NCHRP Project 20-44(16)
IMPLEMENTATION OF THE IDEAL CRACKING TEST FOR ASPHALT MIX DESIGN AND QC/QA

FINAL REPORT

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EXECUTIVE SUMMARY

Many state departments of transportation (DOTs) have been implementing the balanced mix design (BMD) method to address the durability issue of asphalt mixes. One of the critical components of any BMD method is the cracking performance test. The ideal cracking test (IDEAL-CT) developed under the National Cooperative Highway Research Program (NCHRP) IDEA Project 195 has been adopted by 14 states as their cracking test. To further facilitate implementation and adoption, the research team assisted six DOTs (Kentucky, Maine, Minnesota, Oklahoma, Texas, and Virginia) with their implementation efforts via a demonstration workshop and by developing webinars, training videos, and flyers for technicians, managers, and engineers. Furthermore, a coherent framework for BMD and quality control/quality acceptance (QC/QA) was recommended, with an emphasis on using the same performance tests for both BMD and QC/QA. Moreover, the research team developed two practical loose-mixture aging protocols, one for short-term aging used in the process of the volumetric mix design, the mixture performance evaluation, and the production QC/QA testing, and the other for mid-term aging employed in mixture performance verification. The recommended short-term aging protocol is to age the loose mixture in a force draft oven for 2 hr at the mixture compaction temperature, while the mid-term aging protocol consists of three steps: (1) short-term aging, (2) 20-hr loose-mixture aging at 100°C, and (3) reheating for compaction. A case study presented in Chapter 4 demonstrates the whole process of the framework, including the actual plant production QC testing.

CHAPTER 1. INTRODUCTION

BACKGROUND

The focus in recent years has been to make asphalt mixes more affordable, and this emphasis has led to the increased use of recycled materials and binder modifications. Consequently, premature cracking of asphalt mixes has become a national problem, and an urgent need exists for a practical and reliable cracking test for routine use in the process of mix design, QC, and QA testing. Various cracking tests have been developed, but none of them are simple enough for routine use, especially for QC testing in contractors' field labs. To address this problem, NCHRP 20-30/IDEA 195 has developed an IDEAL-CT integrated with seven features:

- Simplicity: no instrumentation, cutting, gluing, drilling, or notching.
- Practicality: minimum training needed for routine operation.
- Efficiency: test completion within 1 min.
- Affordable test equipment: existing or low-cost equipment.
- Repeatability: coefficient of variation (COV) less than 20 percent.
- Sensitivity: sensitive to mix factors (recycled materials, aggregates, binder, aging).
- Good correlation with field cracking performance: validated with field test sections in Texas, at long term pavement performance - specific pavement studies-10 (LTPP SPS-10) in Oklahoma, at the Federal Highway Administration (FHWA)-Accelerated Loading Facility, and at the National Center for Asphalt Technology (NCAT) test track.

The researchers also established and partially validated cracking criteria for different types of asphalt mixes and developed an ASTM standard for the test: D8225-19 *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*. Furthermore, the researchers collaborated with several equipment manufacturers to make low-cost, stand-alone IDEAL-CT equipment or test fixtures intended for use with existing load frames.

OBJECTIVE

The overall objective of this project was to demonstrate and assist six DOTs in implementing the IDEAL-CT for BMD and QC/QA through a demonstration workshop and development of webinars, training videos, and flyers for technicians, managers, and engineers. The six DOTs are Kentucky, Maine, Minnesota, Oklahoma, Texas, and Virginia.

REPORT ORGANIZATION

This report documents the overall research results of NCHRP 20-44(16) and contains four chapters in addition to this introduction. The IDEAL-CT demonstration workshop is described in Chapter 2 and documents the IDEAL-CT test results of the asphalt mixes sent from six DOTs. Chapter 3 presents the webinars, training videos, and flyers for technicians, managers, and engineers. Chapter 4 recommends a coherent framework for BMD and QC/QA with the IDEAL-CT. Chapter 5 concludes the report with a summary and recommendations.

CHAPTER 2. IDEAL-CT DEMONSTRATION WORKSHOP

INTRODUCTION

Demonstration is an effective way to assist in implementing something new. To help the IDEAL-CT implementation, the research team held a demonstration workshop at the Texas A&M Transportation Institute (TTI). The overall goal of this workshop was to demonstrate the IDEAL-CT with specific mixes from each participating state and to address practical issues each state may encounter in the process of implementing the IDEAL-CT (Figure 1). The following section describes the demonstration workshop.

DEMONSTRATION WORKSHOP

The IDEAL-CT demonstration workshop was held in College Station, Texas, on November 13, 2019. One or two representatives from five states—Kentucky, Maine, Oklahoma, Texas, and Virginia—attended the demonstration workshop. Note that no representative attended from the state of Minnesota because of a schedule conflict.

Before the workshop, the research team received two mixes from each of the six participating states. For each specific mix, the research team prepared three IDEAL-CT specimens following the steps described below:

- Mold trial specimens: Use the first bucket of plant mix to mold trail specimens with different weights.
- Determine the weight for molding specimens with 7 percent air voids: Measure the air voids of those trial specimens to determine the weight of each loose mix for an IDEAL-CT specimen with 7 percent air voids.
- Mold demonstration specimens: Use the second bucket of the plant mix to mold three test specimens for demonstration testing on November 13, 2019.

At the workshop, the research team made a presentation (see Appendix A) to discuss the latest work on the IDEAL-CT. Moreover, the state representatives updated the status of the IDEAL-CT implementation in each state. Next, the search team demonstrated specimen preparation and conditioning, performed the IDEAL-CT test at the TTI asphalt laboratory, and interpreted data. In addition, the research team also demonstrated two more test apparatuses:

- IDEAL Rutting Test (IDEAL-RT): IDEAL-RT (Figure 2) has similar features to those of IDEAL-CT, but it is for evaluating rutting resistance of asphalt mixes. It is a companion test to the IDEAL-CT for BMD and QC/QA testing.
- IDEAL-CT validator: An IDEAL-CT validation device was demonstrated at the workshop. The validator has a constant CT_{Index} value, and it can be used to check validity of each IDEAL-CT machine. It is critical to ensure that IDEAL-CT machines are comparable in terms of CT_{Index}. Otherwise, many conflicts will arise when comparing test results among laboratories and consequently also arise for QC/QA testing.

Finally, the research team tested all the specimens prepared with the plant mixes sent from each participating state. Table 1 presents the IDEAL-CT test results. The test results matched the expectations of the participating states.

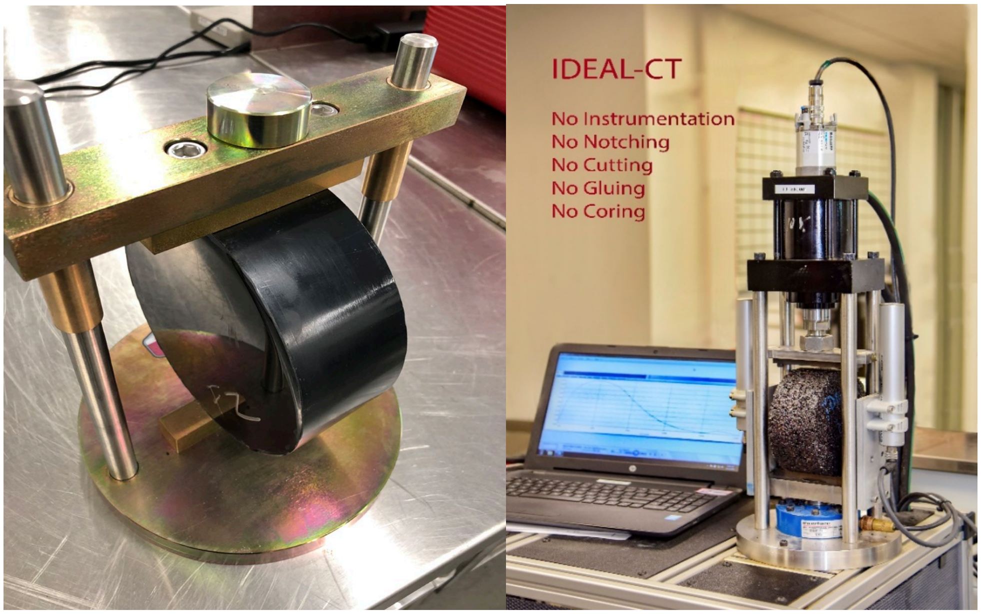


Figure 1. IDEAL-CT.

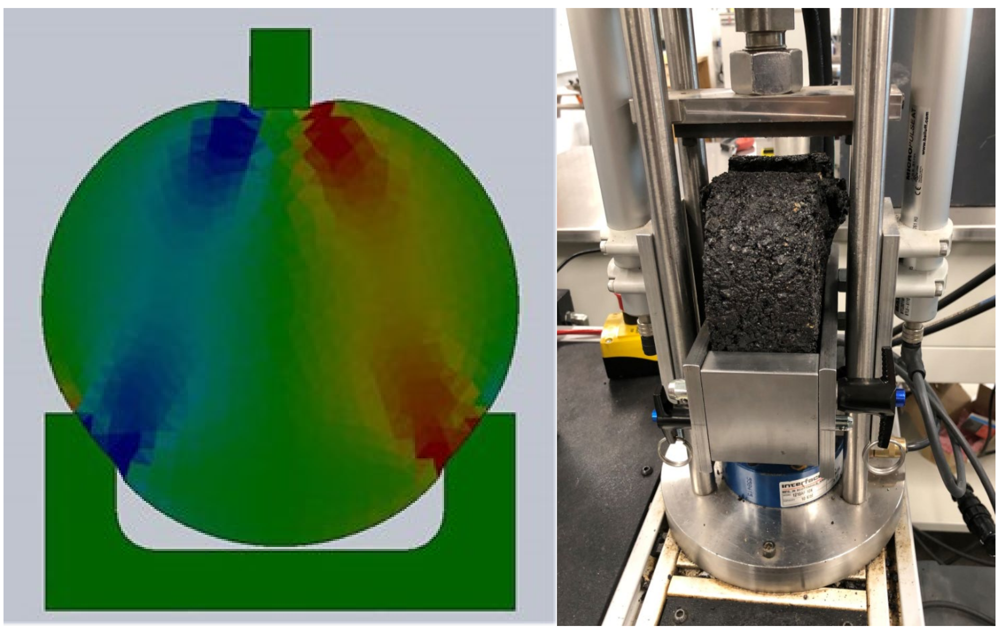


Figure 2. IDEAL-RT.

SUMMARY

The research team demonstrated to the representatives from participating states specimen preparation and conditioning and tested all the specimens made with plant mixes from each state at the workshop. The test results matched the expectations of the participating states. Furthermore, the research team also demonstrated the IDEAL-RT and the IDEAL-CT validator, which are critical for both BMD and QC/QA testing.

Table 1. IDEAL-CT Results of Asphalt Mixes from Six DOTs.

State	Mix	IDEAL-CT Index				
		Replicate	Individual CT_{Index}	Average	Standard deviation	COV (%)
Maine	Mix 1	1	200.4	226.77	23.06	10.17
		2	243.2			
		3	236.7			
	Mix 2	1	85.4	72.10	13.15	18.24
		2	59.1			
		3	71.8			
Minnesota	Mix 1	1	112.1	109.23	3.97	3.64
		2	110.9			
		3	104.7			
	Mix 2	1	59.6	75.10	14.49	19.29
		2	77.4			
		3	88.3			
Virginia	Mix 1	1	158.3	153.03	7.94	5.19
		2	143.9			
		3	156.9			
	Mix 2	1	84.3	97.80	15.29	15.63
		2	94.7			
		3	114.4			
Texas	Mix 1	1	87.9	84.00	5.91	7.04
		2	86.9			
		3	77.2			
	Mix 2	1	290.6	272.67	17.70	6.49
		2	272.2			
		3	255.2			
Kentucky	Mix 1	1	158.9	154.07	5.69	3.69
		2	147.8			
		3	155.5			
	Mix 2	1	231.1	200.30	27.34	13.65
		2	190.9			
		3	178.9			
Oklahoma	Mix 1	1	229.5	248.80	17.17	6.90
		2	254.5			
		3	262.4			
	Mix 2	1	118.8	122.12	17.54	14.36
		2	106.5			
		3	141.1			

CHAPTER 3. DEVELOPMENT OF IDEAL-CT WEBINARS, TRAINING VIDEO FOR TECHNICIANS, AND FLYERS FOR BOTH MANAGERS AND ENGINEERS

INTRODUCTION

In addition to the demonstration workshop documented in Chapter 2, the research team developed a series of IDEAL-CT webinars for the participating states, a training video for laboratory technicians, and flyers for managers and engineers to further facilitate implementation of the IDEAL-CT in BMD and QC/QA testing. Moreover, a presentation was made at the 2020 annual meeting of the Transportation Research Board (TRB). Details are provided below.

DEVELOPMENT OF IDEAL-CT WEBINARS AND TRB PRESENTATION

The research team held seven webinars with the implementation group on August 28, 2019, October 25, 2019, December 16, 2019, February 27, 2020, June 3, 2020, August 4, 2020, and December 17, 2020, respectively. An example of the webinar presentations is given in Appendix B. The research team communicated the latest development of the IDEAL-CT and addressed several practical implementation issues, such as test equipment from different manufacturers, air voids correction factor, validator, and precision and bias through the round robin test. In addition, the research team also presented the IDEAL-CT at the 2020 annual meeting of the TRB.

DEVELOPMENT OF AN IDEAL-CT TRAINING VIDEO FOR TECHNICIANS

The research team also developed an IDEAL-CT training video to assist laboratory technicians. The video describes the critical steps of ASTM D8225, including specimen preparation, air voids measurement, specimen conditioning, running the IDEAL-CT test, and interpreting the test data. The research team uploaded the training video to YouTube at the following link: https://www.youtube.com/watch?v=MNcaOpc9QRE.

DEVELOPMENT OF FLYERS AND A VIDEO FOR BOTH MANAGERS AND ENGINEERS

To facility the adoption and implementation of the IDEAL-CT, the research team developed two one-page flyers. One of the flyers, intended for DOT senior management, describes the benefits and the cost implications. The second flyer is for DOT bituminous engineers and hot mix specialists so they will have more technical information on the test set-up, proposed criteria, and step-by-step implementation recommendations. Specifically, the research team interviewed representatives from DOTs, research institutions, and asphalt industry private laboratories to discuss different aspects of the IDEAL-CT. The interview video can be viewed at https://www.youtube.com/watch?v=GZrDaHGM-4M.

SUMMARY

To facilitate implementation of the IDEAL-CT in BMD and QC/QA testing, the research team developed seven IDEAL-CT webinars for the participating states, one training video for laboratory technicians, and two flyers and one interview video for managers and engineers. The research team also presented the IDEAL-CT at the 2020 TRB meeting in Washington, DC.

CHAPTER 4. RECOMMENDATION OF A COHERENT FRAMEWORK FOR BMD AND QC/QA WITH IDEAL-CT

INTRODUCTION

Asphalt mixtures are becoming increasingly complex. In the last 10 years, the use of reclaimed asphalt pavements (RAP), recycled asphalt shingles (RAS), fibers, and rejuvenators in some cases, has become the new norm. Furthermore, asphalt binder sources, refineries, and modification techniques (polyphosphoric acid, re-refined engine oil bottom, recycled plastics, and others) are dynamically changing the landscape for mixtures. Given ever-changing components of asphalt mixtures, many state DOTs are in the process of developing or preliminarily implementing some type of performance specification for asphalt mixtures to ensure mixture durability. For example, many DOTs initiated the BMD approaches (Zhou et al. 2007, Bennert 2011, Zhou et al. 2014, Mohammad and Cooper 2016, Buttlar et al. 2016, Ozer and Al-Qadi 2018, West et al. 2018, Newcomb and Zhou 2018). BMD is a crucial step forward in designing a well-performing mix with balanced rutting and cracking resistance, but it is not the whole performance specification. Another critical component of a performance specification is QC/QA testing during the production process. Regardless of how well a mixture is designed in a laboratory, if the mixture quality is not properly controlled during production, the mixture performance in the field could be jeopardized. Current production QC/QA testing focuses on three major characteristics of asphalt mixtures: asphalt content, aggregate gradation, and laboratory-compacted density. These characteristics are important, but sometimes they are not directly related to mixture performance. For example, during the production process, one may have to replace one source of PG64-22 asphalt binder with another binder source due to supply shortage. This replacement of the binder source often has no influence on asphalt binder content, aggregate gradation, and volumetric properties, so the produced mixture will pass all three QC/QA tests. However, such replacement could have a significantly negative influence on cracking resistance (Mogawer et al. 2019). To ensure what is produced at the plant is similar to what was originally designed in the laboratory, the same (or similar) performance tests used for BMD are preferred for production QC/QA testing. However, some performance tests are suitable for BMD, but they may not be practical for QC testing. For example, the Hamburg Wheel Tracking Test (HWTT) has been widely used by many DOTs in mixture design to ensure adequate rutting/moisture damage resistance. However, the long testing period of HWTT prevents it from being an efficient test to implement for production QC. Therefore, the main objective of Chapter 4 is to recommend a coherent framework for both laboratory BMD and production QC/QA, which includes the newly developed concept of *mid-term* aging.

This chapter first presents the envisioned framework, which includes four major components: (1) volumetric mix design, (2) performance evaluation of multiple asphalt contents and selection of a balanced binder content, (3) performance verification of the selected balanced asphalt content, and (4) a QC/QA testing plan and associated acceptance criteria. This chapter further discusses the following three areas:

- Selection of performance tests for the framework.
- Laboratory aging (or conditioning) protocols for preparing specimens.
- Performance tests' criteria and strategies for meeting those criteria.

In addition, a case study is presented to demonstrate the whole process of the coherent BMD/QC/QA framework.

ENVISIONED COHERENT BMD/QC/QA FRAMEWORK

Designing stable and durable asphalt mixtures has been pursued by different methods for decades. Generally, mixture stability (or rutting resistance) is controlled through a strength test, such as Marshall stability, while mix durability (e.g., cracking resistance) is often ensured by adequate asphalt binder content through volumetric requirements—for example, air voids and voids in mineral aggregate. The BMD concept was not introduced until 2007 when Zhou et al. (2007) employed two performance tests—the HWTT and Texas Overlay Test (OT)—to evaluate rutting and cracking resistance of asphalt mixtures under multiple asphalt contents selected based on volumetric mix design. Three specific features of the original BMD concept are as follows (Zhou et al. 2007): (1) allowing air void variation from 2 to 5 percent when selecting asphalt contents for performance evaluation, (2) multiple (3 or 4) asphalt contents selected for performance evaluation, and (3) relying on rutting/moisture damage and cracking performance tests and associated criteria to define a balanced asphalt content zone/range meeting both rutting and cracking requirements. Since then, different forms of BMD have been explored. In 2015, FHWA formed a BMD task force, and the task force identified three potential approaches to the use of BMD: (1) volumetric design with performance testing validation, (2) performance-modified volumetric mix design, and (3) performance design. Each approach has its advantages and limitations. Comparatively, Approach 1 is the easiest one to understand and implement, but it is limited to the evaluation of a single selected asphalt content with 4 percent air voids. A necessary enhancement to Approach 1 is to test three asphalt contents with the same aggregate blend but that correspond to air voids varying from 2 to 5 percent, as proposed by Zhou et al. (2007). Approach 2 is a performance-modified volumetric mixture design. This approach is similar to the first approach in that it starts by determining the optimum binder content using the Superpave volumetric design method but subsequently focuses on meeting mixture performance test criteria. The mixture design binder content and/or proportions can be adjusted to accommodate the performance test requirements. The final design may not be required to meet all the volumetric Superpave criteria. The accuracy of the performance tests and performance models in Approach 2 becomes extremely important since final mix design is dictated by performance tests and models rather than volumetric properties. Approach 3 is a reverse version of Approach 1. Performance requirements are met first, and then the mixture volumetric properties are determined. Implementing Approach 3 requires mindset changes that are not intuitive to most asphalt mix technologists. These design approaches have been attempted with varying degrees of success in the past. However, only limited work has been done for production QC/QA testing within the BMD framework. Building on existing knowledge and experiences with BMD and QC/QA testing at asphalt plants, the research team developed a coherent framework for BMD/QC/QA (see Figure 3), including four major components: (1) volumetric mix design, (2) performance evaluation at multiple asphalt contents to select the balanced asphalt content, (3) performance verification at the balanced asphalt content, and (4) development of QC/QA testing plan and acceptance criteria. Each of the components is briefly described below.

Volumetric Mix Design

Volumetric properties of asphalt mixtures have been the backbone of asphalt mix design methods and production QC/QA testing for decades. Not only are current mix designers very familiar with the volumetric designs, but they have also accumulated much useful experience that can help implement a coherent BMD/QC/QA framework. In the envisioned framework, the volumetric mix design will serve the following two purposes:

- The next-step selection of multiple asphalt binder contents for performance evaluation: Based on longstanding practice, the asphalt content at 96 percent lab-molded density (or 4 percent air voids) is often selected for performance evaluation (as in Approach 1). However, such a practice may inhibit mix designers from innovation and developing a good performing mixture. Moreover, the selection of 96 percent lab-molded density is based on the assumption that the density of the asphalt mixture ultimately becomes 96 percent at the end of its life—from the initial 92–93 percent construction density—after years of traffic densification. This process is also known as terminal density (96 percent). However, NCHRP 9-09(1) reported that most Superpave mixes never reach 96 percent density (Prowell and Brown 2007). Historically, design densities can vary from 95 to 97 percent in the Marshall mix design method. Furthermore, various field test sections designed with a laboratory-molded density ranging from 96.5 to 98 percent were constructed in Texas under Projects 0-6092, 0-6614, and 0-6738, and no rutting was observed (Zhou et al. 2011, Zhou et al. 2013, Im et al. 2015). Thus, the envisioned framework is not limited to 96 percent lab-molded density for selecting asphalt binder content. Instead, at least three asphalt contents will be selected at lab-molded densities ranging from 95–98 percent for performance evaluation.
- Defining lab-molded density (or air voids) requirement for production QC/QA: Lab-molded density is still a critical component of performance-related QC/QA testing (or specification). Although the final asphalt content is not determined at the volumetric mix design stage of this framework, the density versus asphalt contents curve obtained here will be used to define the acceptance lab-molded density for production QC/QA after the final design asphalt content is verified later.

