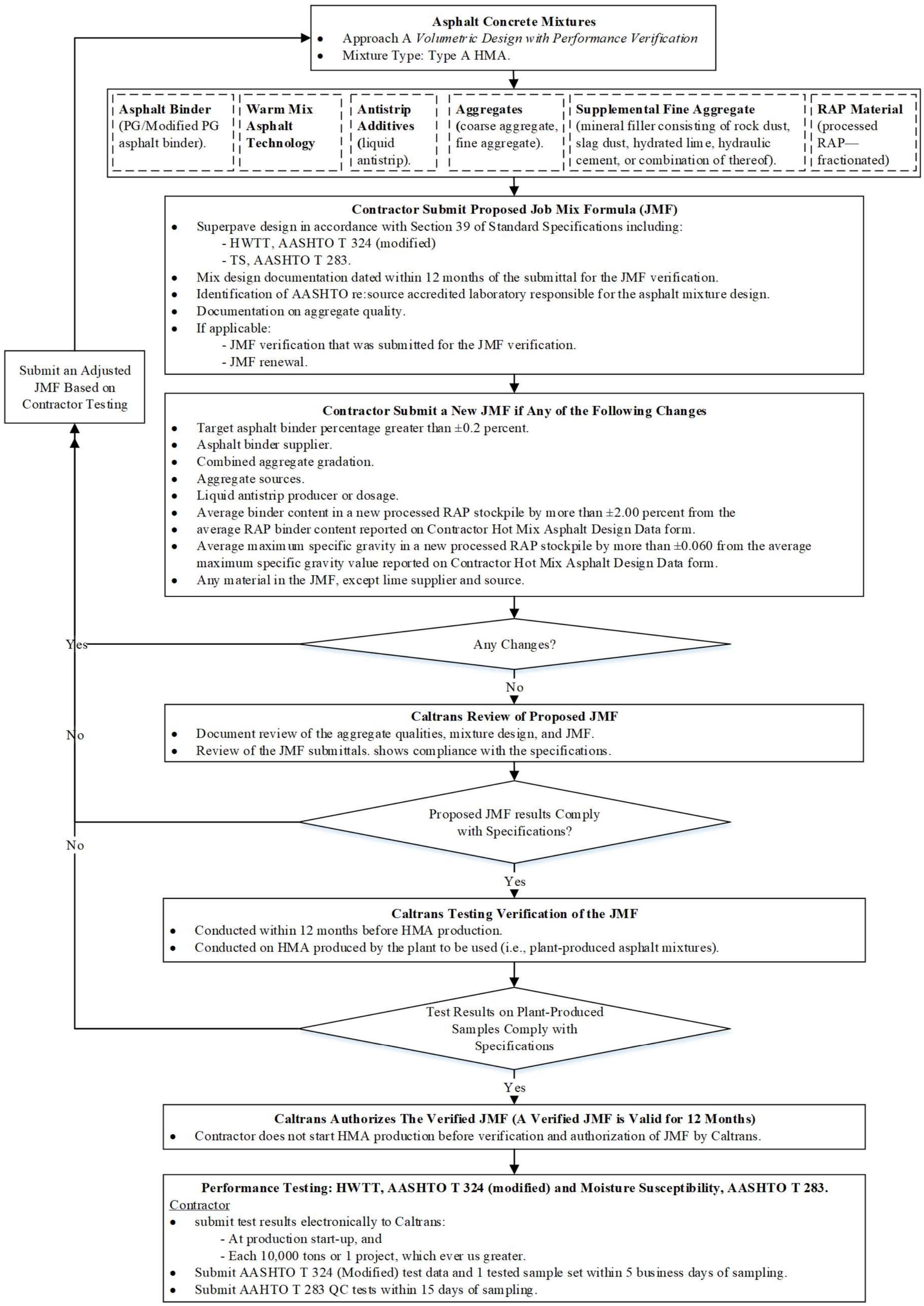


Figure 2. Chart. Overview of Caltrans asphalt mixture design process for Type A HMA.

Table 2. Mix Design Volumetric Requirements for Non-PRS Projects.

Quality Characteristic	Test Method	Requirement	
		Type A HMA	RHMA-G
Air voids content (%)	AASHTO T 269	> 8.0 at $N_{initial}$ = 4 at N_{design} (= 5 at N_{design} for 1-inch aggregate) > 2.0 at N_{max}	= 4 at N_{design}
Gyration compaction (No. of gyration)	AASHTO T 312	$N_{initial}$ = 8 N_{design} = 85 N_{max} = 130	N_{design} = 50–150
Voids in mineral aggregate, VMA (min. %) Gradation:	MS-2 Asphalt Mixture Volumetrics (Type A HMA); SP-2 Asphalt Mixture Volumetrics (RHMA-G)		
No. 4		16.5–19.5	
3/8 inch		15.5–18.5	
1/2 inch		14.5–17.5	18.0–23.0
3/4 inch		13.5–16.5	18.0–23.0
1 inch			
With NMAS = 1 inch		13.5–16.5	
With NMAS = 3/4 inch		14.5–17.5	
Dust proportion	MS-2 Asphalt Mixture Volumetrics (Type A HMA); SP-2 Asphalt Mixture Volumetrics (RHMA-G)	0.6–1.3	Report only

Table 3. Mixture Design and Acceptance Performance Testing Requirements for Non-PRS Projects.

Mixture Type	HWTT (Modified AASHTO T 324), Number of Wheel Passes at 0.5-inch Rut Depth[1]				HWTT (Modified AASHTO T 324), Number of Wheel Passes at Inflection Point[1]				TS (AASHTO T 283), psi	
	PG 58	PG 64	PG 70	PG 76 or higher	PG 58	PG 64	PG 70	PG 76 or higher	Dry	Wet
Type A HMA	≥ 10,000	≥ 15,000	≥ 20,000	≥ 25,000	Report only	Report only	Report only	Report only	≥ 100	≥ 70
RHMA-G	≥ 15,000	≥ 15,000	≥ 20,000	–	Report only	Report only	Report only	–	≥ 100	≥ 70

–Not applicable.
[1]Test plant-produced asphalt mixture.

The Caltrans approval for JMF comprises the following three major steps. A contractor may start production only if all three steps were successfully completed (figure 2).

1. Caltrans first reviews the proposed JMF submittals from contractor. The review of the JMF needs to show compliance with the specifications.
2. Caltrans verifies the JMF within 12 months before HMA production by testing the asphalt mixture produced at the plant to be used.
3. Caltrans authorizes the verified JMF by proving the tested asphalt mixture is in compliance with specifications.

In the case of PRS or LLAP projects, the BMD for designing and approving JMFs follows Approach C *Performance-Modified Volumetric Design*. The RLT (AASHTO T 378, modified) is used to select the OBC for each of the HMA-LL Surface and HMA-LL Intermediate—originally the RSST test (AASHTO T 320) was used. The FBF test (AASHTO T 321, modified) is used to determine the asphalt mixture response to fatigue at the selected OBC. The HWTT (AASHTO T 324, modified) is used to evaluate the moisture sensitivity response of each of the asphalt mixtures. Table 4 shows the PBS implemented on the on-going I-5 (Sacramento) LLAP project. It should be noted that the PBS criteria is project specific.

Table 4. Mixture Design and Acceptance Performance Testing Requirements for I-5 (Sacramento) LLAP or PRS Project.

