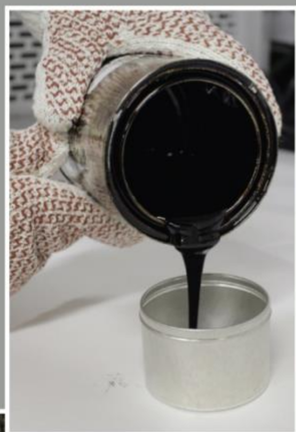

NCAT Report 20-02

PERFORMANCE TESTING FOR QUALITY CONTROL AND ACCEPTANCE OF BALANCED MIX DESIGN

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May 2020

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Performance Testing for Quality Control and Acceptance of Balanced Mix Design

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EXECUTIVE SUMMARY

The objective of this study was to develop a framework for quality control and acceptance testing of balanced mix design (BMD). Specifically, the study sought to determine the expected difference in performance test results between mix design and production and to evaluate the feasibility of using surrogate performance tests for BMD production testing. Five BMD mixes from the 2018 NCAT Test Track research cycle were studied. For each mix, lab-mixed, lab-compacted (LMLC), hot-compacted plant-mixed, lab-compacted (HC-PMLC), and reheated plant-mixed, lab-compacted (RH-PMLC) specimens were prepared and tested in various mixture rutting and cracking tests. Notable differences were found in the performance test results between mix design and production. Three BMD production mixes failed the rutting or cracking test requirement used for mix design approval, and thus, fell outside the performance "sweet zone." The impact of mix reheating on the performance test results was mixed and varied from test to test. No correlation was found between IDEAL-CT versus I-FIT and OT results. Therefore, it is not recommended for highway agencies to utilize an "universal" correlation to determine a production criterion for IDEAL-CT based on the mix design criteria using I-FIT or OT. Mix-specific correlations, however, may exist among these cracking tests and need further investigation. The HT-IDT and HT-CS tests showed reasonable correlations to HWTT, and thus, have the potential of being used as a surrogate rutting test for BMD production testing. Finally, a draft outline of procedure for quality control and acceptance testing of BMD was provided along with two illustrative examples with actual performance testing data.

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1 INTRODUCTION

In the United States, asphalt mixtures are primarily designed using the Superpave system where proportioning of mixture components relies largely on volumetric properties. Early Superpave implementation focused on improving mixture rutting resistance. However, most transportation agencies now report that rutting problems have been virtually eliminated; instead, durability-related distresses such as cracking and raveling now govern the service life of asphalt pavements and overlays. To overcome these concerns, transportation agencies have made strategic changes to their Superpave mix design specifications, including lowering design gyrations, lowering design air voids, increasing voids in mineral aggregates (VMA), and limiting the allowable recycled materials contents, among others (*1-2*). Nevertheless, the effectiveness of these changes varies significantly. Meanwhile, many agencies are interested in a new approach of designing and approving asphalt mixtures based on performance test results; this approach is known as balanced mix design (BMD).

BMD is defined as a mix design procedure using performance tests on appropriately conditioned specimens to address multiple modes of distress while taking into consideration mix aging, traffic, climate, and location within the pavement structure. BMD typically includes two or more performance tests, such as a rutting test and a cracking test, to assess how well the mixture resists the two common forms of distress. As shown in Figure 1, there are three general BMD approaches: 1) volumetric design with performance verification, 2) performance-modified volumetric design, and 3) performance design. Different from the Superpave mix design, BMD requires agencies to check the performance properties of the final mixture instead of specifying their recipe components and volumetric properties, which is expected to motivate mix designers to use innovative materials and technologies for mix design and provide agencies with a more reliable way of accepting asphalt mixtures.

A recent survey of state transportation agencies and asphalt contractors conducted under NCHRP project 20-07, task 406 identified a list of challenges and obstacles for the implementation of BMD. On top of the list was the validity of various mixture cracking tests (*1*). A robust cracking test for use in BMD should be practical, reliable, repeatable, sensitive to mix design variables, and more importantly, should correlate to field cracking performance. Over the last decade, many research studies have been conducted in this respect, with the most noteworthy one being the ongoing NCAT/MnROAD Cracking Group (CG) study. The overall objective of the NCAT/MnROAD CG study is to validate laboratory cracking tests by establishing correlations between test results and measured cracking in real pavements using real loading conditions (*3*). The study includes two standalone field experiments: one on the NCAT test track focusing on top-down cracking and the other on the Minnesota Road Research Facility focusing on thermal cracking. Upon completion, the CG study will provide transportation agencies and the asphalt paving industry with recommendations on the use of mixture cracking test(s) for BMD.

