BALANCED MIX DESIGN RESOURCE GUIDE

Fan Yin, Ph.D., P.E.
Randy West, Ph.D., P.E.
National Center for Asphalt Technology

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NATIONAL ASPHALT PAVEMENT ASSOCIATION

6406 Ivy Lane, Suite 350, Greenbelt, MD 20770-1441
Tel: 301-731-4748 | Fax: 301-731-4621 | Toll free 1-888-468-6499
www.AsphaltPavement.org

Audrey Copeland, Ph.D., P.E., *President & CEO*
Monica Dutcher, *Editorial Director*
PJB Marketing, *Design / Layout*

@NAPATweets
at National Asphalt Pavement Association
at National Asphalt Pavement Association
at National Asphalt Pavement Association
@goasphalt

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Deborah Schwerman
Wisconsin Asphalt Pavement Association

Richard Willis
National Asphalt Pavement Association

Brett Williams
National Asphalt Pavement Association

GLOSSARY

AL-CT	Alabama Cracking Test
ALDOT	Alabama Department of Transportation
ALF	Accelerated Loading Facility
APA	Asphalt Pavement Analyzer
APL	Approved Products List
BBF	Bending Beam Fatigue
BDWSC	Bridge Deck Waterproof Surface Course
BMD	Balanced Mix Design
BRIC	Binder Rich Intermediate Course
Caltrans	California Department of Transportation
CFE	Critical Fracture Energy
COV	Coefficient of Variation
CPR	Crack Progression Rate
CRI_{Env}	Environmental Cracking Resistance Index
CT_{index}	Cracking Tolerance Index
D/B Ratio	Dust-to-binder Ratio
d2s	Allowable Range of Two Results
DCT	Disc-shaped Compact Tension
ESAL	Equivalent Single Axle Load
ETG	Expert Task Group
FHWA	Federal Highway Administration
FI	Flexibility Index
FN	Flow Number
G_f	Fracture Energy
G_{sb}	Bulk Specific Gravity
HMA	Hot Mix Asphalt
HPTO	High Performance Thin Overlay
HRAP	Hot Mix Asphalt High RAP
HT-IDT	Hot Indirect Tensile Strength
HVS	Heavy Vehicle Simulator
HWTT	Hamburg Wheel Tracking Test
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
IDEAL-RT	Indirect Tensile Asphalt Rutting Test
IDOT	Illinois Department of Transportation
I-FIT	Illinois Flexibility Index Test
JMF	Job Mix Formula
LaDOTD	Louisiana Department of Transportation and Development
LAS	Liquid Anti-strip
LMLC	Laboratory-mixed Laboratory-compacted
LTPP	Long-Term Pavement Performance
MnROAD	Minnesota Road Research Facility
MoDOT	Missouri Department of Transportation
NCAT	National Center for Asphalt Technology
N_{design}	Design Gyration
N_f	Number of Cycles to Failure
NJDOT	New Jersey Department of Transportation
NMAS	Nominal Maximum Aggregate Size
OBC	Optimum Binder Content
ODOT	Oklahoma Department of Transportation
OT	Overlay Test
PMA	Polymer Modified Asphalt
PMLC	Plant-mixed Laboratory-compacted
PWL	Percent within Limits
QA	Quality Assurance
Q_L	Lower Quality Index
Q_U	Upper Quality Index
RAP	Reclaimed Asphalt Pavements
RAS	Recycled Asphalt Shingles
SAPA	State Asphalt Pavement Association
SCB	Semi-Circular Bend
SHA	State Highway Agency
SHRP	Strategic Highway Research Program
SIP	Stripping Inflection Point
TDOT	Tennessee Department of Transportation
TSR	Tensile Strength Ratio
TxDOT	Texas Department of Transportation
UTSST	Uniaxial Thermal Stress and Strain Test
V_a	Air Voids
V_{be}	Volume of Effective Binder
VDOT	Virginia Department of Transportation
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate
VTrans	Vermont Agency of Transportation
VTRC	Virginia Transportation Research Council
WMA	Warm Mix Asphalt

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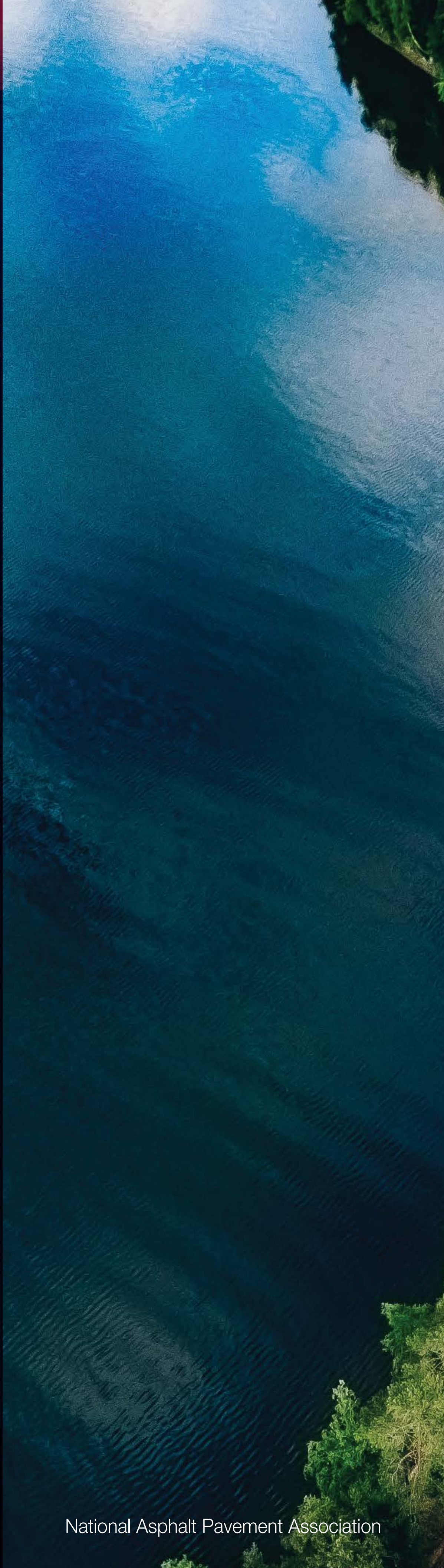


01 WHAT IS BMD?

In September 2015, the former Federal Highway Administration (FHWA) Expert Task Group (ETG) on Mixtures and Construction formed a Balanced Mix Design Task Force, which consisted of asphalt researchers, practitioners, and pavement engineers from federal and state highway agencies, asphalt contractors, consultants, and academic and research institutions. The task force defined balanced mix design (BMD) as “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.”

02 WHY IS BMD NEEDED?

The original vision of the Superpave mix design system was to include three levels. Level I was envisioned for use in low traffic pavements and the mix design requirements would be primarily based on traditional volumetric properties. Level II would be used for the majority of moderate traffic projects and would include volumetric requirements plus a limited set of mixture performance tests. Level III would be for high traffic pavements and would start with a volumetric based mix design followed by an expanded set of advanced performance tests. However, the proposed mixture performance tests in the Strategic Highway Research Program (SHRP) were never implemented except for a few special projects, primarily because these tests were not considered practical for routine use for the thousands of mix designs used each year in the United States at that time.

In the early years of Superpave implementation, the primary focus was on rutting resistance. Mix designs for moderate and high traffic pavements were designed to improve rutting resistance by using angular aggregates, binder grade adjustments, and high compactive efforts, among others. Many state highway agencies (SHAs) also added rutting test requirements to mix designs for moderate and high traffic projects. As the Superpave system has matured over the past decades, most SHAs have recognized that rutting problems have been virtually eliminated, but also indicate that the primary form of distress for asphalt pavements is now cracking of some form or another. There are a variety of factors contributing to the increased pavement cracking problems, which include failure to adequately address underlying pavement distresses, problems with construction quality, and issues with mix designs. To overcome the cracking issues, many SHAs have adjusted their mix design requirements from AASHTO M 323 in an attempt to improve the durability and cracking resistance of asphalt mixtures. Unfortunately, the effectiveness of these mix design adjustments varied greatly from state to state, and in many cases, was not sufficient to address the fundamental problems.

The two key properties in the Superpave mix design system are the design air voids (V_a) and volume of effective binder (V_{be}). V_a represents the volume of voids space within the mix at a specific number of design gyrations (N_{design}), which is largely dependent on the proportion of mixture components and has been widely used as an indirect indicator of mix quality. V_{be} represents the volume of effective binder in the mix, which is defined as the total volume of asphalt binder minus the volume of asphalt binder absorbed into the aggregate. V_{be} is an important mix design parameter affecting the durability of asphalt mixtures, where a higher V_{be} is desired for better durability and cracking resistance. However, solely relying on V_a and V_{be} for mix design have limitations because these two parameters provide no indication about the quality of virgin and recycled asphalt binders or their interactions with different types of asphalt additives if used. As a result, the Superpave mix design system alone may not be sufficient to determine how the use of reclaimed asphalt pavements (RAP), recycled asphalt shingles (RAS), and asphalt additives (e.g., polymers, warm mix asphalt additives, anti-strip additives, rejuvenators, etc.) would affect the performance properties of asphalt mixtures because these impacts cannot be captured by volumetric properties.

Another limitation of the Superpave mix design system is that V_{be} is highly dependent on the aggregate bulk specific gravity (G_{sb}), which is not a reliable property. Some aggregate sources may have consistent G_{sb} values over decades, whereas others could have significant variations within a single year due to the site's geology and mining operations. If the G_{sb} values are subject to change over time but are not often verified, the resultant mix designs will have inaccurate volumetric properties. Furthermore, there are major issues and concerns regarding the accuracy and variability associated with the measurement of aggregate G_{sb}. Even a relatively small difference that is well within the allowable range of two results (d2s) provided in the single-operator and multilaboratory precision estimates of AASHTO T 84 and T 85 could result in a considerable change in the voids in mineral aggregate (VMA) and possibly affect the mix design and/or production acceptance decisions. Finally, for asphalt mixtures containing RAP and RAS, it remains questionable as to what is the most accurate method of measuring G_{sb} of aggregates in RAP and RAS. Although different test methods have been adopted by SHAs, they do not always yield consistent results and their accuracy varies greatly depending upon the type of aggregate used.

In summary, increasing concerns about the durability and cracking issues of asphalt pavements along with the growing awareness of the shortcomings of volumetric mix design systems have driven many SHAs and the asphalt pavement industry to explore the use of BMD as a new approach to asphalt mix design and production acceptance.

03 BMD APPROACHES

Figure 1 through Figure 4 present graphical illustrations of the four BMD approaches identified in AASHTO PP 105-20. The major differences among these approaches are the degree of strictness on meeting volumetric criteria and the potential allowed for innovation in meeting the performance criteria. Each approach is discussed in detail as follows.

Approach A: Volumetric Design with Performance Verification

This approach starts with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) for determining an optimum binder content (OBC) that meets all the existing volumetric requirements. Alternatively, an existing agency-approved mix design can be used. The mix design at OBC is then tested with the selected mixture rutting and cracking tests. If the mix design fails the rutting and/or cracking test criteria, the entire mix design is repeated using different materials (e.g., aggregates, asphalt binders, recycled materials, and additives) or mix proportions until all the volumetric, rutting, and cracking criteria are satisfied. After passing the rutting and cracking tests, the mix design is then evaluated with the selected moisture damage test. If the design passes the moisture test criterion, the job mix formula is established for production. Otherwise, anti-strip agents such as liquid anti-strip (LAS) additives or hydrated lime need to be added and the modified mix is re-evaluated using the same moisture damage test until a passing result is obtained. If a LAS additive is used, it may be necessary to also repeat the rutting test on the modified mix for compliance verification due to the concern that use of excessive dosage rates could soften the asphalt binder and increase the rutting potential of asphalt mixtures. Other than adding anti-strip agents, changing the asphalt binder source or aggregate type could also improve the moisture damage test result. However, these remedial modifications are not preferred because they would require the mix to be redesigned to maintain compliance with all the volumetric and performance criteria.

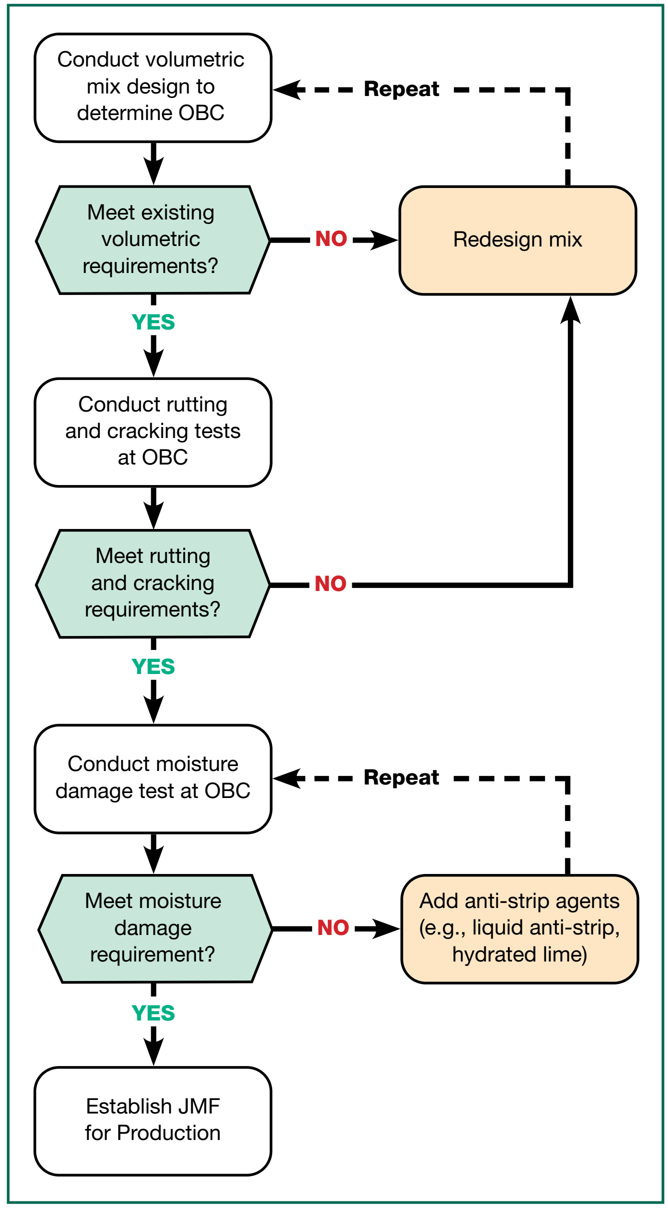


Figure 1. Graphical Illustration of the Volumetric Design with Performance Verification Approach (Approach A)

Approach B: Volumetric Design with Performance Optimization

This approach is an expanded version of Approach 1. It also starts with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) for determining a *preliminary OBC* that meets all the existing volumetric requirements. Alternatively, an existing agency-approved mix design can be used. The mix design is then tested with the selected mixture rutting and cracking tests at the *preliminary OBC* and two or more additional binder contents at intervals of ± 0.3 to 0.5 percent that bracket the *preliminary OBC*. Then, a binder content (not necessarily the lowest content) that satisfies both the rutting and cracking test criteria is selected as the *final OBC*. In cases where a passing binder content does not exist, the entire mix design process is repeated using different mix components or proportions (e.g., aggregates, asphalt binders, recycled materials, and additives) until both the rutting and cracking criteria are satisfied. After the *final OBC* is selected, the mix design is then evaluated with the selected moisture damage test. If the design passes the moisture test criterion, the job mix formula is established for production. Otherwise, anti-strip agents such as LAS additives or hydrated lime need to be added and the modified mix is re-evaluated using the same moisture damage test until the criterion is satisfied. Additional rutting and cracking tests could also be conducted on the modified mix for performance verification purposes.

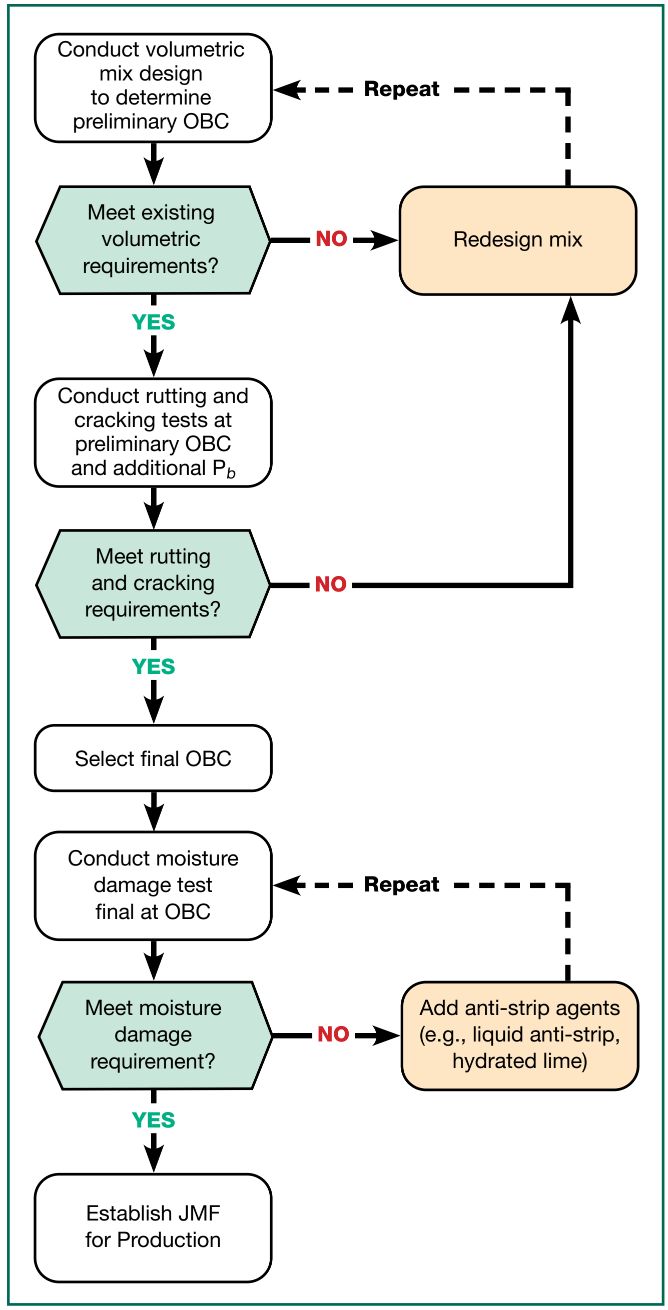


Figure 2. Graphical Illustration of the Volumetric Design with Performance Optimization Approach (Approach B)

Approach C: Performance-Modified Volumetric Design

This approach starts with the current volumetric mix design method (i.e., Superpave, Marshall, or Hveem) to establish an initial aggregate gradation and binder content. Alternatively, an existing agency-approved mix design can be used. The initial design is then tested with the selected rutting and cracking tests. Test results are used to adjust either the binder content or other mix component properties and proportions (e.g., aggregates, asphalt binders, recycled materials, and additives) until both the rutting and cracking criteria are satisfied. Then, the mix design is evaluated with the selected moisture damage test. If the design passes the moisture test criterion, certain volumetric properties are measured and verified for compliance with the agency's relaxed requirements prior to establishing the job mix formula. Otherwise, anti-strip agents such as LAS additives or hydrated lime need to be added and the modified mix is re-evaluated using the same moisture damage test until the criterion is satisfied. Additional rutting and cracking tests could also be conducted on the modified mix for performance verification purposes.