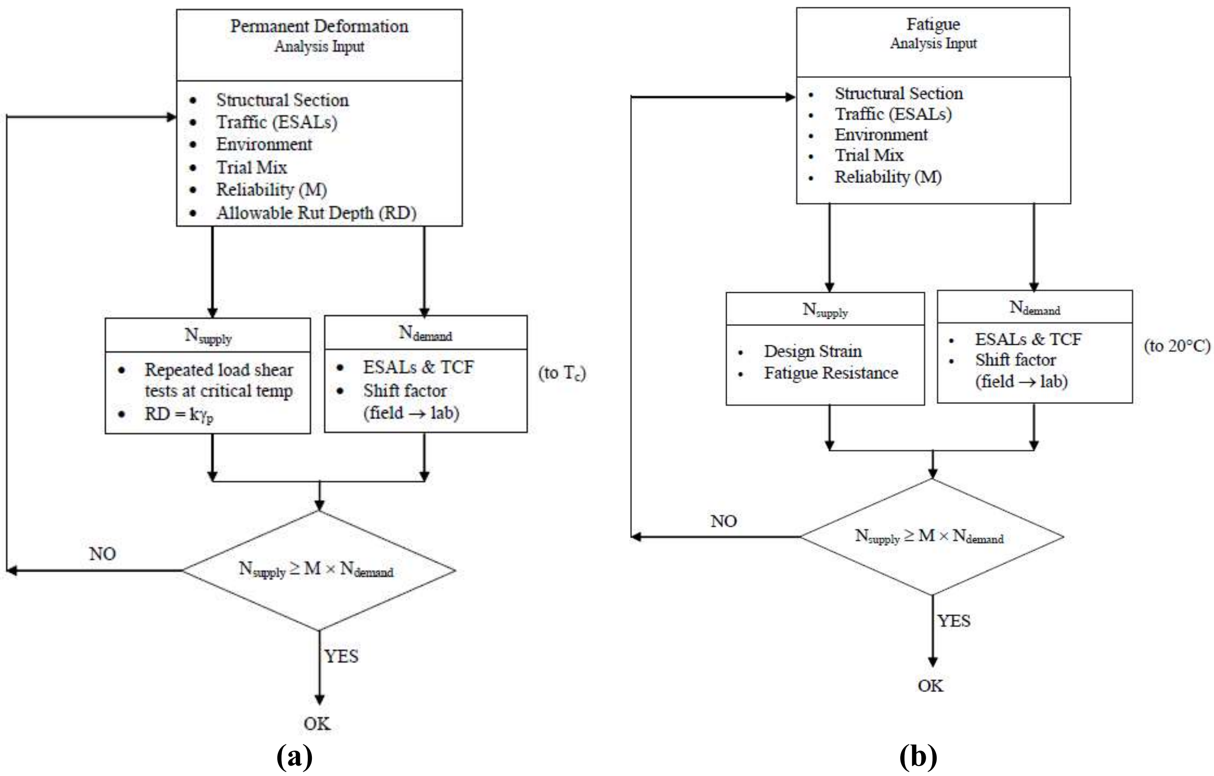
Design Parameters	Test Method	Sample Air Voids	Requirements		
			HMA-LL Surface	HMA-LL Intermediate	HMA-LL Rich Bottom
Permanent Deformation:[1,2] Minimum number of cycles to 3% permanent axial strain at 122°F.	AASHTO T 378 (Modified)[3]	Mixture Specific[4]	941	3,007	–
Beam stiffness (ksi):[2,5] Minimum stiffness at the 50th cycle at the given testing strain level.	AASHTO T 321 (Modified)[3]	Mixture Specific[4]	210 at 893×10^{-6} inch/inch	782 at 433×10^{-6} inch/inch	707 at 420×10^{-6} inch/inch
Beam fatigue:[2,5] Minimum of 1,000,000 cycles to failure at this strain. Minimum of 250,000 cycles to failure at this strain.	AASHTO T 321 (Modified)[3]	Mixture Specific[4]	495×10^{-6} inch/inch 893×10^{-6} inch/inch	220×10^{-6} inch/inch 443×10^{-6} inch/inch	269×10^{-6} inch/inch 420×10^{-6} inch/inch
Semicircular beam fracture potential:[2] Minimum flexibility index (FI).	AASHTO TP 124[3]	Mixture Specific[4]	3.0	0.5	0.5
Moisture Sensitivity: Minimum repetitions for rut depth of 0.5 inch at 122°F.	CT 389 (AASHTO T 324 Modified)[3]	Per Test Method	20,000	20,000	–

–Not required.
[1]Tested unconfined, 4.4 psi contact stress, and 70 psi repeated axial stress.
[2]Average value determined from tests on 3 specimens and calculated as the geometric mean.
[3]Included in the testing procedure, LLP-AC3, "Sample Preparation and Testing for Long-Life Asphalt Concrete Pavements" located in the Information Handout.
[4]6 ± 0.5% for HMA-LL Surface and HMA-LL Intermediate mixtures, and 3 ± 0.5% for HMA-LL Rich Bottom mixture all following AASHTO T 331.
[5]Tested at 10 Hz load frequency and 68°F test temperature.

The overall Caltrans approach for LLAP or PRS comprises the following three major activities (stages) and their associated steps. Figure 3 summarizes the overall framework for both the asphalt mixture and structural pavement section designs for a PRS or LLAP project.

- Stage 1 consists of selecting a project location (including route and post mile range) and developing a conceptual asphalt pavement design.
    - *Step 1.1*. After selecting a PRS or LLAP project, Caltrans completes a preliminary pavement structural design using CalME software design methodology. The specific material parameters from the State Standard Materials Library (SML), if available in the design software CalME, are used in this step. If not, a new set of material parameters will have to be developed and added to the SML.
    - *Step 1.2*. After a review of as-built information and use of CalME, Caltrans selects the asphalt mixture type for each of the surface, intermediate, and bottom courses. This is accomplished with due considerations given to the asphalt binder PG for the project area, structural condition of the pavement, and other types of distress (e.g., thermal cracking).
    - *Step 1.3*. Caltrans submits the information from Step 1.2 to UCPRC for the development of the PBS in Stage 2. UCPRC will be involved during piloting stages until Caltrans is fully capable of conducting all necessary testing.
- Stage 2 consists of obtaining representative materials and establishing performance-related test specifications (criteria) for each of the asphalt mixtures in the pavement design used on the project. The following are the steps completed under this stage.
    - *Step 2.1*. UCPRC and in collaboration with local District Materials Engineers and the Office of Asphalt Pavement develops asphalt mixture designs from the materials identified as potential sources of aggregate and asphalt binder that local contractors might use.
    - *Step 2.2*. Using site-specific temperature data and corresponding traffic data provided by Caltrans, UCPRC develops the minimal performance requirements (i.e., performance specifications) for AASHTO T 378 (RLT) testing (originally RSST was used) testing, which is based on the procedure developed by UCPRC researchers and reported in the Strategic Highway Research Program (SHRP-A 415).
    - *Step 2.3*. UCPRC performs RSST testing at the climate-based temperature calculated in Step 2.2 to determine the OBC for each of the asphalt mixtures using the materials identified by Caltrans.
    - *Step 2.4*. UCPRC performs AASHTO T 321 (FBF and stiffness) and AASHTO T 378 (RLT) at the OBCs developed in Step 2.3. Based on statistical analyses of the AASHTO T 321 and T 378 test results, flexural fatigue, stiffness and permanent deformation specifications (i.e., performance requirements) are developed
    - *Step 2.5*. UCPRC performs moisture sensitivity testing in accordance with AASHTO T 324 (HWTT) at 50°C. The test results are checked against the test parameters (i.e., performance requirements) recommended by Caltrans standard specifications.
    - *Step 2.6*. UCPRC provides Caltrans with the PBS for each of the asphalt mixtures that were established based on laboratory testing and the traffic and environment (temperature) in the location of the PRS or LLAP project.
- Stage 3 consists of creating the final PRS or LLAP design for the project utilizing the ME concept and measured properties for locally available materials.

- *Step 3.1*. Using the measured shear and fatigue performance test data, Caltrans designs the final structural pavement section for the PRS or LLAP using CalME design methodology.
- *Step 3*.2. Caltrans update the State SML available in the design software CalME with the new rutting and fatigue test data for use on future PRS or LLAP projects.



Notes: ESAL = equivalent single axle load; TCF = temperature conversion factor

Figure 3. Chart. Framework for asphalt mixture design: (a) performance deformation system; (b) fatigue system (SHRP-A 415 augmented by research from UCPRC).

Specification limits are selected based on the 95% confidence interval for the given property based on replicate tests (Caltrans accepts 95% of the risk of laboratory test variability). The PBS is applied to plant-produced asphalt mixture in accordance with specifications. While contractors can use laboratory- or plant-produced asphalt mixtures to develop their preliminary designs, a plant-produced asphalt mixture must be used for design acceptance testing. Conventional design requirements for aggregate gradation, asphalt binder content, and volumetric properties are also included in the specifications; e.g., air void content, aggregate specifications, voids in mineral aggregate (VMA), voids filled with asphalt (VFA), dust proportion, and tensile strength ratio (TSR). Some of the volumetric requirements are relaxed or removed. Specifically, the air voids at N_{design} and VMA are report only for JMF submittal. The air voids at N_{design} must be within +/-1.5% of the reported value during JMF verification as well as startup evaluation. The VMA is not checked in JMF verification. Because of the time requirements for performance-related repeated load tests, the quality control and quality assurance (QC/QA) testing during construction are still based on conventional tests (i.e., air voids, VMA, etc.).