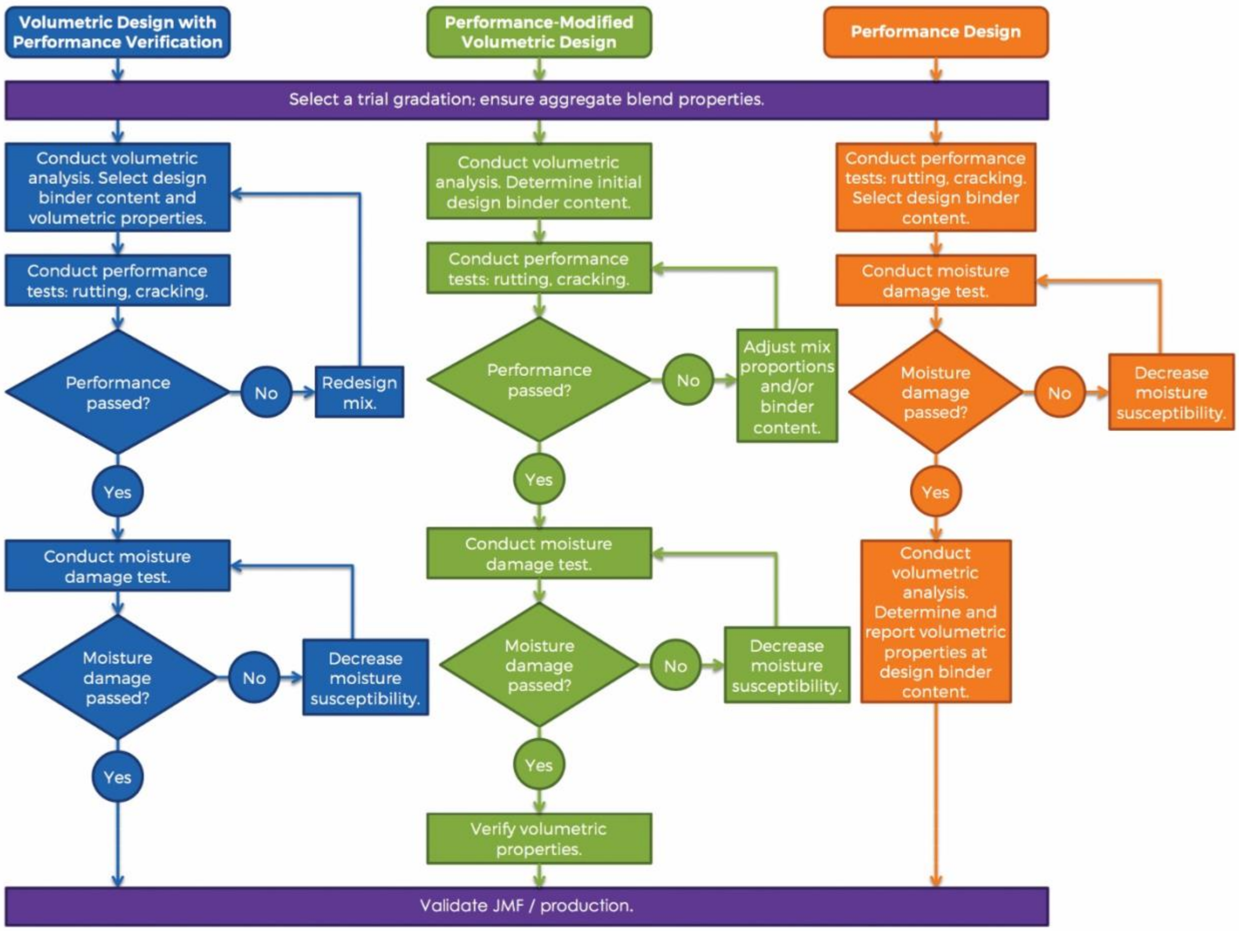


Figure 1. Illustration of Three BMD Approaches

Another reported concern with the implementation of BMD in the survey is the lack of knowledge for addressing quality control (QC) and acceptance testing. Using the same performance criteria for production and mix design may not be appropriate, because many factors allowed in normal production adjustments (e.g., changes in binder source, minor variations in asphalt binder content and aggregate gradation, etc.) could affect the performance test results. Additionally, most of the performance tests being evaluated for use in BMD require a time-consuming specimen fabrication and testing procedure. Hence, it is difficult, if not impossible, for agencies and contractors to conduct these tests without delaying production. A potential approach to shorten the time window of BMD production testing is to use surrogate tests that are faster, simpler, and can correlate to mix design performance test results and properties. For example, the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) could possibly be used as a surrogate cracking test to the Illinois Flexibility Index test (I-FIT) or Overlay Test (OT), and the High-Temperature Indirect Tensile (HT-IDT) Strength test and High-Temperature Compact Shear (HT-CS) test could be used as surrogate rutting tests to the Hamburg Wheel Tracking Test (HWTT) or Asphalt Pavement Analyzer (APA). However, very little effort has yet been made to verify if this approach is feasible.