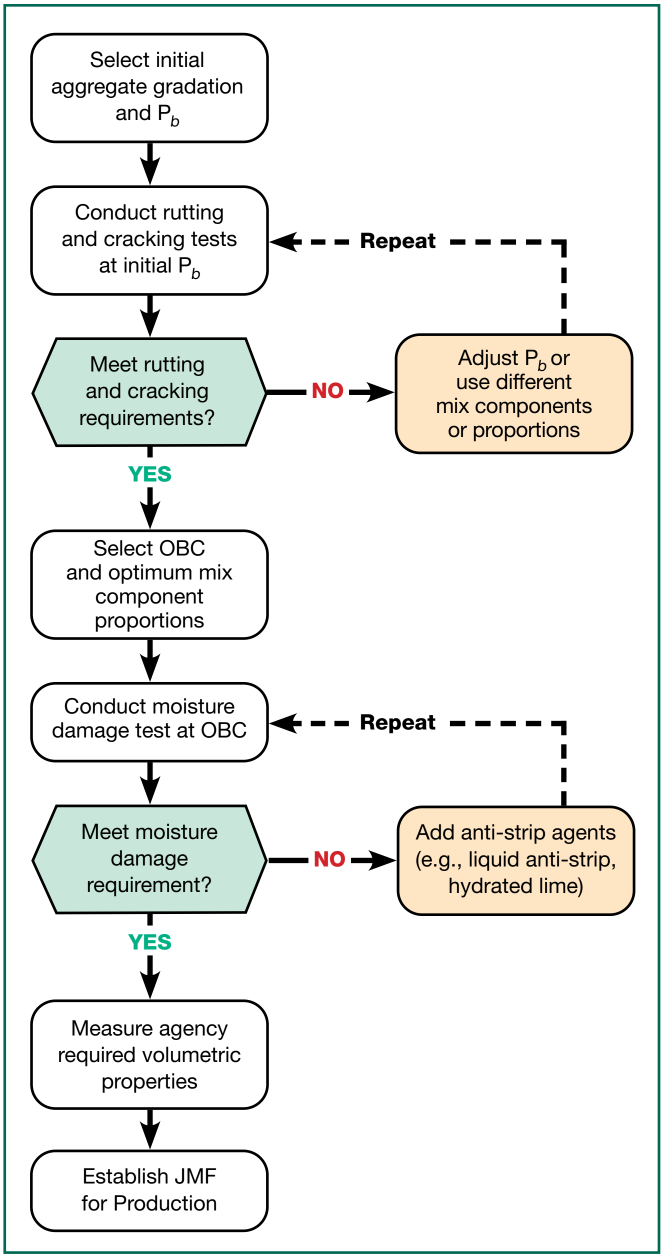


Figure 3. Graphical Illustration of the Performance-Modified Volumetric Design Approach (Approach C)

Approach D: Performance Design

This approach starts with the selection of an initial aggregate gradation, recycled asphalt materials content, and virgin binder grade. Alternatively, an existing agency-approved mix design can be used. The initial mix design is then tested with the selected rutting and cracking tests at three or more binder contents at intervals of 0.3 to 0.5 percent. A binder content (not necessarily the lowest content) that satisfies both the rutting and cracking criteria is selected as the OBC. In cases where a passing binder content does not exist, the initial mix design needs to be adjusted using different mix components or proportions (e.g., aggregates, asphalt binders, recycled materials, and additives) until both the rutting and cracking criteria are satisfied. Then, the mix design is evaluated with the selected moisture damage test. If the design passes the moisture test criterion, the job mix design is established. Otherwise, anti-strip agents such as LAS additives or hydrated lime need to be added and the modified mix is re-evaluated using the same moisture damage test until the criterion is satisfied. Additional rutting and cracking tests could also be conducted on the modified mix for performance verification purposes.

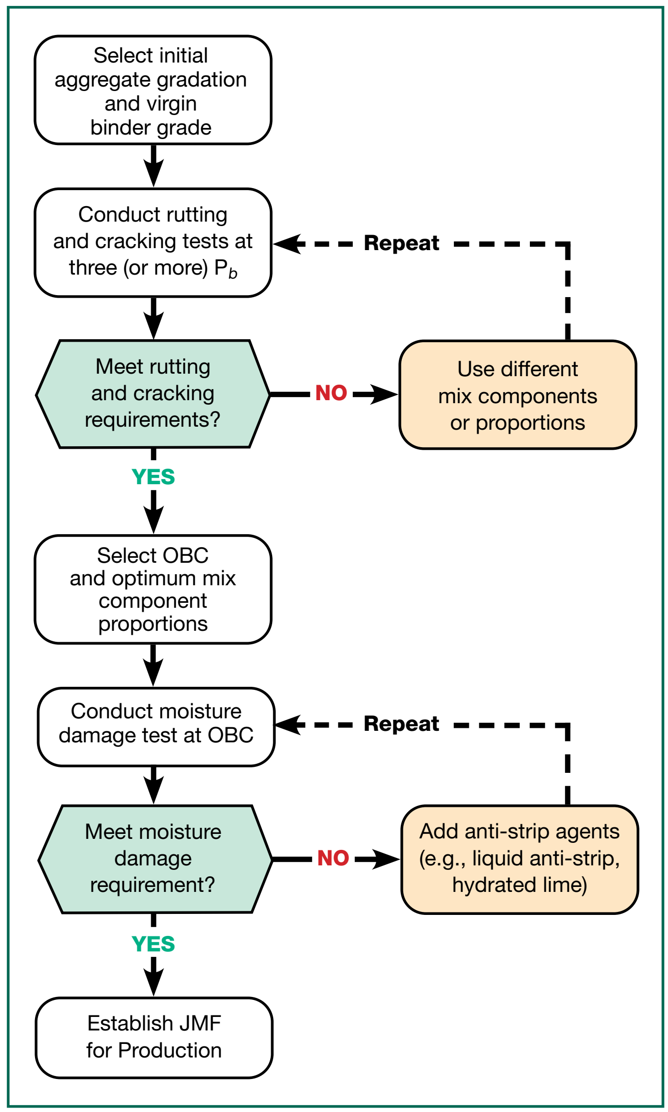
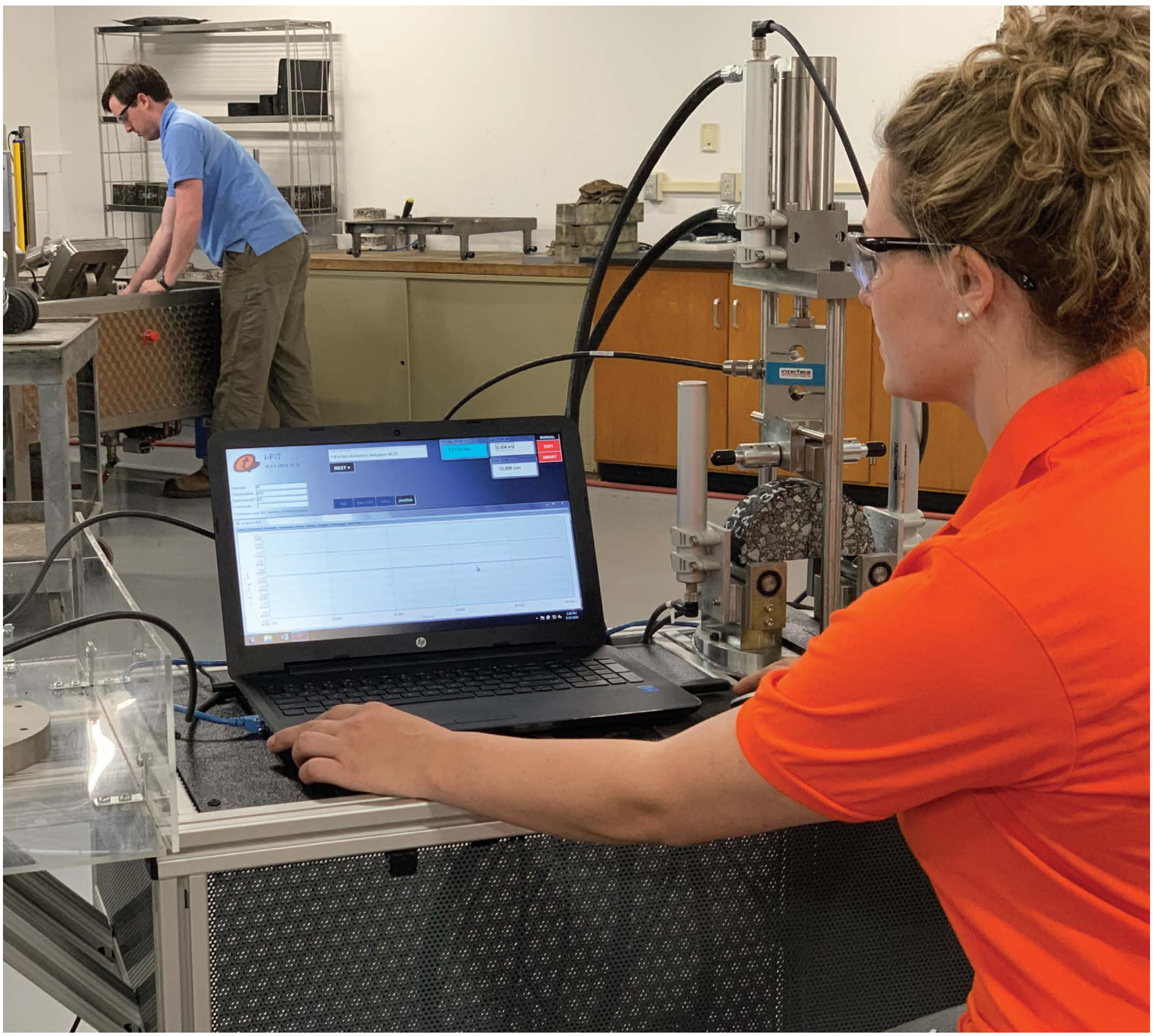


Figure 4. Graphical Illustration of the Performance Design Approach (Approach D)

Summary

Approach A requires full compliance with the existing volumetric requirements and additional performance requirements and thus, is the most conservative approach and has the lowest innovation potential. Approach B requires full compliance with the existing volumetric requirements at the preliminary OBC but allows moderate changes in asphalt binder content for performance optimization based on mixture performance test results. Although Approach B is slightly more flexible than Approach A, it is still considered a conservative approach with limited innovation potential. Approach C allows some of the volumetric requirements to be relaxed or eliminated provided that the performance criteria are satisfied. The mix design modifications allowed for performance optimization are not limited to changes in asphalt binder content. Therefore, it is less conservative than Approach A and Approach B and provides a medium degree of innovation potential. Finally, Approach D has no requirement on volumetric properties and relies solely on mixture performance test results for mix design optimization, and thus, is considered the least conservative approach with the highest degree of innovation potential.



04 STATE-OF-THE-PRACTICE ON BMD IMPLEMENTATION (AS OF JANUARY 2021)

Figure 5 presents a U.S. map of SHAs that have developed either a draft, provisional, or standard specification on BMD. This information was mainly collected from a survey of SHAs and the asphalt pavement industry conducted by the National Center for Asphalt Technology (NCAT) in May 2020. Among the 11 BMD states identified, Illinois, Louisiana, New Jersey, Texas, and Vermont use Approach A, *Volumetric Design with Performance Verification*; California, Missouri, and Oklahoma currently use Approach C, *Performance-Modified Volumetric Design*; Alabama and Tennessee are exploring Approach D, *Performance Design*; while Virginia allows both Approach A and Approach D. No states have yet to move forward with Approach B, *Volumetric Design with Performance Optimization*. Table 1 summarizes additional information regarding the state-of-the-practice on the implementation of BMD for the 11 states in Figure 5, which includes the applicable mixture type, selected rutting and cracking tests, and use of performance testing for production acceptance.

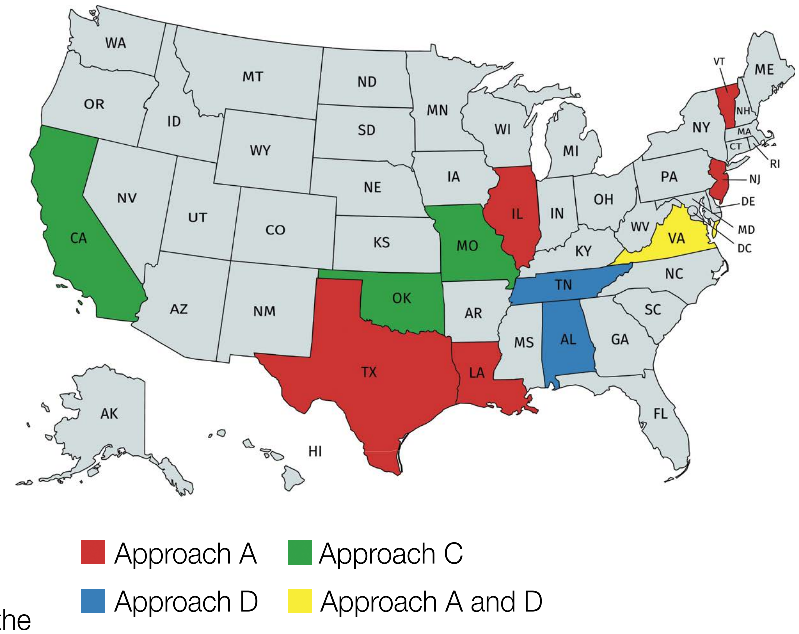


Figure 5. Map of SHAs with Draft, Provisional, or Standard BMD Specifications

Table 1. Summary of State-of-the-Practice on BMD Implementation

BMD Approach	State	Applicable Mixture Type	Rutting Test	Cracking Test	Performance Testing for Production Acceptance?
Approach A	Illinois	High ESAL mixtures	HWTT	I-FIT	Yes, HWTT for "Pass/Fail"
	Louisiana	Wearing and binder course mixtures	HWTT	SCB-Jc	Yes, "Pass/Fail"
	New Jersey	Specialty mixtures	APA	OT, BBF	Yes, "Pass/Fail" or Pay Adjustment
	Texas	Surface mixtures	HWTT	OT, IDEAL-CT	Yes, "Pass/Fail"
	Vermont	Superpave Type IVS mixtures	HWTT	I-FIT	Yes, PWL
Approach A and D	Virginia	Surface mixtures	APA	Cantabro, IDEAL-CT	Yes, "Pass/Fail"
Approach C	California	Long-life pavement mixtures	FN, HWTT	BBF, I-FIT	Yes, HWTT for "Pass/Fail"
	Missouri	Mainline pavement mixtures	HWTT	I-FIT, IDEAL-CT	Yes, HWTT for "Pass/Fail", I-FIT & IDEAL-CT for Pay Adjustment
	Oklahoma	Superpave mixtures	HWTT	IDEAL-CT	No
Approach D	Alabama	Superpave mixtures	HT-IDT	AL-CT	Yes, "Pass/Fail"
	Tennessee	All mixtures	HWTT	IDEAL-CT	To be determined

Table 2. ALDOT CT_{index} Criteria for Mix Design Approval and Production Acceptance

Design Traffic (ESALs)	Mix Design Approval	Production Acceptance
< 1 million	≥ 55	≥ 50
1 to 10 million	≥ 83	≥ 75
10 to 30 million	≥ 110	≥ 100

Alabama

The Alabama Department of Transportation (ALDOT) developed *Balanced Asphalt Mix Design for Local Roads*, a special provision for BMD in 2020. The provision allows asphalt contractors to design Superpave mixtures following the Performance Design approach, where mix design approval is primarily based on mixture performance test results with minimal requirements on maximum aggregate size and carbonate stone content for surface mixtures. The mixture performance tests used are the Hot Indirect Tensile Strength (HT-IDT) per ALDOT 458 and the Alabama Cracking Test (AL-CT) per ALDOT 459 for the evaluation of rutting resistance and cracking resistance, respectively. Both tests are conducted on specimens that have been short-term conditioned for four hours at 135°C prior to compaction. Performance test criteria for mix design approval include a minimum HT-IDT strength of 20 psi and a minimum cracking tolerance index (CT_{index}) of 55, 83, and 110 for mixtures with various equivalent single axle load (ESAL) Range designations, as shown in Table 2. During production, the contractor is responsible for conducting both performance tests on plant produced mixes every 700 tons for quality control, while the agency is responsible for conducting the tests at a frequency of one test per day per LOT for verification. The performance test results are for informational purposes only. Production acceptance is purely based on asphalt binder content and voids in total mix at N_{design}. However, if two consecutive performance test results fall below the minimum HT-IDT strength of 20 psi or the minimum CT_{index} criteria in Table 2, production will not be accepted until the performance test criteria are satisfied. ALDOT completed one BMD pilot project in 2020.

California

The California Department of Transportation (Caltrans) is one of the first six SHAs that implemented BMD. Caltrans currently requires the Performance-Modified Volumetric Design approach for the design of asphalt mixtures for long-life pavements (i.e., asphalt pavements lasting 40 years or more with minimal maintenance to the surface layer), where the mix design is required to meet performance test requirements with minimum requirements on mixture volumetrics. The mixture performance tests used for mix design approval and job mix formula (JMF) verification include the Flow Number (FN) test per a modified AASHTO T 378-17 procedure for the evaluation of rutting resistance (for surface and intermediate mixtures only), Flexural Bending Beam Fatigue (BBF) test per a modified AASHTO T 321-17 procedure and Illinois Flexibility Index Test (I-FIT) per AASHTO TP 124-20 for the evaluation of fatigue cracking resistance, and Hamburg Wheel Tracking Test (HWTT) per AASHTO T 324-19 for the evaluation of moisture susceptibility. FN is conducted at 50°C in an unconfined condition with 4.4 psi contact stress and 70 psi repeated axial stress. HWTT is conducted at 50°C. Specimens prepared for mixture performance testing are short-term aged for four hours at 135°C prior to compaction per AASHTO R 30. The target air voids content of the test specimens is 6.0 ± 0.5 percent for surface and intermediate mixtures and 3.0 ± 0.5 percent for rich bottom mixtures. Table 3 summarizes the performance test criteria for mix design and JMF verification. The only volumetric requirement for mix design approval is a dust-to-binder ratio (D/B ratio) of 0.6 to 1.3 percent for surface and intermediate mixtures, while air voids and VMA are reported for informational purposes only.

During production, asphalt contractors are required to conduct FN (for surface and intermediate mixtures only), I-FIT, and HWTT on plant produced mixes for quality control. The minimum testing frequency for FN and I-FIT is three specimens per day, while HWTT is required for at least every 10,000 tons of production or once per project. Production acceptance is primarily based on changes in asphalt binder and aggregate gradations from JMF as well as the air voids content at N_{design} (85 gyrations) and D/B ratio. A passing HWTT result is also required for the acceptance of surface and intermediate mixtures using a “Pass/Fail” criterion.

Table 3. **Caltrans Performance Test Requirements for Mix Design of Asphalt Mixtures for Long-life Pavements**

Laboratory Test	Test Parameter	Surface Mixture	Intermediate Mixture	Rich Bottom Mixture
FN	Number of cycles to 3% axial strain	≥ 941	≥ 3,007	Not required
BBF	Stiffness at the 50th cycle	≥ 210,000 at 893 microstrain	≥ 782,000 at 433 microstrain	≥ 707,000 at 420 microstrain
	Strain to endure minimum 1,000,000 cycles before failure	≥ 495 microstrain	≥ 220 microstrain	≥ 269 microstrain
	Strain to endure minimum 250,000 cycles before failure	≥ 893 microstrain	≥ 443 microstrain	≥ 420 microstrain
I-FIT	Flexibility index	≥ 3.0	≥ 0.5	≥ 0.5
HWTT	Number of passes to 12.5 mm rut depth	≥ 20,000	≥ 20,000	Not required

Illinois

The Illinois Department of Transportation (IDOT) started the implementation of BMD in 2016. The current specification, *Standard Specifications for Road and Bridge Construction*, and a recent memorandum, *Special Provision for Hot-Mix Asphalt – Mixture Design Verification* and Production (Modified for I-FIT Data Collection), requires the Volumetric Design with Performance Verification approach for high ESAL asphalt mixtures, where the mix design is required to meet both the volumetric and performance test requirements. The existing volumetric requirements include air voids, VMA, voids filled with asphalt (VFA), and D/B ratio. The design air voids content is 4.0 percent at a N_{design} of 50 to 90 gyrations depending upon the design traffic level. The minimum VMA criteria vary from 12.0 to 16.0 percent as a function of aggregate nominal maximum aggregate size (NMAS).