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 Caltrans to their volumetric design criteria (table 2 and table 5):

- Specified lower number of gyrations for design of asphalt mixtures.
- Increased the VMA requirement for Type A HMA by 0.5–3.5% for the 4.75, 9.5, 12.5, ad 19.0 mm mixtures and by 1.5–4.5% for the 25.0 mm mixtures.
- Increased the VMA requirement for RHMA-G by 4–9% and 5–10% for the 12.5 and 19.0 mm mixtures.
- Increased by 0.1% the upper limit of the dust-to-asphalt binder ratio requirement for Type A HMA.
- Excluded the requirement for the dust-to-asphalt binder ratio for RHMA-G.

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 lower the N_{design} and the higher the VMA, the higher the asphalt binder content for a given air void level).

Table 5. Modifications to AASHTO Standard Volumetric Design Criteria.

Requirements	Mixture Types	
	Type A HMA	RHMA-G
Number of Design Gyrations (N_{des})	↓	↓
Density at N_{des}	↔ / ↓	↔
Density at Initial Number of Gyrations ($N_{initial}$)	↑	–
Density at Maximum Number of Gyrations (N_{max})	↔	–
Design Asphalt Binder Content	–	–
Voids in Mineral Aggregate (VMA)	↑	↑
Voids Filled with Asphalt (VFA)	–	–
Dust-to-asphalt binder ratio	↑ UL	R
HWT Passes at 12.5 mm Rut Depth	Min	Min
TS – Dry	Min	Min
TS – Wet	Min	Min

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

SELECTION OF PERFORMANCE TESTS

Table 6 summarizes the performance tests currently used by Caltrans for their BMDs of asphalt mixtures on both non-PRS and PRS projects. The HWTT was implemented in 2015 along with Superpave for non-PRS projects to replace the Hveem stability test. Caltrans selected the HWTT after reviewing related specifications and procedures for other SHAs. The following performance-related tests have been used for developing PRS for asphalt mixtures. The tests, which were selected based on past SHRP studies, provide properties and performance models necessary for the ME pavement design and performance life prediction in CalME.

- For permanent deformation (rutting): the RSST at constant height (AASHTO T 320) has been used until recently, this test got replaced with the RLT test (AASHTO T 378) using the AMPT. This transition from the RSST to the RLT test is because of the lack in a critical mass of numbers of deployed and operational RSST devices.
- For fatigue cracking: the four-point bending beam fatigue test using controlled displacement (adapted from AASHTO T 321) is used.
- For stiffness: the four-point bending beam frequency sweep test (adapted from AASHTO T 321) or the initial flexural stiffness in four-point bending beam fatigue test is used.

Table 6. Summary of Performance Tests Considered by Caltrans for BMD.

Elements	Stability/Rutting	Durability/Cracking	Moisture Damage/Stripping
Test Name	Non-PRS: • Hamburg Wheel Track test (HWTT) PRS: • Repeated Load Triaxial (RLT).	Non-PRS: • None. PRS: • Flexural Beam Fatigue (FBF). • Illinois Flexibility Index test (I-FIT).	Non-PRS: • Tensile Strength (TS) • Hamburg Wheel Track test (HWTT) PRS: • Hamburg Wheel Track test (HWTT)
Test Method	Non-PRS: • AASHTO T 324 / California Test 389. PRS: • AASHTO T 378 (modified).	Non-PRS: • None. PRS: • AASHTO T 321 (modified). • AASHTO TP 124.	Non-PRS: • AASHTO T 283. PRS: • California Test 389.
Test Criteria	Non-PRS: Refer to table 3. PRS: Refer to table 4.	Non-PRS: Refer to table 3. PRS: Refer to table 4.	Non-PRS: Refer to table 3. PRS: Refer to table 4.
Test Implemented in Asphalt Mixture Design	Yes.	Yes.	Yes.
Aging Protocol	Design verification is based on plant-produced asphalt mixtures. No additional laboratory aging is specified.	Design verification is based on plant-produced asphalt mixtures. No additional laboratory aging is specified.	Design verification is based on plant-produced asphalt mixtures. No additional laboratory aging is specified.
Notes/Comments	RLT implemented for I-5 (Sacramento) LLAP project. Prior LLAP projects used RSST.	Caltrans is exploring the use of I-FIT or IDEAL Cracking Tolerance test (IDEAL-CT) (ASTM D8225) to evaluate the cracking resistance of asphalt mixtures for routine asphalt mixture design, quality control, and assurance testing.	–

–Not applicable.

Caltrans is considering and evaluating suitable performance-related tests for routine asphalt mixture design, quality control, and assurance testing. The RLT test is being evaluated for use in HMA mix design and QC/QA testing for rutting evaluation. On the other hand, the I-FIT and the IDEAL Cracking Tolerance test (IDEAL-CT) (ASTM D8225) are being evaluated for cracking resistance. The performance tests for both cracking and rutting need to be calibrated against the currently used performance-related tests and field performance. This effort involves an aging study to evaluate differences in plant- and laboratory-produced asphalt mixtures. Caltrans ultimate goal is to incorporate the tests into standard Superpave asphalt mixture design procedures and construction specifications.

The top three factors for Caltrans in selecting a performance test for routine use are: material sensitivity, field validation, and repeatability. The test should be sensitive to asphalt mixture component properties or proportions (e.g., aggregates, asphalt binders, recycled materials, additives), air voids, and aging. Caltrans recognizes that a repeated load test is likely to have a higher variability in test results. Field validation and correlation of performance test results with measured field performance data is the basis for any BMD approach and was one of Caltrans motivations for implementation of performance tests. In the selection process, consideration is 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. Having an acceptable repeatability (within laboratories) and reproducibility (between laboratories) of test results is key for successful implementation of specifications.

Other important factors for Caltrans are sample preparation, specimen conditioning and testing time, and equipment cost. The duration needed for sample preparation, specimen conditioning, and testing have been key considerations for Caltrans in the selection of performance tests for routine use. The aim was also to maintain a low-cost for specimen fabrication and testing equipment. Having qualified and trained technicians help to reduce the impact this factor might have on the overall implementation effort of performance tests.

PERFORMANCE TESTS DEVELOPMENT TO IMPLEMENTATION

The following section summarizes Caltrans 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 modified test procedures available for AASHTO T 321, AASHTO T 324 (Caltrans Test 389), AASHTO T 378, AASHTO TP 124, and AASHTO T 283 supported efficient implementation of performance tests for asphalt mixtures.

All of the specimens for the performance tests are prepared using rolling wheel compaction (RWC) that was originally developed during SHRP (AASHTO PP3). The RWC method is aimed to simulate the aggregate structure obtained in asphalt mixtures during pavement construction. The AASHTO procedures are modified for performance testing evaluation of asphalt mixtures and are published in the Caltrans Lab Procedure – LLP-AC3.

Caltrans 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. For example, in response to raised concerns with HWTT variability and the specified number of passes to maximum rut depth for RHMA-G, the Pavement and Materials Partnering Committee formed a working group comprised of industry representatives and Caltrans to evaluate AASHTO T 324 (modified) test protocol and specifications. The working group came up with 12 modifications that were implemented through a new California Test 389, specification changes necessary to implement California Test 389, and changes to the specified number of passes to maximum rut depth for RHMA-G. These changes were included in the Revised Standard Specifications published April 17, 2020.

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

The sensitivity of performance test results to 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 Caltrans. The use of PRS on LLAP projects resulted in new challenges for materials producers and contractors who have never had to relate volumetric mixture design parameters to mechanistic parameters from performance-related laboratory tests for fatigue life and rutting resistance. 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.

Accordingly, Caltrans funded a UCPRC research study (UCPRC-RR-2017-12, 2015–2017) to provide asphalt mixture designers and contractors guidance regarding changes to mixture designs to achieve PRS requirements. A guidance was established based on past experience that was then validated and demonstrated using an approved plant-produced asphalt mixture by Caltrans. The plant-produced asphalt mixture was used as the starting point for a set of adjustments applied to the mixture (e.g., adjustments in aggregate gradation, natural sand content, dust-to-asphalt binder proportion, asphalt binder stiffness). The effects of each adjustment on the mechanistic performance indicators (i.e., stiffness, fatigue resistance, and rutting resistance) were measured and compared. Furthermore, CalME simulations were conducted to evaluate the impact of the performance test results on predicted pavement performance when the asphalt mixture is used as a pavement surface layer. The laboratory test results for the evaluated asphalt mixtures were used as inputs for the CalME analyses. Based on the findings from this study, a flowchart for asphalt mixture design guidance was provided as shown in figure 4.

Step 3. Preliminary field performance relationship.