A later section of this chapter demonstrates these two purposes with actual mix design data, including the development of the QC/QA density requirement.

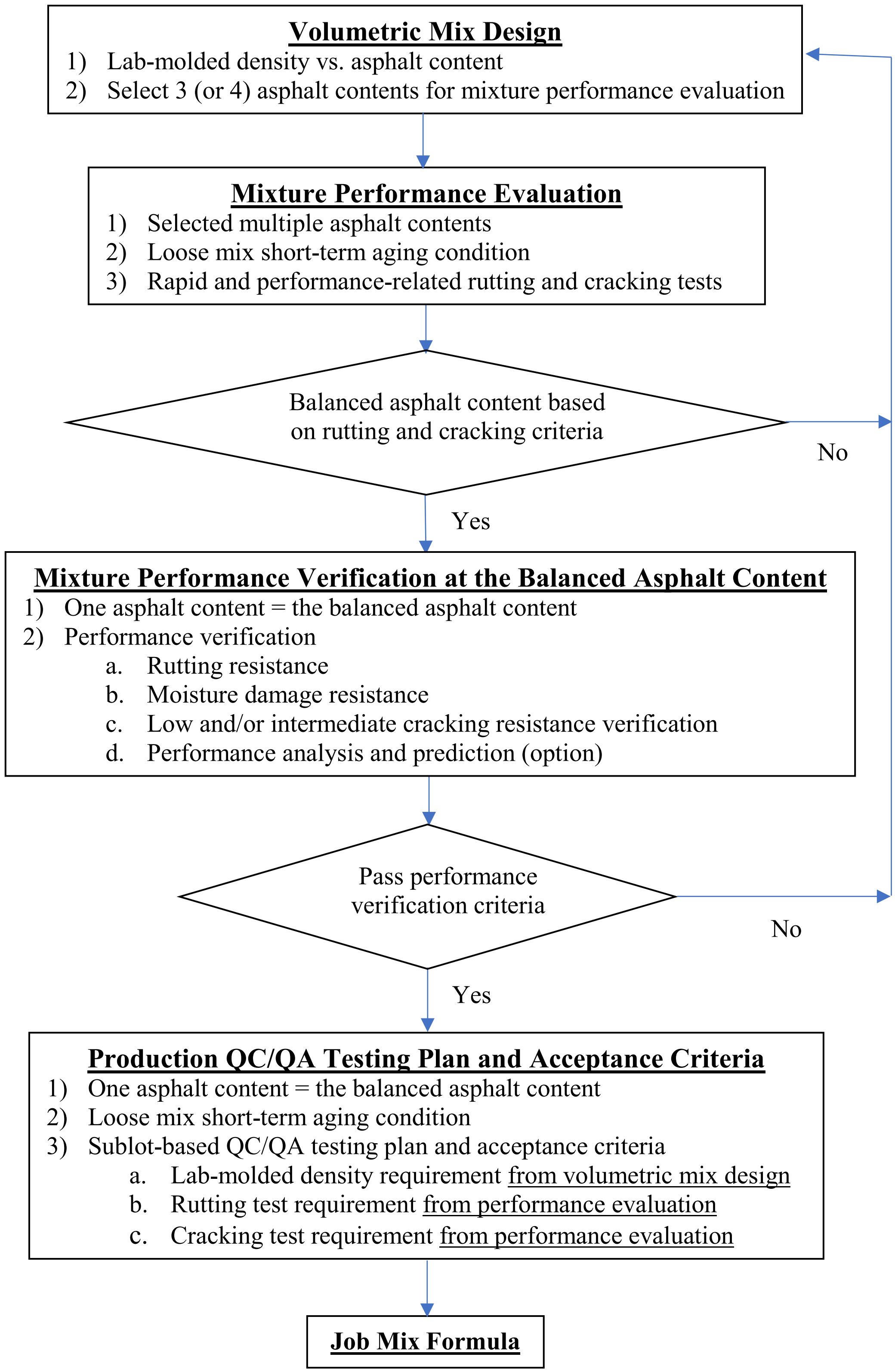


Figure 3. Envisioned Coherent Framework for BMD/QC/QA.

Mixture Performance Evaluation

The performance evaluation component of this framework evaluates rutting and cracking resistances of asphalt mixtures at multiple (3 or 4) asphalt contents rather than one asphalt content at 96 percent lab-molded density so that a balanced asphalt content is selected (or optimized) within a balanced zone. Since multiple asphalt contents are involved, many specimens are required. Thus, a set of simple, rapid, and performance-related rutting and cracking tests are preferred. Further, the same set of rutting and cracking tests will be employed during the production QC/QA testing. In this manner, the results of mixture performance evaluation in the lab mix design stage can be used to develop plant production QC/QA acceptance criteria. Moreover, since time is limited for QC/QA testing, short-term aging is desired at this stage versus long-term aging.

Mixture Performance Verification at the Balanced Asphalt Content

Different from the mixture performance evaluation described above, the performance verification focuses on verifying mixture properties at the selected balanced asphalt content rather than multiple asphalt content, specifically verifying those mixture properties not evaluated in the stage of the mixture performance evaluation, such as moisture susceptibility and cracking resistance at intermediate temperature or low temperature after long-term aging. Moreover, since only one asphalt content is considered here, some repeated loading tests with relatively long testing time (such as OT, flexural beam fatigue test, Asphalt Mixture Performance Tester cyclic fatigue test, etc.) can be employed. If preferred, field performance of the asphalt mixture at the balanced asphalt content can be predicted using software such as the American Association of State Highway and Transportation Officials (AASHTO) AASHTOWARE Pavement ME, CalME (Ullidtz et al. 2010), TxME (Hu et al. 2014), or FHWA Flexpave™ (Wang et al. 2018).

Production QC/QA Testing Plan and Acceptance Criteria

The production QC/QA testing plan and acceptance criteria are a critical component of the framework. To overcome the deficiencies of the current QC/QA testing plan focusing on lab-molded density, asphalt content, and aggregate gradation, Zhou et al. (2020) developed a performance-related QC testing plan relying on three mixture properties: lab-molded density, rutting resistance, and cracking resistance. The acceptance criteria of these three mixture properties can be determined directly from previous volumetric mix design and performance evaluation stages, respectively. In this fashion, not only are the BMD and the production QC/QA interconnected, but the same tests measuring lab-molded density, rutting and cracking resistance, and associated criteria employed for selecting the balanced asphalt content can be used for the production QC/QA testing, which will save time and resources. It is advantageous to use the same asphalt mixture-aging condition(s) for the production QC/QA testing as was used for the volumetric mix design and QC/QA performance evaluation.

In short, a coherent BMD/QC/QA framework was established. However, the research team believed some details were still missing: (a) laboratory tests for the performance evaluation and verification stages, (b) laboratory aging (or conditioning) protocols for preparing specimens for volumetric mix design, mixture performance evaluation and verification, and production QC/QA testing, and (c) performance test criteria and strategies to meet those criteria.

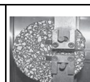
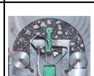
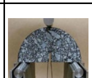
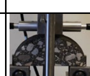
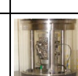
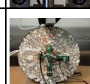
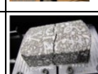
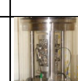
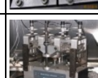
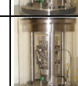
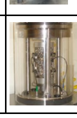
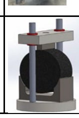
SELECTION OF LABORATORY PERFORMANCE TESTS FOR THE COHERENT BMD/QC/QA FRAMEWORK

Currently, all forms of cracking—reflective, top-down, low temperature, and fatigue—are a major concern for state highway agencies. Meanwhile, to perform well in the field, an asphalt mixture must have good resistance to rutting and moisture damage, which are traditional mix design criteria. Thus, BMD, at minimum, should have three performance tests: (1) cracking, (2) rutting, and (3) moisture damage. As shown in Figure 3, this framework requires laboratory tests for the performance evaluation and verification and production QC/QA testing. Due to different requirements for each application (performance evaluation, verification, and QC/QA), two sets of performance tests were selected, as described below:

Laboratory Tests for the Mixture Performance Evaluation and the Production QC/QA

As discussed previously, two types of performance tests—rutting and cracking tests—are needed for both the BMD performance evaluation and the production QC/QA testing. Many different laboratory tests, as shown in Table 2, have been developed for characterizing cracking and rutting properties of asphalt mixtures in the literature (Zhou et al. 2016, West et al. 2018, Hajj et al. 2019, Zhou et al. 2020).

Table 2. Common Performance Tests for Cracking, Rutting, and Moisture Susceptibility.

Cracking test		Rutting test		Moisture damage test	
ASTM D7313 Disk-shaped compact tension (DCT) test		ASTM D6927 Marshall stability test		AASHTO T283 Tensile strength ratio (TSR) test	
AASHTO TP105 Semi-circular bend (SCB)-low temperature		AASHTO T324 HWTT		AASHTO T324 HWTT	
ASTM D8044 SCB-critical strain energy release rate (Jc) test		AASHTO T340 Asphalt pavement analyzer (APA) test			
AASHTO TP124 [24] Illinois flexibility index test		AASHTO TP79 Flow number test			
IDT-University of Florida method or AASHTO T322		AASHTO T320 Superpave simple shear test			
Tex-248-F OT		AASHTO TP116 iRLPD test			
AASHTO T321 Beam fatigue test		AASHTO TP 134 Stress sweep rutting test			
ASTM D8225 IDEAL-CT		High-temperature IDT strength test (Christensen et al. 2002)			
AASHTO TP107 AMPT cyclic fatigue test		ASTM WK71466 IDEAL-RT shear strength test (Zhou et al. 2019)			

Each test has its own features and applications, and not all performance tests are suitable for production QC testing. When selecting tests for both the BMD performance evaluation and production QC/QA testing, the research team considered many aspects (such as sensitivity, repeatability, etc.) and gave special attention to the factors listed below:

- Use of same set of laboratory tests for both the BMD performance evaluation and the production QC/QA testing: Zhou et al. (2020) established a hybrid approach wherein different sets of laboratory tests are used for BMD performance evaluation and the production QC/QA testing, respectively. In order to establish QC/QA acceptance criteria, extra work was needed to develop the correlations between the BMD performance tests and the production QC/QA tests. To avoid this extra effort and reduce potential errors induced by correlations between different laboratory tests, the research team recommends the use of the same set of laboratory tests for both the performance evaluation and the production QC/QA testing so that the test data collected during performance evaluation can be used for establishing the production QC/QA acceptance criteria.
- Test correlates well with field performance: The selected laboratory performance tests must correlate with observed field performance. Otherwise, the tests should not be chosen, regardless of how rapid, simple, or repeatable they may be.
- Simplicity and rapidity: The production QC testing is performed at asphalt plants that are often located in remote areas where sophisticated laboratory testing equipment or sample preparation tools (such as a saw or drill/core machine) are often not available. Thus, those performance tests not requiring instrumentation, cutting/notching, gluing, or coring/drilling are favored. Quick turnaround is another preferred feature for production QC testing. These preferences often exclude many research-level performance tests from consideration, although these tests could be used for BMD performance verification.

Considering the three major factors, the research team selected one cracking and two rutting performance tests for BMD performance evaluation and production QC/QA testing, as noted below.

- One cracking test:
  - IDEAL-CT: IDEAL-CT is standardized in ASTM D8225. It is run at the loading rate of 50 mm/min at 25°C. This test is often completed within 2 min after taking a specimen out of a conditioning chamber (e.g., water bath). The IDEAL-CT uses the Cracking Tolerance Index (CT_{Index}) as its cracking parameter. The larger the CT_{Index}, the better the cracking resistance of the mixture. The IDEAL-CT has a good correlation with field cracking performance (Zhou et al. 2017, West 2019). A minimum of three specimens (preferably more) 150 mm in diameter and 62 mm in height are molded at 7±0.5 percent air voids using a Superpave gyratory compactor. The IDEAL-CT is a rapid, simple, repeatable test that is sensitive to asphalt mix composition (aggregate, binder, recycled materials) and aging conditions. It is recommended that the IDEAL-CT be used for the BMD cracking performance evaluation and the production QC/QA testing to ensure the mix's adequate cracking resistance. The IDEAL-CT is being adopted by 14 DOTs as their cracking test (West 2020)
- Two rutting tests:
  - IDEAL-RT: IDEAL-RT is currently being balloted in ASTM *WK71466: Standard Test Method for Determination of Rutting Tolerance Index of Asphalt Mixture Using the Rapid Rutting Test*. It is run at a loading rate of 50 mm/min at the high temperature of 50°C and is often completed within 2 min after taking a specimen out

of the conditioning chamber (e.g., water bath). The IDEAL-RT uses the Rutting Tolerance Index (RT_{Index}) as its rutting parameter. The larger the RT_{Index}, the better the rutting resistance of the mix. The IDEAL-RT has a good correlation with field cracking performance (Zhou et al. 2019). Three specimens with 150 mm in diameter and 62 mm in height are molded at 7±0.5 percent air voids using a Superpave gyratory compactor. The IDEAL-RT is a rapid, simple, repeatable test that is sensitive to asphalt mixture composition (aggregate, binder, recycled materials) and aging conditions. It is recommended that the IDEAL-RT be used for the BMD rutting performance evaluation and then for production QC/QA testing to ensure the mixture's adequate rutting resistance.

- High-Temperature Indirect Tensile (IDT) Strength Test: Contrary to the IDEAL-RT directly measuring shear strength, the high-temperature IDT strength test measures the cohesion component of the shear strength of asphalt mixtures (Christensen et al. 2002), although it cannot capture the friction angle that also contributes to the shear strength of asphalt mixes. The NCHRP Project 9-33 recommended this test and some preliminary acceptance criteria for evaluating rutting resistance during the mix design (Advanced 2011). Recently, Bennert (2011) and Bennert et al. (2020) employed this test for the production QC tool, and it was conducted at 50 mm/min at a test temperature 10°C lower than the 50 percent reliability, 7-day average maximum pavement temperature obtained from LTPPBind Version 3.1. Overall, the high-temperature IDT test is rapid, simple, and repeatable, and has acceptable correlation with field rutting performance (Advanced 2011). Thus, this test method is also selected as an alternative rutting test for the BMD rutting performance evaluation and the production QC/QA testing.

Laboratory Tests for the Mixture Performance Verification

As described previously, the mixture performance verification needs to address (a) moisture susceptibility, (b) intermediate temperature cracking resistance after long-term aging, (c) low-temperature cracking after long-term aging, and (d) rutting resistance under repeated loading test(s). Furthermore, recognizing that each DOT may have their own preferred test(s) for each specific distress, the research team provided multiple options for the mixture performance verification testing, as detailed below:

- Moisture susceptibility test: As listed in Table 2, the two most often used moisture susceptibility tests are AASHTO T324: HWTT and T283: Lottman (or TSR) test. Both tests are recommended for verifying performance of the asphalt mixture at the balanced asphalt content, and users can choose either one based on their experiences and preference. The research team selected the HWTT for verifying moisture susceptibility in the demonstration case study because the HWTT can also serve as the rutting verification test.
- Rutting verification test: Although many rutting tests are available, most DOTs are using either AASHTO T324: HWTT or T340: APA, as noted by West et al. (2018). Thus, both tests are recommended for verifying the performance of asphalt mixture at the balanced asphalt content, and users can choose either one based on their experiences and preference. The research team selected the HWTT for verifying rutting resistance in the following case study since the HWTT can serve as the moisture susceptibility test as well.

- Cracking verification test at intermediate temperature: Various suitable cracking tests exist, as listed below:
    - AASHTO TP124: SCB-IFIT used by Illinois.
    - ASTM D8044: SCB-Jc used by Louisiana.
    - AASHTO T321: Flexural beam fatigue test used by California.
    - Tex-248-F: OT used by Texas and New Jersey.
    - ASTM D8225: IDEAL-CT used by Virginia, Oklahoma, Kentucky, Texas, and more.
    - AASHTO TP107: AMPT cyclic fatigue test recommended by FHWA.

  Each DOT can choose their own cracking test to ensure adequate cracking resistance of asphalt mixtures after long-term aging. The research team chose IDEAL-CT to verify cracking resistance after mid-term aging, defined later in the following case study, due to its simplicity and good correlation with field performance.
- Low-temperature cracking verification test: Low-temperature cracking can be a serious concern for northern states or cold climate areas. Laboratory tests developed to characterize low-temperature cracking resistance of asphalt mixes include AASHTO TP105: SCB-low temperature; AASHTO T322: low-temperature IDT; ASTM D7313: DCT; and more. However, most of these methods are generally used as research-level performance tests. ASTM D7313: DCT was used by Minnesota DOT in a few pilot projects (Dave et al. 2019). Thus, the research team recommends ASTM D7313 DCT for verifying the low-temperature cracking performance of asphalt mixtures at the balanced asphalt content. The resulting fracture energy can also be used in conjunction with a software (Illi-TC) to further enhance pavement low-temperature cracking predictions.

In summary, for rutting, cracking, and moisture susceptibility, a series of laboratory tests with a high flexibility of fitting different needs and preferences of DOTs are recommended for the framework. This chapter specifically focuses on three laboratory tests (IDEAL-CT, IDEAL-RT, and HWTT) as the primary performance tests for the framework, and those tests will also be used in the case study:

- IDEAL-CT and IDEAL-RT for the BMD mixture performance evaluation and the production QC/QA testing.
- HWTT for BMD rutting and moisture susceptibility performance verification.
- IDEAL-CT for BMD cracking performance verification after mid-term aging.

After selecting performance tests, the identification of appropriate asphalt mixture conditioning protocols for loose mixtures to mimic field aging is an important next step because aging protocols have a significant impact on mixture performance, and consequently, mixture acceptance criteria depend on how the mixture is aged. Thus, the next section discusses aging protocols.

LABORATORY AGING PROTOCOLS FOR PREPARING PERFORMANCE TESTS SPECIMENS

Asphalt mixtures experience two stages of the aging process in the field: (1) short-term aging at elevated high temperatures during production, transport, placement, and compaction, and (2) long-term aging under local climatic conditions. To characterize the short- and long-term aging impact, various conditioning standards or protocols have been proposed in the literature (Bell et al. 1994, Aschenbrener and Far 1994, Braham et al. 2009, Petersen 2009, Epps-Martin et al. 2014, Newcomb et al. 2015, Reinke et al. 2015, Kim et al. 2018, Chen et al. 2018). Table 3 lists some major laboratory aging protocols for asphalt mixtures established since the Strategic Highway Research Program (SHRP) concluded in 1992. It is a well-known fact that the rutting and cracking properties of asphalt mixtures are not only significantly impacted by aging, but they are impacted in opposite directions, as illustrated in Figure 4. The longer the mixture ages, the more rutting resistance increases, but cracking resistance decreases. Thus, completely different aging protocols are needed for evaluating rutting and cracking resistance of asphalt mixtures.

Table 3. Major Laboratory Aging Protocols.

Aging protocol		**Mix property evaluated**	**Reference**	**Note**
Short-term aging	2 hr at compaction temperature for loose mixes	Mix design: volumetric properties	AASHTO R30	
		Mix design: rutting, cracking, and moisture damage	Aschenbrener and Far (1994) Texas Department of Transportation (TxDOT) specifications (2014)	Aschenbrener and Far (1994) established it based on HWTT data
		QC: compaction density	TxDOT specifications (2014)	
	2 hr at 116°C for loose warm mix asphalt (WMA)	Mix design: mix mechanical properties	Epps-Martin et al. (2014)	This protocol was developed based mainly on resilient modulus (Mr)
	4 hr at 135°C for loose hot mix asphalt (HMA)	Mix design: mix mechanical properties	AASHTO R30 Bell et al. (1994)	This protocol was developed based mainly on Mr
	2 hr at 135°C for loose HMA	Mix design: mix mechanical properties	Newcomb et al. (2015)	This protocol was developed based mainly on Mr
Long-term aging	120 hr at 85°C for compacted specimens	Mix design: mix mechanical properties	AASHTO R30 Bell et al. (1994)	This protocol was developed based mainly on Mr
	24 to 696 hr at 95°C for loose mixes	Mix design and structural performance evaluation	Kim et al. (2018)	This protocol was developed based on asphalt binder chemistry and rheological property
	8 hr at 135°C for loose mixes	Mix design: mix mechanical properties	Chen et al. (2018)	This protocol was developed based on asphalt binder chemistry and rheological property
	24 hr at 135°C for loose mixes	Mix fracture property	Braham et al. (2009) Reinke et al. (2015)	

Note: Table 3 is not a comprehensive list of various aging protocols in the literature

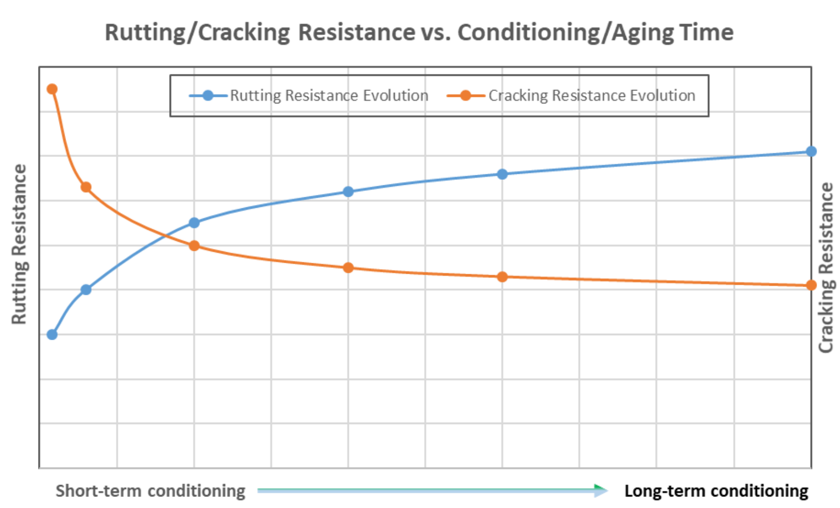


Figure 4. Rutting and Cracking Resistance Evolution vs. Conditioning/Aging Time.