The mixture performance tests used include HWTT, I-FIT, and Tensile Strength Ratio (TSR) for the evaluation of mixture resistance to rutting, cracking, and moisture damage, respectively. HWTT is conducted in accordance with the Illinois Modified AASHTO T 324 procedure at 50°C. HWTT specimens are conditioned for 1 or 2 hours at the compaction temperature for hot mix asphalt (HMA) and 3 to 4 hours at the compaction temperature for warm mix asphalt (WMA) prior to compaction. The variation in the mix conditioning time is dependent on the aggregate absorption. Test criteria are based on the minimum number of wheel passes to 12.5mm rut depth, which corresponds to 5,000, 7,500, 15,000, and 20,000 passes for projects with a PG 58-xx (or lower), PG 64-xx, PG 70-xx, and PG 76-xx (or higher) binder grade requirement, respectively. I-FIT is conducted in accordance with the Illinois Modified AASHTO TP 124 procedure. Table 4 summarizes the proposed flexibility index *(FI)* criteria effective in January 2021. The short-term aging procedure for I-FIT is the same as HWTT, while the long-term aging procedure for I-FIT requires the aging of compacted specimens for three days at 95°C. TSR is conducted in accordance with the Illinois Modified AASHTO T 283 procedure. Test criteria include a minimum conditioned tensile strength of 60 psi for non-polymer modified asphalt binder and 80 psi for polymer modified asphalt binder, as well as a maximum unconditioned tensile strength of 200 psi.

In addition to mix design approval, HWTT and I-FIT testing are also required on plant produced mixes that are representative of the test strip at the beginning of mixture production. The acceptance of subsequent production is mainly based on mixture volumetrics although IDOT may require additional HWTT testing during production. Over the last few years, IDOT completed over 100 BMD field projects with HWTT and I-FIT conducted for both mix design approval and production start-up. IDOT is currently in the process of constructing shadow projects where plant produced mixes are sampled behind the paver and tested for I-FIT on both reheated and long-term aged plant-mixed laboratory-compacted (PMLC) specimens on a daily basis (or sublot of every 1,000 tons).

Table 4. **IDOT I-FIT Criteria for Mix Design Verification**

Mixture Type	Short-Term Aging, Minimum *FI*	Long-Term Aging, Minimum *FI* [2]
HMA [1]	8.0	5.0 [3]
SMA	16.0	10.0
IL-4.75	12.0	-

Notes:
1. All mix designs, except for SMA and IL-4.75 mixtures.
2. Required for surface courses only.
3. Production long term aging FI for HMA shall be a minimum of 4.0.

Louisiana

The Louisiana Department of Transportation and Development (LaDOTD) implemented BMD in late 2015. Section 502 of LaDOTD's current specification, *Standard Specifications for Roads and Bridges*, requires the Volumetric Design with Performance Verification approach on all asphalt mixtures for wearing and binder courses. The mix design is required to meet both the volumetric and performance test requirements. The design air voids content is 3.5 percent at a N_{design} of 55 or 65 gyrations depending on the traffic level and mix type. The minimum VMA criteria vary from 11.5 to 13.5 percent as a function of aggregate NMAS. Other mixture volumetric requirements include VFA and D/B ratio. HWTT per AASHTO T 324 is conducted at 50°C for the evaluation of mixture rutting resistance. Test criteria are based on the total rut depth at 20,000 passes, where a maximum threshold of 10 mm is specified for Level 1 mixtures and 6 mm for Level 2 mixtures. The Semi-Circular Bend test (SCB-J_c) per DOTD TR 330 is used for the evaluation of mixture cracking resistance. Test criteria include a minimum J-integral (J_c) threshold of 0.5 KJ/m^2 for Level 1 mixtures and 0.6 KJ/m^2 for Level 2 mixtures.

Mix design validation and approval requires HWTT and SCB-J_c testing on the validation plant lot with up to 2,000 tons of plant produced mix. HWTT is conducted by LaDOTD and SCB-J_c is conducted by the Louisiana Transportation Research Council. JMF is considered validated with passing HWTT results while the SCB-J_c results are for informational purposes only. After JMF is approved, the actual production can continue. The acceptance of production lots is purely based on volumetric requirements with no mixture performance testing required.

Missouri

The Missouri Department of Transportation (MoDOT) developed a job special provision for BMD in 2019, *Superpave Performance Testing and Increased Density*. The special provision specifies the Performance-Modified Volumetric Design approach, where asphalt mixtures used for the mainline pavement are required to meet the performance test requirements with some of the existing volumetric requirements relaxed or eliminated. The mixture performance tests used are HWTT and I-FIT for the evaluation of rutting resistance and cracking resistance, respectively. HWTT is conducted in accordance with AASHTO T 324 and at 50°C. Test criteria are based on the number of wheel passes to 12.5 mm rut depth, where a minimum threshold of 5,000, 7,500, 15,000, and 20,000 passes is required for mixtures containing a PG58S-xx, 64S-22, 64H-22, and 64V-22 virgin binder, respectively.

Table 5. **MoDOT Design Gyration Requirements**

Design Traffic (ESALs)	N_{design} for Superpave	N_{design} for BMD
< 0.3 million	50	≥ 35
0.3 to 3 million	75	≥ 50
3 to 30 million	80 or 100	≥ 60
> 30 million	125	≥ 65

I-FIT is conducted following the Illinois Test Procedure 405 (dated 01/01/16). For mix design approval, I-FIT specimens are tested after being conditioned for four hours at 135°C prior to compaction per AASHTO R 30. Test criteria include a minimum FI threshold of 2.0 for Superpave mixtures and 6.0 for SMA mixtures. To help meet the performance test requirements, contractors are allowed to lower N_{design} from those specified in the Superpave mix design approach but remain in compliance with the minimum N_{design} requirements in Table 5, or use a reduced design air voids of 3.0 to 4.0 percent. If a lowered N_{design} is used, the minimum VMA criteria will be increased by 1.0 percent.

Table 6. **MoDOT Performance Test Criteria for Production Acceptance**

Mix Type	I-FIT *FI* Criteria	IDEAL CT_{index} Criteria	Percent of Contract Price
Superpave (NMAS < 19.0 mm)	< 2.0	< 32	98%
	2.0 to 3.9	32 to 60	100%
	4.0 to 7.9	60 to 97	102%
	> 8.0	> 97	103%
SMA	< 6.0	< 80	98%
	6.0 to 11.0	80 to 159	100%
	12.0 to 15.0	160 to 180	102%
	> 15.0	> 180	103%

In addition to mix design approval, mixture performance testing is also required for quality control and acceptance at a frequency of every 10,000 tons. Testing is conducted by both the contractor and agency. The contractor results will be used for acceptance provided that the difference between the contractor and agency results is within 30 percent. For the evaluation of cracking resistance, Indirect Tensile Asphalt Cracking Test (IDEAL-CT) per ASTM D8225 can be used as an alternative to I-FIT at the contractor's discretion. Either test should be conducted on reheated PMLC specimens using plant produced mixes that have been cooled to ambient temperature and then reheated to compaction temperature for gyratory compaction. Table 6 summarizes the pay adjustments for production acceptance based on the performance test results. The HWTT criteria for production acceptance are the same as those for mix design approval. The I-FIT criterion for receiving a 100 percent pay is a minimum *FI* of 2.0 for Superpave mixtures and 6.0 for SMA mixtures. Alternatively, the minimum IDEAL CT_{design} criteria are 32 and 80. With a passing HWTT result, the production VFA requirement can be eliminated.

New Jersey

The New Jersey Department of Transportation (NJDOT) was one of the first six SHAs that implemented BMD. In its most recent specification, *Standard Specifications for Road and Bridge Construction*, the Volumetric Design with Performance Verification approach is required for the mix design and production of four types of specialty asphalt mixtures: high performance thin overlay (HPTO), binder rich intermediate course (BRIC), hot mix asphalt high RAP (HRAP), and bridge deck waterproof surface course (BDWSC).

The HPTO mixture has a design air void content of 3.5 percent at a N_{design} of 50 gyrations. The minimum VMA criterion is 18.0 percent and the acceptable D/B ratio range is 0.6 to 1.2. The mixture performance tests used are the Asphalt Pavement Analyzer (APA) per AASHTO T 340-10 and Overlay Test (OT) per NJDOT B-10. Both tests are conducted on specimens compacted to an air voids content of 5.0 ± 0.5 percent. The APA test temperature is 64°C. Performance test criteria for mix design approval include a maximum 4.0mm rut depth at 8,000 cycles in the APA and a minimum of 600 cycles to failure in OT. For production acceptance, APA and OT are conducted on plant produced mixes sampled from the test strip and every LOT of production thereafter. Test results are compared against the acceptance criteria in Table 7 to determine percent pay adjustments on a LOT-by-LOT basis.

The BRIC mixture has a design air voids content of 2.5 percent at a N_{design} of 50 gyrations. The minimum VMA criterion is 18.0 percent and the acceptable D/B ratio range is 0.6 to 1.2. The BRIC mixture uses the same performance tests as the HPTO mixture except that the tests are conducted on specimens with a compacted air voids content of 3.5 ± 0.5 percent. Performance test criteria for mix design approval include a maximum of 6.0 mm rut depth at 8,000 cycles in the APA and a minimum of 700 cycles to failure in OT. For production acceptance, APA and OT are conducted on plant produced mixes sampled from the test strip and every second LOT of production thereafter. Production acceptance is determined based on the "Pass/Fail" criterion using a maximum 7.0mm rut depth in APA and a minimum 650 cycles to failure in OT.

The HRAP mixture has a design air voids content of 4.0 percent at a N_{design} of 50 gyrations for a low compaction level and 75 gyrations for a medium compaction level. The minimum VMA criteria vary from 13.0 to 17.0 percent as a function of aggregate NMAS. Other volumetric requirements include VFA and D/B ratio. The HRAP mixture uses the same performance tests as the HPTO mixture, except that the tests are conducted on specimens with a compacted air voids content of 6.5 ± 0.5 percent. Performance test criteria for mix design approval include a maximum 7.0 mm rut depth (for PG 64S-22 binder) or 4.0 mm rut depth (for PG 64E-22 binder) at 8,000 cycles in the APA, and a minimum number of cycles to failure of 100 (for subsurface mixtures with PG 64S-22 binder), 150 (for subsurface mixtures with PG 64E-22 binder), 200 (for surface mixtures with PG 64S-22 binder), and 275 (for surface mixtures with PG 64E-22 binder) in the OT. For production acceptance, APA and OT are conducted on plant produced mixes sampled from the test strip and every LOT of production thereafter. Test results are compared against the acceptance criteria in Table 7 to determine percent pay adjustments on a LOT-by-LOT basis.

The BDWSC mixture has a design air voids content of 1.0 percent at a N_{design} of 50 gyrations. The minimum VMA criterion is 18.0 percent. Other volumetric requirements include VFA and D/B ratio. The mixture performance tests used are the APA per AASHTO T 340-10 and BBF per AASHTO T 321-17. Both tests are conducted on specimens with a maximum air voids content of 3.0 percent. The APA test temperature is 64°C. The BBF test is conducted at 15°C, 10Hz loading frequency, and 1,500 microstrains. Performance test criteria for mix design approval include a maximum 3.0 mm rut depth in APA and a minimum fatigue life of 100,000 cycles in BBF. For production acceptance, APA and BBF are conducted on plant produced mixes sampled from the first LOT of production and every second LOT thereafter. Production acceptance is determined based on the "Pass/Fail" criterion using the same performance test criteria for mix design approval.

Table 7. **NJDOT Performance Test Criteria for Production Acceptance of HPTO and HRAP Mixtures**

Mix Type	Performance Test	Test Result (t)	Percent Pay Adjustment
HPTO	APA Rut Depth (mm)	≤ 5.0	0
		5.0 to 12.0	-50(t-5)/7
		> 12.0	-100 or Remove & Replace
	OT Cycles to Failure	≥ 600	0
		400 to 600	-(600-t)/4
		< 400	-100 or Remove & Replace
HRAP Surface (64S-22)	APA Rut Depth (mm)	≤ 7.0	0
		7.0 to 10.0	-50(t-7)/3
		> 10.0	-100 or Remove & Replace
	OT Cycles to Failure	≥ 200	0
		150 to 200	-(200-t)
		< 150	-100 or Remove & Replace
HRAP Surface (64E-22)	APA Rut Depth (mm)	≤ 4.0	0
		4.0 to 7.0	-50(t-4)/3
		> 7.0	-100 or Remove & Replace
	OT Cycles to Failure	≥ 275	0
		200 to 275	-(275-t)/1.5
		< 200	-100 or Remove & Replace
HRAP Subsurface (64S-22)	APA Rut Depth (mm)	≤ 7.0	0
		7.0 to 10.0	-50(t-7)/3
		> 10.0	-100 or Remove & Replace
	OT Cycles to Failure	≥ 100	0
		75 to 100	-(2t-200)
		< 75	-100 or Remove & Replace
HRAP Subsurface (64E-22)	APA Rut Depth (mm)	≤ 4.0	0
		4.0 to 7.0	-50(t-4)/3
		> 7.0	-100 or Remove & Replace
	OT Cycles to Failure	≥ 150	0
		110 to 150	-1.25(150-t)
		< 110	-100 or Remove & Replace

Oklahoma

The Oklahoma Department of Transportation (ODOT) started to move forward with the implementation of BMD in 2017. In ODOT's most recent draft special provision, *Balanced Mix Design Requirements*, the Performance-Modified Volumetric Design approach is allowed for the design and production of Superpave asphalt mixtures that meet the BMD requirements but not necessarily the volumetric requirements. The design air voids content is 3.0 to 4.0 percent at a N_{design} of 50, 65, and 80 for mixtures containing a PG 64-xx, PG 70-xx, and PG 76-xx binder, respectively.

The minimum VMA criteria vary from 12.5 to 16.5 percent as a function of aggregate NMAS. Other volumetric requirements include VFA and $\%G_{mm}$ at N_{ini}. The mixture performance tests used are HWTT per AASHTO T 324 and IDEAL-CT per ASTM D 8225. Both tests are conducted on specimens that have been short-term conditioned for four hours at 135°C prior to compaction per AASHTO R 30. The HWTT criteria are based on the number of passes to 12.5 mm rut depth at 50°C, where a minimum threshold of 10,000, 15,000, and 20,000 passes is required for mixtures containing a PG 64-xx, PG 70-xx, and PG 76-xx binder, respectively. The IDEAL-CT criterion is a minimum CT_{index} of 80 for all mixtures regardless of virgin binder grade. Production acceptance is purely based on mixture volumetric properties with no requirements on HWTT and IDEAL-CT results. ODOT completed four BMD pilot projects in 2019 and 2020.

Tennessee

The Tennessee Department of Transportation (TDOT) has decided to move forward with the implementation of BMD and developed a draft sketch of a future specification, *Performance Based Mix Design of Asphalt Mixtures*, in 2020. The specification will allow contractors to design asphalt mixtures using the Performance Design approach with no requirements on mixture volumetrics. The anticipated mixture performance tests for mix design approval are HWTT per AASHTO T 324 and IDEAL-CT per ASTM D8225. The HWTT test temperature is 50°C. IDEAL-CT will be conducted on specimens that have been short-term conditioned for four hours at 135°C prior to compaction per AASHTO R 30. The specimen conditioning procedure for HWTT remains to be determined. The anticipated performance test criteria vary among asphalt mixtures designed for different road classifications, as shown in Table 8. In addition to a set of passing HWTT and IDEAL-CT results, contractors also need to report G_{mm} and the air voids content at 75 Marshall blows (per side) for informational purposes only. TDOT has not decided on the processes for production acceptance of BMD mixtures. Two options are being considered; the first option is to accept production based on asphalt binder content and gradation. The second option is to determine production acceptance based on the volumetrics and performance test results; in this case, IDEAL-CT and a yet to-be-determined surrogate rutting test to HWTT [e.g., the Indirect Tensile Asphalt Rutting Test (IDEAL-RT) or HT-IDT strength test], will be conducted on plant produced mixes during production.

Texas

The Texas Department of Transportation (TxDOT) has a long history of using mixture performance tests for mix design approval and is one of the first six SHAs that implemented BMD. The BMD approach specified in TxDOT's most recent specification, *Special Specification 3074: Superpave Mixtures – Balanced Mix Design*, is the Volumetric Design with Performance Verification approach, where all surface mixtures are required to meet the existing volumetric requirements as well as performance test requirements. The design air voids content is 4.0 percent at a N_{design} of 50 gyrations for all traffic levels, although N_{design} can be reduced to no less than 35 gyrations at the contractor's discretion.

Table 8. TDOT Performance Test Criteria for Mix Design Approval

Road Classification	HWTT Passes to 12.5 mm Rut Depth	HWTT SIP	IDEAL-CT CTindex
State Routes (not controlled access) < 10,000 ADT	≥ 10,000	≥ 10,000	≥ 50
State Routes (not controlled access) > 10,000 ADT	≥ 15,000	≥ 10,000	≥ 75
Interstates and controlled access State Routes	≥ 20,000	≥ 10,000	≥ 100

The minimum VMA criterion of SP-C Surface mixture (12.5mm NMAS) is 15.0 percent for mix design and 14.5 percent for production, while that of SP-D Fine mixture (9.5mm NMAS) is 16.0 percent for mix design and 15.5 percent for production.

HWTT is used to evaluate mixture resistance to rutting and moisture damage for mix design approval. The test is conducted in accordance with Tex-242-F and at 50°C. The test criterion is based on the number of passes to 12.5 mm rut depth, where a minimum threshold of 10,000, 15,000, and 20,000 passes is specified for mixtures containing a PG 64 (or lower), PG 70, and PG 76 (or higher) virgin binder, respectively. The mixture cracking resistance is assessed using OT per Tex-248-F. Test criteria include a minimum threshold of 1.0 in.-lb/in.^{2} for the critical fracture energy (CFE) parameter and a maximum threshold of 0.45 for the crack progression rate (CPR) parameter. If the mix design passes both the HWTT and OT requirements, then additional OT and IDEAL-CT testing will be conducted at the OBC, OBC plus 0.5 percent, and OBC minus 0.5 percent. IDEAL-CT is conducted in accordance with Tex-250-F. A mix-specific correlation between the OT and IDEAL-CT results at three asphalt binder contents is then established, which is used to determine the IDEAL-CT acceptance criteria for production. All mixture performance tests for mix design approval are conducted at TxDOT or a TxDOT-designated laboratory.

For trial batch production, plant produced mixes are sampled and tested for HWTT at TxDOT or a TxDOT-approved laboratory and for OT and IDEAL-CT. If the trial batch results pass the HWTT and OT requirements for mix design approval, the contractor is then allowed to proceed with the production of LOT 1 using the original mix design (JMF1). Otherwise, the contractor needs to make adjustments to mixture proportions and submit a revised mix design for production (JMF2). In this case, HWTT, IDEAL-CT, and possibly OT (if the IDEAL-CT does not meet the correlation limit) will be conducted on LOT 1 mixes for compliance verification purposes. For the production of subsequent LOTs, IDEAL-CT will be conducted on a sublot basis, either at TxDOT or a TxDOT-designated laboratory.

TxDOT has been collaborating with asphalt contractors, the Texas Asphalt Pavement Association, and research universities in Texas on an implementation effort toward constructing 12 field projects using the most recent BMD specification in 2019, 2020, and 2021. Each project will have multiple test sections including a volumetric control section and at least one or two BMD sections. As of October 2020, TxDOT has completed four projects in Atlanta, San Antonio, and Yoakum districts.