2 OBJECTIVES AND SCOPE

The objectives of this study are threefold:

1) Determine the expected difference in performance test results between mix design and production;
2) Evaluate the feasibility of using surrogate performance tests for production testing; and
3) Recommend a framework for quality control and acceptance testing of BMD.

In the 2018 NCAT Test Track research cycle, five test sections were constructed using asphalt mixtures designed with a BMD approach, which provided a platform for the NCAT team to evaluate the viability of performance testing for QC and acceptance of BMD. Among the five mixes, two were designed with the *Volumetric Design with Performance Verification* approach and the other three with the *Performance-Modified Volumetric Design* approach. The performance tests used to design these BMD mixes varied. During construction of the test sections, plant mixture was sampled for testing with the mix design performance tests under the Test Track experiment agreement. As shown in Figure 2, additional testing was conducted in this study to include the use of three candidate surrogate performance tests (i.e., IDEAL-CT, HT-IDT strength, and HT-CS tests) as well as the testing of lab-mixed, lab-compacted (LMLC) and hot-compacted plant-mixed, lab-compacted (HC-PMLC) specimens in addition to reheated plant-mixed, lab-compacted (RH-PMLC) specimens.

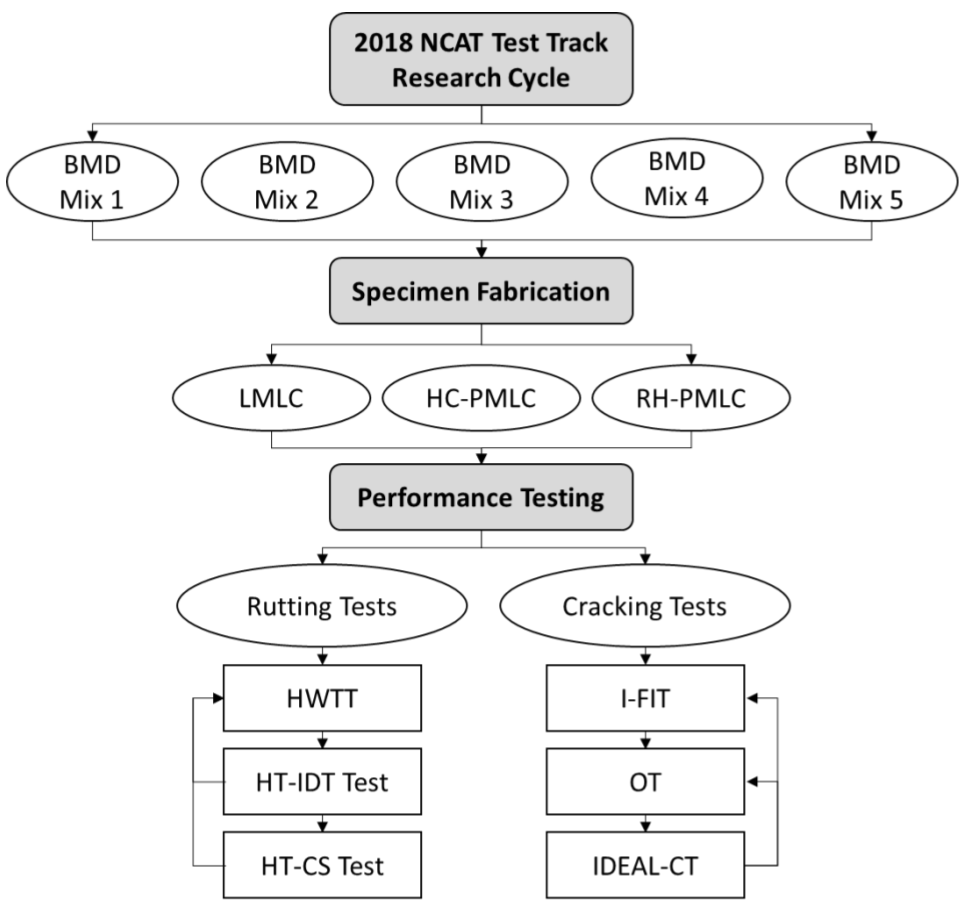


Figure 2. Illustration of Project Scope

3 EXPERIMENTAL DESIGN

3.1 Mix Design and Production

Table 1 summarizes the job mix formula (JMF) of the five BMD mixes evaluated in the study.