Aging Protocol for Preparing IDEAL-RT Specimens

As conceptualized in Figure 4, rutting resistance of asphalt mixtures keeps increasing with aging (or conditioning) time. Ideally, each aging condition of the full aging curve is evaluated, but it will make a routine mix design very difficult (if not impossible). The practical (or conservative) approach is to evaluate rutting resistance of an asphalt mixture at its most critical (or poorest) condition. It is well known that rutting often occurs in the very early stage of the pavement life when short-term rather than long-term aging plays a dominant effect on rutting resistance. Thus, the most critical condition for rutting is the compacted asphalt mixture immediately after the placement. The research team selected the 2-hr loose-mixture conditioning at compaction temperature for evaluating rutting resistance of asphalt mixtures during the performance evaluation and the production QC/QA testing based on the following common practices and research findings:

- The 2-hr loose-mixture aging at compaction temperature has been widely adopted by many DOTs for Superpave volumetric mix design, as specified by AASHTO R30. Furthermore, different compaction temperatures are being used by different states due to different types of binders or binder sources. To avoid any potential confusion and to ensure a smooth implementation and transition to the framework, the 2-hr loose-mix conditioning at compaction temperature is preferred.
- Many DOTs already used the 2-hr loose-mixture aging at compaction temperature for preparing rutting test specimens. For example, TxDOT uses such mixture-aging protocol for preparing HWTT specimens using Tex-241: *Compacting Bituminous Specimens Using the Superpave Gyratory Compactor*.
- Epps-Martin et al. (2014), under NCHRP 9-49, found that laboratory loose mixture aged for 2 hr at compaction temperature matched well with field cores taken either immediately after construction or 6 months after construction in terms of Mr. Meanwhile, Epps-Martin et al. (2014) also found it difficult to define the compaction temperature for each project, so a fixed compaction temperature of 135°C was recommended for HMA mixtures and 116°C for WMA mixtures. Newcomb et al. (2015), under NCHRP 9-52,

verified the aging protocol—2 hr at 135°C for HMA and 116°C for WMA—for nine field projects across the United States.

Aging Protocol for Preparing IDEAL-CT Specimens

In contrast to rutting, cracking frequently occurs in a later stage of pavement life. Thus, it is more appropriate to employ a long-term aging protocol for evaluating cracking resistance of asphalt mixtures. However, aging characteristics of asphalt mixtures, as illustrated in Figure 4, continue to evolve. Moreover, asphalt mixture aging depends on the layer depth within the pavement structure (Kim et al. 2018), and the same mixture can have completely different mixture properties if it is a surface layer than the layer 150 mm below the surface. The complexity of asphalt aging makes it extremely difficult to fully simulate the field aging in the laboratory. Further, it is often impractical to use a long-term aging protocol for conditioning loose mixtures during the production QC/QA testing. Thus, the research team devised and subsequently recommend a hybrid short- and mid-term aging protocol for preparing IDEAL-CT specimens, as noted below:

- BMD performance evaluation: IDEAL-CT specimens at multiple asphalt contents are compacted after short-term aging—the 2-hr loose mixture aged at compaction temperature.
- BMD performance verification: IDEAL-CT specimens at the balanced asphalt content are compacted after a mid-term aging period that is a 3-step process, as described below:
    - Step 1: Short-term aging process—Short-term age a loose mixture for 2 hr at its compaction temperature with the loose-mix thickness of 25–50 mm, preferably 38–50 mm, where the target depth is 38 mm +/− 12 mm. This depth of material will accommodate 4.75-mm, 9.5-mm, 12.5-mm, and 25-mm Superpave nominal maximum aggregate sizes (NMASs).
    - Step 2: Mid-term aging process—After Step 1, split the short-term aged loose mixture into multiple shallow pans (e.g., 25 mm by 330 mm by 457 mm) with a thickness of one NMAS (Kim et al. 2018); no stirring is required. Note that time and temperature used for mid-term aging of 20 hr at 100°C are intended to be the same as those used in the pressure aging vessel (PAV) conditioning for conventional and modified asphalt binders. The 20-hr aging duration is convenient for lab operation (i.e., no need of working before or after office hours) and acceptable for routine mix designs in the BMD performance verification stage. The goal of proposing a mid-term aging condition is not to simulate how aging occurs in the field but rather to stabilize the aging characteristics of loose mixtures so that it becomes possible to rank and compare cracking resistances of asphalt mixtures. More discussion is presented later when discussing acceptable criteria for the IDEAL-CT.
    - Step 3: Reheating process—After Step 2, combine the mid-term aged loose mixture into the same pan(s) used in Step 1 with the same thickness as in Step 1, then reheat the combined mixture for 2 hr at its compaction temperature and stir it each hour to ensure uniform temperature before compacting IDEAL-CT specimens.
- Production QC/QA stage: IDEAL-CT specimens are compacted after short-term aging—the loose mixture aged at compaction temperature for 2 hr.

The advantage of this hybrid aging protocol is to address the needs of evaluating the impact of both short- and mid-term aging on cracking resistance of asphalt mixtures; meanwhile, it considers the impact of aging on cracking resistance and avoids the long duration of long-term aging process in the whole BMD/QC/QA process. In this approach, the same short-term aging protocol for the IDEAL-RT is applied here to the IDEAL-CT. In such a way, the performance evaluation data can be used for developing production QC/QA acceptance criteria for both cracking and rutting resistance of asphalt mixtures.

Aging Protocol for Preparing HWTT Specimens

As noted previously, HWTT has been widely used for characterizing rutting and moisture damage of asphalt mixes. Aschenbrener and Far (1994) evaluated a variety of asphalt mixtures and recommended 2 hr at compaction temperature for aging the loose mixtures before compacting HWTT specimens in order to match field performance. Furthermore, many DOTs are using the 2-hr loose-mixture aging at compaction temperature as the aging protocol for preparing HWTT specimens. Thus, the 2-hr loose-mixture aging at compaction temperature is recommended for preparing HWTT specimens in the coherent BMD/QC/QA framework.

In summary, Table 4 lists the selected protocols for aging loose mixtures for preparing performance test specimens.

Table 4. Laboratory Aging Protocols for Preparing Performance Tests Specimens.

Stage	Test	Loose-mix aging protocol	
BMD performance evaluation at multiple asphalt contents	IDEAL-RT	Short-term aging	2 hr at compaction temperature with a loose-mix thickness of preferably 38–50 mm; stir the loose mix every hour
	IDEAL-CT		
BMD performance verification with one asphalt content	HWTT	Short-term aging	2 hr at compaction temperature with a loose-mix thickness of preferably 38–50 mm; stir the loose mix every hour
	IDEAL-CT* (**)	Mid-term aging	(1) 2 hr at compaction temperature (just like short-term aging) (2) 20 hr at 100°C with a thickness of one NMAS and no stirring (3) 2 hr at compaction temperature (just like short-term aging)
QC/QA	IDEAL-RT	Short-term aging	2 hr at compaction temperature with a loose-mix thickness of preferably 38–50 mm; stir the loose mix every hour
	IDEAL-CT		
	Lab-molded density		

* The same long-term aging protocol for the IDEAL-CT can be used for other types of cracking tests, such as DCT, beam fatigue test, or AMPT cyclic fatigue test.

** The use of WMA additives may require aging at alternative temperatures that mimic anticipated field production temperatures in order to obtain the full benefit of producing WMA mixture.

DEVELOPMENT OF PERFORMANCE TESTS CRITERIA AND STRATEGIES FOR MEETING THOSE CRITERIA

Performance tests criteria are critical components of the coherent BMD/QC/QA framework. Without the performance tests criteria, one cannot determine the maximum and the minimum allowable asphalt contents to avoid premature rutting, cracking, or moisture damage problems in the field. The following subsections establish the acceptance criteria of the three performance tests.

IDEAL-RT Acceptance Criteria and Strategies for Meeting Such Criteria

A direct way of establishing acceptance criteria for a performance test is to construct and monitor multiple field performance test sections, but this process is very costly and takes considerable time. Alternatively, one can develop acceptance criteria for a performance test by establishing a correlation with an existing performance test and associated criteria. This chapter uses a hybrid approach for establishing the IDEAL-RT acceptance criteria, as described below.

- Development of IDEAL-RT acceptance criteria based on the relationship between IDEAL-RT and HWTT: As noted previously, the HWTT has been widely adopted by many DOTs. The most commonly used HWTT rutting parameter is total rut depth at a specified number of passes, and associated acceptance criteria have also been well established. For example, TxDOT requires a maximum rut depth of 12.5 mm at 10,000, 15,000, and 20,000 passes for asphalt mixtures with PG 64-XX, PG 70-XX, and PG 76-XX (or higher) binders, respectively. To develop a relationship between the IDEAL-RT and the HWTT, a total of 23 dense-graded mixtures (see Table 5) were evaluated in this study. Eleven of the 23 mixtures were laboratory-mixed and laboratory-compacted (LMLC), and the remaining 12 mixtures were reheated plant-mixed and laboratory-compacted (PMLC). For the 11 LMLC mixtures, the short-term aging protocol as described in Table 5 was followed to age the loose mixtures before compacting the IDEAL-RT and HWTT specimens; for the 12 PMLC mixtures, they were reheated in a forced draft oven at their respective compaction temperature. When each plant mixture became loose and workable, and reached uniformly the compaction temperature, both the IDEAL-RT and the HWTT specimens were molded. The overall heating process in the oven took approximately 2 hr. Both tests were performed at 50°C, and the test results are listed in Table 5.

  As seen in Table 5, almost half of the 23 mixtures reached 12.5-mm rut depth before 20,000 passes. Thus, it becomes difficult to directly make comparisons even among 23 mixtures in terms of the rut depth at 20,000 passes. To address this issue, the research team defines a new rutting resistance index (RRI) parameter in Equation 1. The RRI parameter not only incorporates the combined effect of the number of passes and the rutting depth, it also addresses the nonlinear impact of number of loading passes (or repetitions) on pavement rutting (or permanent deformation) through using $N^{0.3}$ rather than N^{1}, unlike the work by Wen et al. (2016). The calculated RRI for each mix is listed in Table 5 as well.

$$RRI = N^{0.3}\left(1 - \frac{RD}{25.4}\right) \quad (1)$$

where,

RRI = Rutting resistance index.
N = 20,000 or number of passes reaching 12.5-mm rut depth.
RD = Rut depth at 20,000 passes or 12.5 mm for those reaching 12.5-mm rut depth before 20,000 passes.

The target maximum RRI values for mixtures with PG64-XX, PG70-XX, and PG76-XX are 8, 9, and 10, respectively.

The relationship between HWTT (RRI) and IDEAL-RT (RTIndex) is shown in Figure 5. The 95 and 98 percent confidence intervals are also added to the graph. As seen in Figure 5, there is a good linear relationship between RRI and RTIndex. The larger the RTIndex, the larger the RRI and the better rutting resistance.

Based on the relationship shown in Figure 5 and the existing HWTT acceptance criteria, one can calculate the RTIndex values corresponding to HWTT rutting criteria for mixtures with PG64-XX, PG70-XX, and PG76-XX. Note that the research team used different confidence intervals when setting the minimum RT_{Index} requirements for different mixtures, in consideration of the importance of avoiding rutting and potential safety issues, as listed below:

- For mixtures with PG64-XX (or lower) with 95 percent confidence: $RT_{Index} \geq 60$.
- For mixtures with PG70-XX with 95 percent confidence: $RT_{Index} \geq 65$.
- For mixtures with PG76-XX (or higher) with 98 percent confidence: $RT_{Index} \geq 75$.

Generally, it is expected that an asphalt mixture with PG64-XX used in a hot climate ruts quickly under heavy traffic; in contrast, an asphalt mixture with PG76-XX will have no (or much less) rutting problem when used in the same environment. Alternatively, a mixture with $RT_{Index} < 60$ will very likely rut prematurely in comparison to a mixture with $RT_{Index} \geq 75$, which is discussed in the next subsection.

Table 5. IDEAL-RT and HWTT Test Results of 23 Asphalt Mixes.

Asphalt mix					HWTT			IDEAL-RT
Mix No.	**Virgin asphalt binder**	**RAP by weight of total mix (%)**	**RAS by weight of total mix (%)**	**Total binder content (%)**	**Rut depth at 20,000 passes (mm)**	**No. of passes at 12.5-mm rut depth**	**RRI**	**RT_{Index}**
1	PG58-28	10	0	5.4	N/A	4,860	6.5	35.2
2	PG64-28	20	0	5.3	N/A	18,792	9.7	58.3
3	PG64-22	15	2	4.8	6.82	N/A	14.3	90.6
4	PG70-22	0	0	4.8	N/A	12,864	8.7	61.0
5	PG64-28	15	0	4.8	N/A	15,004	9.1	59.8
6	PG64-22	15	2	5.3	9.63	N/A	12.1	66.9
7	PG64-28	20	0	5.7	N/A	12,652	8.6	67.7
8	PG64-28	20	0	6.4	N/A	18,980	9.8	58.2
9	PG58-28	7	3	6.0	N/A	10,196	8.1	64.5
10	PG64-22	15	5	5.0	3.21	N/A	17.0	107.5
11	PG64-22	30	0		N/A	12,856	8.7	64.3
12	PG64-22	40	0		4.15	N/A	16.3	97.1
13	PG64-22	20	0	5.1	N/A	13,056	8.7	72.0
14	PG76-22	0	0	6.8	11.51	N/A	10.7	78.4
15	PG64-22	25	0	5.3	10.59	N/A	11.4	62.6
16	PG76-22	0	0	5.5	2.89	N/A	17.3	118.1
17	PG64-22 and 3.2% rejuvenator	25	0	5.0	12.5	7,696	7.4	53.4
18	PG64-22 and 4.0% rejuvenator	25	0	5.0	12.5	7,376	7.3	43.1
19	PG64-22	15	2	5.0	8.94	N/A	12.6	74.9
20	PG64-22	0	0		12	N/A	10.3	80.7
21	PG64-22	20		5.2	4	N/A	16.4	92.7
22	PG64-22	10	5	5.2	1.85	N/A	18.1	127.1
23	PG70-22	10	2	5.6	2.28	N/A	17.8	119.8

Note: N/A stands for not applicable.

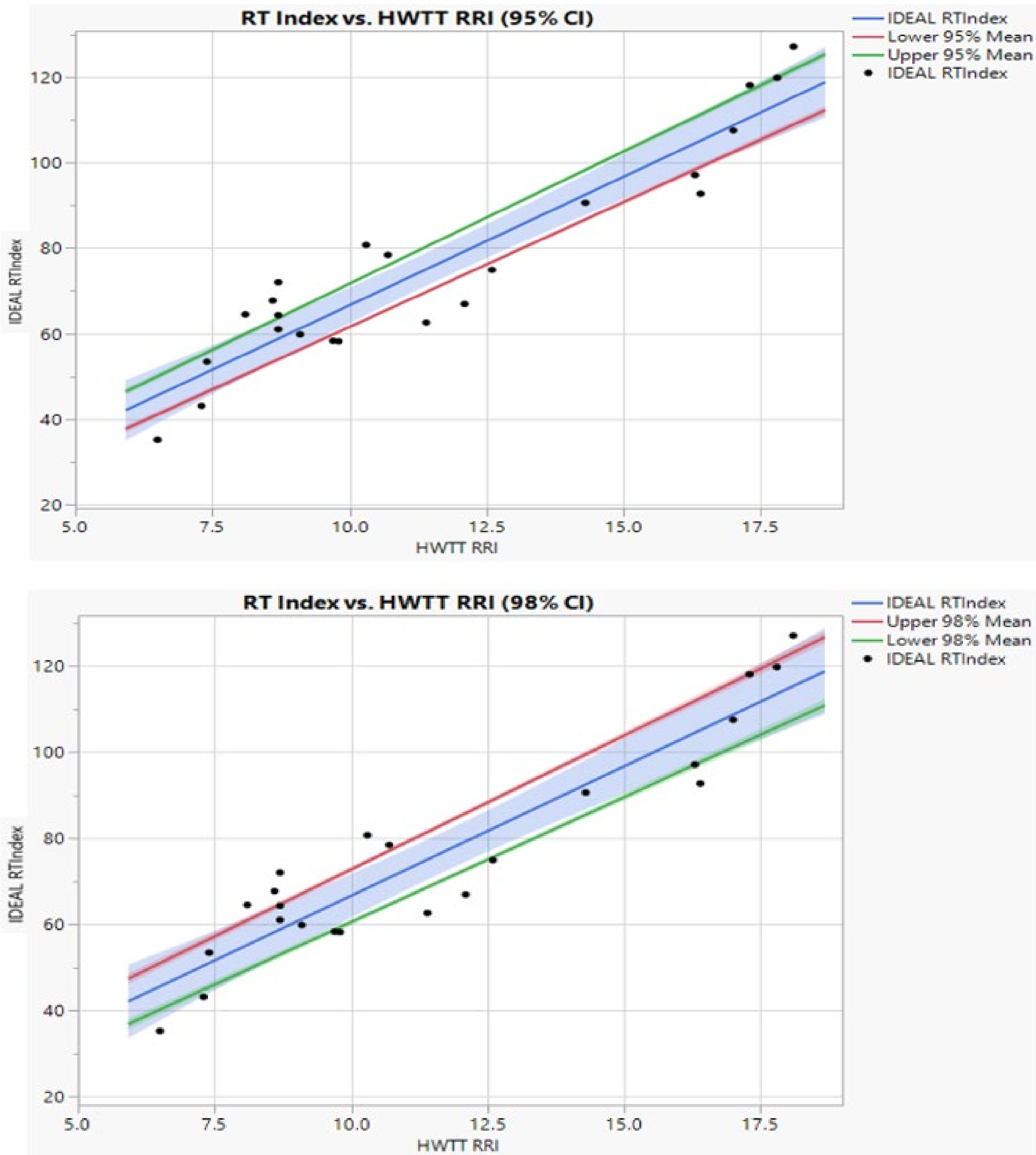


Figure 5. Linear Relationship between IDEAL-RT and HWTT.

- Strategies for meeting the IDEAL-RT criteria: In the last two decades, rutting has been substantially minimized, if not completely eliminated, from asphalt pavements. To improve rutting resistance and increase RT_{Index}, one can employ the following one or combined measures:
  - Use stiffer binders, typically polymer-modified binders.
  - Replace natural sand with manufactured sand or crushed particles.
  - Use angular (or more crushed) aggregates.
  - Reduce asphalt content.

- Use RAP/RAS (if allowed by the agency).
- Change binder source (Note that the asphalt binders with the same PG do not always perform the same).

IDEAL-CT Acceptance Criteria and Strategies for Meeting Such Criteria

As discussed previously, cracking resistances of asphalt mixtures are evaluated under two aging conditions: short-and mid-term aging. Thus, two IDEAL-CT criteria are established below.

- Short-term aging IDEAL-CT criteria: In a previous study, Zhou et al. (2020) established IDEAL-CT criteria for dense-graded mixtures and stone matrix asphalt (SMA) mixtures (Table 6) based on the correlation between the IDEAL-CT and Texas OT. Note that the CT_{Index} criteria in Table 6 are intended to address reflective cracking in asphalt overlays because reflective cracking in overlays is the primary distress pavement each DOT is facing. Furthermore, Zhou et al. (2020) showed that $CT_{Index} = 90$ corresponds to flexibility index (FI) = 8 based on limited data.

Table 6. IDEAL-CT Acceptance Criteria for Different Mixtures.

Mix type	SMA	Superpave dense-graded mixes
Minimum CT_{Index}	135	90

- Validation of the short-term aging CT_{Index} criteria: To validate the short-term aging CT_{Index} criteria, the research team turned to LTPP-SPS10, Warm Mix Asphalt (WMA) Overlay of Asphalt Pavements. Six test sections were constructed on SH66, west of Yukon, Oklahoma, in November 2015. Before the 50-mm asphalt overlay, LTPP surveyed and recorded existing pavement distresses of the six test sections. All test sections exhibited a large amount of cracking, except Section 400A62, with no transverse cracking. For the purpose of validating the short-term aging CT_{Index} criteria with a focus of reflective cracking, Section 400A62 was excluded from this study. Thus, only five test sections (400A01, 400A02, 400A03, 400A61, and 400A63) are employed here for the validation of the CT_{Index} criteria. The latest distress survey data in LTPP-Inforpave database were recorded in March 2019 after 40 months trafficking (Figure 6). Note that the reflective cracking rate is the ratio of the transverse cracking length observed on March 5, 2019, to the transverse cracking length observed on April 15, 2015 (the last survey before the asphalt overlay). Meanwhile, plant mixture from each test section was tested under the IDEAL-CT by following ASTM D8225. For each test section, three replicates of IDEAL-CT specimens with 7±0.5 percent air voids were molded after short-term aging. The IDEAL-CT was performed at 25°C with a loading rate of 50 mm/min. Figure 6 shows both the IDEAL-CT test results and the reflective cracking of each test section. As seen in Figure 6, the CT_{Index} has a very good correlation with field reflective cracking development; the smaller the CT_{Index} value, the higher the reflective cracking rate. Furthermore, when the CT_{Index} value is larger than 90, its reflective cracking rate is less than 10 percent after 40 months trafficking for a 2-inch asphalt overlay. Thus, $CT_{Index} = 90$ is a reasonable number to start with, although a more robust field validation effort is still needed.