Vermont

The Vermont Agency of Transportation (VTrans) developed a special specification on BMD, *Superpave Bituminous Concrete Pavement, Performance Engineered Method*, for Superpave Type IVS (9.5mm NMAS) mixtures in 2019. This special specification calls for the Volumetric Design with Performance Verification approach, where asphalt mixtures are required to meet both the existing Superpave volumetric requirements and performance test requirements. The design air voids content is 4.0 ± 1.0 percent at a N_{design} of 65 gyrations and the minimum VMA criterion is 16.5 percent. HWTT per AASHTO T 324-19 is conducted at 45 ± 1.0°C to evaluate resistance to rutting and moisture damage. Test criteria include a maximum 10.0 mm rut depth at 20,000 passes and a minimum threshold of 15,000 passes for the stripping inflection point (SIP). Mixture cracking resistance is evaluated using I-FIT per AASHTO TP 124-20. The I-FIT criterion is a minimum FI of 10.0 on specimens that have been short-term conditioned for four hours at 135°C prior to compaction per AASHTO R 30.

In addition to mix design approval, HWTT and I-FIT are required for production acceptance. Both tests are conducted on plant produced mixes sampled from the truck at the plant without additional short-term conditioning. For performance testing on pilot projects, the entire project is considered a LOT with each sublot defined as 3,000 tons (except for the final sublot). The testing frequency is one test per sublot. Production acceptance is on the LOT-by-LOT basis using the percent within limits (PWL) method, where a minimum of three sublots is required to constitute a valid LOT.

The same performance test criteria for mix design approval are used as the specification limits to calculate upper quality index (Q_U), lower quality index (Q_L), and PWL for production acceptance. The rejectable quality limit (i.e., minimum acceptance PWL) is 60 percent. VTrans completed eight shadow projects in 2018 and 2019, and two pilot projects in 2020.

Virginia

The Virginia Department of Transportation (VDOT) is in the process of implementing BMD. VDOT allows two different BMD approaches for the design and production of surface mixtures in its most recent special provisions, *Balanced Mix Design Surface Mixtures Designed using Performance Criteria and High Reclaimed Asphalt Pavement Content Surface Mixtures Designed using Performance Criteria*. Note that "high RAP surface mixtures" refer to asphalt mixtures containing 40 percent RAP or more, while the current Superpave mix designs are permitted to have no more than 30 percent RAP in surface mixtures. The first BMD approach is based on the "Performance + Volumetric (BP+V)" criteria, where the mix design is required to meet both the existing volumetric and performance test requirements. This corresponds to the Volumetric Design with Performance Verification approach. The second BMD approach requires mix design using the "Performance Only (BP)" criteria, where mix design is purely based on the mixture performance test results with no requirements on aggregate gradation (except NMAS), virgin binder grade, and volumetric properties. This approach is essentially the Performance Design approach.

The mixture performance tests used in both BMD approaches are APA, Cantabro, and IDEAL-CT for the evaluation of rutting resistance, overall durability, and cracking resistance, respectively. APA tests are conducted in accordance with AASHTO T 340-10 at 64°C. The APA specimens are conditioned for two hours at the design compaction temperature prior to compaction. Test criterion is a maximum 8.0 mm rut depth at 8,000 passes. Cantabro is conducted per AASHTO TP 108 on N_{design} specimens that have been conditioned for two hours at the compaction temperature prior to compaction. Test criterion is a maximum Cantabro mass loss of 7.5 percent. IDEAL-CT is conducted in accordance with ASTM D8225. Different from the APA and Cantabro tests, IDEAL-CT requires specimens conditioned for four hours at the compaction temperature on loose mix prior to compaction. Test criterion is a minimum CT_{index} of 70. Additionally, the contractor is required to prepare a set of long-term aged IDEAL-CT specimens (aging the loose mix for eight hours at 135°C in addition to four hours at the compaction temperature) and submit with the JMF for mix design approval. The long-term aged IDEAL-CT results are for information only.

Mixture performance testing is also required for production acceptance using the same test criteria as mix design approval. VDOT completed a total of five trial projects in 2019 and 2020. Four out of the five projects used high RAP BMD mixtures modified with a PG 58-28 softer binder and various recycling agents and additives, while the other one used the contractor's standard production mixture with 26% RAP. All the trial projects were performed through change orders applied to maintenance schedule work. During production, the contractor was responsible for Cantabro and IDEAL-CT testing at a frequency of one test every 500 tons, while VDOT was responsible for the same testing at a 1/1,000-ton frequency. Furthermore, the Virginia Transportation Research Council (VTRC) conducted APA on hot-compacted (without reheating) PMLC specimens and Cantabro and IDEAL-CT on reheated PMLC specimens at a frequency of every 500 tons. The contractor, VDOT, and VTRC also tested aggregate gradation, asphalt binder content, and mixture volumetrics for every 500 to 1,000 tons of plant produced mixes. In 2021, VDOT is planning to construct several pilot projects as maintenance schedule work, which will implement the BMD special provisions and have specific routes designated for BMD mixes.

05 SUMMARY OF ASPHALT MIXTURE PERFORMANCE TESTS

Appendix A provides an overview of asphalt mixture performance tests that are commonly used in asphalt research and are being considered for implementation by SHAs for BMD. The appendix was initially developed in NCHRP Project 20-07/Task 406 (West et al., 2018) but was recently updated with new information and three mixture rutting tests that have been developed since 2018. The performance tests are organized in three categories: rutting tests, cracking tests, and moisture damage tests. With each category, the tests are presented in alphabetical order. Each test is summarized in a one-page table format that includes a brief description of the test procedure, test results, equipment and cost, specimen fabrication, testing time, data analysis complexity, test variability, field validation, and overall practicality for mix design and quality assurance (QA). In addition, key references are provided for each test for readers interested in seeking further information. Information categories based on subjective assessments include data analysis complexity, test variability, overall practicality for mix design and QA, and field validation. Data analysis and complexity has three levels: "Simple", "Fair", or "Complex". This assessment is based on two parts; the first part considers the complexity of the procedure to obtain test results considering the availability of software to automate the process, while the second part considers the complexity of interpretation of the test results for use in specifications. Test variability has three levels depending on the typical coefficient of variation (COV); "Low" for COVs ≤ 10%, "Medium" for COVs between 10 and 25%, or "High" for COVs > 25%. Overall practicality for mix design and QA also has three levels: "Poor", "Fair", or "Good". This assessment is based on the cost and time needed to prepare samples and obtain test results as well as the practicality of establishing specification criteria for the test. Lastly, field validation has three levels: "Not Available", "Fair", or "Good". "Fair" indicates that there are limited studies on relating the test result to field performance, while "Good" indicates several lab-to-field studies have been conducted by multiple independent organizations and regions of the U.S.

06 GUIDANCE FOR SELECTING MIXTURE PERFORMANCE TESTS

NCHRP Project 20-07/Task 406 identified nine critical steps needed to move a test method from concept to full implementation (West et al., 2018); they are graphically illustrated in Figure 6. Although the order of these steps is the logical sequence, some tests have been developed in different orders. It should also be noted that the results of a step may indicate that the test method needs significant refinement, and the preceding steps need to be repeated. Therefore, an objective review of the test method should be made after each step to determine whether the process should proceed.

1. Develop draft test method and prototype equipment
2. Evaluate sensitivity to materials and relationship to other lab properties
3. Establish preliminary field performance relationship
4. Conduct ruggedness experiment to refine its critical aspects
5. Develop commercial equipment specification and pooled fund purchasing
6. Conduct round-robin testing to establish precision and bias information
7. Conduct robust validation of the test to set criteria for specifications
8. Conduct training and certification
9. Implement into engineering practice

Figure 6. Nine Steps Needed to Advance Mixture Performance Tests from Development to Implementation

Although this is a long and expensive process to complete, SHAs interested in the implementation of BMD are highly recommended to consider these steps when selecting mixture performance tests. Performance tests that have completed these important steps through collaborative research, training, and implementation efforts are considered the most robust and readily implementable for BMD. Using performance tests that fail to complete these steps could ultimately lead to the implementation of a poor BMD specification that is costly to the highway agency, the contracting industry, or both. In addition to the steps in Figure 6, two important factors that should be considered when selecting mixture performance tests for BMD are the complexity of test method and the cost of test equipment. Mixture performance tests requiring expensive equipment, tedious specimen fabrication, long testing time, and complicated data analysis may not be appropriate for use in quality control and acceptance testing because of lack of practicality. On the other hand, mixture performance tests that are simple, quick, repeatable, and robust are preferred because they can be implemented for mix design and production testing to ensure balanced rutting and cracking resistance of both laboratory-produced and plant-produced mixes.

Step 1. Develop draft test method and prototype equipment

The motivation to develop a new test method is generally born from recognition of an important material characteristic (typically a material deficiency) that is not detected by existing methods or from a desire to correct flaws in an existing method. Researchers often look to the technical literature in the same or related fields for inspiration and guidance on how to measure the desired characteristic. In some cases, researchers may develop a test that attempts to simulate the critical condition at which the material deficiency occurs. Developing prototype equipment for the new test can be an arduous process with numerous iterations and refinements. Drafting of a written method often occurs when it is necessary for someone other than the original developer(s) to perform the test. Several revisions of the draft procedure are typically necessary to refine a method so that an independent technician or engineer can use it.

Step 2. Evaluate sensitivity to materials and relationship to other lab properties

Early research with a new test method often includes evaluating how the test results are affected by the changing properties of the material. For example, how sensitive is the test to materials variables considered in asphalt mix design including asphalt content, grade of asphalt binder, aggregate gradation, aggregate type, recycled materials contents, air voids, and possibly other factors? Early experiments often also compare or contrast results of the new test to an existing method(s). Caution should be exercised in relying on another existing laboratory test to justify the results of a new test since the existing test may lack proper field validation.

Step 3. Establish preliminary field performance relationship

For a test method to be seriously considered for use in specifications, there must be a clear relationship between its results and field performance. However, this is a very difficult step to successfully accomplish. Challenges in this step can include obtaining materials used in field projects, confounding factors that impact field performance, and the long period of time necessary to obtain meaningful field performance data, especially for distresses that take more than just a few years to develop. Therefore, most tests have a very limited amount of data to relate results to field performance in the early stages of development. At best, these initial studies are typically based on limited data from a single state. Regardless of how well the test results match or correlate with observed field performance, those findings should still be published so that all stakeholders are aware of the outcomes and possible test limitations. If the test is subsequently improved, another lab-to-field study should be conducted. For load related distresses (i.e., rutting and fatigue cracking), an experiment using an accelerated pavement testing facility may be ideal for establishing preliminary relationships between lab tests and field performance because these facilities are able to test multiple cells/lanes/sections under the same loading, environments, and support conditions. However, since loading systems such as an accelerated loading facility (ALF) or heavy vehicle simulator (HVS) operate at much slower speed than highway traffic, such results are not applicable for setting criteria for typical pavement specifications.

Step 4. Conduct ruggedness experiment to refine its critical aspects

A ruggedness experiment is critical to refining a test procedure to establish appropriate controls/limits for factors that significantly affect the test's results. For example, test methods typically state specific dimensions for the specimens. Some dimensions may affect the test results, so tolerances (e.g., X.X ± X.X mm) must be established to minimize such undesired sources of variability. Other examples of test controls that likely need to be evaluated in a ruggedness experiment include mixture aging temperature and time, specimen relative density, preconditioning time, test temperature, loading plate/strip geometries, loading frame compliance, loading/displacement rate, and data acquisition rate. For asphalt materials tests, ruggedness experiments should be conducted in accordance with ASTM E1169 (or ASTM C1067). Historically, few tests used in asphalt specifications have had formal ruggedness experiments conducted prior to the test's use in routine practice.

Step 5. Develop commercial equipment specification and pooled fund purchasing

For labs to purchase equipment for preparing test specimens and conducting the test, detailed specifications are needed for that equipment. In some cases, a standardized program or worksheet should also be developed to ensure that results are calculated/analyzed in a consistent manner. A ruggedness experiment conducted prior to writing the equipment specification will help set tolerances for the equipment. When several equipment manufacturers produce the equipment, it is recommended to conduct an experiment with units from each manufacturer to verify that results from each unit are similar. When a large number of labs need to purchase the equipment, there may be significant advantages to purchasing a large number of units at the same time, such as with a pooled-fund equipment purchase.

Step 6. Conduct round-robin testing to establish precision and bias information

For tests whose results are used for materials approval and/or acceptance, it is necessary to establish the method's precision and bias information. The standard for conducting a round-robin (a.k.a. interlaboratory) study is ASTM E691. An interlaboratory study is used to establish the acceptable range of two test results from a single operator (i.e., within-lab) and the acceptable range of split-sample results from two different laboratories (i.e., between-lab). Knowing the within-lab and between-lab test variabilities of different candidate tests determined using ASTM E691 is useful information to help select the most preferred test option.

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

Before the test is used in a specification, an agency should have confidence that the criteria used for a material's approval and/or acceptance are appropriately set. Criteria that are too strict will increase contractor risks and eventually increase bid prices. Criteria that are too lenient will ultimately lead to accepting poor performing materials. Robust validation of a test is a more rigorous experiment or group of experiments to make sure that the test provides results that provide a strong indicator of field performance. As with Step 3, there are numerous challenges to establishing a relationship between lab test results and pavement performance. The ideal validation experiment would include sites with moderate to high traffic levels and in different regions of the country with each site having five to ten test sections with mixtures expecting to have a range of performance from bad to good for the distress being evaluated. It is recommended for the validation experiment to include mixtures containing typical materials in the state. Tight controls on the construction of the test sections are critical to avoid undesired or confounding effects. To eliminate potential bias, the laboratory testing for the validation effort should be completed such that the results of the field performance of the test sections are unknown and preferably by an organization other than the test's primary developer. The desired result for each site is a strong correlation between the measured field distress and the laboratory test results from which a limit or limits can be established for specification purposes. In other words, it is necessary to have some poor-performing test sections in the field so that the criteria can be set to exclude such mixtures in the future.

Another option for robust validation is to test mix designs that already have known field performance. This has been referred to as benchmarking. The challenges with this approach are (1) if the mix designs contained recycled materials, those materials may no longer be available, and (2) field performance is likely to be influenced by other factors that differ from project to project (e.g., traffic, underlying conditions), which confound an analysis of field to lab correlations.

Step 8. Conduct training and certification

Training of engineers and technicians on the test procedure and analysis of its results is vital to the successful implementation of a new test method. Agencies should facilitate the development of a training course and require participation by all personnel who are involved in specimen preparation, testing, and analysis of results. Periodic retraining is also appropriate as a test method is revised. Workshop type courses where participants are given hands-on time with sample preparation, testing, and analysis are preferred.

Step 9. Implement into engineering practice

Industry-agency task groups can be helpful in establishing an implementation plan. It is generally considered a best practice to begin implementation of a new specification through a series of shadow projects and pilot projects using a phased-in approach. The first phase is typically a limited number of shadow projects that add the new test(s) for information only and are helpful to work out sampling and testing logistics, assess how results compare to the proposed criteria, and make adjustments. Shadow projects may be added to existing contracts to facilitate early buy-in. The second phase is a series of pilot projects that use the test results for approving and accepting materials. The number of pilot projects should start out with just a few in the first year, then one to two projects in each district the second year, and so on. Adjustments may be made to each round to improve the processes and criteria. These projects enable more stakeholders to become more familiar with the test and how its results will impact the design and acceptance of their materials. Some agencies have also added a pay item to pilot projects for the purchase of new test equipment. The agency or the task group should consider whether the new tests and specifications should apply to all asphalt paving projects or only apply to certain roadway classifications and projects of a minimum size. Overall, it may take four to five years to reach full implementation.

07 GUIDANCE FOR ESTABLISHING MIXTURE PERFORMANCE TEST CRITERIA

In addition to the lab to field validation experiment previously discussed in Step 7 of Guidance for Selecting Mixture Performance Tests, a statewide benchmarking experiment is also highly recommended to help establish appropriate mixture performance test criteria. The objective of the benchmarking experiment is to test existing mix designs being designed and produced in the state using the selected mixture performance tests to determine the distribution of test results. When selecting asphalt mixtures for the benchmarking experiment, priority should be given to those with a known history of field performance. Ideally, the benchmarking experiment would include testing of laboratory-mixed laboratory-compacted (LMLC) specimens for mix design approval and PMLC specimens for production acceptance. Comparing the test results of LMLC versus PMLC specimens will provide insights on how mix quality can change from mix design to production. There are many factors that may contribute to the difference in the test results between these two types of samples, which include changes in the binder content and aggregate gradations due to normal production variability, differences in asphalt aging and absorption, breakdown of aggregate through the plant, and variations in baghouse fines return, among others.

All performance testing for the benchmarking experiment should be conducted in a single laboratory (e.g., the SHA central laboratory or a designated third-party laboratory) to exclude between-lab variability in the test results. If contractors or other labs are involved in sampling mixtures and/or preparing specimens, then the entity leading the benchmarking experiment should provide detailed, step-by-step procedures to those labs for the sake of consistency. Once testing is completed, a database of mixture performance test results can be developed and analyzed to determine the impact of mix design and production variables on the test results, identify mix design modifications to improve test results, and most importantly, establish preliminary specification criteria for use in shadow projects.

When selecting the preliminary performance criteria, one of the questions that SHAs need to answer is, “are you satisfied with the current pavement performance in the state?” If the answer is “yes”, then the preliminary performance criteria should be selected so that they can pass most of the existing mix designs but fail those with known quality issues. If the answer is “no”, then the criteria should be set at a higher level with expectations that the overall mix quality and pavement performance would be improved upon execution of a BMD specification. Several recently completed or ongoing research studies have provided useful guidance on setting performance test criteria based on a benchmarking experiment; they are briefly discussed as follows.

- Researchers at the Illinois Center for Transportation developed a set of preliminary criteria for I-FIT to discriminate asphalt mixtures from good-, intermediate-, and poor-performing pavement sections in Illinois (Al-Qadi et al., 2015). These criteria were then further refined with additional field performance data collected since they were first developed. Based on these efforts, a minimum flexibility index criterion of 8.0 on short-term aged specimens was adopted by the Illinois DOT for mix design approval in 2016.

- In 2018, researchers at VTRC completed an in-house research study to benchmark the performance of 11 existing mix designs using a variety of mixture performance tests. Based on the test results collected, the APA, IDEAL-CT, and Cantabro test were selected as the mixture performance tests for BMD in Virginia. Furthermore, a set of preliminary test criteria were developed for use in a provisional specification on BMD by considering the historical performance of these 11 mix designs along with findings and recommendations from other relevant research studies.

- NCAT researchers have been conducting two benchmarking experiments to assist the Georgia DOT and Wisconsin DOT with the implementation of BMD. The Wisconsin benchmarking experiment consists of testing LMLC specimens for 18 mix designs using the HWTT, IDEAL-CT, and Disc-shaped Compact Tension (DCT) test, while the Georgia experiment focuses on the IDEAL-CT testing of PMLC specimens for 42 mix designs. Test results, data analysis, and research findings of these two benchmarking experiments will become available in spring 2021.

In addition to conducting a benchmarking study, SHAs should consider performance criteria recommended from well-designed, well-constructed field experiments. Examples of such experiments include the top-down cracking experiment at the NCAT Test Track, the thermal cracking experiment at the Minnesota Road Research Facility (MnROAD), and other pooled-fund experiments with multiple test sections. Agencies should also consider building one or more Long-Term Pavement Performance (LTPP) style field experiments in their own state to help establish appropriate BMD criteria for their state. This kind of experiment takes a great deal of planning efforts and requires at least five years to obtain useful long-term pavement performance data, but ultimately will serve as a great source of data for establishing preliminary test criteria for BMD. Although not recommended, some SHAs may also opt to adopt the existing performance test criteria used in other states.

There are two key questions that must be answered when setting preliminary criteria: "are the performance criteria under consideration achievable for the existing mix designs in the state?" and "can the performance criteria discriminate the good-performing versus poor-performing mixes with a known history of performance data?" If the answer to at least one of these questions is "no", then the performance criteria should be adjusted to better suit the local conditions in the state.