- Mix 1 is a 9.5mm nominal maximum aggregate size (NMAS) mix with a PG 76-28 styrene-butadiene-styrene (SBS) modified binder and 15% reclaimed asphalt pavements (RAP), which was designed with the *Volumetric Design with Performance Verification* approach using HWTT and I-FIT. The mix has 4.0 percent design air voids and 15.5 percent VMA at 80 gyrations.
- Mix 2 is a 12.5mm NMAS mix with a PG 70-28 SBS modified binder and 12% RAP, which was designed with the *Performance-Modified Volumetric Design* approach using HWTT and I-FIT. The original mix design based on volumetric analyses has 4.0 percent air voids and 16.4 percent VMA at 65 gyrations. The mix after performance modification has 3.4 percent design air voids and 16.2 percent VMA.
- Mix 3 is a 12.5mm NMAS mix with a PG 70-22 SBS modified binder and 20% RAP binder replacement, which was designed with the *Volumetric Design with Performance Verification* approach using HWTT and OT. The mix has 4.0 percent design air voids and 16.6 percent VMA at 50 gyrations.
- Mix 4 is a 9.5mm NMAS mix with a PG 64-22 neat binder and 30% RAP, which was designed with the *Performance-Modified Volumetric Design* approach using APA, IDEAL-CT, and the Cantabro test. The original mix design based on volumetric analyses has 4.0 percent air voids and 16.3 percent VMA at 50 gyrations. The mix after performance modification has 2.9 percent design air voids and 15.8 percent VMA.
- Mix 5 is a 9.5mm NMAS mix with a PG 64-22 neat binder, 45% RAP, and a bio-based rejuvenator. The mix was designed with the same approach as Mix 4. The original design based on volumetric analyses has 4.0 percent air voids and 16.7 percent VMA at 50 gyrations. The mix after performance modification has 2.4 percent design air voids and 16.2 percent VMA.

Table 1 also includes the QC volumetric properties of plant-produced mixes for the construction of test sections on the NCAT Test Track. All five mixes had a notable reduction in air voids and VMA from mix design to production, which varied from 0.2 to 1.9 percent for air voids and 0.2 to 1.8 percent for VMA. For Mix 1 and Mix 3, the changes in volumetric properties were beyond the production tolerances allowed by the sponsoring transportation agencies. Nevertheless, both mixes were accepted given the fact that they passed the performance test requirements.

Table 1. Summary of JMF and QC Volumetric Properties

Volumetrics	Mix 1		Mix 2		Mix 3		Mix 4		Mix 5	
	Design	QC	Design	QC	Design	QC	Design	QC	Design	QC
25 mm (1”)	100	100	100	100	100	100	100	100	100	100
19 mm (3/4”)	100	100	100	100	100	100	100	100	100	100
12.5 mm (1/2")	100	100	94	94	93	93	100	100	100	100
9.5 mm (3/8”)	97	97	88	90	82	78	97	95	97	96
4.75 mm (#4)	77	76	63	68	52	46	6	56	61	56
2.36 mm (#8)	50	48	37	41	30	27	38	36	38	38
1.18 mm (#16)	34	33	24	28	21	19	27	26	28	27
0.60 mm (#30)	25	26	17	20	16	14	20	18	21	20
0.30 mm (#50)	18	18	10	13	11	11	14	11	15	13
0.15 mm (#100)	10	9	5	7	7	8	9	7	10	9
0.075 mm (#200)	6.5	6.0	4.5	5.4	4.9	5.2	5.5	4.9	6.3	6.1
Asphalt Content (%)	5.6	5.6	5.8	5.5	5.5	5.3	5.5	6.0	5.8	6.0
Air Voids (%)	4.0	2.1	3.4	2.3	4.0	2.4	2.9	2.7	2.3	1.5
VMA (%)	15.5	14.0	16.2	14.7	16.6	14.8	16.2	17.3	16.5	16.3
V_{be} (%)	11.5	11.9	12.8	12.4	12.6	12.4	13.3	14.6	14.2	14.8
VFA (%)	74	85	79	85	76	84	82	85	86	91
Dust Proportion	1.3	1.2	0.8	1.0	0.9	1.0	1.1	0.9	1.1	1.1