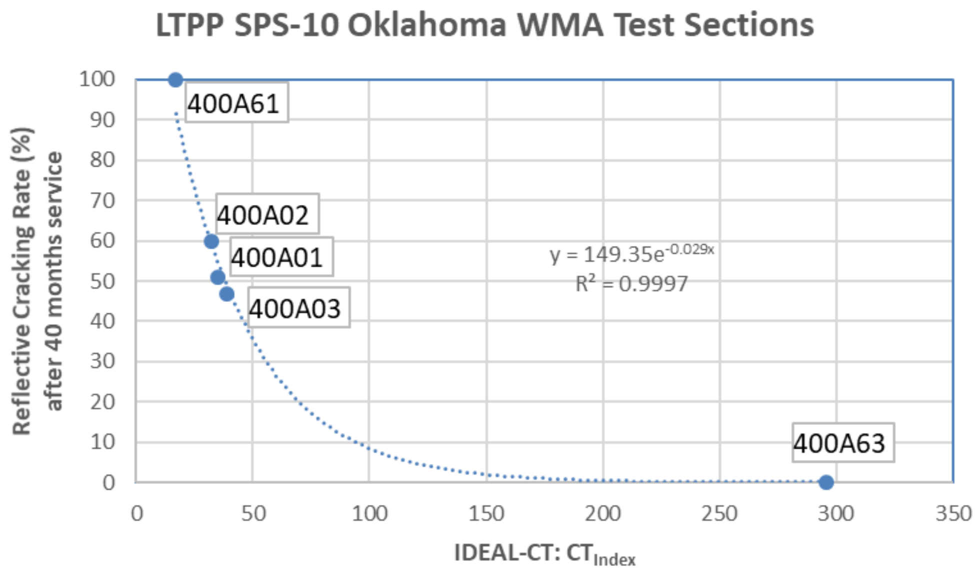


Figure 6. Validation of the Short-Term Aging IDEAL-CT Criteria.

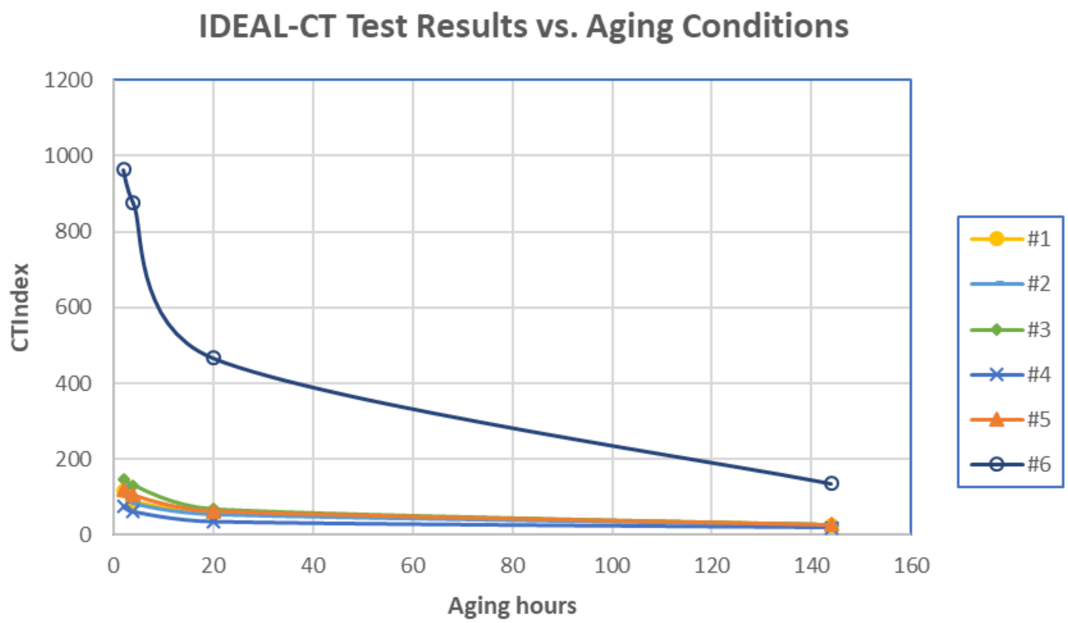
- Mid-term aging IDEAL-CT criteria: Since the mid-term aging concept has not been proposed until now, no information is available in the literature. Instead of directly comparing the mid-term aging to field aging, this chapter establishes the mid-term aging IDEAL-CT criteria by evaluating CT_{Index} reduction from the CT_{Index} value at the short-term aging (2 hr at compaction temperature). If a common CT_{Index} reduction exists, the mid-term aging IDEAL-CT criteria can be developed using the short-term aging IDEAL-CT criteria ($CT_{Index} \geq 90$) × the common CT_{Index} reduction. Based on this philosophy, six typical asphalt mixtures often used in Texas were employed to evaluate CT_{Index} evolution and reduction with aging. Table 7 details each mixture information. For each mixture, the loose mix was aged under four different aging conditions:
  - 2 hr at compaction temperature (short-term aging protocol proposed here).
  - 4 hr at 135°C (AASHTO R 30 aging protocol).
  - 2 hr at compaction temperature + 20 hr at 100°C + 2 hr at compaction temperature (mid-term aging protocol proposed here).
  - 2 hr at compaction temperature + 144 hr at 95°C + 2 hr at compaction temperature (long-term aging protocol equivalent to asphalt binder 40 hr PAV aging [Kim et al. 2018]).

  After the aging, three IDEAL-CT specimens were compacted using the Superpave gyratory compactor and then were tested by following ASTM D8225. The average of the test results for each mixture under four aging conditions are shown in Figure 7(a). In order to investigate the CT_{Index} reduction with aging, the measured CT_{Index} values at different aging conditions were normalized to the CT_{Index} value at the short-term aging (2 hr at compaction temperature), as shown in Figure 7(b).

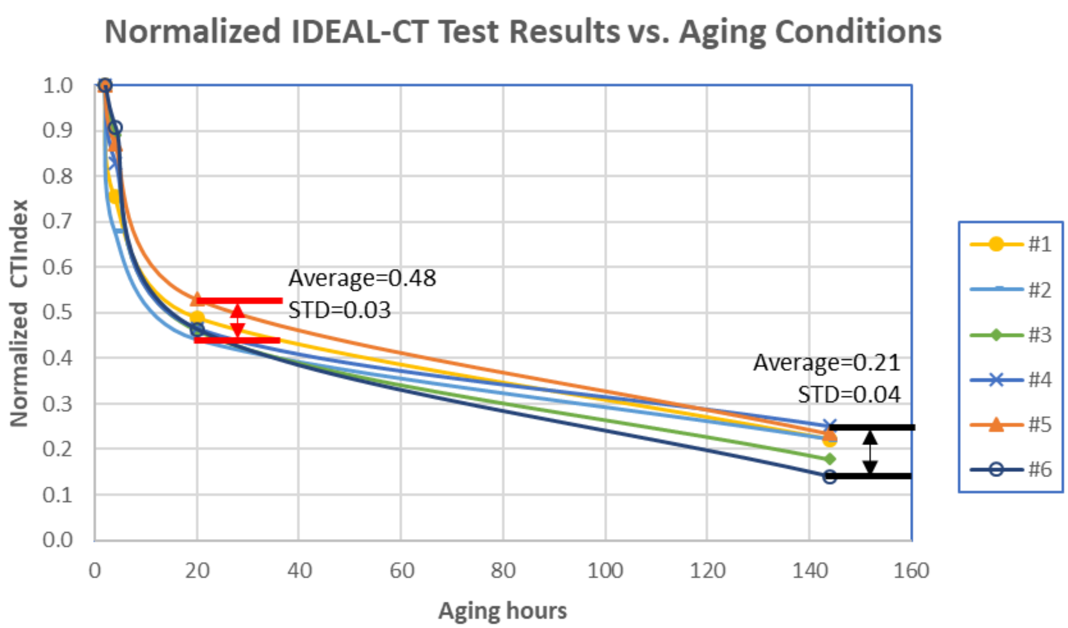
  It can be seen from Figure 7(b) that the CT_{Index} values of all six mixtures consistently drop with increased aging time, although the dropping amount of the CT_{Index} value is different for each mixture. A simple statistical analysis was performed to determine the average drop and associated standard deviation at the mid- and long-term aging conditions. As shown in Figure 7(b), the CT_{Index} drop and standard deviation are 0.48 and 0.03 for the mid-term aging and 0.21 and 0.04 for the long-term aging, respectively. After considering the variation of the CT_{Index} drops, the research team recommended using 0.45 (= 0.48–0.03) as the CT_{Index} drop to calculate the minimum requirement for the CT_{Index} after the mid-term aging. Consequently, the research team recommended the following mid-term aging IDEAL-CT criteria: $CT_{Index} \geq 40$ (= 90*0.45).

Table 7. Six Mixtures Used for Developing Mid-term Aging IDEAL-CT Criteria.

Mixture type		**Virgin binder**	**RAP/RAS (%)**	**Rejuvenator**	**Total asphalt content (%)**
#1	12.5-mm Superpave	PG70-22	10% RAP	None	5.3
#2	12.5-mm Superpave	PG70-22	None	None	5.6
#3	12.5-mm Superpave	PG64-22	15%RAP/2%RAS	Bio-rejuvenator	5.2
#4	9.5-mm Superpave	PG76-22	None	None	5
#5	9.5-mm Superpave	PG76-22	None	None	5.5
#6	12.5-mm SMA	PG76-22	None	None	6.3



(a) CT_{Index} vs. Aging



(b) Normalized CT_{Index} vs. Aging

Figure 7. IDEAL-CT: Cracking Resistance Evolutions with Aging.

- Strategies for meeting the IDEAL-CT criteria: Asphalt industry and pavement engineers have been addressing the cracking or durability problem for the last two decades. Different approaches have been tried in both the laboratory or in the field (Zhou et al. 2007, Im et al. 2015, West et al. 2018, Mogawer et al. 2019, Zhou et al. 2011, Zhou et al. 2013, Zhou et al. 2020, Karki and Zhou 2018, Tran et al. 2019). To improve cracking resistance and increase the CT_{Index}, one can employ the following one or combined measures:

- Increase asphalt content by increasing design density (such as regression air void approach), varying aggregate gradation away from the maximum density line, and reducing design gyration (in case of keeping the same aggregate gradation).
- Use polymer-modified binders designed for cracking resistance.
- Reduce the RAP/RAS amount.
- Use rejuvenators.
- Use chemical WMA and lower production temperatures.
- Add fibers.
- Use less absorptive aggregates.
- Change binder source (Note that the asphalt binders with same PG do not always perform the same).

Multiple field test sections have been constructed and monitored in Texas. Karki and Zhou (2008) reported that effective strategies for improving cracking resistance are to increase asphalt binder content and then use polymer-modified binders designed for cracking resistance (such as polymer-modified softer binders, PGxx-28 or PGxx-34).

HWTT Acceptance Criteria and Strategies for Meeting Those Criteria

As stated previously, the HWTT and associated criteria have been well established. Rut depth at a specified number of passes is the most commonly used parameter for evaluating rutting and moisture damage potential, although some DOTs have an additional requirement of stripping inflection point. To be consistent with current practices, the research team adopted exactly the same criteria being used by DOTs. These same criteria will be used in the framework to exclude any potential moisture susceptible mixtures.

Aggregate characteristics (such as minerals, surface chemistry, porosity) have significant influence on moisture susceptibility of asphalt mixtures. To address moisture damage of asphalt mixtures, the two most often used approaches are chemical liquid antistripping agents and lime (Hicks 1991).

CASE STUDY: DEMONSTRATION OF THE COHERENT BMD/QC/QA FRAMEWORK

The purpose of the case study is to demonstrate the developed the framework with three performance tests selected previously: IDEAL-CT, IDEAL-RT, and HWTT. The asphalt mixture used for this demonstration is an actual mixture designed and placed for an accelerated pavement testing project in Texas. The BMD mixture is a 12.5-mm Superpave mixture with limestone aggregates, a virgin binder PG64-22, and a binder replacement of 24 percent from RAP. Figure 8 shows the aggregate gradation, and the same gradation is used for this whole demonstration process. A step-by-step design process is described below.

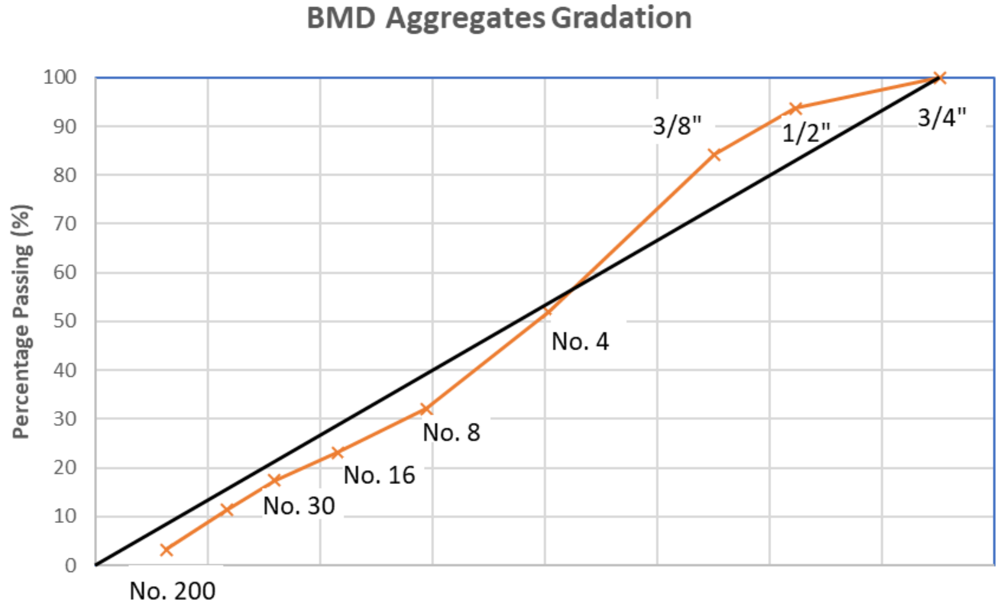


Figure 8. Aggregates Gradation of the 9.5-mm Dense-Graded Mix.

Volumetric Mix Design

The original mix design calls for a 12.5-mm Superpave virgin mixture with PG70-22. According to TxDOT's 2014 construction specification, the virgin binder PG70-22 can be replaced with a PG64-22 binder when 15 percent RAP or more is used in the asphalt mixture. However, the temperatures for mixing the aggregates and asphalt binder and aging the loose mixture should be the same temperatures as used for the original asphalt binder. In this case, the mixing and aging temperatures for a PG70-22 binder are 149°C and 135°C, respectively. Thus, the same mixing and aging temperatures were used for designing the 12.5-mm Superpave virgin mixture with PG64-22 binder and a 25 percent RAP (in weight of the total mixture). The number of gyrations selected for this case study was $N_{design} = 35$, which is a common number for Superpave mixtures with limestone aggregates. Following the aging protocols established previously, the loose mixtures at three asphalt binder contents—4.5, 5.0, and 5.5 percent—were aged for 2 hr at 135°C (aging temperature, or compaction temperature). The measured densities of the compacted asphalt mixture at three asphalt contents are shown in Figure 9.

As discussed previously, three asphalt binder contents within the density range of 95 to 98 percent were selected for performance evaluation. For this case, the asphalt contents corresponding to 95 percent and 98 percent density were 4.6 percent and 5.4 percent, respectively, as shown in Figure 9. Within such range, the research team selected three asphalt contents—4.7, 5.0, and 5.3 percent—for performance evaluation in the next step.

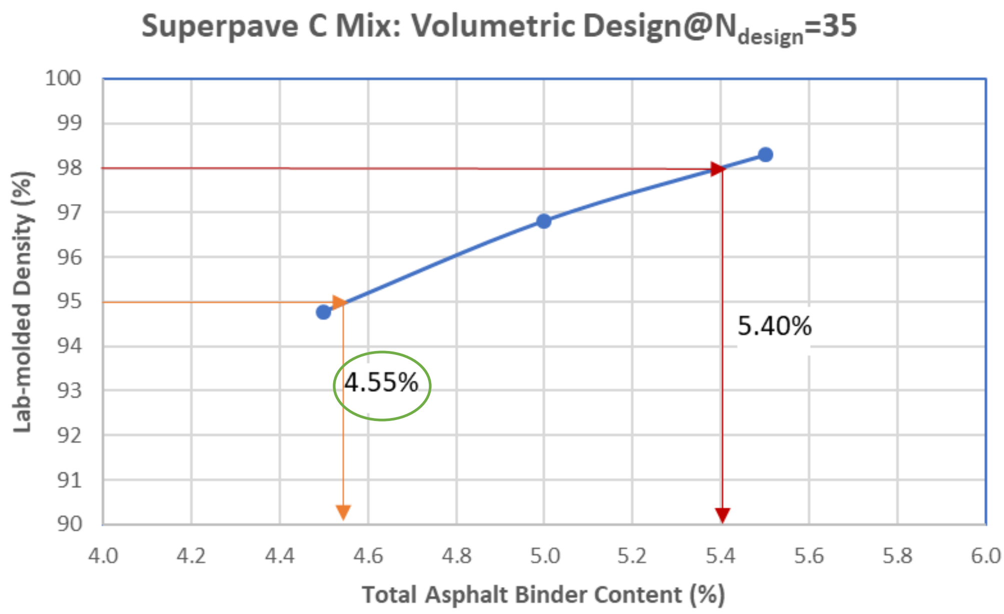


Figure 9. Volumetric Mix Design: Density vs. Asphalt Content.

Performance Evaluation of Asphalt Mixtures with Three Asphalt Contents

The 12.5-mm Superpave mixture with PG64-22 and 25 percent RAP (in weight of the total mixture) was mixed with three asphalt binder contents: 4.7, 5.0, and 5.3 percent. The asphalt binder content is the total asphalt binder content, including the binder from the RAP material. Then, the three loose mixtures were aged at 135°C for 2 hr before compacting the IDEAL-CT and -RT specimens. For each asphalt content, a total of six replicates of specimens at the air voids of 7±0.5 percent were molded, three specimens for the IDEAL-CT test and another three specimens for the IDEAL-RT test. Figure 10 shows the IDEAL-CT and -RT test results.

Based on the IDEAL-CT and -RT criteria—$CT_{Index} \geq 90$ and $RT_{Index} \geq 65$ for asphalt mixtures with PG70-22—the research team established a balanced zone, as shown in Figure 10. For this case, the boundary asphalt binder contents of the balanced zone were 5.10 to 5.24 percent, within which the asphalt mixture met both rutting and cracking criteria. Considering the fact that the asphalt mixtures often become either dryer or finer, the selection of the asphalt content favored the upper boundary of the balanced zone. For this case, the total asphalt binder content of 5.2 percent was selected for performance verification in the next step.

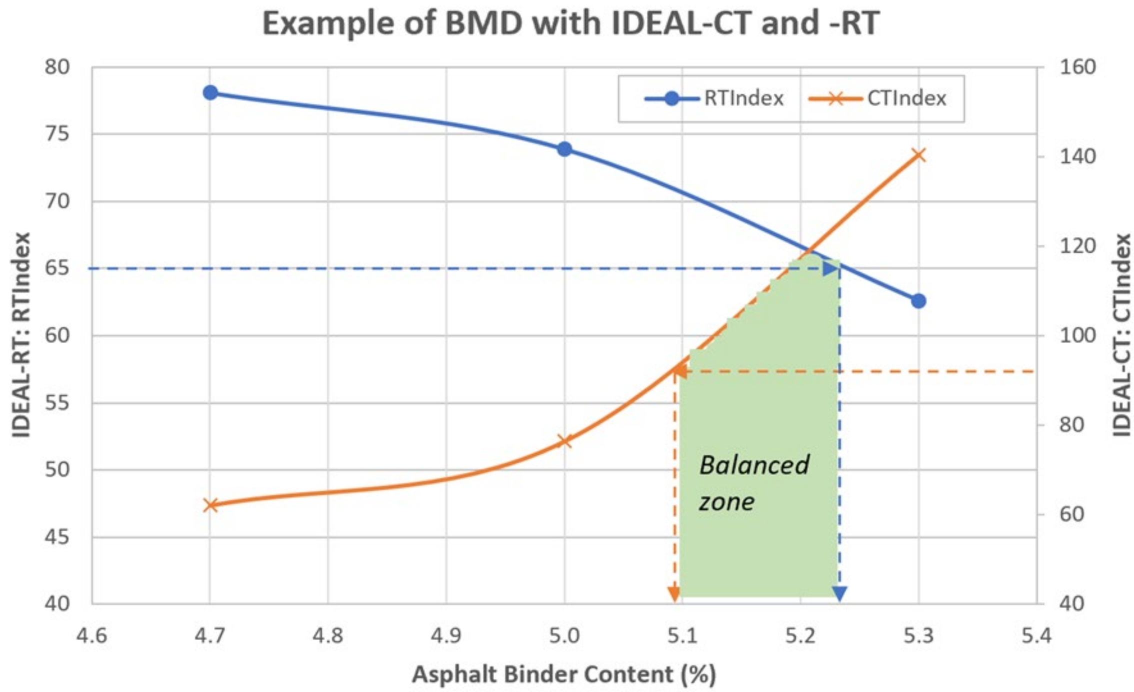


Figure 10. Performance Evaluation with Three Asphalt Binder Contents.