Another step in the effort to set preliminary performance test criteria is the execution of shadow projects. A shadow project is an existing project that using the SHA's current acceptance tests (e.g., asphalt content, gradation, VMA, etc.) but additional plant mix samples are obtained throughout the project for mixture performance testing. The performance test results are for informational purposes only as there would be no changes to either the contract or the specifications for the project. The performance testing would be performed by the SHA at either their central or district laboratory but could also be performed by the contractor. The shadow project has three goals: first, familiarize agency and contractor personnel with the selected performance tests; second, add to the database of test results from the benchmarking experiment; and finally, gather information about the impact of production variability on the performance test results. In addition to the laboratory test results, field performance data of the shadow project should also be collected, which allows the agency to further verify the preliminary performance test criteria and make appropriate adjustments if needed. SHAs are recommended to revisit their performance criteria on a yearly basis to ensure that they are suitable for accepting asphalt mixtures with good rutting and cracking performance for mix design approval and production acceptance.

08 GUIDANCE ON MIX DESIGN MODIFICATIONS FOR IMPROVING PERFORMANCE TEST RESULTS

This section discusses the effects of common mix design variables on mixture performance test results as guidance on mix design modifications for BMD. For each mix design variable discussed here, examples of test results for before-versus-after design modification comparisons are provided for illustrative purposes. In addition to performance test results, material availability and costs should be considered when modifying mix designs, which are not discussed in this document. In the low bid environment, mix designers should always explore the most cost-effective BMD optimization method to remain competitive while meeting the agency's mixture performance test requirements.

Asphalt Binder Content

Asphalt binder content is arguably the most significant mix design variable affecting the performance test results of asphalt mixtures. In general, increasing the asphalt binder content improves the cracking resistance but reduces the rutting resistance of asphalt mixtures. Increasing asphalt binder content is also expected to have a positive effect on resistance to moisture damage due to better aggregate coating and reduced permeability associated with better in-place density. Finally, it should be noted that changing the asphalt binder content without adjusting the aggregate gradation and/or compaction effort will also affect the mixture volumetric properties.

Example 1 – Asphalt Binder Content

- Data source: NCAT
- Mix design: 9.5mm NMAS, PG 67-22 unmodified binder, a blend of granite aggregates and sand, 20% RAP
- Mix design variable: asphalt binder content
  - o Volumetric OBC, 5.5%
  - o Volumetric OBC plus 0.5 percent, 6.0%
  - o Volumetric OBC plus 1.0 percent, 6.5%
- Mixture performance tests: HWTT and IDEAL-CT
- Test results and discussions: As the asphalt binder content increased, both the HWTT rut depth and IDEAL CT_{index} results increased, which indicates reduced rutting resistance but improved intermediate-temperature cracking resistance.

Asphalt Binder Content	HWTT Rut Depth at 20,000 Passes (mm)	Ideal CT_{index}
Volumetric OBC (5.5%)	2.2	49.6
OBC + 0.5% (6.0%)	2.8	56.6
OBC + 1.0% (6.5%)	6.1	89.1

Example 2 – Asphalt Binder Content

- Data source: NCAT
- Mix design: 12.5mm NMAS, PG 58-28 unmodified binder, limestone aggregates, 20% RAP
- Mix design variable: asphalt binder content
  - o Volumetric OBC, 5.70% (4.0% air voids)
  - o Regressed OBC, 5.87% (3.5% air voids)
  - o Regressed OBC, 6.04% (3.0% air voids)
- Mixture performance tests: HWTT, I-FIT, and DCT
- Test results and discussions: As the asphalt binder content increased, the HWTT rut depth, I-FIT *FI*, and DCT fracture energy (G_f) results increased, which indicates reduced rutting resistance but improved resistance to intermediate-temperature cracking and low-temperature cracking.

Asphalt Binder Content	HWTT Rut Depth at 20,000 Passes (mm)	I-FIT *FI*	DCT G_f (J/m^2)
Volumetric OBC, 5.70%	4.3	5.8	366
Regressed OBC, 5.87%	4.8	9.6	384
Regressed OBC, 6.04%	5.6	12.5	425

Virgin Binder Grade and Source

There are two factors relevant to asphalt binder that affect the performance test results of asphalt mixtures: the volume and the quality of asphalt binder. The former is governed by the total binder content and effective binder content (or the volume of effective binder, V_{be}), while the latter is primarily dependent on the grade and source of virgin binder as well as those of recycled binders and asphalt additives if used. In general, stiffer asphalt binders are expected to yield mixtures with improved rutting resistance but reduced cracking resistance, although there are exceptions such as polymer modified asphalt (PMA) binders. Therefore, mix designers can consider using a stiffer virgin binder to improve the rutting test results, or a softer binder to improve the cracking test results for BMD. In addition to binder grade, the source of virgin binder may also affect the mixture performance test results. Asphalt binders with the same PG grade are not necessarily of the same quality due to differences in the crude source and refining process. Therefore, additional binder parameters other than those specified in the Superpave PG specification (such as the Delta Tc and Glover-Rowe parameter) should be considered when selecting a virgin binder for BMD. Changing the virgin binder grade or source is not likely to have a significant impact on the volumetric properties of asphalt mixtures provided that the mixing and compaction temperatures are appropriately adjusted to account for the differences in binder viscosity.

Example 1 – Virgin Binder Grade

- Data source: NCAT
- Mix design: 12.5mm NMAS, a blend of limestone aggregates, granite aggregates, and sand, 45% RAP, 5.0% asphalt binder content
- Mix design variable: virgin binder type
  - o PG 52-28 unmodified binder
  - o PG 67-22 unmodified binder
- Mixture performance test: APA
- Test results and discussions: The APA rut depth decreased as the virgin binder grade increased from PG 52-28 to PG 67-22, which indicates improved rutting resistance for asphalt mixtures containing a stiffer binder *versus* a softer binder.

Virgin Binder Type	APA Rut Depth at 8,000 Cycles (mm)
PG 52-28 Unmodified	5.1
PG 67-22 Unmodified	4.1

Example 2 – Virgin Binder Grade

- Data source: Texas A&M University (Epps Martin et al., 2019; Hand and Epps Martin, 2020)
- Mix design: 12.5mm NMAS, 36% RAP, 5.4% asphalt binder content, 14.5% VMA.
- Mix design variable: virgin binder grade
  - o PG 58-28 unmodified binder
  - o PG 52-34 unmodified binder
- Mixture performance tests: I-FIT and Uniaxial Thermal Stress and Strain Test (UTSST)
- Test results and discussions: The asphalt mixture prepared with a PG 52-34 virgin binder had significantly higher I-FIT *FI* and UTSST environmental cracking resistance index (CRI_{Env}) results, which indicates better resistance to intermediate-temperature cracking and low-temperature cracking compared to the same mixture prepared with a PG 58-28 virgin binder.

Binder Grade	I-FIT *FI*	UTSST CRI_{Env}
PG 58-28	10	8
PG 52-34	17	22

Example 3 – Virgin Binder Source

- Data source: NCAT
- Mix design: 12.5mm NMAS, PG 64-28 SBS modified binder, a blend of chat, granite aggregates, and sand, 12% RAP, 5.8% asphalt binder content, 16.2% VMA.
- Mix design variable: virgin binder source
  - o Binder source 1
  - o Binder source 2
- Mixture performance tests: HWTT and I-FIT
- Test results and discussions: Asphalt mixtures prepared with two PG 64-28 virgin binders from different crude sources had similar I-FIT *FI* but significantly different HWTT rut depth results.

Binder Source	HWTT Rut Depth at 20,000 Passes	I-FIT *FI*
PG 64-28, Source 18	4.0	11.0
PG 64-28, Source 2	8.2	12.7

Example 4 – Virgin Binder Source

- Data source: University of Illinois at Urbana-Champaign (Zhu et al., 2020)
- Mix design: 9.5mm NMAS, PG 64-22 unmodified binder, no RAP/RAS, 6.4% asphalt binder content, 15.2% VMA.
- Mix design variable: virgin binder source
  - o Binder source 1
  - o Binder source 2
- Mixture performance test: I-FIT
- Test results and discussions: An asphalt mixture prepared with two PG 64-22 virgin binders from different crude sources had statistically different I-FIT *FI* results at both short-term and long-term aging conditions.

Binder Source	I-FIT *FI* (short-term aged for 4 hours at 135°C on loose mix)	I-FIT *FI* (long-term aged for 3 days at 95°C on compacted specimen)
PG 64-22, Source 1	10.2	3.4
PG 64-22, Source 2	15.5	5.2

Polymer Modification

The asphalt pavement industry has a long history of using polymer modified asphalt to improve the performance and service life of asphalt pavements. Extensive research efforts have confirmed the benefit of polymer modification in improving the rutting resistance of asphalt mixtures due to increased binder stiffness and in some cases, improved binder elasticity. Furthermore, a vast number of field projects have demonstrated improved fatigue cracking performance of pavements containing polymer modified asphalt compared to pavements with unmodified asphalt (Asphalt Institute, 2005). However, several recent studies have shown that use of PMA does not always yield better results in some intermediate-temperature cracking tests, especially those requiring the analysis of post-peak load versus displacement data (Hanz, 2017; Fort, 2018). These test results do not agree with many existing field cracking performance data and thus, warrant further investigation (National Road Research Alliance, 2021). Polymer modification is not likely to affect the volumetric properties of asphalt mixtures provided that the mixing and compaction temperatures are adjusted to accommodate the differences in viscosity of asphalt binders.

Example 1 – Virgin Binder Type (Polymer Modification)

- Data source: NCAT
- Mix design: 12.5mm NMAS, a blend of limestone, granite, and natural sand, 45% RAP, 5.0% asphalt binder content
- Mix design variable: virgin binder type
  - o PG 52-28 unmodified binder
  - o PG 67-22 unmodified binder
  - o PG 76-22 SBS modified binder
- Mixture performance test: APA
- Test results and discussions: The asphalt mixture prepared with a PG 76-22 SBS modified binder had a lower APA rut depth, and thus, better rutting resistance than those prepared with PG 52-28 and PG 67-22 unmodified binders.

Virgin Binder Type	APA Rut Depth at 8,000 Cycles (mm)
PG 52-28 Unmodified	5.1
PG 67-22 Unmodified	4.1
PG 76-22 SBS Modified	2.8

Example 2 – Virgin Binder Type (Polymer Modification)

- Data source: Texas A&M Transportation Institute (Zhou et al., 2017)
- Mix design: 12.5mm NMAS, 20% RAP, 5.0% asphalt binder content
- Mix design variable: virgin binder type
  - o PG 64-22 unmodified binder
  - o PG 64-28 SBS modified binder
  - o PG 64-34 SBS modified binder
- Mixture performance test: IDEAL-CT

- Test results and discussions: The asphalt mixtures prepared with PG 64-28 and PG 64-34 SBS modified binders had higher IDEAL CT_{index} and thus, were expected to have better intermediate-temperature cracking resistance than that containing a PG 64-22 unmodified binder.

Virgin Binder Type	IDEAL CT_{index}
PG 64-22 Unmodified	42.4
PG 64-28 SBS Modified	82.2
PG 64-34 SBS Modified	126.2

Example 3 – Virgin Binder Type (Polymer Modification)

- Data source: NCAT
- Mix design: 9.5mm NMAS, a blend of granite aggregates and sand, 20% RAP, 5.5% asphalt binder content, 15.6% VMA
- Mix design variable: virgin binder type
  - o PG 67-22 unmodified binder
  - o PG 76-22 SBS modified binder
- Mixture performance test: IDEAL-CT
- Test results and discussions: The asphalt mixture prepared with a PG 67-22 unmodified binder had a higher IDEAL CT_{index} than that containing a PG 76-22 SBS modified binder, which does not agree with many existing field performance data showing the enhanced cracking resistance of PMA mixtures.

Virgin Binder Type	IDEAL CT_{index})
PG 67-22 Unmodified	49.6
PG 76-22 SBS Modified	26.7

Aggregate Gradation

Aggregate gradation plays a significant role in volumetric mix design by affecting the skeleton structure of the mixture and the amount of asphalt binder needed to achieve a target air voids content at N_{design}. It has been widely acknowledged that better aggregate interlock contributes to improved rutting resistance of asphalt mixtures due to enhanced load-carrying capability and shear strength. However, the impact of aggregate gradation on the cracking resistance of asphalt mixtures has yet to be evaluated in a systematic manner. This lack of investigation is partially due to the fact that changing aggregate gradation will trigger changes in the volumetric optimum asphalt binder content. As a result, the performance evaluation on the impact of aggregate gradation under a volumetric mix design framework is always confounded by other factors. However, because BMD allows certain volumetric properties to be relaxed or eliminated, it provides an opportunity to assess the impact of aggregate gradation as an independent mix design variable on the mixture performance test results. Unfortunately, very limited information is currently available on this matter.

Example – Aggregate Gradation

- Data source: University of Texas at El Paso (Nazarian et al., 2018) and NCAT
- Mix design: 12.5mm NMAS, PG 70-22 SBS modified binder, a blend of igneous aggregates, limestone aggregates, and sand, 20% RAP binder replacement
- Mix design variable: aggregate gradation
  - o Mix 1: 5.5% asphalt binder content, 4.0% air voids, 16.6% VMA (calculated using G_{se} per TxDOT specification)
  - o Mix 2: 4.7% asphalt binder content, 4.0% air voids, 15.0% VMA (calculated using G_{se} per TxDOT specification)

Sieve Size	Mix 1	Mix 2
25 mm	100	100
19 mm	100	100
12.5 mm	93.4	92.3
9.5 mm	81.9	80.6
4.75 mm	51.5	52.9
2.36 mm	29.8	33.9
1.18 mm	20.9	23.6
0.60 mm	15.6	17.1
0.30 mm	11.0	11.5
0.075 mm	4.9	4.8

- Mixture performance tests: HWTT and OT
- Test results and discussions: The slightly coarser gradation of Mix 1 resulted in an 0.8% increase in the total asphalt binder content at 4.0% air voids compared to Mix 2. Because of the higher asphalt binder content, Mix 1 had a higher HWTT rut depth but a lower OT β parameter, which indicates reduced rutting resistance but improved cracking resistance, than Mix 2.

Gradation ID	HWTT Rut Depth at 20,000 Passes (mm)	OT β Parameter
Mix 1	11.7	0.37
Mix 2	6.6	0.57

Recycled Asphalt Material Content

Recycled asphalt materials including RAP and RAS contain heavily aged asphalt binders that are stiffer and more brittle than virgin binders. Therefore, increasing the RAP/RAS content generally improves the stiffness and rutting resistance of asphalt mixtures but makes them more susceptible to fatigue cracking and low-temperature cracking. Changing the RAP/RAS content for a mix design will also affect mixture volumetrics due to the associated changes in asphalt binder content and aggregate gradation.

Example 1 – RAP Content

- Data source: NCAT
- Mix design: 12.5mm NMAS, PG 70-28 SBS modified binder.
- Mix design variable: RAP content
  - o 0% RAP: 5.0% asphalt binder content, 4.0% air voids, 15.2% VMA
  - o 15% RAP: 4.7% asphalt binder content, 4.0% air voids, 14.6% VMA
  - o 30% RAP: 4.8% asphalt binder content, 4.0% air voids, 14.3% VMA
- Mixture performance tests: HWTT, I-FIT, IDEAL-CT, and DCT
- Test results and discussions: At both short-term and long-term aging conditions, the virgin (0% RAP) mixture exhibited the highest I-FIT *FI*, IDEAL CT_{index}, and DCT Gf results, and thus is expected to have the best cracking resistance, followed by the 15% RAP mixture and 30% RAP mixture, respectively. On the other hand, the 15% and 30% RAP mixtures had better rutting resistance, as indicated by lower HWTT rut depth results compared to the virgin mixture when tested at the short-term aging condition.

RAP Content	Aging Condition	HWTT Rut Depth at 20,000 Passes (mm)	I-FIT *FI*	IDEAL CT_{index}	DCT G_f (J/m²)
0% RAP	Short-term Aged (4 hours at 135°C)	5.6	16.3	124	938
15% RAP		3.0	9.3	77	719
30% RAP		2.1	3.4	37	537
0% RAP	Long-term Aged (8 hours at 135°C)	-	5.2	38	647
15% RAP		-	3.0	23	636
30% RAP		-	1.7	18	526

Example 2 – RAP Content

- Data source: Texas A&M University (Epps Martin et al., 2019; Hand and Epps Martin, 2020)
- Mix design: 12.5mm NMAS, PG 58-28 unmodified binder.
- Mix design variable: RAP content
  - o 27% RAP: 5.6% asphalt binder content, 4.0% air voids, 15.4% VMA
  - o 36% RAP: 5.4% asphalt binder content, 4.0% air voids, 14.5% VMA
- Mixture performance tests: I-FIT and UTSST
- Test results and discussions: The 36% RAP mixture had significantly lower I-FIT *FI* and UTSST CRI_{Env} results, indicating reduced resistance to intermediate-temperature cracking and low-temperature cracking, than the corresponding 27% RAP mixture.

RAP Content	I-FIT *FI*	UTSST CRI_{Env}
27% RAP	14	23
36% RAP	10	8

Recycling Agents

Recycling agents are organic materials with chemical and physical characteristics selected to restore aged binder to desired specifications. Recycling agents can be grouped into two categories: softening agents and rejuvenators (Asphalt Institute, 1986; Willis and Tran, 2015). Softening agents are mainly used to reduce the viscosity of virgin and recycled binder blends, while rejuvenators may reduce the viscosity but are primarily intended to partially restore the chemical balance and rheological properties of binder blends (Epps Martin et al., 2019; Hand and Epps Martin, 2020). Over the past few years, there has been increasing use of recycling agents for the design and production of asphalt mixtures containing high RAP and/or RAS contents. The addition of recycling agents is expected to improve the cracking resistance but reduce the rutting resistance of asphalt mixtures. However, the effectiveness of recycling agents on mixture performance test results varies significantly depending on the type of recycling agent, RAP/RAS source, source of virgin binder, and compatibility between recycling agent, virgin binder, and recycled binder, among others. The impact of recycling agents on the volumetrics and moisture susceptibility of asphalt mixtures has not been investigated in a comprehensive manner and warrants further research.

Example 1 – Rejuvenator

- Data source: NCAT
- Mix design: 9.5mm NMAS, PG 67-22 unmodified binder, a blend of granite aggregates and sand, 45% RAP, 6.5% asphalt binder content, 16.1% VMA.
- Mix design variable: rejuvenator
  - o Control, no rejuvenator
  - o Control + 3% bio-based rejuvenator (by weight of RAP asphalt binder)
  - o Control + 8% bio-based rejuvenator (by weight of RAP asphalt binder)
- Mixture performance tests: HWTT and IDEAL-CT
- Test results and discussions: The rejuvenated 45% RAP mixtures had consistently higher HWTT rut depth and IDEAL CT_{index} results than the control (no rejuvenator) mixture, which indicates reduced rutting resistance but improved intermediate-temperature cracking resistance.

Rejuvenator	HWTT Rut Depth at 20,000 Passes (mm)	IDEAL CT_{index}
Control, no Rejuvenator	2.7	54.5
+ 3% Bio-based Rejuvenator	3.8	79.8
+ 8% Bio-based Rejuvenator	5.5	105.9

Example 2 – Rejuvenator

- Data source: NCAT
- Mix design: 9.5mm NMAS, PG 64-22 unmodified binder, igneous aggregates, 45% RAP, 6.0% asphalt binder content, 16.3% VMA.

- Mix design variable: rejuvenator
  - o Control, no rejuvenator
  - o Control + 3% bio-based rejuvenator (by weight of total asphalt binder)
- Mixture performance tests: I-FIT, IDEAL-CT, OT, and DCT
- Test results and discussions: The rejuvenated 45% RAP mixture had consistently higher I-FIT *FI*, IDEAL CT_{index}, OT number of cycles to failure (N_f), and DCT G_f results than the control (no rejuvenator) mixture, which indicates improved resistance to intermediate-temperature cracking, reflective cracking, and low-temperature cracking.