3.2 Specimen Fabrication

As discussed previously, three sets of performance specimens were tested for each mix. The LMLC specimens represent the original mix design, while the HC-PMLC and RH-PMLC specimens represent the production mixes used for QC and acceptance testing, respectively. For the preparation of LMLC specimens, the construction raw materials (aggregate, RAP, and binder) were sampled from the plant during section construction. For Mixes 1, 2, and 3, the production binder was used to prepare the LMLC specimens for this study. For Mix 4 and Mix 5, the design binder (same as the production binder) was used to maintain continuity with some of the performance testing that had already been completed during the mix design process. Specimens were prepared in accordance with the component proportions in the JMF. These specimens were short-term oven aged using the 'Short-Term Conditioning for Mixture Mechanical Property Testing' procedure in AASHTO R30-02 (2015), *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)*. For this procedure, the mix is aged for four hours at 135°C and stirred every hour to promote uniform conditioning prior to compaction.

For the HC-PMLC specimens, plant loose mix was collected at the NCAT Test Track during construction and transported to NCAT's main laboratory approximately 30 minutes away. To keep the mix warm during transport, an oven with additional insulation (not powered) was placed on the back of a truck and used as a hot transport container. Four five-gallon buckets of each plant-produced mix were sampled for testing. All four buckets of mix were blended using a Quartermaster prior to splitting the samples into the required individual sizes in accordance with AASHTO R47-19, *Standard Practice for Reducing Samples of Asphalt Mixtures to Testing Size*. The first order of business for each mix was to establish a theoretical maximum specific gravity (G_{mm}) and to establish the required mass in the mold to give the desired target air voids for each height of specimen (62 mm, 125 mm, and 160 mm). A minimum of one trial specimen to determine the bulk specific gravity (G_{mb}) was required per mix and additional trials were sometimes needed to have confidence in the compaction mass. Once the mix had reached compaction temperature (verified with a dial thermometer) and the trial weights had been established, compaction began on the main body of specimens. Two gyratory compactors were used simultaneously: a Pine G2 was used to compact the 62mm tall specimens for HWTT, HT-IDT, and HT-CS tests, while a Troxler 5850 was used to compact the 125mm and 160mm tall specimens for I-FIT and OT, respectively. Two to three workers were required per mix for this compaction effort. Approximately 30 specimens were fabricated per mix to satisfy the requirements of the testing plan for this study. The number of specimens needed for this study necessitated more time than a typical production effort that would only require specimens for one or two tests.

Table 2 summarizes the approximate total time required to fabricate HC-PMLC specimens, both for this study (where 30 specimens were made) and for a more 'normal' BMD performance testing scenario where samples would only be made for one rutting and one cracking test. For this study, it took approximately five hours from the time of mix production to complete sample fabrication due to the large volume of specimens. If only 10 specimens were required, that time would likely be reduced to between three and four hours from production. While performing only two tests would require less time for splitting and compaction, time would still be required to establish the G_{mm} and trial masses.

Table 2. Summary of Time Required to Prepare HC-PMLC Specimens

Activities	Time since Production – This Study (30 samples) - NCAT	Time since Production – Single Test (10 samples) – NCAT	Time Since Production – Single Test (10 samples) – On-Site Laboratory
1. Sample mix at Test Track	30 minutes	30 minutes	30 minutes
2. Transport mix to main lab	60 minutes	60 minutes	35 minutes
3. Split mix into specimen sizes	1 hour, 45 minutes	1 hour, 30 minutes	1 hour, 5 minutes
4. Condition mix in oven and measure trial weights and G_{mm}	3 hours	2 hours, 30 minutes	2 hours, 5 minutes
5. Compact specimens for performance testing	5 hours	3 hours, 30 minutes	3 hours, 5 minutes

For the RH-PMLC specimens, buckets of plant-produced mix were re-heated for between two and three hours at the compaction temperature in order to become workable. Multiple buckets were re-heated and blended using a Quartermaster to obtain a more representative sample. Individual specimens were quartered from the larger bucket sample in accordance with AASHTO R47-19. Buckets would only be re-heated once and the split mix was stored in sealed plastic bags until the time the specimens would be prepared. The mix for the individual specimens was placed in pans and re-heated in an oven set at the compaction temperature plus 10°F until a dial thermometer in the mix registered the compaction temperature. In summary, each bucket of plant mix was only re-heated once and the individual specimens were re-heated only until they reached the compaction temperature. The amount of time required to re-heat plant mix (after being split into individual specimens) to the compaction temperature varied significantly depending on several factors such as pan size, oven configuration, etc., but was generally approximately one hour for the 62mm specimens and two hours for the 125mm and 160mm specimens.