Caltrans based its selection of HWTT criteria on existing research studies and specifications from other SHAs. A preliminary relationship to field performance is confirmed based on general observations and comparisons of HWTT results to pavement performance. Caltrans and in collaboration with industry continues to update and modify the HWTT criteria as found needed.

The CalME is calibrated using APT from different studies and some other field sections. The calibration of the CalME was achieved by comparing simulated to measured distress data. The calibrations increase the confidence in the CalME models for use on the non-PRS and PRS projects.

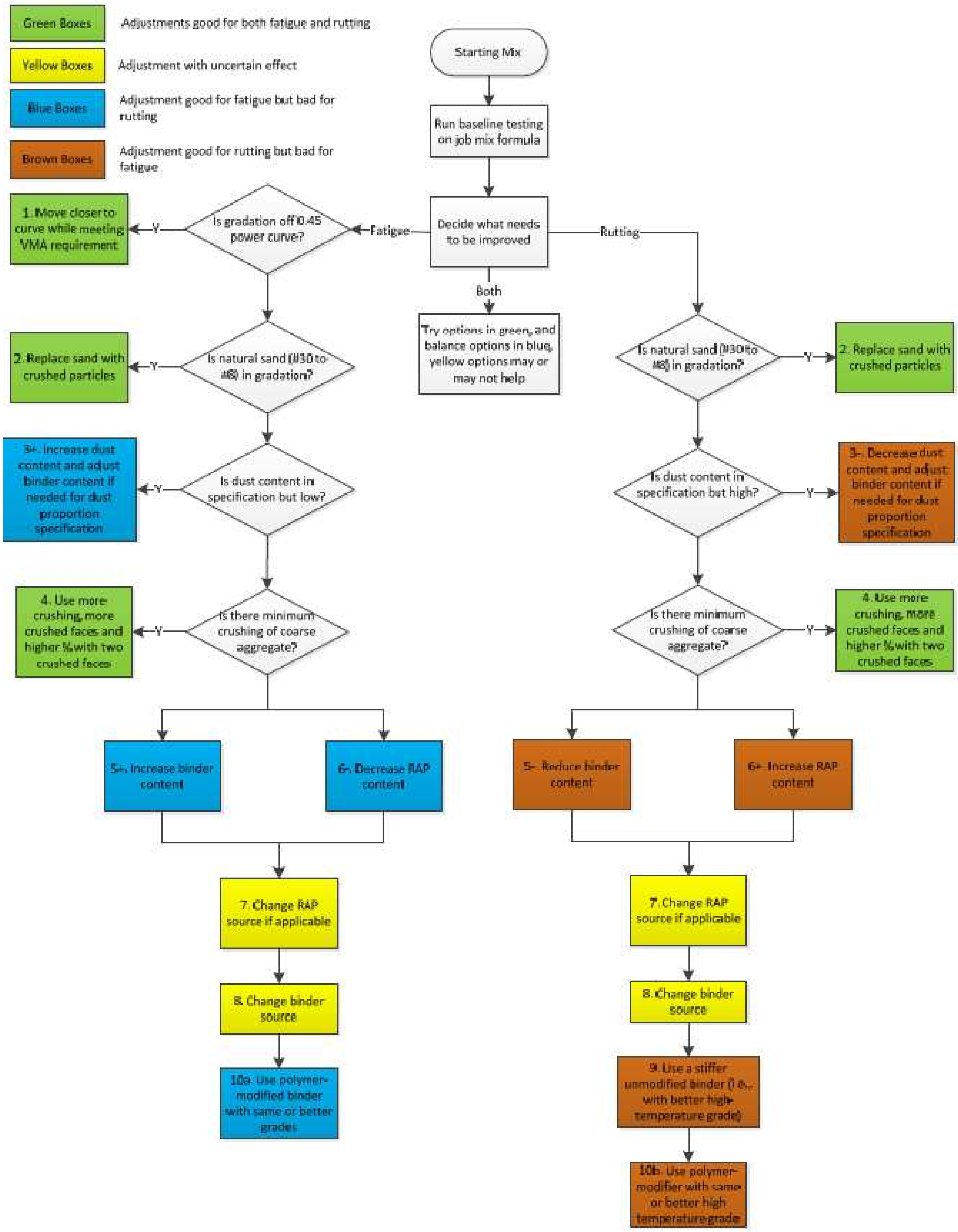


Figure 4. Chart. Revised flowchart proposed for improving the fatigue or rutting performance of an asphalt mixture (UCPRC-RR-2017-12).

Step 4. Ruggedness experiment.

Caltrans did not conduct or participate in any formal ruggedness testing yet. The NCHRP project 09-57A Ruggedness of Laboratory Tests to Assess Cracking Resistance of Asphalt Mixtures (https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4471) recently completed a ruggedness study for the I-FIT (AASHTO TP124-18) and the IDEAL-CT (ASTM D8225).

The following seven factors were considered for the I-FIT in the ruggedness experiments: specimen thickness, notch depth, notch location, specimen height, air voids, loading rate, and test temperature. Based on this study, air voids and test temperature were the two significant factors for the I-FIT. The study recommended reducing the tolerance of air voids from +/-1% to +/-0.5%.

The following seven factors were considered for the IDEAL-CT in the ruggedness experiments: specimen thickness, specimen center location, air voids, loading rate, contact load, test temperature, and conditioning method. Based on this study, only air void was identified significant for IDEAL-CT. Recommended tolerances were provided for all seven factors of the IDEAL-CT.

Step 5. Commercial equipment specification and pooled fund purchasing.

While Caltrans central and district laboratories are very well equipped to run and analyze HWTT and TS implemented for the BMD approach, it continues to rely on UCPRC for all other performance tests required on PRS projects (i.e., RLT, FBF, I-FIT, and IDEAL-CT). A large number of private (e.g., contractors, consultants) laboratories that conduct business in California are capable of conducting the HWTT as shown in the Statewide Independent Assurance Database (SIAD) for laboratory accreditation and tester certification information.

One of the main challenges for contractors was the turn-around time between ordering the testing equipment and receiving the equipment on-site for use on the project. An example would be the waiting time for the contractor AMPT machine and the beam cutting saw for the AASHTO T 378 (RLT) and AASHTO T 321 (FBF), respectively. Both equipment took five months to arrive from Europe. To ensure the asphalt mixture design schedule could be maintained, this required sending plant-produced asphalt mixture out to university laboratories that could roll the beams and cut them for testing—sometimes it takes 1-2 months for the test results for a single trial mixture design. The contractors took the risk and purchased the equipment prior to the job being awarded to shorten the asphalt mixture design timelines.

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

The AASHTO T 321, Caltrans Test 389 (or AASHTO T 324), AASHTO T 378, and AASHTO T 283 performance tests have no information regarding the precision and bias of the test method. This may create a potential issue if two separate laboratories achieve different test results for the same asphalt mixture.

As part of a Superpave implementation initiative, the reproducibility of the HWTT (AASHTO T 324) results was evaluated through a round robin testing program that included 20 participating laboratories (UCPRC-RR-2016-05, 2015–2016): 5 district laboratories; 14 industry laboratories;

1 UCPRC. The study included different makes and models for the HWTT devices. Each laboratory conducted four HWTTs: two of the tests were conducted on Superpave gyratory-compacted (SGC) specimens prepared by UCPRC, and the other two were conducted on SGC specimens prepared by each of the participating laboratories using loose asphalt mixture supplied by UCPRC. A typical plant-produced asphalt mixture was used in this study. The following HWTT results were reported: rut depth after 5,000, 10,000, 15,000, and 20,000 wheel passes; number of passes to 0.5 inch (12.5 mm) rut depth; creep slope; stripping slope; and stripping inflection point. Raw test data from certain laboratories were also submitted to UCPRC for further analysis.

In summary, the single-operator variability was found to be relatively high and the between-laboratory variability was shown to be strongly related to several measurement and result-interpretation aspects that are not fully defined in the AASHTO T 324 test method. This between-laboratory variability was reduced when unique criteria were used in the data analysis. Precision indices were determined for only the number of passes to the stripping inflection point. The single-operator and multi-laboratory coefficients of variation (COV) were 22 and 33%, respectively. The multi-laboratory COV improved to 22% when fixed criteria was used by all laboratories in the analysis. The precision estimates of the number of wheel passes to 12.5 mm could not be determined (very limited number of tests reached this threshold value). Recommendations were made to improve the HWTT single-operator and multi-laboratory variability:

- Provide laboratories conducting HWTT with additional instructions that supplement or clarify aspects of the AASHTO T 324 test method that can be interpreted in different ways. Items that need to be clarified, specified, defined, or expanded include the following: wheelpath length; locations along the wheelpath that should be used to compute rut depth; procedure to compute the rut depth from the different measuring locations (e.g., the maximum, the average, etc.).
- Provide detailed guidelines, with examples, for defining the creep and stripping stationary phases and for determining the stripping inflection point. These guidelines, along with training and practice can reduce the between-laboratory variability in data analysis.
- Include both good- and marginal-performing asphalt mixtures in future round robin studies. Also include a raw data set for analysis by participating laboratories. This analysis can be used in the determination of the between-laboratory variability related to data analysis.