Performance Verification with the Selected Asphalt Binder Content

For this case study, the asphalt mixture was paved in Dallas District, Texas. Low-temperature cracking was not a major concern. Thus, the research team verified three distresses only: cracking, rutting, and moisture susceptibility of the 12.5-mm Superpave mixture with PG64-22 and 25 percent RAP (in weight) at the total asphalt binder content of 5.2 percent. As noted previously, the IDEAL-CT is employed for evaluating cracking resistance of the mixture after mid-term aging, and the HWTT is used for rutting and moisture susceptibility of the mixture after short-term aging. One set of the HWTT specimens were compacted using the Superpave gyratory compactor after short-term aging the loose mix for 2 hr at 135°C. For the IDEAL-CT, three test specimens were prepared using the Superpave gyratory compactor after mid-term aging the loose mixture, as detailed in Table 4.

The HWTT was performed at 50°C, following Tex-242-F: Hamburg Wheel Tracking Test, and the test result is shown in Figure 11. For this case study, since the mix was originally designed with PG70-22 binder, the associated requirement of the rut depth at 15,000 passes was less than 12.5 mm. As shown in Figure 11, the rut depth at 15,000 passes was 7.5 mm, and it met TxDOT's requirement for both rutting and moisture susceptibility.

The mid-term aged IDEAL-CT specimens were tested at 25°C—following ASTM D8225—and the average CT_{Index} values of the mid-term aged specimens was 55. Compared to the CT_{Index} = 117 (estimated from Figure 10) after the short-term aging, the CT_{Index} ratio of the mid-term aging to the short-term aging was 0.47 (55/117 = 0.47), which is larger than the minimum acceptance value: 0.45. Thus, the 12.5-mm Superpave mixture with PG64-22 and 25 percent RAP (in weight) at the total asphalt binder content of 5.2 percent passes the cracking requirement after the mid-term aging. Thus, the next step was to develop the QC/QA testing plan and acceptance criteria for plant production.

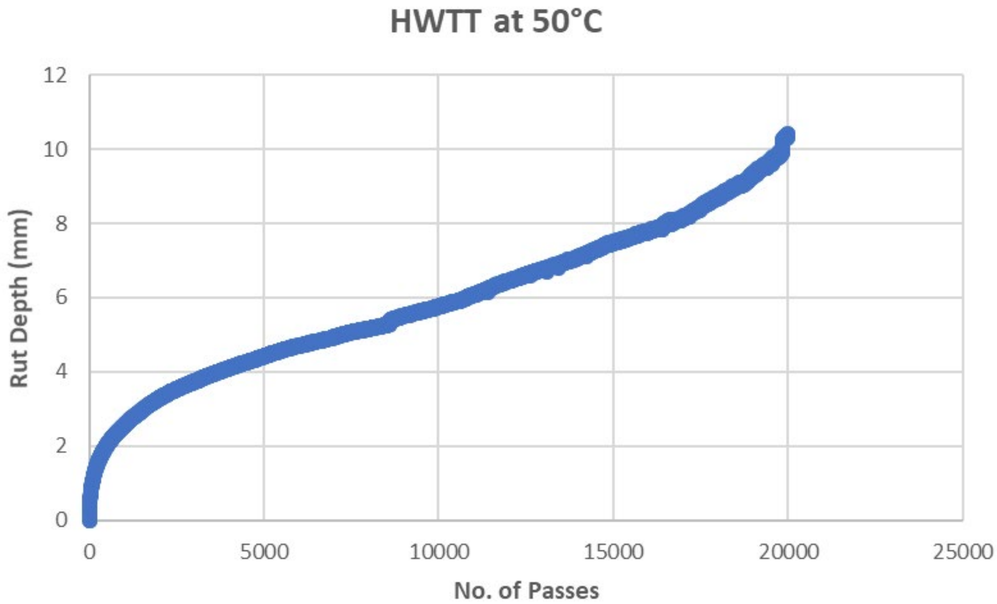


Figure 11. HWTT Test Results of the 12.5-mm Superpave Mixture at the Asphalt Content of 5.2 Percent.

Development of QC/QA Testing Plan and Acceptance Criteria

The new QC/QA testing plan focuses on three material properties: compacted density, CT_{Index}, and RT_{Index} corresponding to the balanced asphalt content. For this case study, the balanced asphalt content was 5.2 percent. As seen in Figure 9, 5.2 percent asphalt content corresponds to 97.5 percent density. As discussed previously, the maximum density cannot be greater than 98 percent. Thus, considering variability of plant production, the QC/QA density requirement will be 97.5±0.5 percent.

For the CT_{Index} and RT_{Index} acceptances, two ways to establish the acceptance criteria for the IDEAL-CT and -RT exist, which are described below:

- General minimum value approach: QC/QA acceptance for cracking and rutting will be the same minimum cracking and rutting requirements as those used for the mix design. For this case study, the minimum cracking and rutting requirements were $CT_{Index} \geq 90$ and $RT_{Index} \geq 65$. As long as the measured CT_{Index} and RT_{Index} values are equal or larger than these criteria, the mix passes the production QC/QA check, regardless of the CT_{Index} and RT_{Index} values of the original mix design corresponding to the balanced asphalt content. This approach is clear, straightforward, and easy to understand and implement, but it may lower the quality of an asphalt mix. For example, during the mix design, consider an asphalt mix that has a very good cracking resistance of $CT_{Index} = 180$. If the minimum value approach is employed during the production QC/QA testing, the cracking resistance of the production mix may drop to $CT_{Index} = 90$, but it still passes the production QC/QA testing because it meets the minimum cracking resistance requirement, although the mix cracking resistance is significantly reduced during plant production.

- Mix-specific acceptance approach: Contrary to the general minimum value approach, the mix-specific approach establishes mix-specific acceptance criteria for the IDEAL-CT and -RT at the balanced asphalt content during the mix design stage. The acceptance criteria are still minimum values of CT_{Index} and RT_{Index} at the balanced asphalt content. For this case study, the minimum CT_{Index} and RT_{Index} values were determined from the data presented in Figure 10; they are $CT_{Index} \geq 117$ and $RT_{Index} \geq 67$.

  For this case, both the mix-specific and the general acceptance criteria of CT_{Index} and RT_{Index} were close. Furthermore, considering production variability, the chosen acceptance criteria of CT_{Index} and RT_{Index} for QC/QA testing were as follows: $CT_{Index} \geq 90$ and $RT_{Index} \geq 65$ for this case study. Note that the original mixture was a virgin PG70-22 binder. Thus, $RT_{Index} \geq 65$ was selected.

Production QC/QA Testing

The asphalt mixture designed above was one of seven mixtures evaluated under a large, accelerated pavement testing study. This mixture was actually produced at an asphalt plant located in Dallas, Texas, and then paved on the accelerated pavement testing site. During the production, the asphalt mixture was sampled at the asphalt plant just like the conventional QC sampling. The sampled asphalt mixture was conditioned at the plant QC lab oven for 2 hr at the compaction temperature of 135°C before compacting specimens for density measurement (at $N_{design} = 35$) and then for three IDEAL-CT specimens at 7±0.5 percent air voids and another three IDEAL-RT specimens at 7±0.5 percent air voids. The QC test results are listed in Table 8. Thus, the produced asphalt mixture at the asphalt plant met all the acceptance criteria.

Table 8. QC/QA Requirements and Actual Test Results.

QC/QA Parameters	Compacted Density (%)	CT_{Index}	RT_{Index}
Acceptance criteria	97.5±0.5	90	65
Actual QC test result	97.5	99	75

SUMMARY

Asphalt mixtures are becoming increasingly complex, and given the ever-changing components of asphalt mixtures, both BMD and production QC/QA are critical in order for a mixture to perform well in the field. This chapter established a coherent BMD/QC/QA framework that has four interconnected components: (a) volumetric mix design and selection of multiple asphalt contents for mixture performance evaluation, (b) mixture performance evaluation at multiple asphalt contents and selection of the balanced asphalt content, (c) mixture performance verification at the balanced asphalt content, and (d) production QC/QA testing. One set of laboratory tests and associated acceptance criteria are recommended for the mixture performance evaluation and the production QC/QA testing and the other set is recommended for the mixture performance verification wherein DOTs can choose their preferred performance verification tests. Furthermore, two practical loose-mixture aging protocols were developed, one for short-term aging used in the process of the volumetric mix design, the mixture performance evaluation, and the production QC/QA testing, and the other for mid-term aging employed in the mixture performance verification. The recommended short-term aging protocol is to age the loose mixture in a force draft oven for 2 hr at the mixture compaction temperature, while the mid-term aging protocol consists of three steps: (1) short-term aging, (2) 20-hr loose-mixture aging at 100°C, and (3) reheating for compaction. A case study was presented in this chapter to demonstrate the whole process of the framework, including the actual plant production QC testing.

CHAPTER 5. SUMMARY AND RECOMMENDATIONS

SUMMARY

Many state DOTs have been implementing the BMD method to address the durability issue of asphalt mixes. One of the critical components of any BMD method is the cracking performance test. As discussed previously, the IDEAL-CT developed under NCHRP IDEA Project 195 has been adopted by 14 states as their cracking test. To further facilitate implementation and adoption, the research team assisted six DOTs—Kentucky, Maine, Minnesota, Oklahoma, Texas, and Virginia—in their implementation efforts via a demonstration workshop and development of webinars, training videos, and flyers for technicians, managers, and engineers. Furthermore, a coherent framework for BMD and QC/QA was recommended, with an emphasis on the same performance tests being used for both BMD and QC/QA. In addition, the research team developed two practical loose-mixture aging protocols, one for short-term aging used in the process of the volumetric mix design, the mixture performance evaluation, and the production QC/QA testing, and the other for mid-term aging employed in the mixture performance verification. A case study was presented in Chapter 4 to demonstrate the whole process of the framework, including the actual plant production QC testing.

RECOMMENDATIONS AND FUTURE RESEARCH

The IDEAL-CT has been adopted by many state DOTs because of its simplicity, repeatability, practicality, and good correlation with field cracking performance. However, further research is needed in several areas. Two of them are listed below:

- Acceptance criteria: Some preliminary CT_{Index} acceptance criteria are recommended in this report. However, different states use different types of aggregates, various sources of asphalt binders, and different levels of recycled materials. One acceptance criterion in one state may not be applicable to another state. Each state should establish its own acceptance criteria when considering traffic level, climate, existing pavement conditions, aggregates/binder sources, existing asphalt mix performance, and so forth.
- Testing temperature: Currently, the IDEAL-CT is often run at 25°C. Due to the overall climate difference between the north and south in the United States, a colder test temperature, such as 15°C, may be a better fit in the colder climate of the northern states.

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APPENDIX A: PRESENTATION ON THE IDEAL-CT UPDATE ON NOVEMBER 13, 2019

IDEAL Cracking Test Update: Mix Design and QC/QA

Texas A&M Transportation Institute

Fujie Zhou, Ph.D., P.E.
November 13, 2019

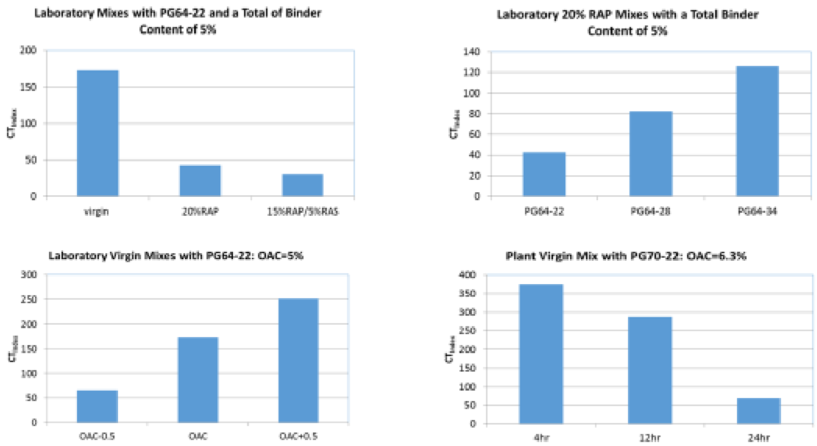
Outline

- Recap: Ideal Cracking Test
- Ideal cracking test for balanced mix design
- Ideal cracking test for QC/QA
- Practical issues
  - Testing machines
  - QC specimen quickly cooling
  - QA delayed testing time
  - Air voids correction factor

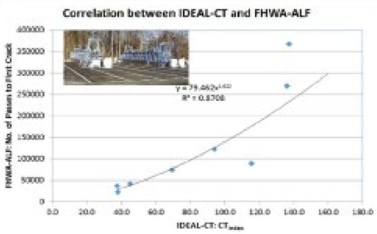
Recap: Ideal Cracking Test: Features

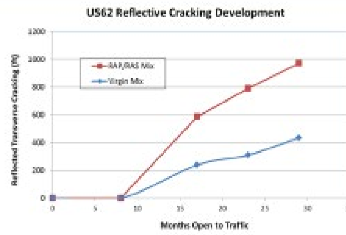
- Mechanism: matching pavement distress mechanisms;
- Simplicity: no instrum., cutting, gluing, drilling, or notching;
- Practicality: min. training needed for routine operation;
- Efficiency: test completion within 1 min.;
- Test equipment: use of existing equipment or <$10,000;
- Repeatability: coefficient of variation (COV) less than 20 %;
- Sensitivity: sensitive to asphalt mix composition (binder, others);
- Correlation to field: a good correlation with field distresses.

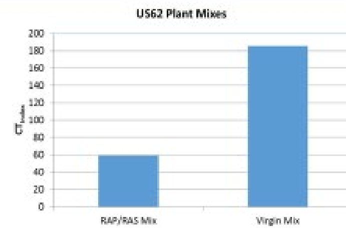
Recap: Ideal Cracking Test-Sensitivity

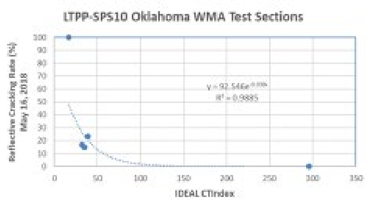


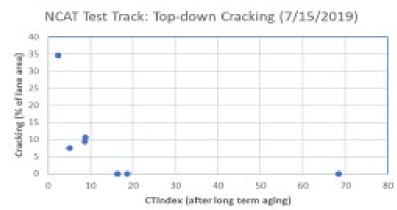
Recap: Ideal Cracking Test-Field Validation











Recap: Ideal Cracking Test-Test Procedure

Designation: D8225 – 19

Standard Test Method for
Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature[1]

This standard is issued under the fixed designation D8225; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the procedures for preparing, testing, and measuring asphalt mixture cracking resistance using cylindrical laboratory-prepared asphalt mix samples or pavement cores. Testing temperatures are selected from the long-term pavement performance (LTPP) database intermediate temperatures. The test method describes the determination of the cracking tolerance index, CT_{Index}, and other parameters

mendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[2]
D8 Terminology Relating to Materials for Roads and Pavements
D3203/D3203M Test Method for Percent Air Voids in Com-

IDEAL CRACKING TEST *TXDOT DESIGNATION: TEX-250-F*

Test Procedure for

IDEAL CRACKING TEST

TxDOT Designation: Tex-250-F

Effective Date: June 2019

1. SCOPE

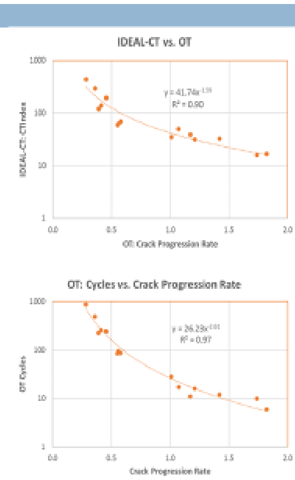
1.1 This test method determines the cracking tolerance index (CT_{Index}) of compacted bituminous mixtures.

1.2 The values given in parentheses (if provided) are not standard and may not be exact mathematical conversions. Use each system of units separately. Combining values from the two systems may result in nonconformance with the standard.

Recap: Ideal Cracking Test-Acceptance Criteria

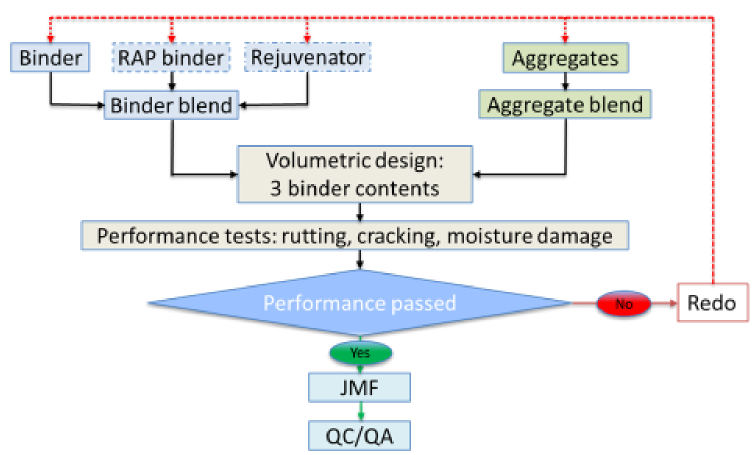
- Virginia DOT: CT_{Index}>70
- Recommendation for TxDOT:

Crack Progression Rate	CT_{Index} Predicted Value	CT_{Index} Recommended Criteria	OT Cycles
0.27	335	>320 (CAM)	800
0.28	316		727
0.39	187	>185 (TOM)	300
0.45	149	>145 (SMA)	211
0.46	143		199
0.55	108	>105 (Superpave)	125
0.56	105		119
0.72	70	>65 (Dense-graded)	62
0.75	66		56
1.00	42	Unacceptable	26



Ideal Cracking Test for BMD

- BMD framework
  - Volumetrics
  - Performance tests
  - Performance criteria
  - QC/QA



Ideal Cracking Test for BMD

- BMD framework
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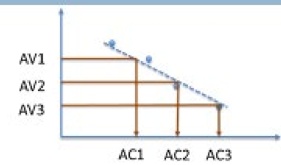
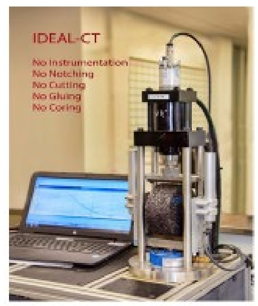
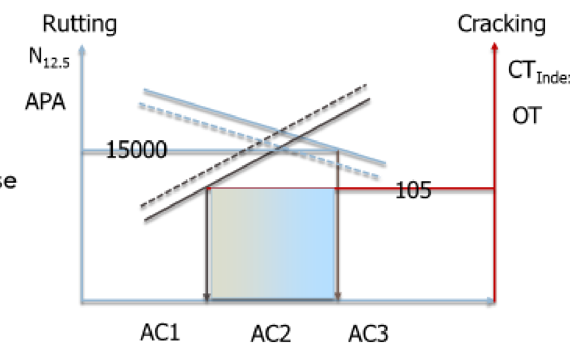




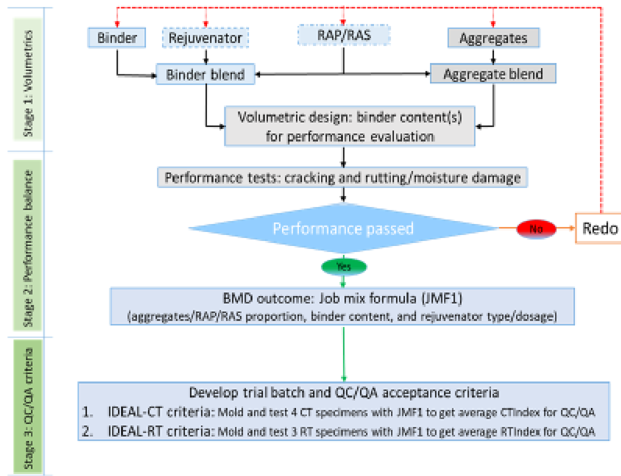
Ideal Cracking Test for BMD

- Select binder/RAP/RAS/rejuvenator contents
  - Traffic
  - Environment
  - Overlay vs. new constr.
    - Existing pavem. condi.
    - Surface, binder, base course



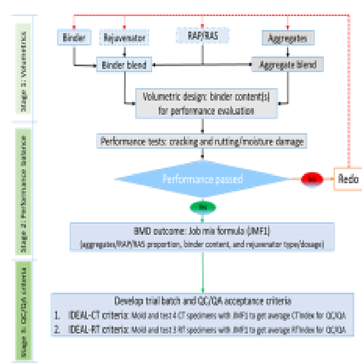
Ideal Cracking Test for QC/QA

- Current QC (QA)
  - Binder content
  - Gradation
  - Density (or air voids)
  - Sublot based
- New QC (QA)
  - Density
  - Cracking
  - Rutting
  - Sublot based



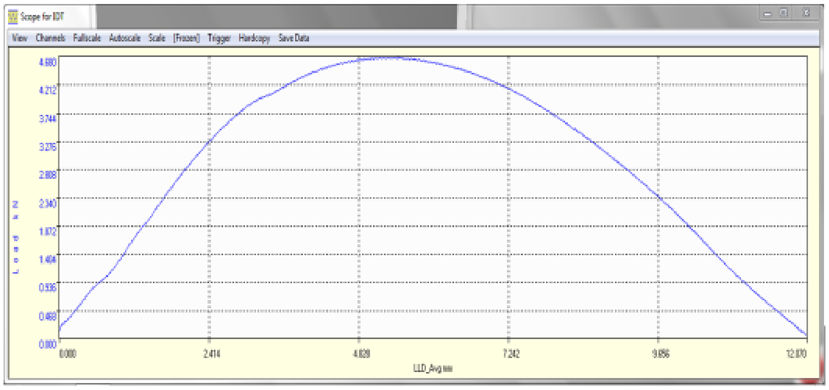
Ideal Cracking Test for BMD and QC/QA: Practical Issues