For all three specimen types, IDEAL-CT, HWTT, HT-IDT, and HT-CS specimens were prepared to a target air void content of 7.0 ± 0.5 percent. Air voids on the I-FIT and OT were controlled on the final saw cut specimens. I-FIT specimens were prepared to a final air void level of 7.0 ± 0.5 percent and OT specimens were prepared to a final air void level of 7.0 ± 1.0 percent per Tex-248-F, *Test Procedure for Overlay Test*.

3.3 Mixture Performance Tests

3.3.1 Rutting Tests

HWTT was the rutting test used for the design of Mix 1, Mix 2, and Mix 3. The test was conducted in accordance with AASHTO T 324-17, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)*. The two most commonly used HWTT test parameters are total rut depth at 20,000 passes (TRD_{20k}) and stripping inflection point. In this study, the HWTT criterion used for the design of Mix 1, Mix 2, and Mix 3 is a maximum rut depth of 12.5 mm at 10,000 passes for PG 64-xx or lower binders, 15,000 passes for PG 70-xx binders, and 20,000 passes for PG 76-xx or higher binders (*4-5*). However, because HWTT was mainly used in this study to evaluate the mixture rutting resistance, two non-traditional rutting parameters were used for data analysis. One of the parameters is the corrected rut depth at 20,000 passes (CRD_{20k}), which is a simplified version of the viscoplastic strain increment ($\Delta\varepsilon^{vp}$) parameter proposed by Yin et al. (*6*). Figure 3 illustrates the determination of CRD_{20k} based on the HWTT rut depth curve. As compared to the traditional TRD_{20k}, CRD_{20k} has an advantage of isolating the rut depth caused by permanent deformation of the mixture due to stripping, and thus, provides a more accurate indication of mixture rutting resistance. The other rutting parameter used is rutting resistance index (*RRI*), which was developed by Wen et al., in order to overcome the difficulty of comparing HWTT results with different test termination points (e.g., results terminated at 20,000 passes versus those terminated at a specific maximum rut depth) (*7*). As expressed in Equation 1, *RRI* considers both rut depth and the number of wheel passes at completion of the test. For example, if a mixture reached a critical rut depth of 12.5 mm at 20,000 passes, its RRI would be 10,000. Note that mixtures with lower CRD_{20k} and higher *RRI* values are expected to have better rutting resistance. Minimum turnaround time on the HWTT results in a production setting is approximately 12 hours, including 4 hours for specimen preparation and 8 hours for sample conditioning and testing.

$$RRI = N_{max} * (1 - RD_{max}) \tag{1}$$

Where,

N_{max} = number of wheel passes at completion of test; and
RD_{max} = final rut depth in inches at completion of test.

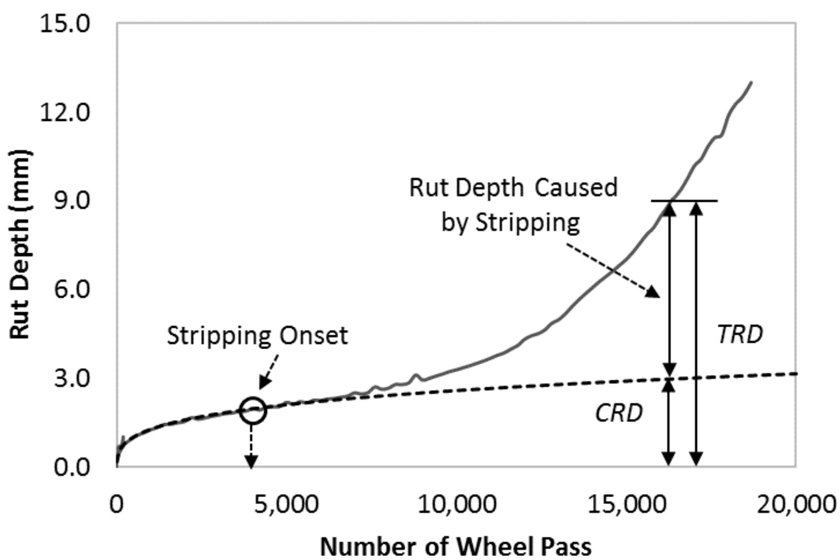
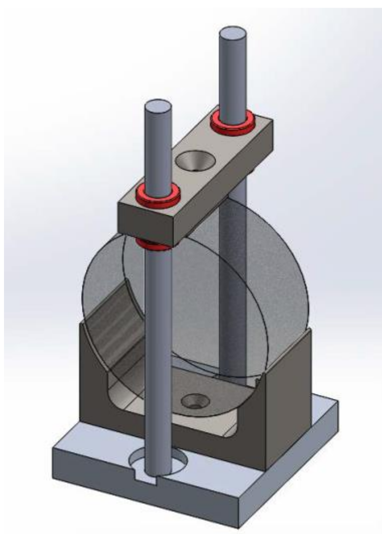