Rejuvenator	I-FIT *FI*	IDEAL CT_{index}	OT N_f	DCT G_f (J/m^2)
Control, no Rejuvenator	3.7	45	73	494
+ 3% Bio-based Rejuvenator	7.5	64	326	562

Example 3 – Rejuvenator

- Data source: NCAT
- Mix design: 12.5mm NMAS, PG 70-22 SBS modified binder, 30% RAP, 4.8% asphalt binder content, 14.3% VMA.
- Mix design variable: rejuvenator
  - o Control, no rejuvenator
  - o Control + 2.4% bio-based rejuvenator (by weight of total asphalt binder)
- Mixture performance tests: HWTT, I-FIT, IDEAL-CT, and DCT
- Test results and discussions: The rejuvenated 30% RAP mixture had higher I-FIT FI and DCT G_f results than the control (no rejuvenator) mixture, indicating improved resistance to intermediate-temperature and low-temperature cracking. However, adding rejuvenator did not have a significant impact on the IDEAL CT_{index} results and slightly increased the HWTT rut depth results.

Rejuvenator	HWTT Rut Depth at 20,000 Passes (mm)	I-FIT *FI*	IDEAL CT_{index}	DCT G_f (J/m^2)
Control, no Rejuvenator	2.1	5.4	37	675
+ 3% Bio-based Rejuvenator	3.1	7.7	40	834

Example 4 – Rejuvenator

- Data source: Texas A&M University (Epps Martin et al., 2019; Hand and Epps Martin, 2020)
- Mix design: 12.5mm NMAS, PG 58-28 unmodified binder, 36% RAP, 5.4% asphalt binder content, 14.5% VMA.
- Mix design variable: rejuvenator
  - o Control, no rejuvenator
  - o Control + 5.5% bio-based rejuvenator (by weight of total asphalt binder)
- Mixture performance tests: I-FIT and UTSST
- Test results and discussions: The rejuvenated 36% RAP mixture had significantly higher I-FIT *FI* and UTSST CRI_{Env} results, which indicate better resistance to intermediate-temperature cracking and low-temperature cracking, than the control (no rejuvenator) mixture.

Rejuvenator	I-FIT *FI*	UTSST CRI_{Env}
Control, no Rejuvenator	10	8
+ 5.5% Bio-based Rejuvenator	16	57

Anti-Strip Agents

LAS additives and hydrated lime are the two most commonly used anti-strip agents for improving the moisture resistance of asphalt mixtures. LAS additives are mainly surface-active agents that are designed to decrease the surface tension between asphalt binder and aggregate surface, thereby allowing aggregate to be more easily wetted by asphalt binder. Adding LAS additives increases the strength of asphalt-aggregate adhesion and reduces its susceptibility to moisture damage. The effectiveness of LAS additives in improving moisture resistance, however, varies greatly from product to product. Overdosing LAS additives could soften the asphalt binders, possibly making the resultant mixtures more susceptible to rutting but more resistant to cracking. Different from LAS additives, hydrated lime serves as an effective anti-strip agent due to its highly alkaline properties that neutralize organic acids in asphalt binder and increase the base surface energy of aggregates, which consequently reduces the moisture and stripping potential of asphalt mixtures (Kennedy et al., 1983; Little and Epps, 2001). Previous research has also indicated that hydrated lime provides asphalt mixtures with additional performance benefits such as improved rutting resistance, low-temperature fracture toughness, and aging resistance (Sebaaly et al., 2006).

Example – LAS Additive

- Data source: NCAT
- Mix design: 12.5mm NMAS, PG 67-22 unmodified binder, granite aggregates, no RAP/RAS, 5.4% asphalt binder content, 14.9% VMA.
- Mix design variable: LAS additives
  - o Control, no LAS additive
  - o Control + 0.5% LAS additive #1 (by weight of asphalt binder)
  - o Control + 0.5% LAS additive #2 (by weight of asphalt binder)
  - o Control + 0.5% LAS additive #3 (by weight of asphalt binder)
  - o Control + 0.5% LAS additive #4 (by weight of asphalt binder)
- Mixture performance tests: TSR and HWTT
- Test results and discussions: Adding LAS additives consistently increased the TSR and HWTT *SIP* results, which indicates improved resistance to moisture damage. The improvements in TSR and HWTT results varied from product to product though.

LAS Additive	TSR (%)	HWTT *SIP*
Control, No LAS	25.7	10,848
+ 0.5% LAS Additive #1	64.5	20,000
+ 0.5% LAS Additive #2	62.5	13,942
+ 0.5% LAS Additive #3	91.2	20,000
+ 0.5% LAS Additive #4	65.1	20,000

09 CASE STUDIES WITH BMD IMPLEMENTATION

An online survey was conducted to obtain information from asphalt contractors (and consulting labs) operating in a BMD state (Figure 5) regarding: (1) their successes and challenges with BMD, and (2) effective practices for implementing mixture performance testing into mix design and production operations. The survey was distributed by NCAT and NAPA with support from the State Asphalt Pavement Associations (SAPAs). A total of 28 responses were received.

Table 9. Agency Requirements on Volumetric Properties for BMD (Total Respondents: 28)

Volumetric Parameters	Mix Design Approval	Production Acceptance	Pay Adjustment
V_a	25	23	17
VMA	23	19	7
VFA	16	8	0
D/B Ratio	24	12	1
$\%G_{mm}$ at $N_{initial}$	10	1	1
$\%G_{mm}$ at N_{max}	12	4	2
In-place Density	-	18	21
Other*	8	8	9

*Note: *Asphalt content, gradation, and TSR*

The number of years of experience in quality control of the survey respondents ranged from 3 to 38 years with an average of 23.4 years. Nine respondents were very familiar with the four BMD approaches specified in AASHTO PP 105-20, while the rest were either somewhat familiar (12 respondents) or not familiar (7 respondents) with the BMD approaches. Table 9 summarizes the reported agency requirements on volumetric parameters for mix design approval, production acceptance, and pay adjustment of BMD. As can be seen, most SHAs require V_a, VMA, and D/B ratio for mix design approval, while some of them also require VFA, $\%G_{mm}$ at $N_{initial}$, and $\%G_{mm}$ at N_{max}. The three most used volumetric parameters for production acceptance and payment adjustment are V_a, VMA, and in-place density.

Figure 7 summarizes the equipment capability of the survey respondents to conduct various mixture performance tests for BMD. HWTT was the most selected rutting test, followed by the HT-IDT test, IDEAL-RT, FN, and then APA. Fourteen respondents indicated that they are equipped with a HWTT device but their experience with this test ranged from 2 to 25 years. Among the various mixture cracking tests, IDEAL-CT was the one most selected, followed by I-FIT, Cantabro, and then SCB-Jc. Nineteen respondents indicated that they are capable of conducting the IDEAL-CT despite the fact that the test was recently developed in 2016. Finally, all survey respondents indicated that they are equipped with an indirect tensile loading frame to conduct the TSR test. Their experience with this test ranged from 6 to 30 years with an average of 20.2 years.

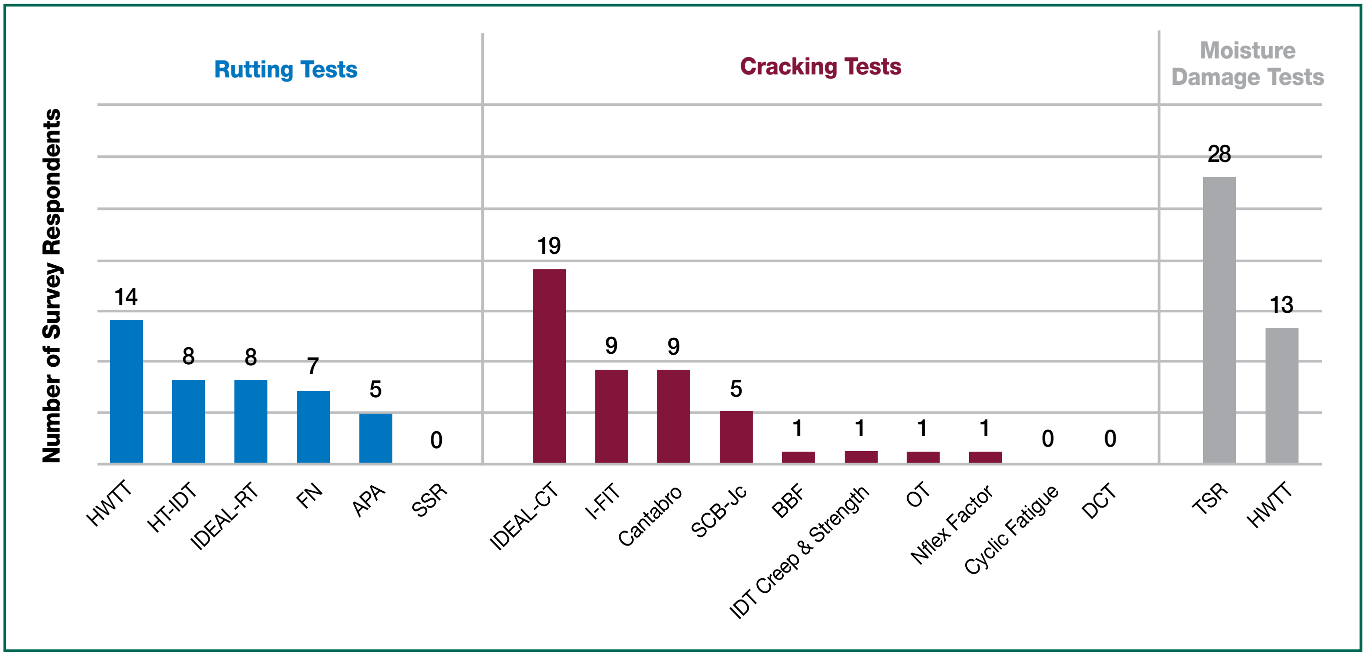


Figure 7. Equipment Capability to Conduct Various Mixture Performance Tests for BMD (Total Respondents: 28)

The survey respondents indicated that it takes an average of five additional calendar days to complete a BMD (approximately 14 days total) compared to a volumetric mix design (approximately nine days total). The additional time is mainly due to preparing specimens for BMD performance tests and in some cases, making mix design adjustments to improve the performance test results. The commonly reported mix design modifications to improve mixture rutting test results are increasing virgin binder grade, coarsening aggregate gradation, lowering asphalt binder content, increasing RAP/RAS content, and using manufactured sand in lieu of natural sand. A few respondents indicated that rutting has not been an issue for their mixes and thus, they do not have much experience with mix design modifications to improve the rutting test results. The commonly reported mix design modifications to improve mixture cracking test results include using a softer virgin binder, adjusting aggregate structure to increase asphalt binder content and VMA, adding a rejuvenator, reducing RAP/RAS content, and using rounded aggregates in lieu of angular aggregates.

Ten survey respondents indicated that they have encountered a situation where they tried several mix design modifications but still could not meet the agency's performance test requirements. Four of these also indicated that their agency was helpful in solving this issue by allowing them to use asphalt additives that are currently not on the agency's approved products list (APL), relaxing some of the existing volumetric requirements, or providing suggestions on the selection of asphalt binder grade and aggregate gradation. Most survey respondents recognized the importance of mix aging for the evaluation of mixture cracking resistance for BMD. Seventeen of them indicated that mixture cracking tests should be conducted on long-term aged specimens for mix design approval only, while five respondents suggested the necessity for considering long-term mix aging for both mix design approval and production acceptance.

When asked about the most appropriate approach for accepting BMD mixes during production, the survey participants expressed different opinions. As shown in Figure 8, the most preferred approach was using asphalt content and gradation together with performance test results [Combination of (b) and (c) as shown in Figure 8]. Other selected approaches include using performance test results only, using mixture volumetric properties and performance test results, and a combination of asphalt content and gradation, volumetric properties, and performance test results.

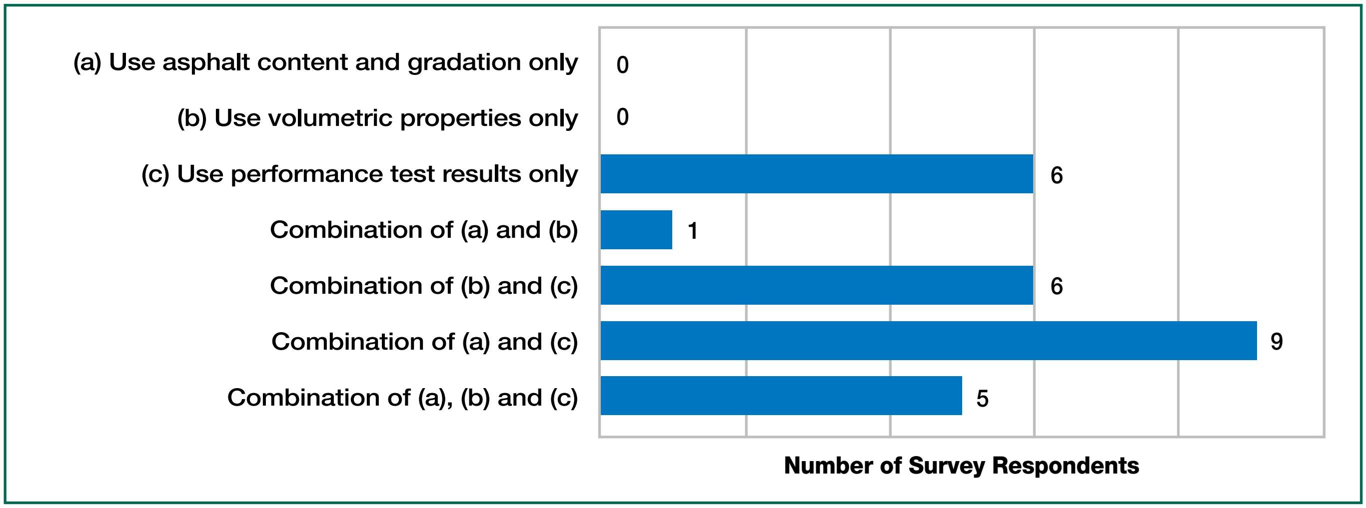


Figure 8. Approaches for Accepting BMD Mixes during Production (Total Respondents: 28)

Most of the survey respondents indicated that if mixture performance testing is required for production acceptance, the mix should be sampled from the haul truck at the plant, while a few others suggested alternative sampling locations such as behind the paver (but prior to compaction) and from the windrow on the roadway. Five respondents indicated that they have test data showing the significant impact of mix sampling location on the performance test results. There was virtually an even split in responses to the survey question, "if mixture performance testing is required for production acceptance, should the **same** or **different** test criteria be used as was used for mix design approval?" For those who selected "different test criteria", they suggested that the following factors should be considered to adjust the test criteria for production acceptance from those for mix design approval:

- Difference in mix aging for lab versus plant produced mixes (11 respondents)
- Variability of mixture performance tests (10 respondents)
- Normal production variability in aggregate gradations (9 respondents)
- Normal production variability in asphalt binder content (8 respondents)
- Normal production variability in RAP/RAS content (8 respondents)

Nine survey respondents indicated that if their BMD production mix fails the agency's performance test requirements, they are required to make mix adjustments under production until passing results are obtained. Others reported remedial actions such as "re-sample and re-test" and "re-design". The most preferred production adjustment methods to improve the performance test results of plant-produced BMD mixes is adjusting asphalt binder content, aggregate gradation, or RAP/RAS content within the agency's production tolerance. Other reported production adjustments include changing virgin binder grade, adding a rejuvenator, and reducing baghouse fines.

Finally, the survey respondents were asked about the benefits and challenges that they have seen from the implementation of BMD in their state. As shown in Figure 9, the most reported benefit associated with BMD implementation is better mix quality, while others include allowed use of asphalt additives, relaxed volumetric requirements, more robust methods for mix design approval and production acceptance, and more economical mixtures. On the other hand, the survey respondents reported several major challenges with the implementation of BMD, with the most common being concern about the variability of mixture performance tests. Other frequently reported challenges include lack of innovation potential for mix design (due to agency adding performance requirements but not relaxing volumetric requirements), concerns with the validity of performance tests, long specimen preparation and testing time, and use of unreasonable or arbitrary test criteria (Figure 10).

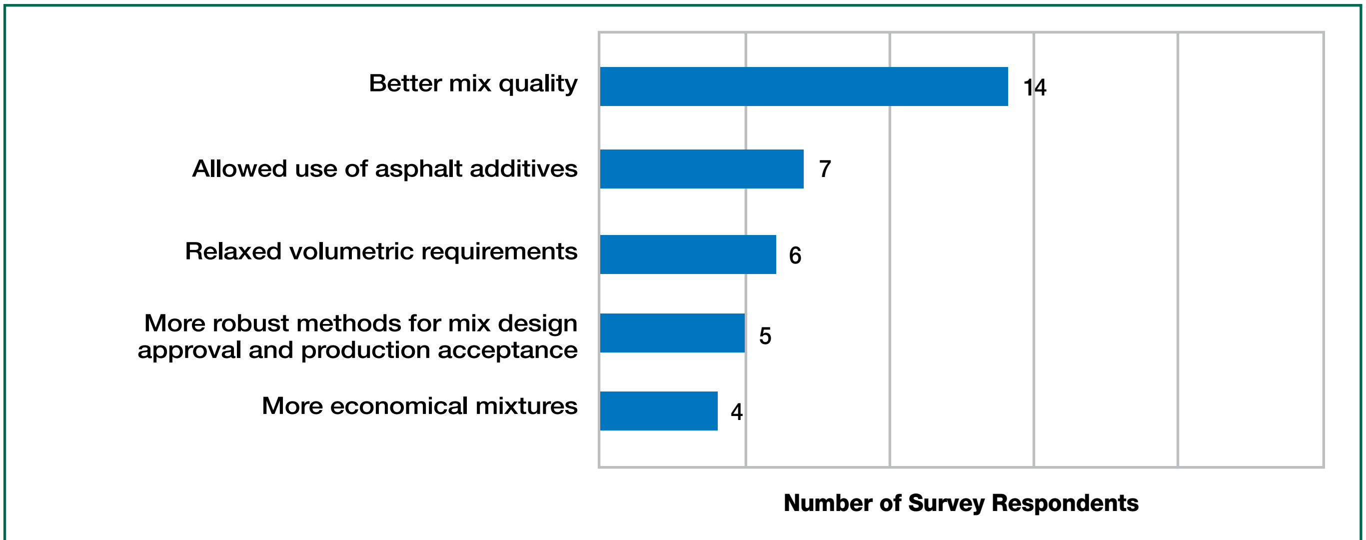


Figure 9. **Benefits Associated with BMD Implementation (Total Respondents: 28)**