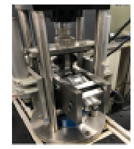
- Test machines:
  - Calibration or validation
  - Screw type vs. hydraulic
- QC specimen quickly cooling
  - 3 hrs completing compaction/cooling/testing
- QA delayed testing time
  - 3hrs to 1 day to 3 days
- Specimen air voids
  - Air void correction factor



Ideal Cracking Test for BMD and QC/QA: Test Machine

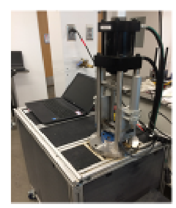
- Test machines: Pine, InstroTek, Testquip, etc.
  - Need a validator to ensure every machine provides same Load-disp. curve





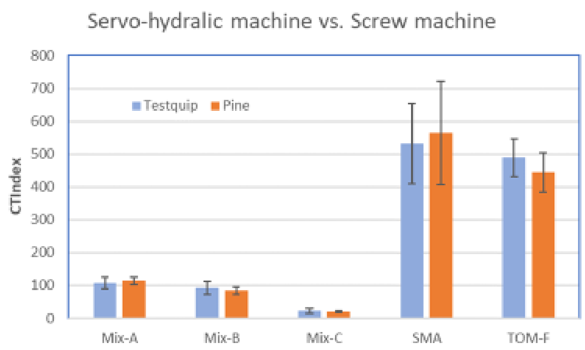
Ideal Cracking Test for BMD and QC/QA: Test Machine

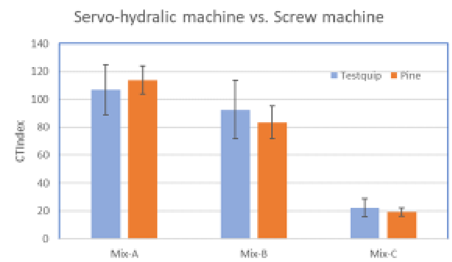
- Test machines: screw type vs. hydraulic
  - 5 mixtures with a wide range of CT_{Index} values
    - Mix-A: lab mix with better cracking resistance
    - Mix-B: plant mix with acceptable cracking resistance
    - Mix-C: plant mix with poor cracking resistance
    - SMA: plant mix with very good cracking resistance
    - TOM-F: plant mix with very good cracking resistance; very fine and uniform mix



Ideal Cracking Test for BMD and QC/QA: Test Machine

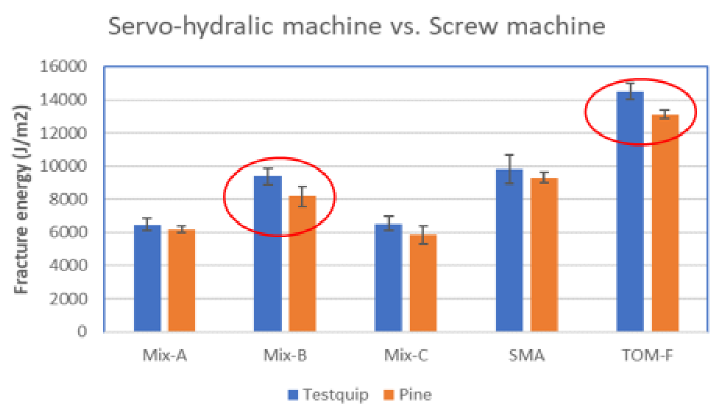
- Test machines: screw type vs. hydraulic





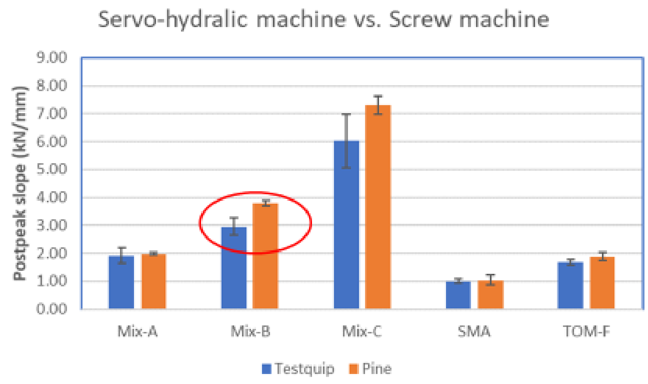
CT_{Index}: No statistical difference between machines

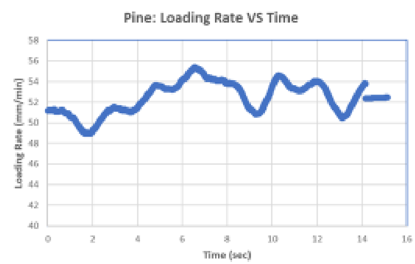
Ideal Cracking Test for BMD and QC/QA: Test Machine



1. Overall, average fracture energy of the screw machine is consistently smaller;
2. For Mix-B and TOM-F, fracture energy is statistically different between machines.

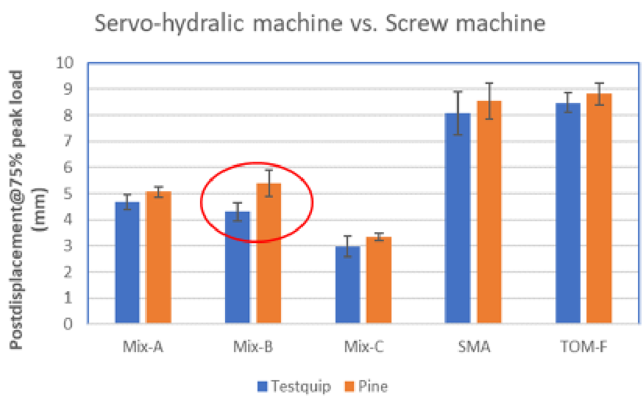
Ideal Cracking Test for BMD and QC/QA: Test Machine

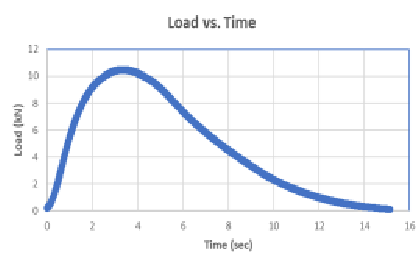




1. Overall, average post peak slope of the screw machine is consistently larger;
2. For Mix-B, post peak slope is statistically different between machines.

Ideal Cracking Test for BMD and QC/QA: Test Machine





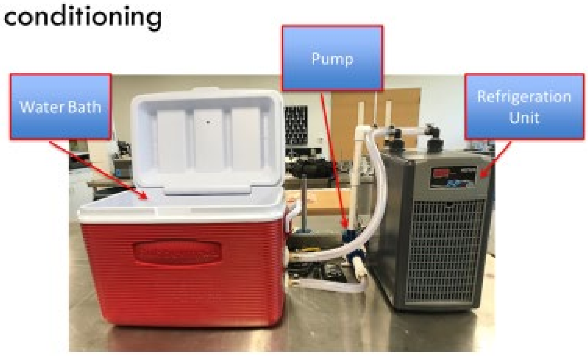
1. Overall, average post peak displacement of the screw machine is consistently larger;
2. For Mix-B, post peak displacement is statistically different between machines.

Ideal Cracking Test for BMD and QC/QA: Test Machine

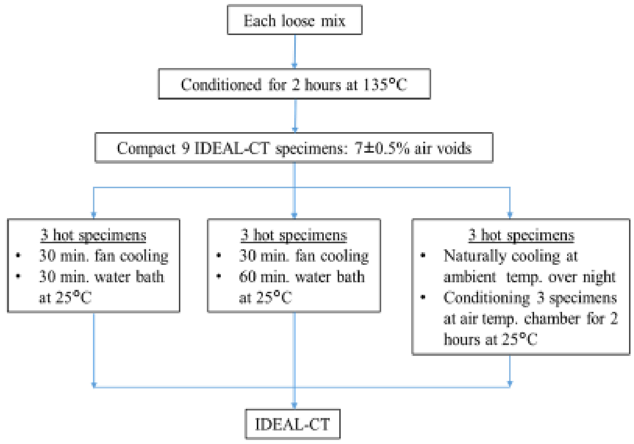
- CT_{Index} is not significantly different between machines.
- Pine machine had consistently lower fracture energy, but both Mix-B and TOM-F showed significant difference between machines.
- Pine machine had consistently higher post peak slope, but only Mix-B showed significant difference between machines.
- Pine machine had consistently larger post peak displacement, but only Mix-B showed significant difference between machines.

Ideal Cracking Test for BMD and QC/QA: QC Specimen Rapidly Cooling

- Specimen temp. out of mold: 200 °F
- IDEAL-CT test temp.: 77 °F
  - 60 min. cooling and conditioning



Ideal Cracking Test for BMD and QC/QA: QC Specimen Rapidly Cooling



Ideal Cracking Test for BMD and QC/QA: QC Specimen Rapidly Cooling

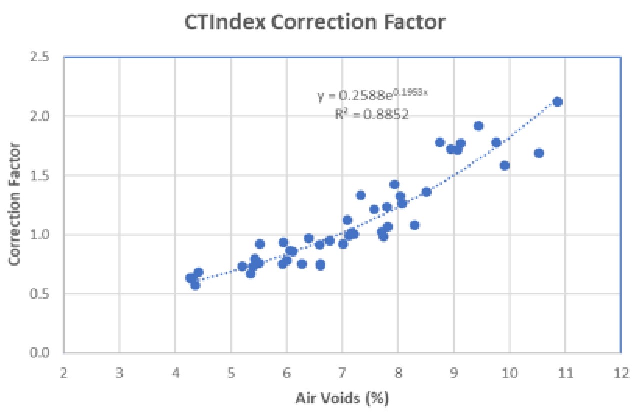
Cooling Conditions	9.5mm Superpave-A Mix	9.5mm Superpave-B Mix	12.5mm Superpave Mix
30min. fan/30min. water	120.7	35.7	64.4
30min. fan/60min. water	115.5	35.6	63.4
Standard cooling and conditioning	116.3	36.2	63.3

Ideal Cracking Test for BMD and QC/QA: QA Delayed Testing Time

Cooling/Conditioning Scenario	9.5mm Superpave Mix with Granite Aggregates	12.5mm Superpave Mix with Limestone Aggregates
30min. fan/30min. water	120.7	24.8
1-day delay/air chamber conditioning	116.3	21.8
3-day delay/air chamber conditioning	115.9	22.2

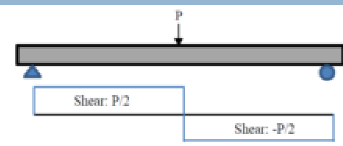
Ideal Cracking Test for BMD and QC/QA: Air Voids Correction Factor

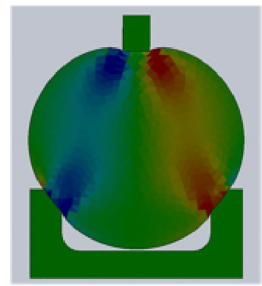
- $CT_{Index=7\%} = CT_{Index} / CF$



Development of IDEAL-Rutting Test (IDEAL-RT)

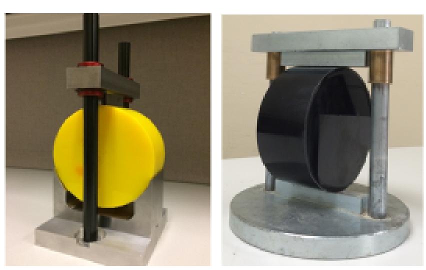
- IDEAL-RT
  - Cylindrical specimen:
    - *150 mm Diam. X 62 mm high*
  - Test temperature:
    - *50°C (or others)*
  - Loading rate:
    - *50 mm/min.*
  - Rutting parameter:
    - *Shear strength, τ_{max}*

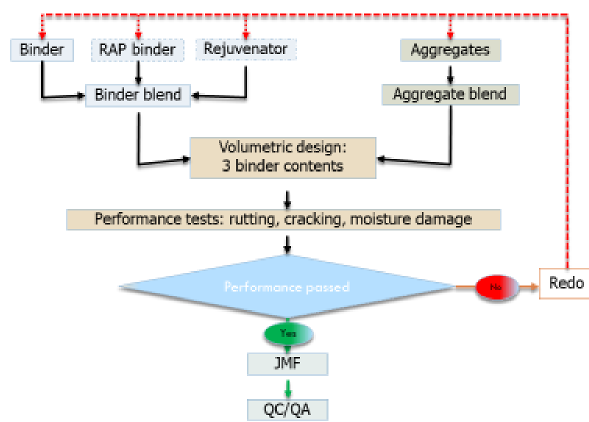




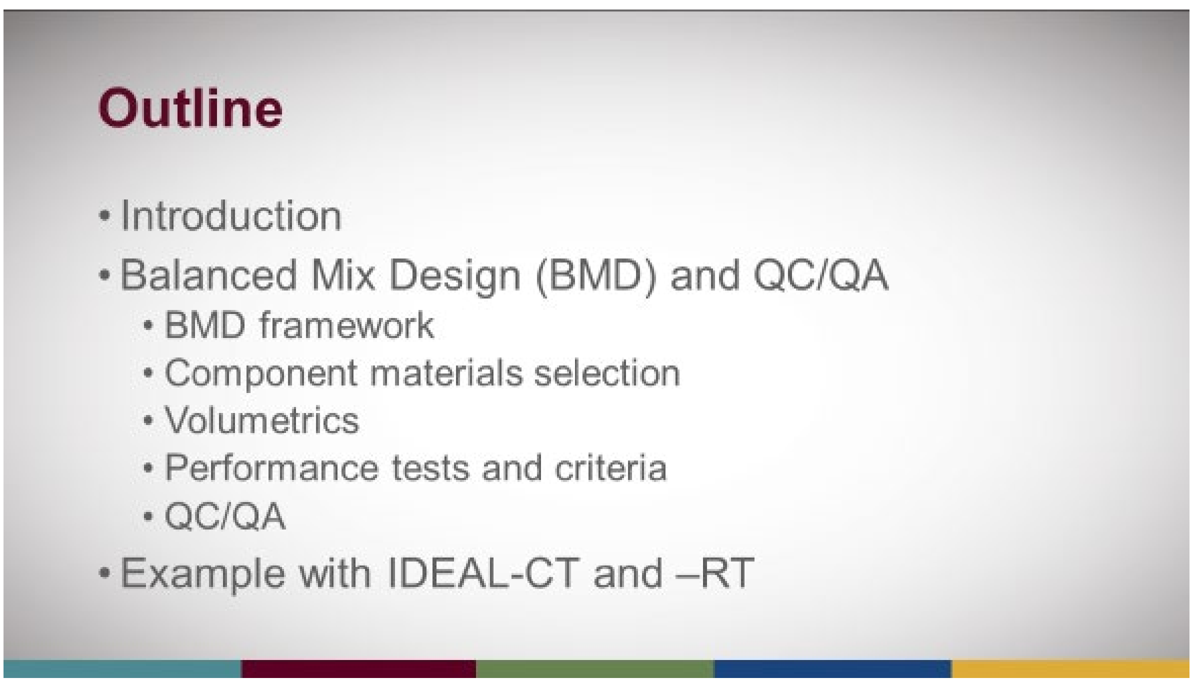
Applications of IDEAL Tests for Balanced Mix Design

- Balanced mix design
  - Volumetric requirements
  - Rutting requirements: IDEAL-RT
  - Cracking requirement: IDEAL-CT





APPENDIX B: IDEAL-CT AND -RT FOR BALANCED MIX DESIGN AND QC/QA ON FEBRUARY 27, 2020



Introduction

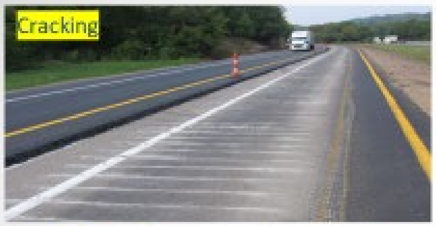
- Past: Every generation of researchers pursued BMD.
- 2005: TTI made it reality using Hamburg and OT.
- 2014: TTI developed BMD for project specific conditions.
- 2015: BMD definition by FHWA task group:

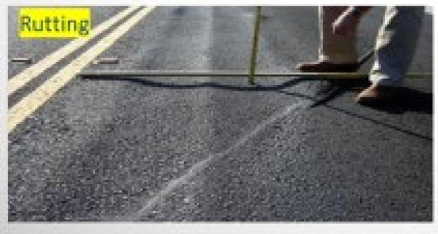
  Asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure.
- BMD for all mixes: virgin, low and high RAP/RAS

BMD framework

- Define modes of distress to address
- Select performance tests and associated criteria
- Determine the role of volumetrics
- Choose loose mix aging/conditioning temperature/time
- Develop guidelines for selecting a balanced asphalt content
- Provide strategies for meeting performance criteria
- Establish QC/QA acceptance requirements