Figure 3. Determination of HWTT Rutting Parameter CRD_{20k}

The HT-IDT test was evaluated in this study as a candidate surrogate rutting test to HWTT. The test was conducted following the procedure recommended by Christensen and Bonaquist (*8*). The test temperature used in the study was 50.2°C, which was determined in the LTPPBind as 9°C lower than the yearly seven-day average maximum pavement temperature 20 mm below the pavement surface in Auburn, Alabama. The final test parameter is the HT-IDT strength; a higher HT-IDT strength value is desired for mixtures with better rutting resistance. Typical turnaround time on the HT-IDT test results is approximately six hours, including four hours for specimen preparation and two hours for sample conditioning and testing.

The HT-CS test was evaluated as another candidate surrogate rutting test to HWTT. The test was developed by Zhou et al. (*9*) and was conducted largely in the same manner as the HT-IDT test, except for using a shear fixture instead of an indirect tension (IDT) fixture, as shown in Figure 4(a). The shear fixture includes a cradle assembled on the base plate, which is designed to create two shear planes within the specimen [Figure 4(b)] for the simulation of shear failure in rutting. The test was conducted at 50.2°C with a constant loading rate of 50 mm/min. For data analysis, the peak load from the load versus displacement curve was used as the final rutting index parameter; a higher HT-CS peak load is desired for mixtures with better rutting resistance. Typical turnaround time on the HT-CS test results is approximately six hours, including four hours for specimen preparation and two hours for sample conditioning and testing.



(a)

(b)

Figure 4. High-Temperature Compact Shear Test; (a) Shear Fixture, (b) Specimen after Testing

3.3.2 Cracking Tests

I-FIT was the cracking test used for the design of Mix 1 and Mix 2. The test was conducted in according with AASHTO TP 124-18, *Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures using the Flexibility Index Test (FIT).* The final test parameter is the flexibility index (*FI*); a higher *FI* value is desired for mixtures with better resistance to intermediate-temperature fatigue cracking. The I-FIT criterion used for the design of Mix 1 and Mix 2 is a minimum *FI* of 8.0 on short-term aged specimens (*4, 10*). Typical turnaround time on the I-FIT results is approximately two days, including one and a half days for specimen preparation and one-half day for sample conditioning and testing.

OT was the cracking test used for the design of Mix 3. The test was conducted in accordance with the most recent Tex-248-F, *Test Procedure for Overlay Test*. The final test parameter used in the study is the crack progression rate (β parameter), which is calculated based on fitting a power function to the normalized load reduction curve. A smaller β parameter indicates a flatter load reduction curve, and thus, is desired for mixtures with better cracking resistance. The OT criterion used for the design of Mix 3 is a maximum β parameter of 0.45 on short-term aged specimens (*5*). Typical turnaround time on the OT results is approximately three days, including two days for specimen preparation and one day for sample conditioning and testing.

IDEAL-CT was used as the cracking test for the design of Mix 4 and Mix 5, which was also evaluated in this study as a candidate surrogate cracking test to I-FIT and OT. The test was conducted in accordance with ASTM D 8225-19, *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*. The final test parameter is the cracking tolerance index (CT_{index}); a higher CT_{index} value is desired for mixtures with better resistance to intermediate-temperature fatigue cracking. The IDEAL-CT criterion for the design of Mix 4 and Mix 5 is a minimum $\mathrm{CT_{index}}$ of 70 on short-term aged specimens (*11*). Typical turnaround time on the IDEAL-CT results is approximately six hours, including four hours for specimen preparation and two hours for sample conditioning and testing.