In 2019, Caltrans completed an interim study in response to the concerns raised by the California Asphalt Pavement Association (CalAPA) regarding the HWTT (AASHTO T 324, modified) being variable and the difficulty in meeting the HWTT requirements for RHMA-G. The two Pavement and Materials Partnering Committee (PMPC) working groups, California Test Method 125 and Hamburg Wheel - Track Test for RHMA-G mixes, continues to work towards a long-term solution.

According to the study, the HWTT was found to have a high interlaboratory variability. The estimate of acceptable difference between two test results (percent of mean) was up to 102.1% for HMA and 107.0% for RHMA-G. Accordingly, the following modifications were proposed by

Caltrans in the interim for the HWTT procedures and RHMA-G specifications to address the Industry's concerns:

- Reduce the number of passes to maximum rut depth for RHMA-G mixtures by 5,000 passes.
- Rather than taking the maximum of the left and right wheels, average the deepest rut depth from the left and right wheels at the specified number of passes.
- Remove the requirements for AASHTO T 324 stripping inflection point.
- Include submittal of dispute resolution data into the Data Interchange for Materials Engineering (DIME) and notification of results to the Materials Engineering and Testing Services (METS) Administrator, instead of conducting all dispute testing by METS.

Caltrans is currently leveraging available pavement condition data to assess the occurrence of rutting in RHMA-G pavements and the potential risk associated with the proposed changes.

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

The HWTT performance criteria were based upon specifications from other SHAs, and revised based on comparison of test results to historical field pavement performance. Caltrans continues to validate the HWTT criteria by sampling and testing of asphalt mixtures, monitoring field pavement performance, and comparing the results.

Caltrans continues to validate the PBS and respective test criteria through long-term performance monitoring of constructed PRS/LLAPs and ME analyses. This is accomplished by conducting distress surveys along with non-destructive testing (NDT) to estimate the in-situ properties and damage. The NDT-based information is then used in the CalME to estimate pavement distresses, which in turns are compared to observed field distresses. After over 17 years of service life, the 710 Freeway rehabilitation project is still crack free with its performance being validated in CalME. Thus, providing Caltrans and industry with additional confidence in the overall PRS approach and in particular in the CalME simulations and calibrations.

Step 8. Training and certification.

Training technicians on the procedures and analysis of test results is necessary. Caltrans, and in accordance with Code of Federal Regulations (CFR) Title 23, requires that all sampling and testing to be performed by qualified laboratories and personnel for project-produced materials used in the acceptance decision. The Caltrans Independent Assurance (IA) Program ensures that sampling and testing is performed correctly through qualification of laboratories and testers (https://dot.ca.gov/programs/engineering-services/independent-assurance-program). The general request process for laboratory accreditation and/or tester certification is as follows:

1. A request form with all required documents are first submitted by the laboratory.
2. A cursory review of the submitted package is performed for completeness.
3. If request documentation is complete, the request is then assigned to an IA staff.
4. The submitted package is reviewed by the assigned IA staff who may request additional information.

5. A laboratory accreditation and/or technician certification will be scheduled and performed by the IA staff.
6. The SIAD will be updated with laboratory accreditation and/or tester certification information (https://sia.dot.ca.gov/index.php?r-=lab%2Fsearch).

The performance tests (AASHTO T 321, AASHTO T 324, AASHTO T 378, AASHTO TP 124, and AASHTO T 283) are included in both the laboratory accreditation and tester certification. The Caltrans IA program also requires laboratory proficiency testing to evaluate laboratory equipment and practices, tester competence, and the repeatability of the test methods. The Reference Sample Program (RSP) provides laboratories an opportunity to compare their performance relative to the entire population of participating laboratories. In 2018, the RSP proficiency test was based on AASHTO T 324 for RHMA-G (https://dot.ca.gov/-/media/dot-media/programs/engineering/documents/mets/2018-aashto-t324-rsp-report-a11y.pdf). A total of 27 state and private laboratories participated in the proficiency testing and Scores of "Acceptable" were given to all participating laboratories.

Recently, Caltrans, local agencies, and industry have established a joint training and certification program (JTCP) to make the certification process more efficient and to ultimately obtain consistent, reliable, quality testing through joint training. The JTCP offers training and certification in "Hot Mix Asphalt (HMA)." The current program does not include performance testing. Caltrans envisions performance testing to be included as part of the training and certification in the future.

Before the start of I-5 (Sacramento) LLAP project, UCPRC provided an in-depth training on performance testing and sample preparation to industry and Caltrans. UCPRC staff were allowed to visit contractors' laboratories and train staff on their machine. Contractors had to quickly develop existing staff for training on a variety of new test methods including AASHTO TP 124 (I-FIT), AASHTO T 324 modified (Caltrans Test 389—HWTT), AASHTO T 331 (Corelok), and AASHTO T321 (FBF specimen preparation using RWC). Performance tests required a higher level of technician competency as compared to what is required for regular QC testing (gradation, asphalt binder content, volumetric properties).

Step 9. Implementation into engineering practice.

Caltrans has been investing significantly in research over the years to support the implementation of performance tests and PRS for design and acceptance. Caltrans originally introduced the HWTT into routine asphalt mixture designs in 2015 in order to minimize the risk of designing mixtures that are prone to rutting and stripping. This was done in partnership with the industry and in conjunction with the implementation of the Superpave asphalt mixture design method.

The increase use of recycled materials (i.e., RAP and RAS) on on-PRS/PRS projects raised additional concerns with the typical asphalt mixtures being drier, brittle, and more prone to premature cracking. Thus, Caltrans is currently evaluating the use of I-FIT or IDEAL-CT as a design and surrogate cracking test for acceptance.

The implementation of PRS on projects involved a cooperative effort between Caltrans, industry, and UCPRC for both design development and construction evaluations. This effort was carried under a Flexible Pavement Task Group for Long Life Pavement Rehabilitation Strategies (LLPRS) Program. The LLAP utilized asphalt mixture and structural pavement section designs based on SHRP developed technologies, results from the California APT Program, and innovations in construction specifications and requirements.

Research roadmaps were developed in order to assure proper and successful implementation of PRS. Figure 5 shows a pavement research roadmap for the PRS for asphalt Superpave and QC/QA with a scope of developing performance related tests and specifications for use with asphalt pavement of all types. Figure 6 show a pavement research roadmap for the ME design asphalt with a scope of establishing ME approaches and tools for asphalt surface pavement evaluation, design, and analysis. Both roadmaps lists the major tasks/projects to be accomplished under "Concept", "Research", "Development", and "Implementation." The listed tasks/projects are identified as either completed, under-going, or planned for the future. It is clear from figure 5 and figure 6 that significant effort and investments are needed for full and complete implementation of PRS for asphalt pavement of all types.