BMD framework: three distresses

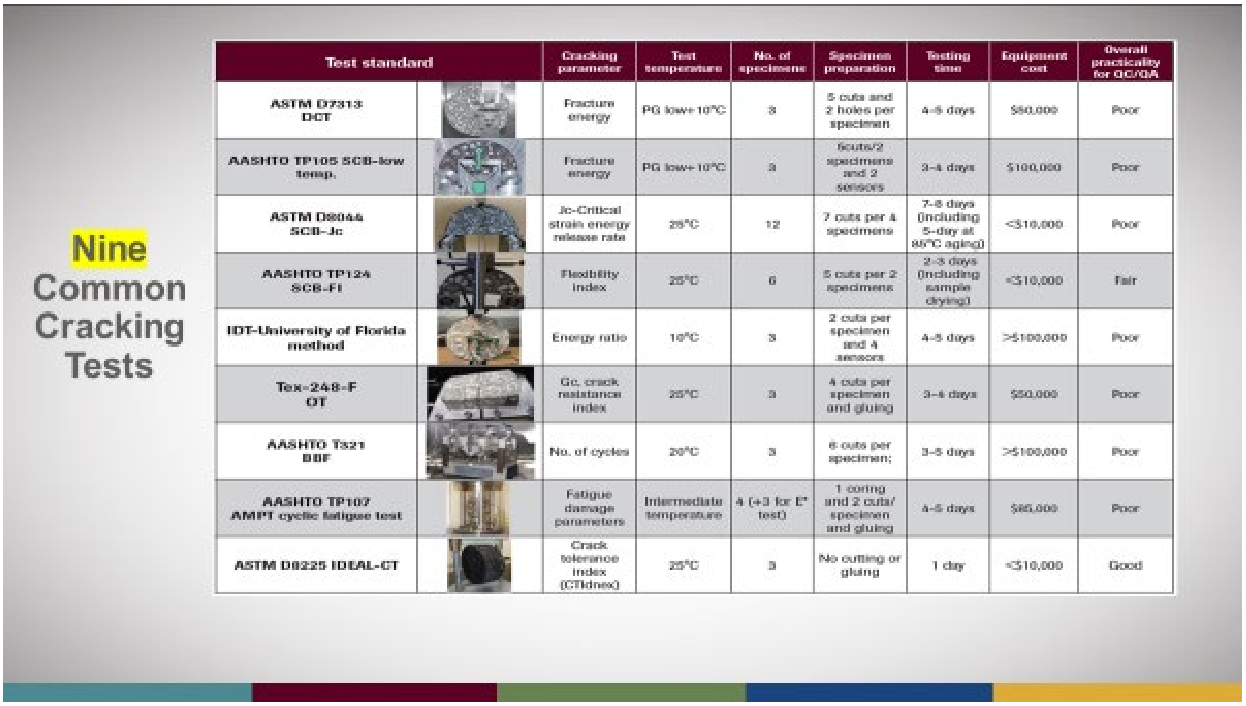




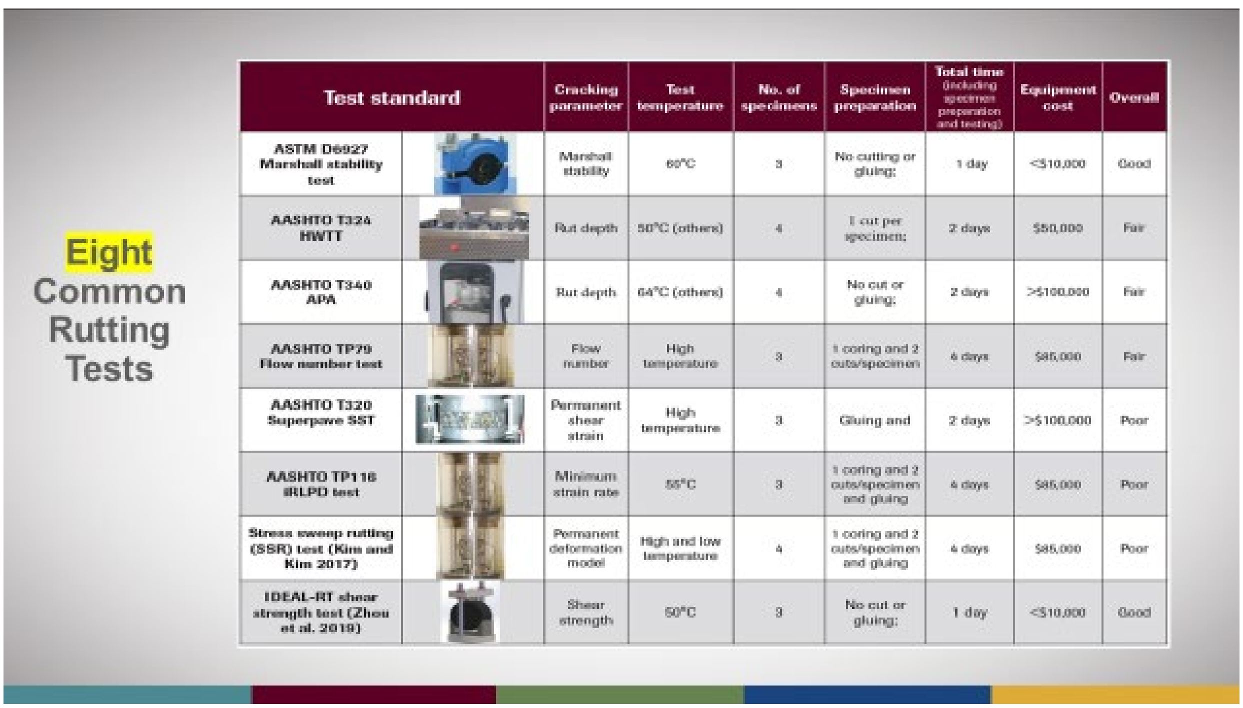
Moisture damage

BMD framework: Performance tests

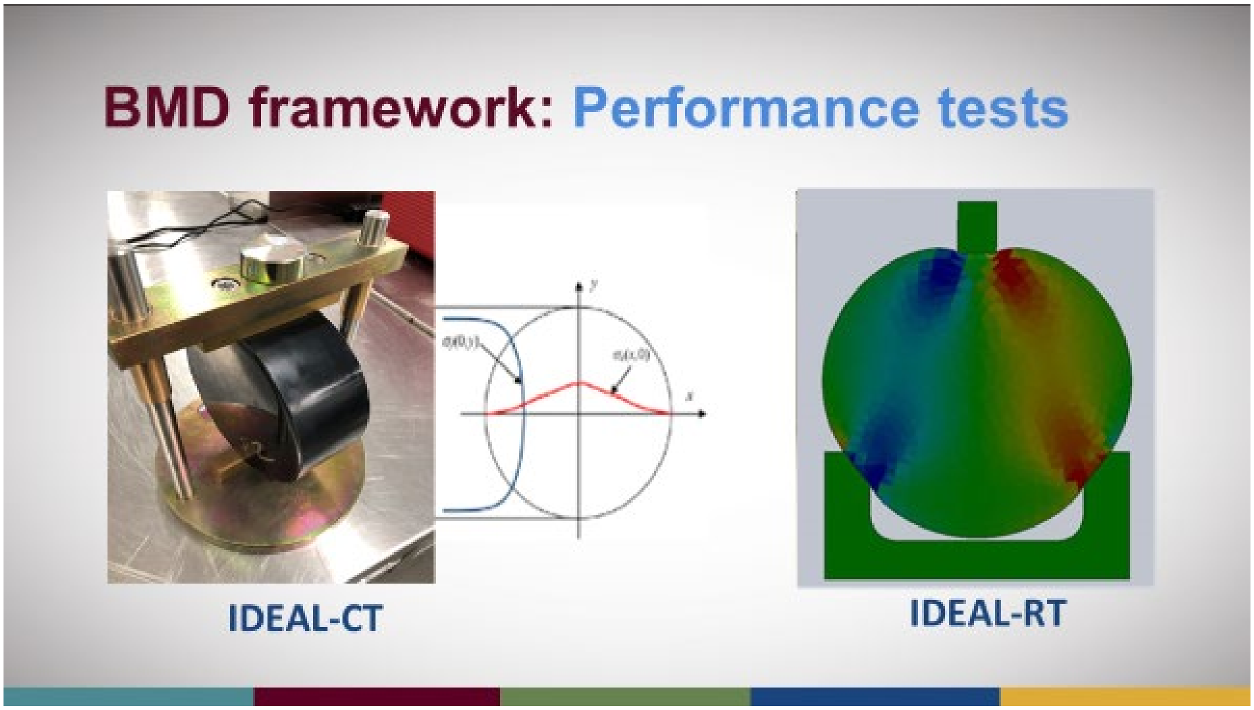
- 9 cracking tests
- 8 rutting tests
- 2 moisture damage tests
  - IDT-TSR and Hamburg wheel tracking test

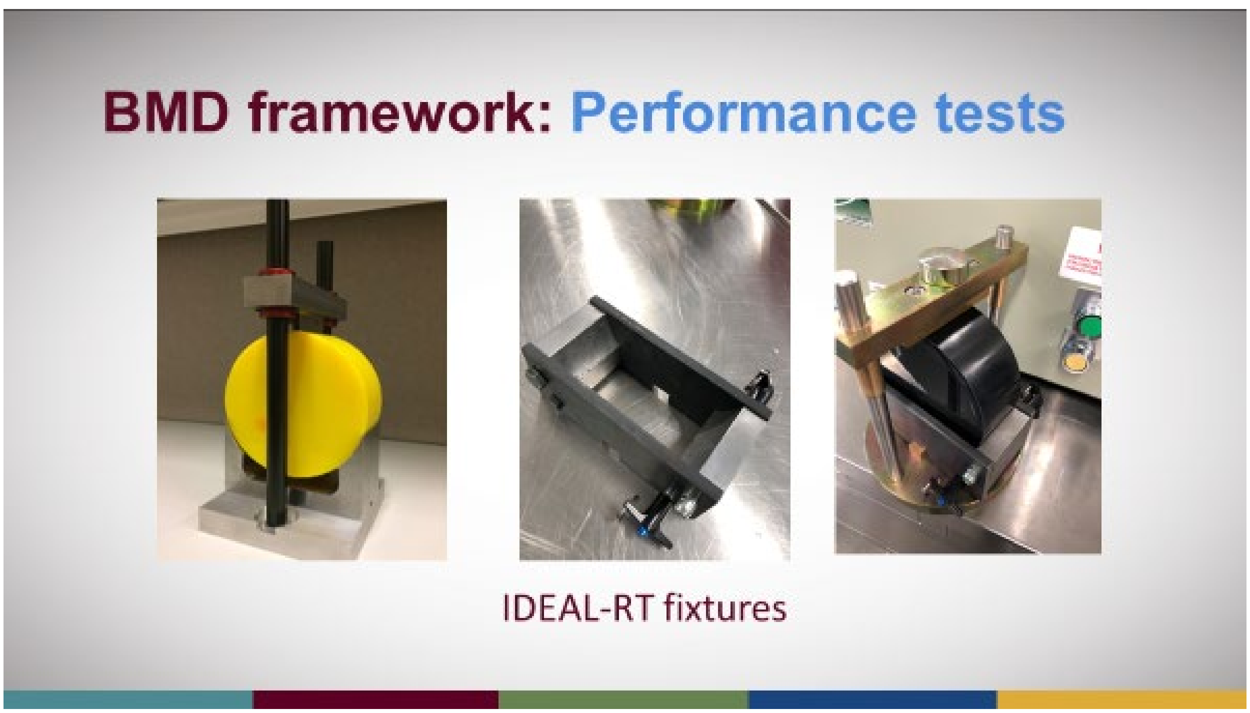


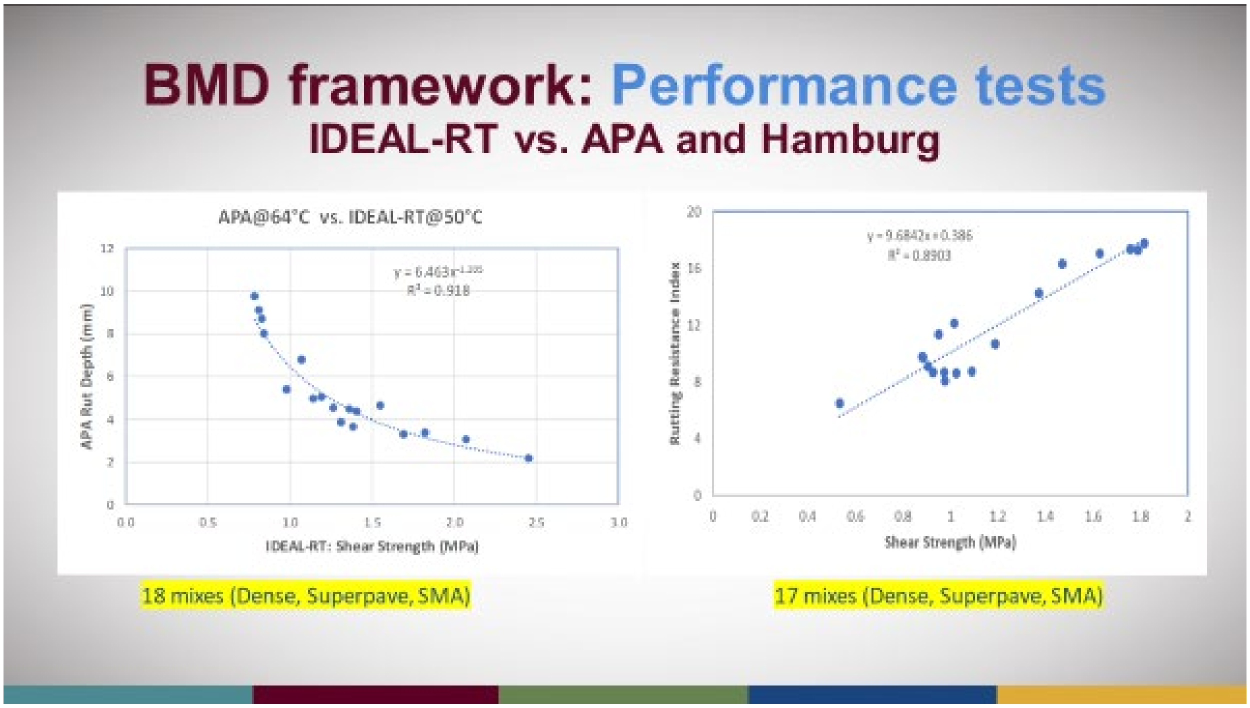
Test standard	Cracking parameter	Test temperature	No. of specimens	Specimen preparation	Testing time	Equipment cost	Overall practicality for QC/QA
ASTM D7313 DCT	Fracture energy	PG low+10°C	3	5 cuts and 2 holes per specimen	4-5 days	$50,000	Poor
AASHTO TP105 SCB-low temp.	Fracture energy	PG low+10°C	3	5cuts/2 specimens and 2 sensors	3-4 days	$100,000	Poor
ASTM D8044 SCB-Jc	Jc-Critical strain energy release rate	25°C	12	7 cuts per 4 specimens	7-8 days (including 5-day at 85°C aging)	<$10,000	Poor
AASHTO TP124 SCB-FI	Flexibility index	25°C	6	5 cuts per 2 specimens	2-3 days (including sample drying)	<$10,000	Fair
IDT-University of Florida method	Energy ratio	10°C	3	2 cuts per specimen and 4 sensors	4-5 days	>$100,000	Poor
Tex-248-F OT	Gc, crack resistance index	25°C	3	4 cuts per specimen and gluing	3-4 days	$50,000	Poor
AASHTO T321 BBF	No. of cycles	20°C	3	6 cuts per specimen;	3-5 days	>$100,000	Poor
AASHTO TP107 AMPT cyclic fatigue test	Fatigue damage parameters	Intermediate temperature	4 (+3 for E* test)	1 coring and 2 cuts/ specimen and gluing	4-5 days	$85,000	Poor
ASTM D8225 IDEAL-CT	Crack tolerance index (CTIndex)	25°C	3	No cutting or gluing	1 day	<$10,000	Good

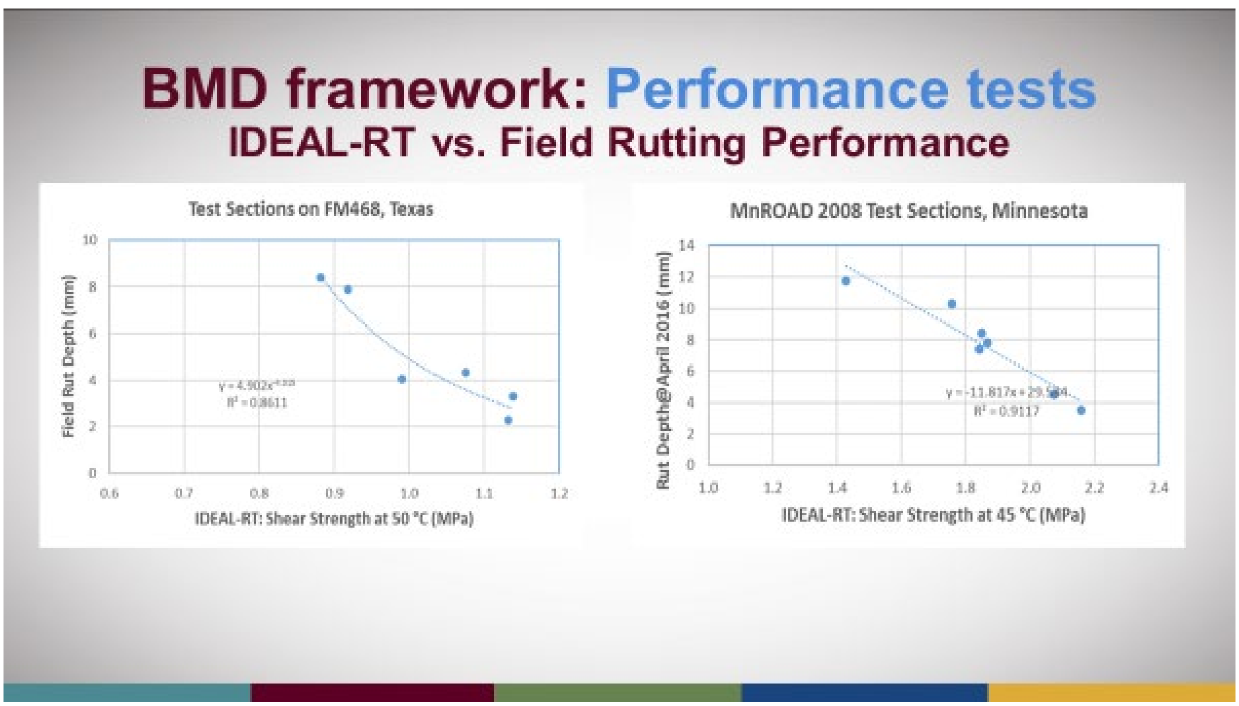


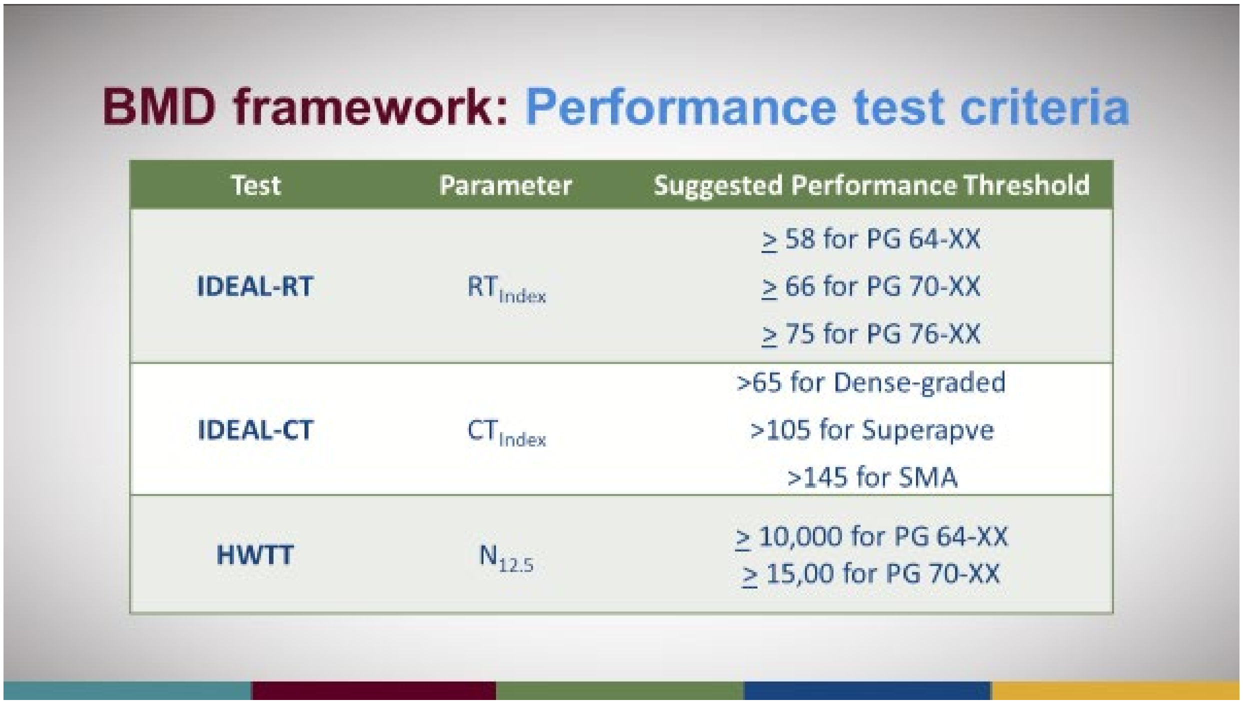
Test standard	Cracking parameter	Test temperature	No. of specimens	Specimen preparation	Total time (including specimen preparation and testing)	Equipment cost	Overall
ASTM D6927 Marshall stability test	Marshall stability	60°C	3	No cutting or gluing;	1 day	<$10,000	Good
AASHTO T324 HWTT	Rut depth	50°C (others)	4	1 cut per specimen;	2 days	$50,000	Fair
AASHTO T340 APA	Rut depth	64°C (others)	4	No cut or gluing;	2 days	>$100,000	Fair
AASHTO TP79 Flow number test	Flow number	High temperature	3	1 coring and 2 cuts/specimen	4 days	$85,000	Fair
AASHTO T320 Superpave SST	Permanent shear strain	High temperature	3	Gluing and	2 days	>$100,000	Poor
AASHTO TP116 IRLPD test	Minimum strain rate	55°C	3	1 coring and 2 cuts/specimen and gluing	4 days	$85,000	Poor
Stress sweep rutting (SSR) test (Kim and Kim 2017)	Permanent deformation model	High and low temperature	4	1 coring and 2 cuts/specimen and gluing	4 days	$85,000	Poor
IDEAL-RT shear strength test (Zhou et al. 2019)	Shear strength	50°C	3	No cut or gluing;	1 day	<$10,000	Good


BMD framework: Performance tests
IDEAL-CT
IDEAL-RT


BMD framework: Performance tests
IDEAL-RT fixtures

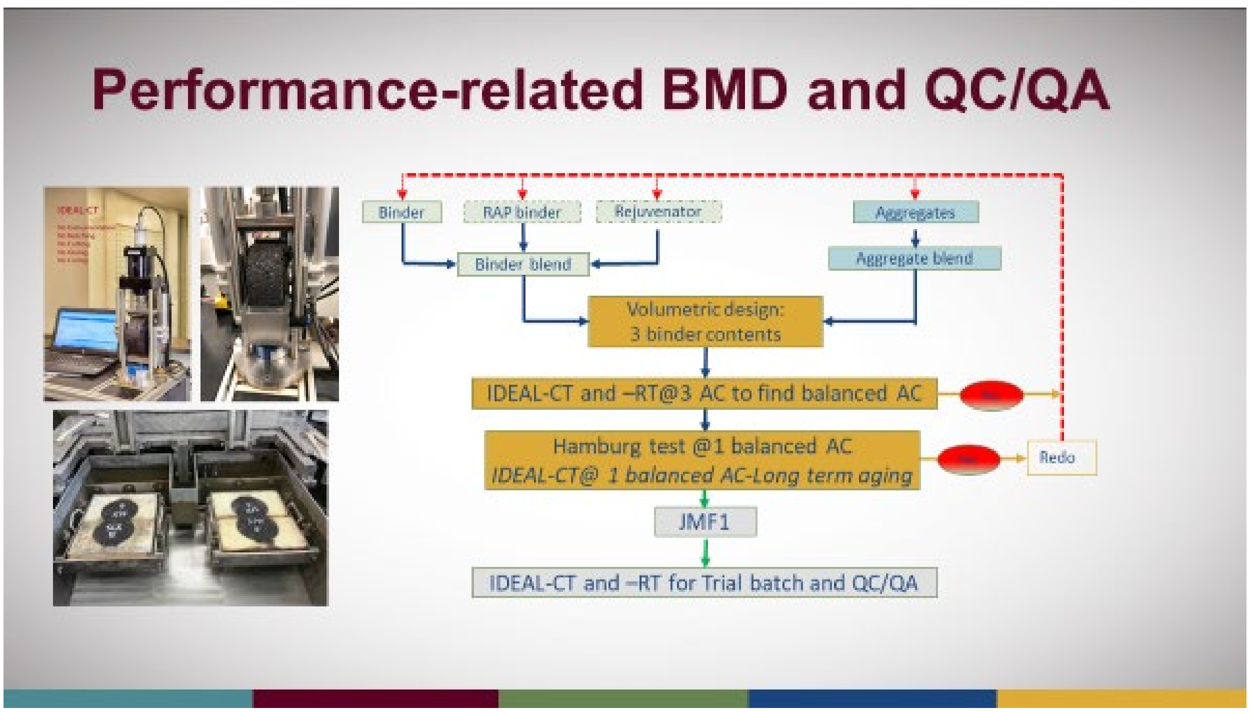

BMD framework: Performance tests
IDEAL-RT vs. APA and Hamburg
APA@64°C vs. IDEAL-RT@50°C
APA Rut Depth (mm)
IDEAL-RT: Shear Strength (MPa)
R² = 0.918
Rutting Resistance Index
Shear Strength (MPa)
y = 9.6842x + 0.386
R² = 0.8903
18 mixes (Dense, Superpave, SMA)
17 mixes (Dense, Superpave, SMA)