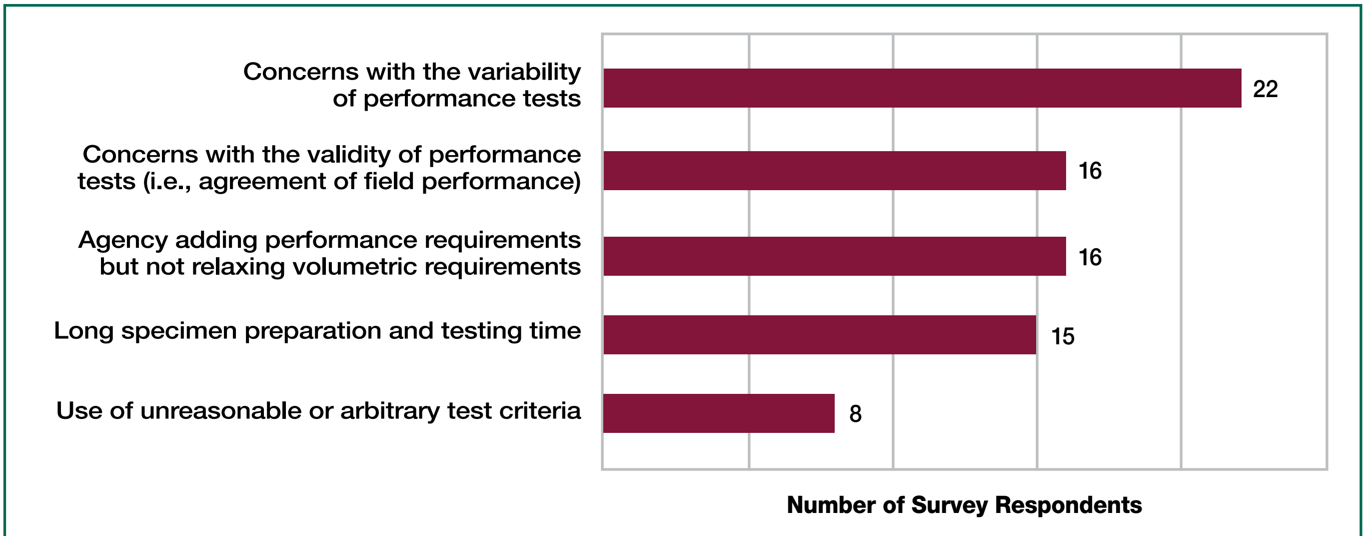


Figure 10. **Challenges Associated with BMD Implementation (Total Respondents: 28)**

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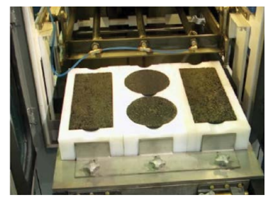
APPENDIX | ONE-PAGE SUMMARY OF MIXTURE PERFORMANCE TESTS

Name of Test	Developer(s)
Asphalt Pavement Analyzer	Lai and Co-workers Georgia DOT
Test Method(s) AASHTO T 340-10 (2019)	Adoption by Agencies Alaska, Alabama, Arkansas, North Carolina, New Jersey, South Carolina, South Dakota, Virginia
Description The asphalt pavement analyzer (APA) is a second-generation device that was originally developed as the Georgia Loaded Wheel Tester. The APA tracks a loaded wheel back and forth across a pressurized linear hose over an asphalt mixture sample. A temperature chamber is used to control the test temperature. Rut depths along the wheel path are measured for each wheel pass. The sample is typically loaded for 8,000 wheel passes.	Photographs/Illustrations  
Test Results Rut depths	Test Temperature(s) Selected based on the high temperature binder grade
Equipment & Approximate Cost Asphalt Pavement Analyzer or APA Jr.	 $60,000 - 125,000
Specimen Fabrication Gyratory specimens (most common) or slab specimen	Number of Replicate Specimens Between 4 and 6 specimens – model dependent
Specimen Conditioning Conditioning for 6 to 24 hours at the test temperature	Testing Time 2.25 hours
Data Analysis Complexity Simple	Test Variability Medium (20% COV)
Field Validations Good (pavement sections on FHWA ALF, WesTrack, NCAT Test Track, MnROAD, and in Georgia and Nevada)	Overall Practicality for Mix Design and QA Good for mix design Fair for QA

Key References

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Name of Test **Flow Number Test**	Developer(s) Witczak and Co-workers University of Maryland
Test Method(s) AASHTO T378-17	Adoption by Agencies Delaware, California
Description The test is conducted by applying repeated haversine axial compressive loads to a cylinder specimen at a specific test temperature. The test may be conducted with or without confining pressure. For each load cycle, the recoverable strain and permanent strain are recorded. The flow number is determined as the number of load cycles corresponding to the minimum rate of change of permanent strain (i.e., onset of tertiary flow).	Photographs/Illustrations 
Test Results Flow Number	Test Temperature(s) LTPPBind v3.1 98% Reliability High Temperature of the paving location adjusted for a depth of 20 mm from the surface (surface mixes)
Equipment & Approximate Cost Asphalt Mixture Performance Tester Core drill Environmental chamber Saw for cutting specimens	 $100,000 $3,000 $3,000 $6,000
Specimen Fabrication Gyratory specimens, 2 cuts, 1 core (3 hours)	Number of Replicate Specimens At least 3 specimens
Specimen Conditioning Until a thermocouple in the center of a dummy specimen reaches the target test temperature	Testing Time Varies between 30 minutes and 4 hours
Data Analysis Complexity Fair	Test Variability High (> 30% COV)
Field Validations Good (pavement sections on FHWA ALF, WesTrack, NCAT Test Track, MnROAD	Overall Practicality for Mix Design and QA Good for Mix Design Poor for QA

Key References

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- Witczak, M.W. (2007). "Specification Criteria for Simple Performance Tests for Rutting," NCHRP report 580, Washington, D.C.
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- Bonaquist, R. (2011) "Precision of the Dynamic Modulus and Flow Number Tests Conducted with the Asphalt Mixture Performance Tester," NCHRP Report 702, Washington, D.C.

Name of Test **Hamburg Wheel-Tracking Test**	Developer(s) Developed in Germany
Test Method(s) AASHTO T 324-19	Adoption by Agencies California, Georgia, Idaho, Iowa, Illinois, Kentucky, Louisiana, Massachusetts, Maine, Missouri, Montana, Oklahoma, Oregon, Tennessee, Texas, Utah, Vermont, Washington
Description During the test, two sets of cylinder or slab specimens are placed side by side, submerged in water, and subjected to repetitive applications of wheel loads. Rut depths at different positions along the specimens are recorded for each wheel pass. The specimens are loaded for a maximum of 20,000 wheel passes or until the specimens deforms by a pre-determined rut depth (typically 12.5mm). Typical result curves consist of post-compaction phase, creep phase, and stripping phase.	Photographs/Illustrations 
Test Results Rut depths, stripping inflection point, creep slope, stripping slope, stripping number, stripping life, rutting resistance parameter	Test Temperature(s) 40 to 70°C
Equipment & Approximate Cost Hamburg Wheel-Tracking Device Saw for cutting specimens	 $40,000-75,000 $6,000
Specimen Fabrication Gyratory specimens, 1 cut (30 minutes) Slab specimens	Number of Replicate Specimens 4 specimens
Specimen Conditioning Conditioning for 45 minutes at the test temperature under water	Testing Time 6.5 hours after conditioning
Data Analysis Complexity Simple	Test Variability Medium (10-30% COV)
Field Validations Good (pavement sections in Colorado, Texas)	Overall Practicality for Mix Design and QA Good for Mix Design Fair for QA

Key References

- Aschenbrener, T., Terrel, R. and Zamora, R. (1994). “Comparison of the Hamburg Wheel-Tracking Device And The Environmental Conditioning System To Pavements Of Known Stripping Performance,” Final Report (No. CDOT-DTD-R-94-1).
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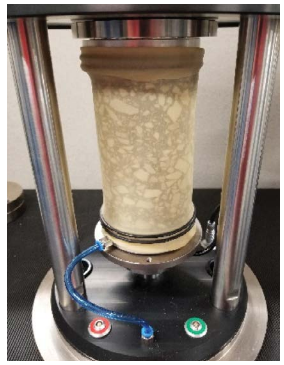
Name of Test **Stress Sweep Rutting (SSR)**	Developer(s) Kim and co-workers North Carolina State University
Test Method(s) AASHTO TP 134-19	Adoption by Agencies None
Description Four specimens are tested under a confining pressure of 10 psi (69 kPa) – two at a low temperature (T_L) and two a high temperature (T_H) determined through LTPPBind. Each specimen is loaded for 200 cycles at 3 different deviator stress conditions that vary based on temperature – a total of 600 compressive load cycles per specimen. Test results are used to generate a permanent deformation shift model that can be used in conjunction with the FlexPAVE™ analysis software to model the total rutting in the asphalt pavement layers.	Photographs/Illustrations 
Test Results Rutting Strain Index (RSI) Permanent Deformation Shift Model	Test Temperature(s) Two Temperatures – High (T_H) and Low (T_L) Based on LTPPBind v3.1 at 98% Reliability
Equipment & Approximate Cost Asphalt Mixture Performance Tester Core drill Environmental chamber Saw for cutting specimens	 $100,000 $3,000 $3,000 $6,000
Specimen Fabrication Gyratory specimens, 2 cuts, 1 core, membrane for confinement (4 hours)	Number of Replicate Specimens 4 specimens (2 at each temperature)
Specimen Conditioning Until a thermocouple in the center of a dummy specimen reaches the target test temperature. Conditioning under confinement for 1 hour in the test chamber prior to testing.	Testing Time 20 minutes per specimen (T_L) 40 minutes per specimen (T_H)
Data Analysis Complexity Fair – RSI FlexMAT™ calculation Complex – model structure using FlexPAVE™	Test Variability Unknown
Field Validations Good (Pavement sections in Alabama, Korea, and Canada)	Overall Practicality for Mix Design and QA Good for Mix Design Poor for QA

Key References

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Name of Test **High Temperature Indirect Tension (HT-IDT)**	Developer(s) Christensen and Bonaquist (adapted from classical indirect tension strength test)
Test Method(s) N/A	Adoption by Agencies Alabama
Description This is a typical indirect tensile strength (ITS) test (conducted at 50 mm/min), with the exception that it is performed on specimens conditioned at a high test temperature. The resulting parameter is the high temperature ITS. It is being evaluated as potential quick test for estimating mixture rutting resistance.	Photographs/Illustrations 
Test Results Indirect Tensile Strength (ITS)	Test Temperature(s) 10°C below the LTPPBind v3.1 yearly 7-day average maximum pavement temperature 20°C below the pavement surface
Equipment & Approximate Cost Load Frame	$10,000 to $20,000
Specimen Fabrication Gyratory specimen	Number of Replicate Specimens At least 3 specimens per mixture
Specimen Conditioning Conditioning for 2 hours at the test temperature	Testing Time 1 minute per specimen
Data Analysis Complexity Simple	Test Variability Low (Less than 10% COV)
Field Validations Not available. Good correlation with APA results (NJ).	Overall Practicality for Mix Design and QA Good for Mix Design Good for QA

Key References

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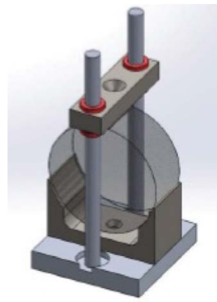
Name of Test **Rapid Shear Rutting Test (IDEAL-RT)**	Developer(s) Zhou and Co-workers Texas A&M Transportation Institute
Test Method(s) Draft ASTM Work Item (WK 71466)	Adoption by Agencies None
Description The IDEAL-RT is a rapid rutting test for specimens pre-conditioned at a high test temperature. Specimens are loaded monotonically at 50 mm/min using a shear fixture, which loads the specimen at 3 points (one upper and two lower supporting strips) creating two shear planes. The peak load from the load frame is used to calculate the rutting tolerance index, RT_{Index}.	Photographs/Illustrations 
Test Results RT_{Index} (scaled and thickness corrected peak load)	Test Temperature(s) May be selected based off LTPPBind or local climate data. Typically 50 +/- 15°C (per ASTM WK 71466)
Equipment & Approximate Cost Load Frame	$10,000 to $20,000
Specimen Fabrication Gyratory specimen	Number of Replicate Specimens At least 3 specimens per mixture
Specimen Conditioning Conditioning for 2 hours at the test temperature	Testing Time 1 minute per specimen
Data Analysis Complexity Simple	Test Variability Low (Less than 10% COV)
Field Validations Good (MnROAD, WesTrack and Texas Test Sections).	Overall Practicality for Mix Design and QA Good for Mix Design Good for QA

Key References

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- Yin, F., Taylor, A. J., & Tran, N. (2020). Performance Testing for Quality Control and Acceptance of Balanced Mix Design. Auburn, AL: NCAT Report 20-02.

Name of Test

Direct Tension Cyclic Fatigue Test

Developer(s)

Kim and co-workers
North Carolina State University

Test Method(s)

AASHTO TP 107-14 (Large Specimens)
AASHTO TP 133-19 (Small Specimens)

Adoption by Agencies

None

Description

First, a non-destructive dynamic modulus fingerprint test is performed to determine the linear viscoelastic property of the asphalt mixture. Then the cyclic fatigue damage tests are performed at a controlled strain level. The stress and strain results are used to determine the damage characteristic curve of the asphalt mixture as well as to predict the pavement fatigue life. The S_{app} index parameter may be calculated from these results as well. An E* master curve is required for conducting cyclic fatigue analysis.

Photographs/Illustrations

Test Results

S_{app} Fatigue Index Parameter
Damage Characteristic Curve (C vs. S)

Test Temperature(s)

Average of the high- and low-temperature PG temperatures minus 3°C (not exceeding 21°C)

Equipment & Approximate Cost

Asphalt Mixture Performance Tester	$100,000
End platens and gluing jigs	$5,000
Core drill	$3,000
Environmental chamber	$3,000
Saw for cutting specimens	$6,000

Specimen Fabrication

Gyratory specimen, 2 cuts, 1 core, gluing gage points, gluing end platens (6 hours)

Number of Replicate Specimens

3 specimens

Specimen Conditioning

Short-term aging for 4 hours at 135°C
Conditioning for 4 hrs. at desired test temperature

Testing Time

Dependent on mixture fatigue life.
2 days per mixture for 3 specimens is typical.

Data Analysis Complexity

Fair – S_{app} FlexMAT calculation
Complex – model structure using FlexPAVE™

Test Variability

N/A

Field Validations

Good (pavement sections in North Carolina and on FHWA-ALF)

Overall Practicality for Mix Design and QA

Fair for Mix Design
Poor for QA

Key References

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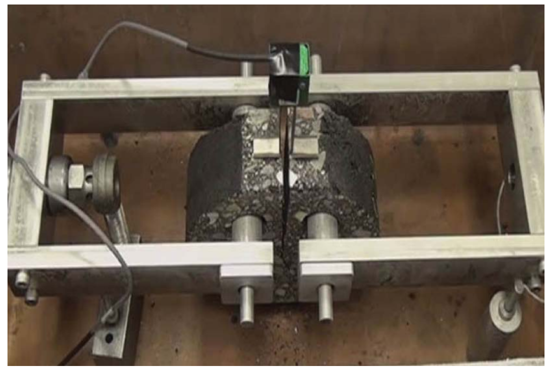
Name of Test **Disc-Shaped Compact Tension Test**	Developer(s) Buttlar and co-workers University of Illinois at Urbana–Champaign
Test Method(s) ASTM D7313-13	Adoption by Agencies Iowa, Minnesota, Missouri
Description The DCT test is performed under tensile loading and the crack mouth opening displacement (CMOD) is measured with a clip-on gage at the crack mouth. After temperature conditioning, specimens are inserted in loading fixtures, subjected to a preload no greater than 0.2 kN, and then tested with a constant CMOD of 1 mm/min. The test is completed when the post peak level reduces to 0.1 kN.	Photographs/Illustrations 
Test Results Fracture energy	Test Temperature(s) PG low temperature limit + 10°C (ASTM)
Equipment & Approximate Cost Stand-alone DCT test system Core drill Saw for cutting specimens Saw for notching specimens	 $50,000 $3,000 $6,000 $1,000
Specimen Fabrication Cylinder specimen, 3 cuts, 1 notch, 2 holes, gluing gauge points (4 hours)	Number of Replicate Specimens Not specified. Minimum 4 (NCAT)
Specimen Conditioning Conditioning for 8 to 16 hours at the desired test temperature	Testing Time 30 Minutes
Data Analysis Complexity Simple	Test Variability Low (10-15% COV)
Field Validations Good (pavement sections in New York, Iowa, Illinois, and on UIUC-ATLAS APT and MnROAD)	Overall Practicality for Mix Design and QA Good for Mix Design Poor for QA

Key References

- Wagoner, M.P., W.G. Buttlar, and P. Blankenship (2005). Investigation of the Fracture Resistance of Hot-Mix Asphalt Concrete Using a Disk-shaped Compact Tension Test. Transportation Research Board. Washington D.C.
- Wagoner, M., W. Buttlar, G. Paulino, and P. Blankenship (2006), Laboratory Testing Suite for Characterization of Asphalt Concrete Mixtures Obtained from Field Cores, Journal of the Association of Asphalt Paving Technologists, Vol. 75, pp. 815-852.
- Marasteanu, M., E.Z. Teshale, K.H. Moon, M. Turos, W. Buttlar, E. Dave, and S. Ahmed (2010). Investigation of Low Temperature Cracking in Asphalt Pavements National Pooled Fund Study – Phase II. United States: Minnesota Department of Transportation.

Name of Test **Flexural Bending Beam Fatigue Test**	Developer(s) Monismith and co-workers University of California at Berkeley
Test Method(s) AASHTO T 321-17 / ASTM D8273-18	Adoption by Agencies California, Iowa, New Jersey, Ohio, Pennsylvania
Description Beam specimen is held by four equally-spaced clamps and a sinusoidal controlled-deflection mode of loading is applied at the two inner clamps. The loading frequency is typically 10 Hz. The magnitude of the load applied by the actuator and the deflection measured at center of beam is recorded and used to calculate the flexural stiffness, cumulative dissipated energy, and the cycles to failure (i.e., the point at which the product of the specimen stiffness and loading cycles is a maximum). Multiple peak-to-peak strain levels are often used to characterize the fatigue behavior of asphalt mixtures.	Photographs/Illustrations 
Test Results Number of cycles to failure (fatigue life), N_f	Test Temperature(s) 20 ± 0.5°C

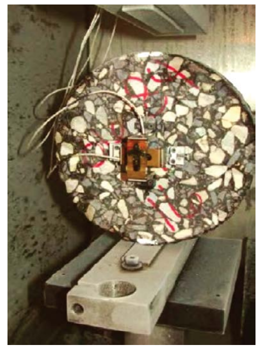
Equipment & Approximate Cost

Loading device and data acquisition system	$50,000
Environmental chamber	$20,000
Beam fatigue device	$34,000
Slab compactor	$70,000
Saw for cutting specimens	$6,000

Specimen Fabrication Slab specimen, 4 cuts, gluing gage points (1 day)	Number of Replicate Specimens 3 specimens per strain level
Specimen Conditioning Conditioning for 2 hours at 20°C	Testing Time Hours to weeks depending on strain level and mix quality
Data Analysis Complexity Simple	Test Variability High (40-50% COV)
Field Validations Good (inputs to AI and AASHTOWare Pavement ME Design)	Overall Practicality for Mix Design and QA Fair for Mix Design Poor for QA

Key References

- Tayebali, A.A., J.A. Deacon, J.S. Coplantz, J.T. Harvey, and C.L. Monismith (1994). Fatigue Response of Asphalt-Aggregate Mixes, SHRP-A-404, National Research Council, Washington D.C.
- Prowell, B., E. Brown, R. Anderson, J. Daniel, A. Swamy, H. Quintus, S. Shen, S. Carpenter, S. Bhattacharjee, and S. Maghsoodloo (2010). Validating the Fatigue Endurance Limit for Hot Mix Asphalt, NCHRP Report 646, National Academies Press.