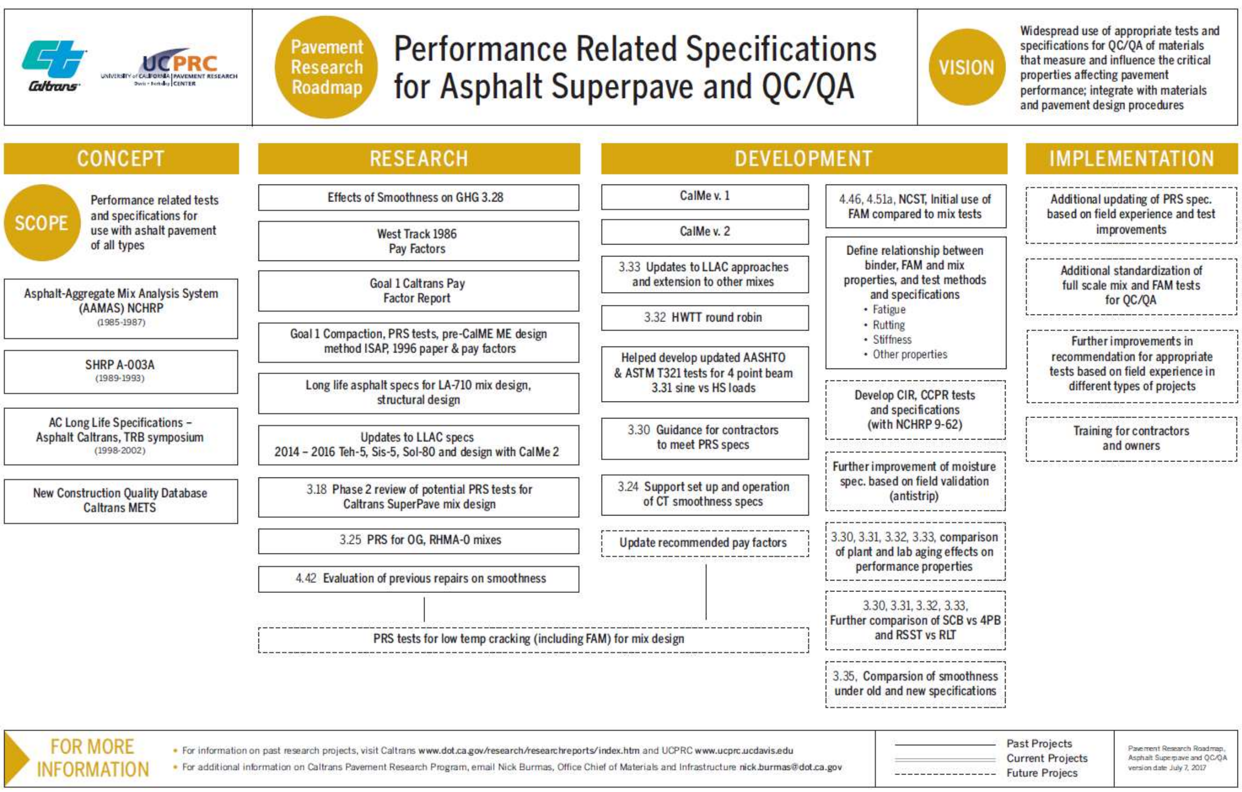


Figure 5. Chart. Caltrans pavement research roadmap for PRS and QC/QA.

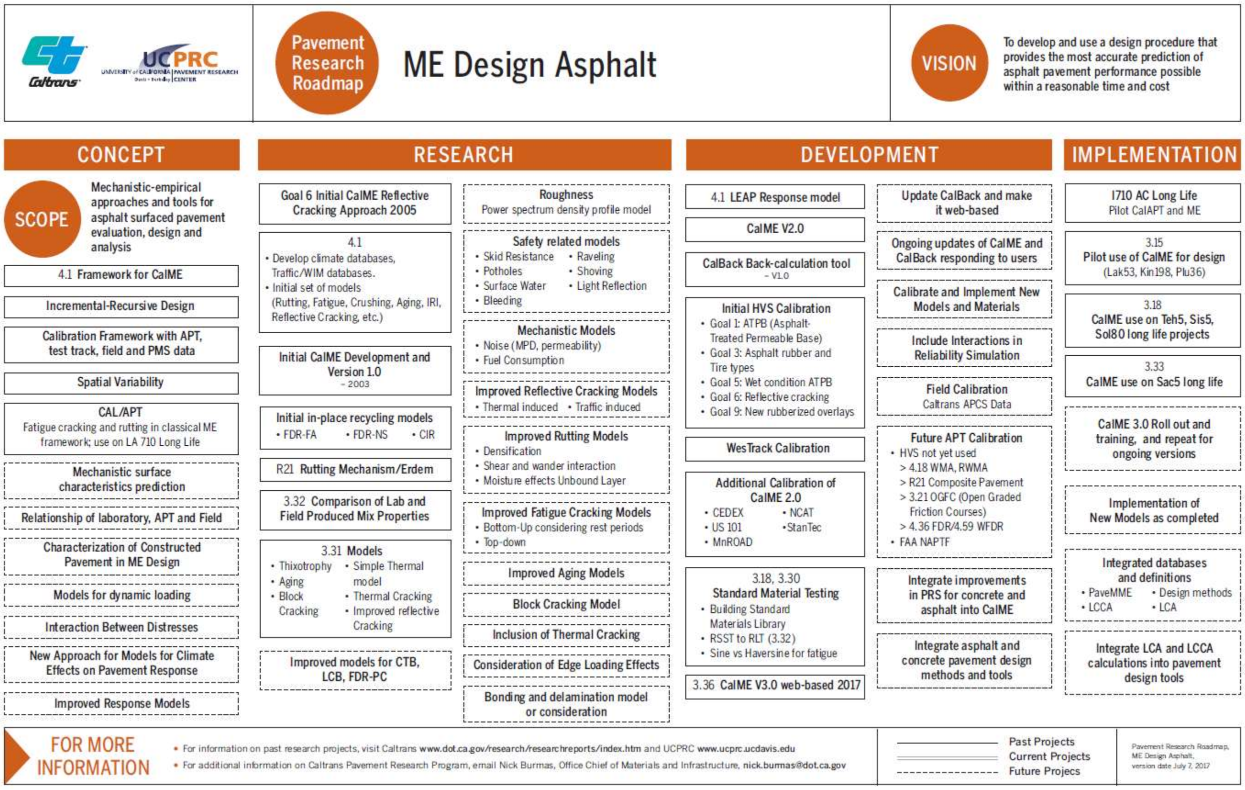


Figure 6. Chart. Caltrans pavement research roadmap for ME design asphalt.

IMPLEMENTATION OF PERFORMANCE TESTS ON PROJECTS

Caltrans has been leading and investing significantly in the process to develop and implement a BMD for all of its asphalt mixtures. Caltrans has been investing and funding PRS/LLAP projects throughout the state. A total of 5 LLAP projects have been funded between 2003 and 2020.

In general contractors were supportive of the BMD and PRS approach as a way to increase the life cycle of asphalt pavements. Continuous communication, dialogue, and partnering with industry helped in balancing both the agency and industry needs and concerns. Based on contractors experience with LLAP projects, the following observations were made:

- Changes to asphalt mixtures to get acceptable performance testing values were material and mixture specific.
    - Approached the design process from a BMD perspective and understood each component's impact on rutting (RLT, and HWTT) and cracking (I-FIT, and FBF).
        - Virgin binder selection was based on stiffness properties (not just asphalt binder being in compliance with specification).
        - Asphalt binder content was increased to improve cracking performance compared to a typical asphalt mixture used by Caltrans.
        - Understand impact of RAP binder stiffness on performance tests.
    - Employed a very structured design process for each of the LLAP mixtures and included the following steps with the goal to submit a blend for acceptance testing

that would pass (avoid wasting Caltrans and contractor resources and time by submitting designs with a marginal chance of passing).
    - Run an initial trial and measure FBF and RLT performance in relation to specifications.
    - Based on the FBF and RLT performance test results, make the appropriate adjustment to the asphalt mixture to improve the specific property in question.
    - Only one adjustment was made at a time so the impact of that adjustment could be clearly understood.
  - Evaluated gradation impact on performance testing (gradation changes from fine to coarse side of the gradation band, proximity to the 0.45 power curve).
  - Removal of natural (rounded) sand and replaced it with manufactured sand (crushed washed dust).
  - Selected the design asphalt binder content at air void contents other than 4.0% while realizing the increase in the asphalt binder content positively impacted FBF and I-FIT results.
  - Varied the RAP content in the asphalt mixture while realizing its impact on the asphalt mixture stiffness
  - Design process resulted in an asphalt mixture design that was significantly different than a typical asphalt mixture used by Caltrans:
    - Included about 0.6–0.8% more asphalt binder content (depending on the asphalt mixture).
    - Utilized a different JMF gradation than what is typically used.
    - Excluded the use of natural sand which strains sand and gravel deposits and aggregate production facilities.
    - Selected the optimum asphalt binder content closer to a 3% air voids content.
    - Required significant focus on understanding differences between coldfeed and post plant gradations and on accounting for these differences as part of plant set up and plant production adjustments. The goal was to ensure the material was produced as close as possible to JMF targets which can be a challenge with coldfeed being acceptance location for HMA gradation.
- Several challenges and risks existed during asphalt mixture acceptance:
  - Lack of performance test history. Because asphalt mixture design acceptance is based on plant-produced material only, contractors were unsure whether to spend time testing laboratory mixed and laboratory compacted specimens or just proceed straight to testing plant-produced asphalt mixtures. Contractors did not understand if there would be a difference in performance test results between the two methods. Due to test turnaround time issues (mainly for FBF), contractors decided to proceed with plant trials only to optimize the blend before doing the actual asphalt mixture design. This led to unanticipated costs and a high number of plant hot drops to complete the designs.
  - Test results from FBF (AASHTO T 321, modified) and RLT (AASHTO T 378, modified) appeared to be highly variable between test samples from the same plant-produced asphalt mixture and plant hot drop. Typically the plant-produced-asphalt mixture had failing RLT test results when the HWTT results for the same