BMD framework: Performance tests
IDEAL-RT vs. Field Rutting Performance
Test Sections on FM468, Texas
Field Rut Depth (mm)
IDEAL-RT: Shear Strength at 50 °C (MPa)
MnROAD 2008 Test Sections, Minnesota
Rut Depth@April 2016 (mm)
IDEAL-RT: Shear Strength at 45 °C (MPa)



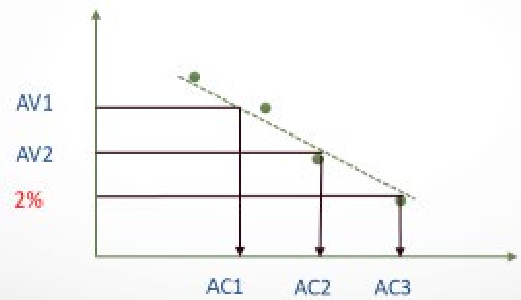
BMD framework: Performance test criteria

Test	Parameter	Suggested Performance Threshold
IDEAL-RT	RT_{Index}	$\geq$ 58 for PG 64-XX $\geq$ 66 for PG 70-XX $\geq$ 75 for PG 76-XX
IDEAL-CT	CT_{Index}	>65 for Dense-graded >105 for Superapve >145 for SMA
HWTT	$N_{12.5}$	$\geq$ 10,000 for PG 64-XX $\geq$ 15,00 for PG 70-XX



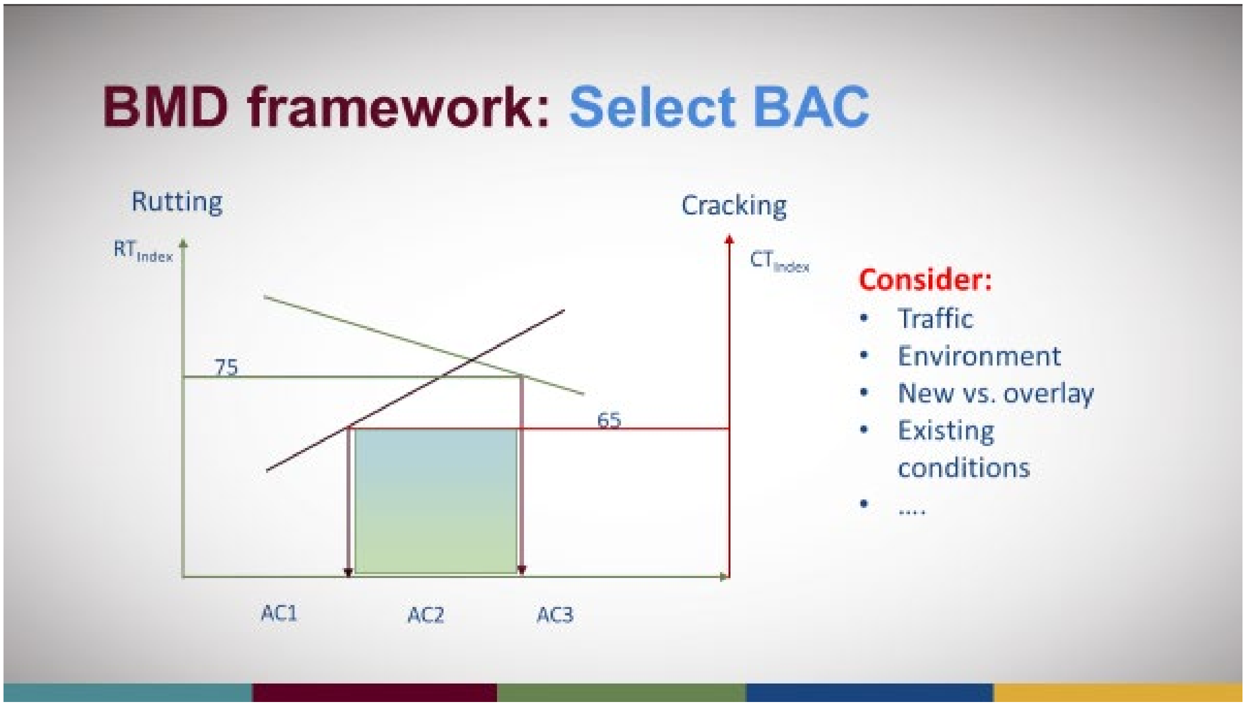
BMD framework: Role of volumetrics

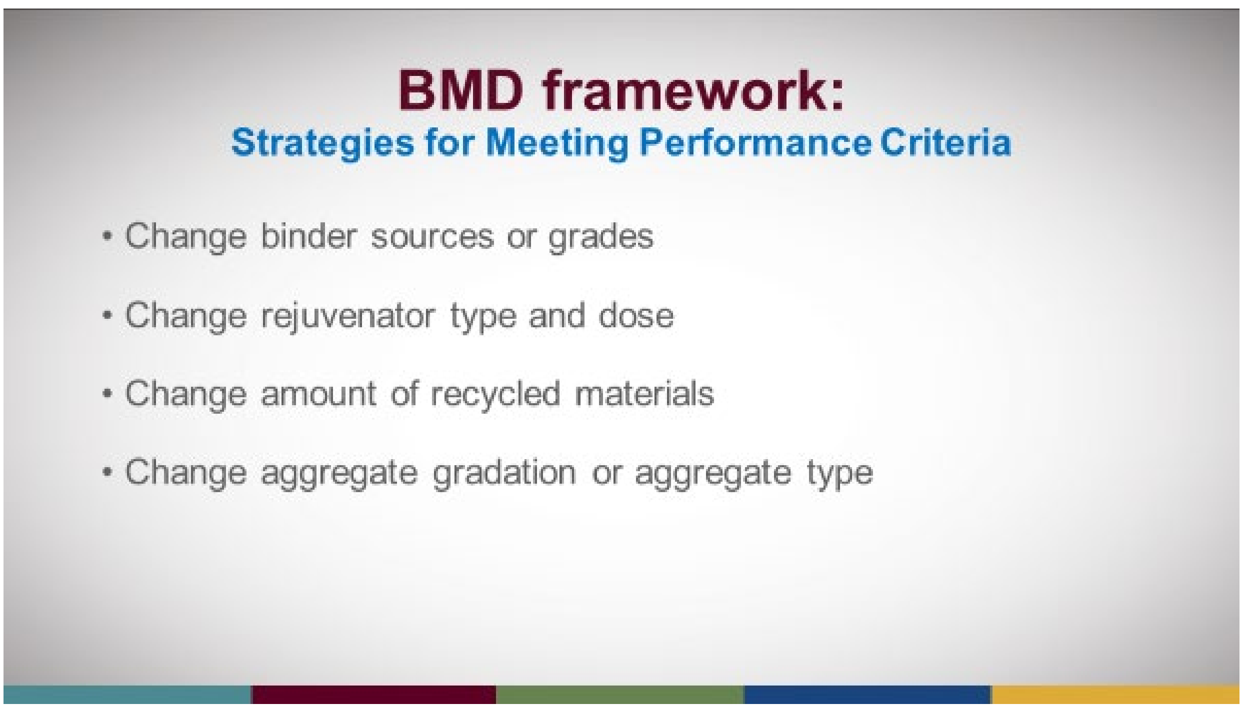
- Select compaction effort
- Control max. density of 98% ONLY: max. asphalt content

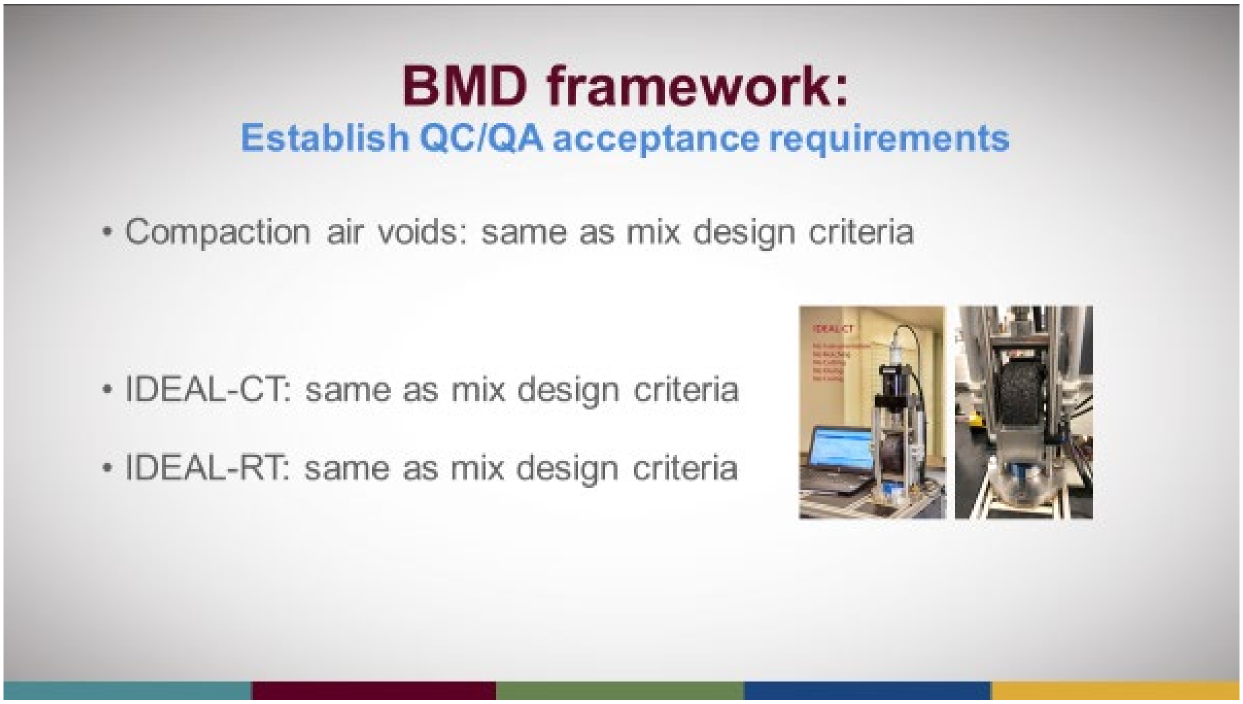


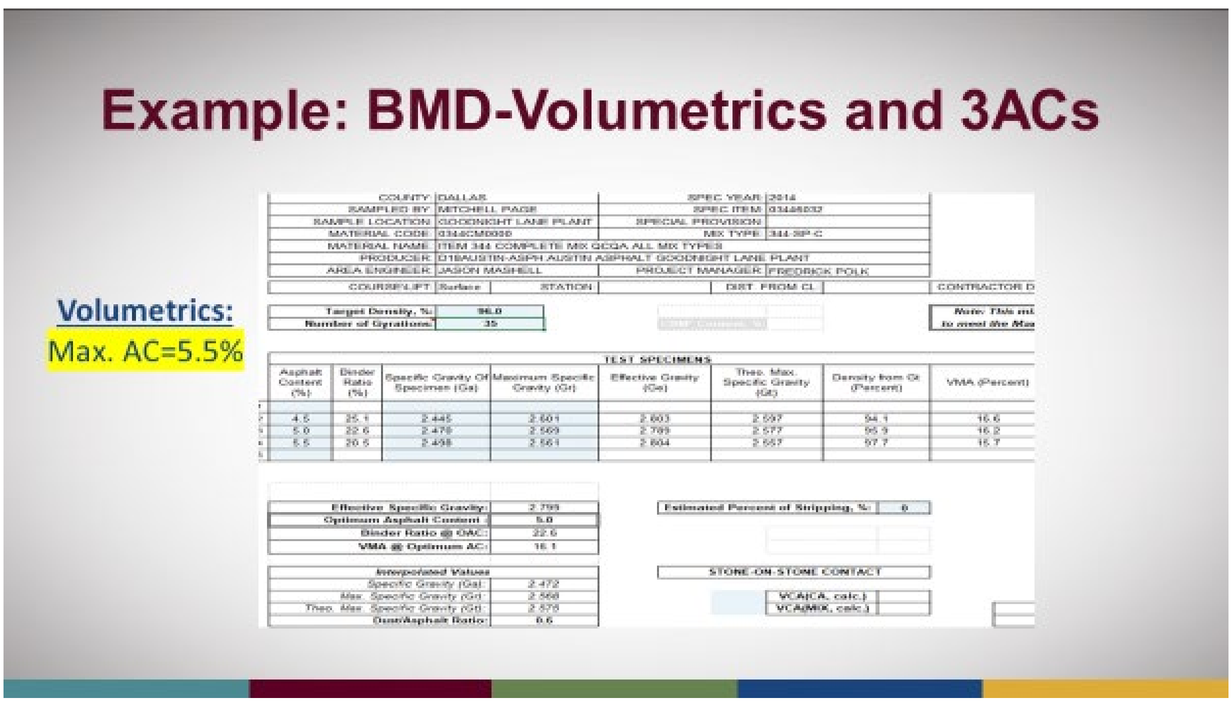
BMD framework: Loose mix conditioning

Stage	Test	Loose mix conditioning
Multiple AC	IDEAL-RT	2 hrs@compaction temperature (or 275F)
	IDEAL-CT	
BAC	HWTT	2 hrs@compaction temperature (or 275F)
	IDEAL-CT	Long term aging (?)


BMD framework: Select BAC
Rutting
Cracking
RT Index
CT Index
75
65
AC1
AC2
AC3
Consider:
• Traffic
• Environment
• New vs. overlay
• Existing conditions
• ....


BMD framework:
Strategies for Meeting Performance Criteria
• Change binder sources or grades
• Change rejuvenator type and dose
• Change amount of recycled materials
• Change aggregate gradation or aggregate type





COUNTY	DALLAS	SPEC YEAR	2014
SAMPLED BY	MITCHELL PAGE	SPEC ITEM	03445032
SAMPLE LOCATION	GOODNIGHT LANE PLANT	SPECIAL PROVISION	
MATERIAL CODE	0344CM0000	MIX TYPE	344-SP-C
MATERIAL NAME	ITEM 344 COMPLETE MIX QCQA ALL MIX TYPES		
PRODUCER	D18AUSTIN-ASPH AUSTIN ASPHALT GOODNIGHT LANE PLANT		
AREA ENGINEER	JASON MASHELL	PROJECT MANAGER	FREDRICK POLK
COURSE/LIFT	Surface	STATION	
DIST. FROM CL			

Target Density, %	96.0
Number of Gyrations	35

TEST SPECIMENS

Asphalt Content (%)	Binder Ratio (%)	Specific Gravity Of Specimen (Ga)	Maximum Specific Gravity (Gr)	Effective Gravity (Ge)	Theo. Max. Specific Gravity (Gt)	Density from Gt (Percent)	VMA (Percent)
4.5	25.1	2.445	2.601	2.803	2.597	94.1	16.6
5.0	22.6	2.478	2.569	2.789	2.577	95.9	16.2
5.5	20.5	2.498	2.561	2.804	2.557	97.7	16.7

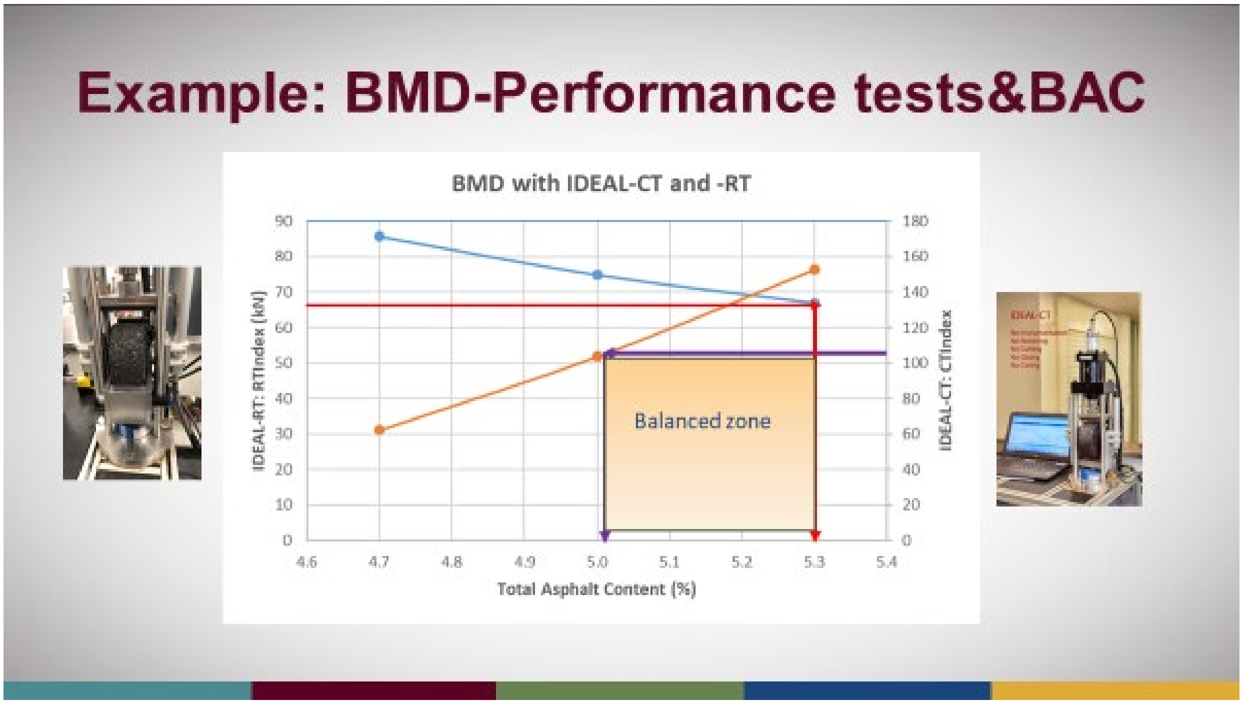
Effective Specific Gravity:	2.799
Optimum Asphalt Content :	5.0
Binder Ratio @ OAC:	22.6
VMA @ Optimum AC:	16.1

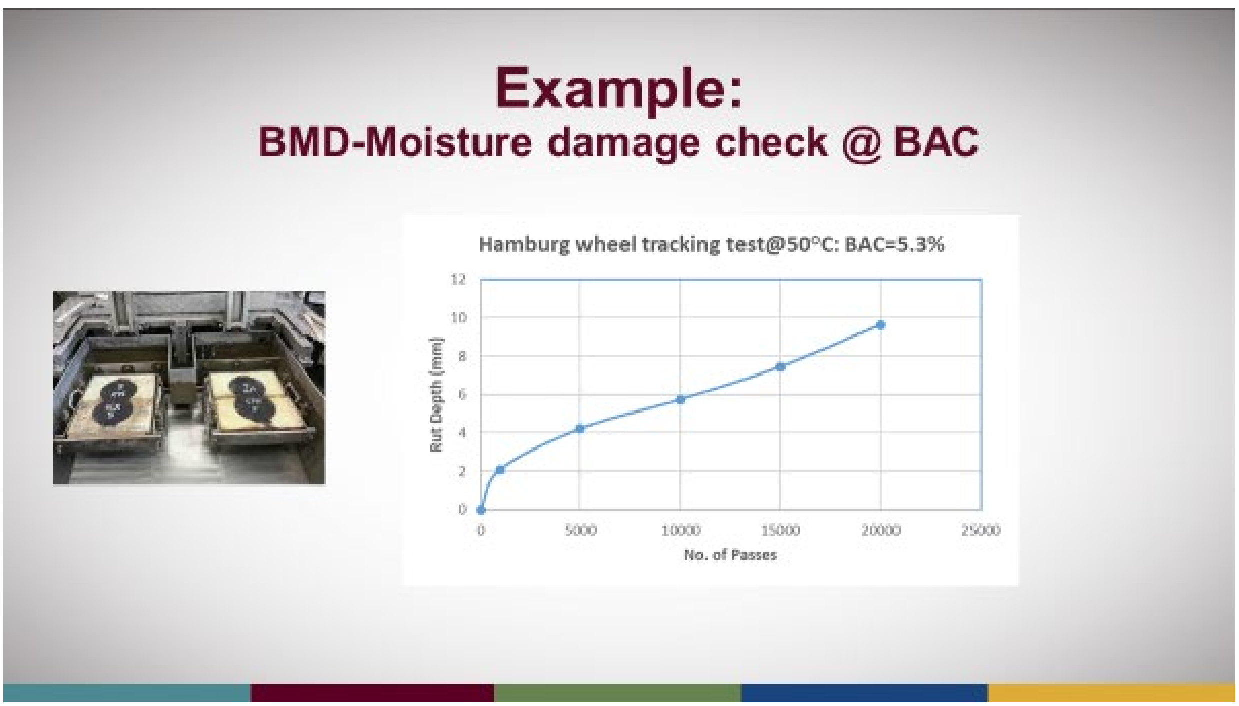
Estimated Percent of Stripping, %:	0

Interpolated Values	
Specific Gravity (Ga):	2.472
Max. Specific Gravity (Gr):	2.568
Theo. Max. Specific Gravity (Gt):	2.575
Dust/Asphalt Ratio:	0.6

STONE-ON-STONE CONTACT

VCA(CA, calc.)	
VCA(MIX, calc.)	


Example: BMD-Performance tests&BAC
BMD with IDEAL-CT and -RT
IDEAL-RT: RTIndex (kN)
IDEAL-CT: CTIndex
Balanced zone
Total Asphalt Content (%)


Example:
BMD-Moisture damage check @ BAC
Hamburg wheel tracking test@50°C: BAC=5.3%
Rut Depth (mm)
No. of Passes

Example: QC/QA requirements

- Compaction air voids
- IDEAL-RT: ≥66
- IDEAL-CT: ≥150 (OR ≥105)

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