Name of Test	Developer(s)
IDT Creep Compliance and Strength Test	Roque and co-workers Pennsylvania State University
Test Method(s) AASHTO T 322-07 (2020)	Adoption by Agencies None
Description The IDT creep test applies a constant load to the specimen for between 100 and 1000 seconds, and measures the vertical and horizontal displacement around the center of the specimen. The displacement data are then used to determine the IDT creep compliance. After the nondestructive IDT creep test is conducted, the tensile strength of the specimen is determined by running the test in the destructive mode (12.5 mm/min loading rate).	Photographs/Illustrations 
Test Results IDT creep compliance IDT tensile strength	Test Temperature(s) Mixtures using binder grades PG XX-34 or softer: −30, −20, and −10°C. Mixtures using binder grades PG XX-28 and PG XX-22: −20, −10, and 0°C. Mixtures using binder grades PG XX-16 or harder: −10, 0, and +10°C.
Equipment & Cost	
Loading device and data acquisition system	$115,000
Specimen deformation measuring device	$15,000
Environmental chamber	$20,000
Saw for cutting specimens	$6,000
Specimen Fabrication Gyratory specimen, 2 cuts, gluing gage points (2 hours)	Number of Replicate Specimens A minimum of 3 specimens
Specimen Conditioning Conditioning for minimum 3 hours at the desired test temperature	Testing Time 1-2 days per mixture (multiple temperatures)
Data Analysis Complexity Complex	Test Variability Low (7 to 11% COV)
Field Validations Good (inputs to TCModel and MEPDG)	Overall Practicality for Mix Design and QA Fair for mix design Poor for QA

Key References

- Roque, R., and W.G. Buttlar (1992). The Development of a Measurement and Analysis System to Accurately Determine Asphalt Concrete Properties Using the Indirect Tensile Mode. Paper presented at The Association of Asphalt Paving Technologist.
- Christensen, D.W., and R.F. Bonaquist (2004). NCHRP 530. Evaluation of Indirect Tensile Test (IDT) Procedures for Low-Temperature Performance of Hot Mix Asphalt. Washington DC, Transportation Research Board.

Name of Test

Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

Developer(s)

Zhou and Co-workers
Texas A&M Transportation Institute

Test Method(s)

ASTM D8225-19

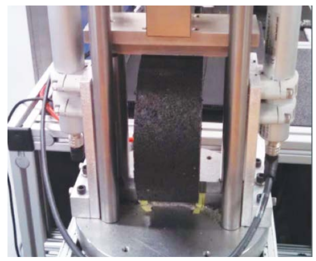
Adoption by Agencies

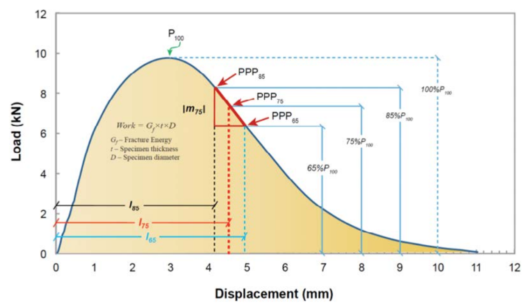
Alabama, Idaho, Kentucky, Missouri, Oklahoma, Tennessee, Virginia

Description

The IDEAL-CT test is similar to the traditional indirect tensile strength test. The test applies a vertical monotonic load on a cylinder specimen at a constant rate of 50 mm/min. The test is stopped when the load is reduced to 0.1kN. During the test, the cross-head displacement is continuously monitored and recorded. Data analysis is conducted based on the load versus displacement curve. The test parameter CT_{Index} is calculated as a function of total fracture energy and the slope of the post-peak curve at 25 percent reduction from the peak load.

Photographs/Illustrations





Test Results

Cracking test index (CT_{Index})

Test Temperature(s)

PG IT = ((PG HT+ PG LT)/2)+4
25°C is common

Equipment & Cost

Stand-alone Load Frame	\$10,000 to 20,000
or Data Acquisition Jig for Existing Load Frame	\$4,000

Specimen Fabrication

Gyratory specimen

Number of Replicate Specimens

A minimum of 3 specimens

Specimen Conditioning

Conditioning for 2 hours at Test Temperature

Testing Time

<1 minute per specimen

Data Analysis Complexity

Simple

Test Variability

Medium (10-25% COV)

Field Validations

Good (pavement sections in Texas and on FHWA ALF, NCAT Test Track, and MnROAD facilities)

Overall Practicality for Mix Design and QA

Good for Mix Design
Good for QA

Key References

- Zhou, F., Im, S., Sun, L., & Scullion, T. (2017). Development of an IDEAL cracking test for asphalt mix design and QC/QA. Road Materials and Pavement Design, 18(sup4), 405-427.
- NCHRP IDEA 20-30/IDEA 195. Development of an IDEAL Cracking Test for Asphalt Mix Design, Quality Control, and Quality Assurance. http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4286, accessed on August 8, 2018.

Name of Test

Illinois Flexibility Index Test (I-FIT)

Developer(s)

Al-Qadi and co-workers
University of Illinois at Urbana–Champaign

Test Method(s)

AASHTO T 124-20

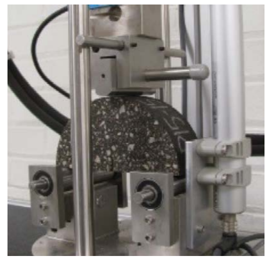
Adoption by Agencies

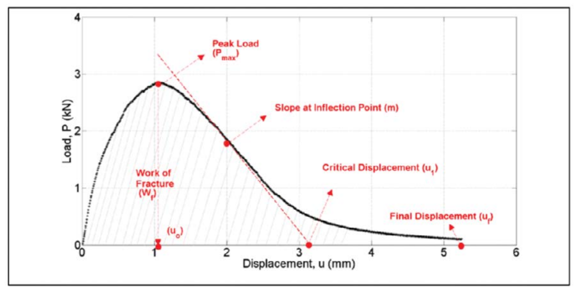
California, Illinois, Missouri, Oregon, Vermont

Description

A 150-mm diameter by 50-mm thick semi-circular specimen with a 15-mm notch is simply supported by two bars on the flat surface. The load is applied to the curved surface above the notch at a vertical rate of 50 mm/min. Load and vertical displacement are recorded until the load drops below 0.1 kN. Fracture energy is calculated from the area beneath the load displacement curve to 0.1 kN. The post-peak slope of the load displacement curve is an indicator of the brittle to ductile failure. The flexibility index parameter is calculated by multiplying the fracture energy by a scaling factor constant and dividing by the slope. A minimum of three specimens are used to calculate the average flexibility index.

Photographs/Illustrations





Test Results

Flexibility Index

Test Temperature(s)

25°C

Equipment & Cost

Load Frame and Fixture	$10,000 to 20,000
Saw for cutting specimens	$6,000
Saw for notching specimens	$3,000

Specimen Type and Aging Condition

Gyratory specimen, 3 cuts, 1 notch (2 hours)

Number of Replicate Specimens

Not specified

Specimen Conditioning

Conditioning for 2 hours at 25°C

Testing Time

<1 minute per specimen

Data Analysis Complexity

Fair (using Excel Spreadsheet)
Simple (using software)

Test Variability

Single-Operator Precision: 27.1% COV (AASHTO)
Multi-laboratory Precision: 34.1% COV (AASHTO)

Field Validations

Good (pavement sections in Illinois and on FHWA ALF)

Overall Practicality for Mix Design and QA

Good for Mix Design
Fair for QA

Key References

- Al-Qadi, I.L., H. Ozer, J. Lambros, A.E. Khatib, P. Singhvi, T. Khan, J. Rivera-Perez, and B. Doll (2015) Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes using RAP and RAS. ICT Report No. FHWA-ICT-15-017. Illinois Center for Transportation.
- Al-Qadi, Imad L., D. L. Lippert, S. Wu, H. Ozer, G. Renshaw, I. M. Said, A. F. Espinoza Luque, et al. *Utilizing Lab Tests to Predict Asphalt Concrete Overlay Performance*. FHWA-ICT-17-020, Urbana, IL: Illinois Center for Transportation, 2017.

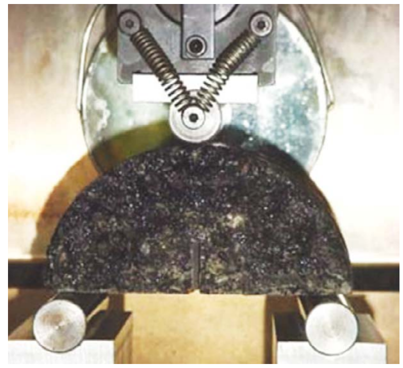
Name of Test
Semi-Circular Bend Test (Louisiana method)

Developer(s)
Mohamad and co-workers
Louisiana Transportation Research Center

Test Method(s)
LADOTD TR 330-14/ASTM D8044-16

Adoption by Agencies
Louisiana

Description
Semi-circular specimens are prepared with three notch depths: 25.4 mm, 31.8 mm, and 38.0 mm. Each specimen is simply supported by two bars on the flat surface and the load is applied to the curved surface above the notch. The load is applied at a vertical rate of 0.5 mm/min. For each specimen, the fracture toughness is calculated based on the load and displacement data. Fracture toughness versus notch depth is used to determine the energy release rate, J-integral. Three specimens are tested at each notch depth for a total of nine specimens per mix.

Photographs/Illustrations


Test Results
J-integral

Test Temperature(s)
25°C

Equipment & Cost

Load Frame and Fixture	$10,000-$20,000
Saw for cutting specimens	$6,000
Environmental chamber	$3,000
Saw for notching specimens	$3,000

Specimen Fabrication
Gyratory specimens, 3 cuts, 1 notch (4 hours)

Number of Replicate Specimens
4 specimens for each notch depth

Specimen Conditioning
Conditioning for a minimum of 0.5 hour at 25°C

Testing Time
1 hour

Data Analysis Complexity
Fair

Test Variability
Medium (20% COV)

Field Validations
Fair (pavement sections in Louisiana)

Overall Practicality for Mix Design and QA
Good for Mix Design
Fair for QA

Key References

- Wu, Z., L. Mohammad, L. Wang, and M. Mull (2005). Fracture Resistance Characterization of Superpave Mixtures Using the Semi-Circular Bending Test, Journal of ASTM International, Vol. 2, No. 3, pp. 1-15.
- Kim, M., L.N. Mohammad, and M.A. Elseifi (2012). Characterization of Fracture Properties of Asphalt Mixtures as Measured by Semicircular Bend Test and Indirect Tension Test, Transportation Research Record, No. 2296, pp. 115-124.

Name of Test
Overlay Test

Developer(s)
Lytton and co-workers (Texas A&M University)
Analysis modified by researchers at the University of Texas at El Paso

Test Method(s)
NJDOT B-10 / Tex-248-F

Adoption by Agencies
New Jersey, Texas

Description
Test specimens are cut from SGC samples or field cores. Trimmed specimens are glued on a set of two steel base plates with one plate fixed and the other moves horizontally back and forth at a specific frequency (0.1 Hz). The maximum opening displacement of 0.025 inch is controlled during the test. The test is stopped when a 93% reduction of the maximum load occurs or after 1,000 cycles.

Photographs/Illustrations

Test Results
Number of cycles to failure (NJ)
Critical Fracture Energy (G_c) (TX)
Crack Resistance Index (Beta) (TX)

Test Temperature(s)
25 ± 0.5°C

Equipment & Cost

Texas overlay tester	$45,000
or Asphalt Mixture Performance Tester	$100,000
Platens and Jigs	$10,000
Environmental chamber	$4,000
Saw for cutting specimens	$6,000

Specimen Fabrication
Gyratory specimens, 4 cuts, gluing to plates (4 hrs.)

Number of Replicate Specimens
3 specimens

Specimen Conditioning
Conditioning for a minimum of 1 hour at 25°C

Testing Time
Up to 3 hrs. per specimen depending on mix

Data Analysis Complexity
Simple (by software)

Test Variability
Cycles to Failure: High (30-50% COV)
Critical Fracture Energy: Medium (10-25% COV)
Crack Resistance Index: Medium (10-25% COV)

Field Validations
Good (pavement sections in Texas, New Jersey, Nevada, FHWA-ALF and NCAT test track)

Overall Practicality for Mix Design and QA
Good for mix design
Poor for QA

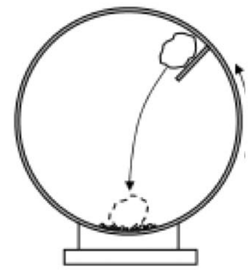
Key References

- Zhou, F., and T. Scullion (2005). Overlay Tester: A Rapid Performance Related Crack Resistance Test, No. FHWA/TX-05/0-4467-2, Texas Transportation Institute, Texas A&M University System.
- Zhou, F., S. Hu, H. Chen, and T. Scullion (2007). Overlay Tester: Simple Performance Test for Fatigue Cracking, Transportation Research Record Vol. 2001, pp.1-8.
- Walubita, L., A. Faruk, G. Das, H. Tanvir, J. Zhang, and T. Scullion (2012). The Overlay Tester: A Sensitivity Study to Improve Repeatability and Minimize Variability in the Test Results, No. FHWA/TX-12/0-6607-1, Texas Transportation Institute, Texas A&M University System.
- Garcia, V. M., Miramontes, A., Garibay, J., Abdallah, I., Carrasco, G., Lee, R., & Nazarian, S. (2017). Alternative Methodology for Assessing Cracking Resistance of Hot Mix Asphalt Mixtures with Overlay Tester. Journal of the Association of Asphalt Paving Technologists, 527-548.

Name of Test **N_{flex} Factor**	Developer(s) West and co-workers (NCAT)
Test Method(s) AASHTO TP 141-20	Adoption by Agencies None
Description The N_{flex} test is similar to the traditional indirect tensile strength test. The test applies a vertical monotonic load on a cylinder specimen at a constant rate of 50 mm/min. During the test, the cross-head displacement is continuously monitored and recorded. Data analysis is conducted based on the load versus displacement curve. The N_{flex} factor is calculated by dividing the material Toughness (area under the load displacement curve) by the slope of the curve at the post-peak inflection point.	Photographs/Illustrations 
Test Results N_{flex} factor	Test Temperature(s) 25 ± 0.5°C
Equipment & Approximate Cost Load Frame	 $10,000 to $20,000
Specimen Fabrication Gyratory specimen	Number of Replicate Specimens At least 3 specimens per mixture
Specimen Conditioning Conditioning for 2 hours at the test temperature	Testing Time 1 minute per specimen
Data Analysis Complexity Simple	Test Variability Medium (10-25% COV)
Field Validations Fair (Correlation to cracking at FHWA ALF)	Overall Practicality for Mix Design and QA Good for Mix Design Good for QA

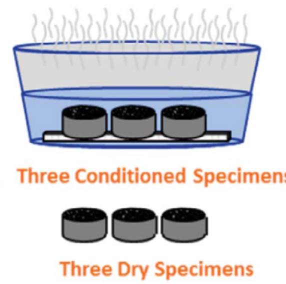
Key References

- West, R. C., Van Winkle, C., Maghsoodloo, S., & Dixon, S. (2017). Relationships between Simple Asphalt Mixture Cracking Tests Using Ndes Specimens and Fatigue Cracking at FHWA's Accelerated Loading Facility. Journal of the Association of Asphalt Paving Technologists, 579-602.
- Yin, F., Garita, J., Taylor, A., and West, R. (2018). Refining the Indirect Tensile (IDT) Nflex Factor Test to Evaluate Cracking Resistance of Asphalt Mixtures for Mix Design and Quality Assurance. Construction and Building Materials, 172, 396-405.
- Yin, F., West, R. C., Xie, Z., Taylor, A., & Julian, G. (2019). Effects of Loading Rate and Mix Reheating on Indirect Tensile Nflex Factor and Semi-Circular Bend J-Integral Test Results to Assess the Cracking Resistance of Asphalt Mixtures. Auburn, AL: NCAT Report 17-09.

Name of Test **Cantabro Test**	Developer(s) Developed in Spain
Test Method(s) AASHTO TP 108-14 (2020)	Adoption by Agencies Virginia
Description The Cantabro test is a mixture toughness test rather than a cracking test. Some researchers suggest that the Cantabro test provides a general indication of durability. SGC specimens are placed one at a time in a Los Angeles abrasion machine for 300 cycles at 30 revolutions per minute. The percent abrasion loss is determined after testing.	Photographs/Illustrations  
Test Results Percent abrasion loss	Test Temperature(s) 25 ± 1°C
Equipment & Cost Los Angeles abrasion machine	$10,000
Specimen Fabrication Gyratory specimen	Number of Replicate Specimens A minimum of 3 specimens
Specimen Conditioning Conditioning for a minimum of 4 hours at 25°C	Testing Time 10 minutes
Data Analysis Complexity Simple	Test Variability Medium (10-25% COV)
Field Validations Fair (FHWA ALF Fatigue Cracking)	Overall Practicality for Mix Design and QA Good for Mix Design Good for QA

Key References

- Alvarez, A.E., A. Epps Martin, C.K. Estakhri, J.W. Button, Z. Kraus, N. Prapaitrakul, and C.J. Glover (2007). Evaluation and Recommended Improvements for Mix Design of Permeable Friction Courses. Texas Transportation Institute; Texas A&M University, 163p.
- Tsai, B.W., A. Fan, J.T. Harvey, and C. Monismith (2012). Improved Methodology for Mix Design of Open-Graded Friction Courses. University of California, Davis; University of California, Berkeley; California Department of Transportation, 123p.
- Howard, I.L., and J. D. Doyle (2015). Durability Indices via Cantabro Testing for Unaged, Laboratory-Conditioned and One-Year Outdoor Aged Asphalt Concrete, TRB 94th Annual Meeting Compendium of Papers, Paper No. 15-1366, Transportation Research Board.
- Doyle, J.D. and Howard, I.L. (2016). "Characterization of Dense-Graded Asphalt with the Cantabro Test," Journal of Testing and Evaluation, Vol. 44, No.1, ASTM International, pp.78-88.
- West, R. C., Van Winkle, C., Maghsoodloo, S., & Dixon, S. (2017). Relationships between Simple Asphalt Mixture Cracking Tests Using Ndes Specimens and Fatigue Cracking at FHWA's Accelerated Loading Facility. *Journal of the Association of Asphalt Paving Technologists*, 579-602.

Name of Test **Tensile Strength Ratio**	Developer(s) Developed by Lottman Modified by Tunnicliff and Root
Test Method(s) AASHTO T 283-14 (2018)	Adoption by Agencies Alabama, California, Colorado, Connecticut, Florida, Georgia, Illinois, Indiana, Kansas, Kentucky, Maryland, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, South Carolina, South Dakota, Tennessee, Virginia, Vermont, Wisconsin, Wyoming
Description The indirect tensile (IDT) strength is determined for one set of dry specimens and another set of wet specimens conditioned according to the modified Lottman procedure. The procedure consists of partial vacuum saturation, one freeze/thaw cycle, and soaking in warm water. Tensile strength ratio (TSR) is then determined as the ratio of the average wet IDT strength over the average dry IDT strength. Several modifications to the moisture conditioning procedure have been adopted by state highway agencies.	Photographs/Illustrations  
Test Results IDT strength, TSR	Test Temperature(s) 25 ± 0.5°C
Equipment & Cost Vacuum container Water bath Freezer Mechanical testing machine Lottman breaking head	 $3,000 $650 $300 $4,000 $500
Specimen Fabrication Gyratory specimens	Number of Replicate Specimens 6 specimens
Specimen Conditioning Conditioning for 2 hours at 25°C in water bath	Testing Time 3 days
Data Analysis Complexity Simple	Test Variability IDT strength: Low (10% COV) TSR: Low (9.3% d2s)
Field Validations N/A	Overall Practicality for Mix Design and QA Good for Mix Design Poor for QA

Key References

- Lottman, R.P. (1982). "Predicting Moisture-Induced Damage to Asphalt Concrete Field Evaluation," NCHRP Report 246, Transportation Research Board, Washington, D.C.
- Tunnicliff, D.G. and Root. R.E. (1984) "Use of Antistripping Additives in Asphaltic Concrete Mixture Laboratory Phase," NCHRP Report 274, Transportation Research Board, Washington, D.C.
- Azari, H. (2010). "Precision Estimates of AASHTO T283: Resistance of Compacted Hot Mix Asphalt to Moisture-Induced Damage," NCHRP Web-Only Document 166, Washington, D.C.

NATIONAL ASPHALT
PAVEMENT ASSOCIATION

6406 Ivy Lane, Suite 350, Greenbelt, MD 20770-1441

www.AsphaltPavement.org

NAPA@AsphaltPavement.org

Tel: 301-731-4748 | Fax: 301-731-4621 | Toll Free: 1-888-468-6499

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