    - mixture had routinely rut depths of only 1.3 to 4 mm with a much higher repeatability compared to the RLT test.
  - Prior to submitting the flexural beam samples to UCPRC for final JMF testing, samples were sent to multiple research laboratories. Samples routinely failed flexural beam stiffness and fatigue specification limits set by the project.
  - Approximately 30 plant hot drops (each a minimum of 100 tons or 20–30 minutes of continuous production) were required for the FBF testing process for the three LLAP mixture designs. Multiple hot drops were ran with little or no changes to plant setup—this resulted in big swings in RLT and FBF test results for very little or no change in plant setup.
  - There was a concern that a passing blend may not be achievable as contractors had exercised asphalt mixture changes that are known to positively impact performance. Consistent passing results were not observed.
  - There appeared to be a disconnect between laboratory mixed data used to develop the specifications and the contractor requirement to base their asphalt mixture designs on plant-produced material.
  - Between bid time and asphalt mixture design verification, specifications for both RLT and FBF were changed driving increased effort, time, and cost.
  - During production test results were going in and out of specification for RLT test that is being run daily with little or no variability in asphalt binder content or aggregate gradation. This was anticipated based on the performance test variability observed during the acceptance process
- The following are proposed future activities that can help improving and advancing the overall process:
  - Ensuring the asphalt mixture design specification is producible (reduce variability and number of plant hot drops).
    - Little to no plant change is resulting in significant variability in RLT and FBF test results.
  - The RLT and FBF test methods being highly variable bring into question the return on investment (ROI) of the design process leading to the following questions:
    - Is the public getting a better asphalt mixture in the most economical way? Would a more simplified BMD system arrive at a similar final design?
    - Is the high capital cost of the AMPT equipment providing sufficient ROI?
  - With the performance testing requirements, understanding the difference between coldfeed and post plant gradations and consistently hitting JMF targets on the post plant gradation is critical. The current Caltrans HMA specification accepts gradation on the coldfeed making it difficult for the contractor to optimize pay on coldfeed while at the same time ensuring post plant gradations are targeting the JMF. It is recommended that Caltrans move gradation acceptance to post plant gradations as to align the gradation acceptance point with the asphalt mixture design JMF where performance testing and volumetric testing occurs.
  - Use of I-FIT and RLT as daily QC tool in production may not be practical due to sample preparation, turnaround time and for the RLT, test method repeatability. In addition, the RLT does not appear to coincide with the low rutting results from the HWTT.

    - Utilize the extensive production testing data for RLT, FBF, and I-FIT generated on the I-5 (Sacramento) LLAP project to understand the test method variability and ensure that variability is built into all future Caltrans project specifications.
        - In addition, share this test method variability information with national efforts working on this topic.
- The I-5 (Sacramento) LLAP project has resulted in a very positive partnering experience with Caltrans, UCPRC, and contractors. All teams have worked together on all issues encountered and relationship is very positive and healthy.
- It is believed that the BMD concept will result in better designed longer lasting pavements. Projects like this help advance the contracting community as a whole and contractors were appreciative to be part of this effort.
- The partnership and continuous discussion between Caltrans, industry, and UCPRC is key for a successful implementation of performance tests for design and acceptance of asphalt mixtures.
- UCPRC has provided significant support related to the new equipment used on the I-5 (Sacramento) LLAP project including joint training and sample exchanges as contractors worked to get their team up to speed and ready for the project. Contractors are very appreciative of UCPRC support.
- Contractors are concerned that the test variability will impact the asphalt mixture design re-verification process in 2021 and could result in many plant hot drops (with little to no plant changes) just to arrive at passing results.

OVERALL BENEFITS

The use of PRS on field projects allowed contractors to optimize the use of recycled materials and still be able to produce asphalt mixtures that are in compliance with Caltrans specifications. The traditional volumetric-based mixture design has lots of changes to 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.

No problems were encountered with constructing asphalt pavements using a BMD mixture. The asphalt mixtures designed using the PBS 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. For the existing LLAPs no major pavement maintenance activities have been warranted yet other than regularly scheduled preventive maintenance.

In summary, the PRS helps to ensure that as-built materials meet the performance requirements assumed in ME pavement structural designs. Furthermore, PRS approach provides Caltrans with a system to evaluate non-traditional material properties such as plastic-modified or high RAP and RAS asphalt mixtures.

FUTURE DIRECTION

Caltrans plans to expand the use of LLAPs approach where the top AC layer is high rut resistant, the intermediate AC layer is stiff and rut resistant, and the bottom AC layer is rich in asphalt binder with high resistance to fatigue cracking. It also plan on implementing a cracking test for Superpave asphalt mixtures used on non-PRS projects. The following summarizes key activities for Caltrans:

- Continue to work on pilot projects and related research studies for the implementation of performance testing for routine asphalt mixture design, quality control, and assurance testing. Modify performance specifications and testing equipment as found needed.
- Complete the CalME software evaluation and calibration including the performance testing on HMA Type A and RHMA-G asphalt mixtures from different geographical regions within California.
- Conduct Heavy Vehicle Simulator testing of trial sections including the evaluation of cold-in place recycling as a base layer, thick lift RHMA-G pavement, coarse aggregate versus fine aggregate size asphalt mixtures (19 mm versus 12.5 mm), high RAP and reclaimed asphalt shingles (RAS) asphalt mixtures, and RHMA-G asphalt mixtures with 5–10% RAP aggregate.
- Establish a project selection criteria based on asphalt mixture tonnage usage for PRS/LLAPs (e.g., 50,000 to 100,000 tons).
- Plan for additional training to laboratory technicians and design engineers to cope the potential future challenges associated with BMD and the LLAP design approach.
- Continue to improve and revise the asphalt mixture guidance that was established to support mixture designers and contractors with their decision making regarding changes to asphalt mixture designs to achieve PRS requirements

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

Positive Practices

- The motivations for implementation of performance tests in Caltrans was primarily two-fold: 1) with the implementation of Superpave asphalt mixture design methodology, there was a need to replace the Hveem stability test with another performance test; and 2) the asphalt pavement industry was faced with the challenge of building LLAPs that can last more than 30 years using PRS that are based on ME design.
- Partnering with and collaboration between Caltrans, 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, having a strong commitment, support, and contribution to the development effort of BMD and PRS have been imperative.
  - Establishing a Flexible Pavement Task Group for Long Life Pavement Rehabilitation Strategies (LLPRS) Program that comprised Caltrans, industry, and academia helped in accelerating the implementation efforts by involving key stakeholders in the related activities and decisions. Things did not always go smoothly, but Caltrans took the lead in keeping the implementation effort moving forward.
  - Externally, having strong and established relationships with academia (i.e., UCPRC at UC Davis) 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.
  - Externally, having industry partners that are providing constructive feedback comments based on their experience with LLAP 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.
- Caltrans uses the HWTT with its non-PRS asphalt mixtures. It first fully implemented the HWTT in 2015. Caltrans uses the RLT (RSST in the past) and FBF with its PRS.
- Caltrans has been going through a rigorous process for implementing PRS into engineering practice. Roadmaps were developed for the implementation of PRS and ME analysis.
- 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.
- Caltrans funded research studies to evaluate the sensitivity of performance tests to material properties for typically used asphalt mixtures in California (Step 2). This provided asphalt mixture designers and contractors guidance regarding changes to asphalt mixture designs to achieve PRS requirements.
  - A guidance was established based on past experience that was then validated and demonstrated using an approved plant-produced asphalt mixture by Caltrans.
  - A flowchart for design guidance was developed for improving the fatigue or rutting performance of an asphalt mixture.
- The top factors in selecting performance tests were (Steps 3 and 7):
  - The material sensitivity, field validation, and repeatability are key considerations in the development and implementation of performance test into the specifications.
  - Sample preparation, specimen conditioning and testing time, and equipment cost are also important factors for Caltrans in the development of test criteria and the implementation of performance tests into the specifications.
  - 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.

- Caltrans has been funding several round robin studies to determine the single and multiple operator variability (Step 6).
    - The round robins help to understand the variability in the test and to provide contractors with comparison data between their device and Caltrans devices.
- Having a training and certification IA program in-place for testing and evaluating asphalt mixtures and aggregates that is supported by Caltrans facilitated the training of technicians on performance tests (Step 8).
    - Contractors had to invest and dedicate time for staff training.
- Keys to implementation (Step 9) included:
    - Having and funding LLAP projects across the state so that contractors can have an opportunity to gain experience and become familiar and comfortable with PRS. The LLAP projects require significant investments.
    - Initially not tying performance test results to pay factors.
    - Helping and supporting contractors with performance tests (offering training on equipment and test result calculations) to gain knowledge about their own asphalt mixtures.
    - Conducting a trial paving before start of project construction was essential for the paving crew to learn about and how to deal with the asphalt mixtures that will be used during construction by adjusting their construction practices (e.g., compaction efforts, rolling patterns, workability of the rich bottom asphalt mixture, etc.).
- There have been benefits:
    - The PRS allowed contractors to use higher amount of recycled materials while producing asphalt mixtures that are in compliance with specifications.
    - The asphalt mixtures designed using the PRS 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.
    - For the existing LLAPs no major pavement maintenance activities have been warranted yet other than regularly scheduled preventive maintenance.
    - The PRS approach provided Caltrans with a system to evaluate non-traditional material properties such as plastic-modified or high RAP and RAS asphalt mixtures.

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 and mixture specific.
        - Approached the design process from a BMD perspective and understood each component's impact on rutting (RLT, and HWTT) and cracking (I-FIT, and FBF).

        - Virgin binder selection was based on stiffness properties (not just asphalt binder being in compliance with specification).
        - Asphalt binder content was increased to improve cracking performance compared to a typical asphalt mixture used by Caltrans.
        - Understand impact of RAP binder stiffness on performance tests.
        - Do not focus solely on changes to aggregate sources and gradations.
    - Employed a very structured design process for each of the LLAP mixtures and included the following steps with the goal to submit a blend for acceptance testing that would pass.
        - Run an initial trial and measure FBF and RLT performance in relation to specifications (start with a typical asphalt mixture with known historical performance).
        - Based on the FBF and RLT performance test results, make the appropriate adjustment to the asphalt mixture to improve the specific property in question.
        - Only one adjustment was made at a time so the impact of that adjustment could be clearly understood.
    - Evaluated gradation impact on performance testing (gradation changes from fine to coarse side of the gradation band, proximity to the 0.45 power curve).
    - Removal of natural (rounded) sand and replaced it with manufactured sand (crushed washed dust).
    - Selected the design asphalt binder content at air void contents other than 4.0% while realizing the increase in the asphalt binder content positively impacted FBF and I-FIT results.
    - Varied the RAP content in the asphalt mixture while realizing its impact on the asphalt mixture stiffness
    - Design process resulted in an asphalt mixture design that was significantly different than a typical asphalt mixture used by Caltrans:
        - Included about 0.6–0.8% more asphalt binder content (depending on the asphalt mixture).
        - Utilized a different JMF gradation than what is typically used.
        - Excluded the use of natural sand which strains sand and gravel deposits and aggregate production facilities.
        - Selected the optimum asphalt binder content closer to a 3% air voids content.
        - Required significant focus on understanding differences between coldfeed and post plant gradations and on accounting for these differences as part of plant set up and plant production adjustments.
- Having technicians dedicated to performance testing would accelerate the turnaround time for test results.
- Establishing an approved JMF is very time consuming (could take 1–2 years) and requires significant investments and resources from the contractor. The cost and

time for establishing a JMF is expected to reduce by gaining more experience with and understanding of the process.

- Plant operation processes:
    - Plant-produced asphalt mixtures typically exhibited different performance test results than laboratory-produced asphalt mixtures.
    - Contractors had to invest in new equipment/test capabilities.
        - Allows contractor for use of equipment outside of this specific project including: Pavement design support including the ability to measure dynamic modulus and forensics.
- Proper planning and preparation for laboratory workspace is needed. One contractor faced an issue with power source when started testing using the AMPT for JMF evaluation. The contractor had to invest $30,000– $40,000 in laboratory upgrades for delivering a clean power source to the AMPT device (to protect the equipment electronics).
- The following are proposed future activities that can help improving and advancing the overall process based on lessons learned and current experience with LLAP project:
    - Ensuring the asphalt mixture design specification is producible (reduce variability and number of plant hot drops).
        - Little to no plant change is resulting in significant variability in RLT and FBF test results.
    - With the performance testing requirements, understanding the difference between coldfeed and post plant gradations and consistently hitting JMF targets on the post plant gradation is critical.
        - The current Caltrans HMA specification accepts gradation on the coldfeed making it difficult for the contractor to optimize pay on coldfeed while at the same time ensuring post plant gradations are targeting the JMF.
        - It is recommended that Caltrans move gradation acceptance to post plant gradations as to align the gradation acceptance point with the asphalt mixture design JMF where performance testing and volumetric testing occurs.
    - Use of I-FIT and RLT as daily QC tool in production may not be practical due to sample preparation, turnaround time and for the RLT, test method repeatability.
    - Utilize the extensive production testing data for RLT, FBF, and I-FIT generated on the I-5 (Sacramento) LLAP project to understand the test method variability and ensure that variability is built into all future Caltrans project specifications.
    - Due to the technical complexity of the project mix design process, this facilitated greater communication between project, plants and quality personnel.

<u>Challenges</u>

- Challenges were faced by contractors with staffing and equipment in order to meet the PRS requirements.
    - On the equipment side, one of the main challenges was the turn-around time between ordering the LLAP testing equipment and receiving the equipment on-site for use on the project. An example would be the waiting time for the contractor AMPT machine and the beam cutting saw for the AASHTO T 378 and

AASHTO T 321, respectively. Both equipment took five months to arrive from Europe (the waiting time for the I-FIT equipment was about 1–1.5 month). To ensure the asphalt mixture design schedule could be maintained, this required sending plant-produced asphalt mixture out to university laboratories that could roll the beams and cut them for testing—sometimes it takes 1-2 months for the test results for a single trial mixture design. The contractors took the risk and purchased the equipment prior to the job being awarded to shorten the asphalt mixture design timelines.

    - Contractors acquired the necessary performance tests equipment made by the same manufacturers of those used at UCPRC. This decision was made by contractors to help in simplifying and accelerating the training and support activities provided by UCPRC.

  - On the staffing side, contractor had to quickly develop existing staff for training on a variety of new test methods including AASHTO TP 124 (I-FIT), AASHTO T 324 (HWTT), AASHTO T 331 (Corelok), and AASHTO T321 (FBF specimen preparation using RWC).
  - Performance tests required a higher level of technician competency as compared to what is required for regular QC testing (gradation, asphalt binder content, volumetric properties).

- The increased use of recycled materials raised additional concerns with the typical asphalt mixtures (non-PRS) designed using only HWT being drier, brittle and more prone to premature cracking.
- Several challenges and risks existed during asphalt mixture acceptance:
  - The lack of performance test history forced contractors to test and optimize the design of plant-produced asphalt mixtures.
    - Contractors did not have a good understanding of the difference in performance test results between laboratory and plant-produced asphalt mixtures.
    - This led to unanticipated costs and a high number of plant hot drops (minimum 100 tons) to complete the asphalt mixture designs.
  - High variability is observed in test results from FBF (AASHTO T 321, modified) and RLT (AASHTO T 378, modified).
  - Asphalt mixture samples were routinely failing the flexural beam stiffness and fatigue specification limits set by the project.
    - Approximately 30 plant hot drops (each a minimum of 100 tons) were required for the FBF testing process for the three LLAP mixture designs.
    - Multiple hot drops were ran with little or no changes to plant setup—this resulted in big swings in RLT and FBF test results for very little or no change in plant setup.
  - There was a concern that a passing blend may not be achievable as contractors had exercised asphalt mixture changes that are known to positively impact performance. Consistent passing results were not observed.
  - There appeared to be a disconnect between laboratory mixed data used to develop the specifications and the contractor requirement to base their asphalt mixture designs on plant-produced material.

  - Between bid time and asphalt mixture design verification, specifications for both RLT and FBF were adjusted driving increased effort, time, and cost.
  - During production test results were going in and out of specification for RLT test that is being run daily with little or no variability in asphalt binder content or aggregate gradation.
- The HWT performance test method lack precision and bias, thus creating a potential issue if two separate laboratories achieve different test results for the same asphalt mixture.
- The results from performance testing are needed promptly so that contractors can make decisions on production based on the results.

RESEARCH AND DEPLOYMENT OPPORTUNITIES

Caltrans suggests the following research and deployment topics:

- Evaluation and assessment of the use of recycled plastic in asphalt mixtures.
- 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.

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