3.4 Preliminary Field Performance on the NCAT Test Track

Table 3 summarizes the preliminary field performance data of the five BMD mixes on the NCAT Test Track. Over 6.4 million equivalent single axle loads (ESALs) of traffic have been applied, and the mixes have been performing well. The percent of lane area cracked varies from 0 to 0.8 percent and the rut depth varies from 0.2 to 5.5 mm.

Table 3. Preliminary Field Performance Data after 6.4 Million ESALs

Mix ID	Percent of Lane Area Cracked (%)	Rut Depth (mm)
Mix 1	0.8	0.2
Mix 2	0	3.5
Mix 3	0.1	5.5
Mix 4	0	1.6
Mix 5	0	1.4

4 TEST RESULTS AND DATA ANALYSES

Table 4 presents a summary of all the performance test results collected in this study. For each mix, there are three specimen types: LMLC, HC-PMLC, and RH-PMLC specimens. The cracking test parameters used in the study are *FI*, β parameter, and CT_{index} from the I-FIT, OT, and IDEAL-CT tests, respectively. The rutting test parameters included are TRD_{20k}, CRD_{20k}, and *RRI* from HWTT, HT-IDT strength, and HT-CS peak load (for HC-PMLC and RH-specimens only). In general, the results in Table 4 have good data quality in terms of variability. The average coefficient of variance (COV) of the cracking test parameters are 21.1% for *FI*, 10.2% for β parameter, and 17.5% for CT_{index}, which agree with the values reported in the literature (e.g., 10 to 20% for *FI* and CT_{index}).

Table 4. Summary of Performance Test Results

Specimen Type	Test Parameter	Mix 1		Mix 2		Mix 3		Mix 4		Mix 5	
		Avg.	COV	Avg.	COV	Avg.	COV	Avg.	COV	Avg.	COV
LMLC	I-FIT FI	12.0	14.6%	12.7	13.1%	17.3	18.5%	4.4	37.2%	5.4	21.0%
	OT β Parameter	0.35	6.5%	0.36	7.6%	0.43	5.0%	0.51	10.5%	0.53	18.3%
	IDEAL CT_{index}	95.5	10.4%	117.5	10.1%	141.5	17.7%	74.6	9.5%	75.6	18.0%
	HWTT TRD_{20k} (mm)	9.2	1.8%	8.2	18.1%	5.3	4.2%	4.6	8.6%	5.7	51.7%
	HWTT CRD_{20k} (mm)	2.9	0.7%	4.0	0.0%	5.0	6.3%	2.7	1.4%	3.1	0.5%
	HWTT RRI	12752.0	1.0%	13527.6	8.6%	15795.3	1.1%	16378.0	1.9%	15543.3	14.8%
	HT-IDT Strength (psi)	34.8	1.3%	25.6	10.9%	30.6	10.3%	43.6	8.0%	34.9	8.3%
HC-PMLC	I-FIT FI	6.4	9.4%	5.6	18.0%	11.7	10.6%	6.0	28.1%	6.0	27.7%
	OT β Parameter	0.42	20.6%	0.43	17.7%	0.40	17.1%	0.39	9.0%	0.43	10.0%
	IDEAL CT_{index}	65.8	18.9%	49.9	20.3%	144.1	13.9%	125.4	21.4%	100.0	19.8%
	HWTT TRD_{20k} (mm)	> 12.5	0.0%	5.4	3.0%	6.9	17.3%	3.1	0.2%	4.6	14.2%
	HWTT CRD_{20k} (mm)	3.0	0.7%	3.5	3.8%	6.2	16.3%	3.1	0.4%	4.2	15.1%
	HWTT RRI	9323.3	1.0%	15759.8	0.8%	14547.2	6.5%	17594.5	0.0%	16393.7	3.1%
	HT-IDT Strength (psi)	35.2	4.5%	30.5	1.7%	22.3	4.8%	38.7	14.9%	39.1	14.4%
	HT-CS Peak Load (lbs.)	1429.6	12.7%	1132.6	7.2%	696.2	12.5%	1160.7	16.8%	2219.7	6.7%
RH-PMLC	I-FIT FI	8.3	13.8%	5.5	13.5%	6.1	35.4%	6.6	20.9%	7.5	35.4%
	OT β Parameter	0.34	11.2%	0.39	10.0%	0.38	1.8%	0.36	3.7%	0.37	3.6%
	IDEAL CT_{index}	73.0	24.2%	50.7	29.1%	212.1	15.4%	102.2	14.9%	63.9	18.2%
	HWTT TRD_{20k} (mm)	> 12.5	0.0%	4.7	6.0%	8.2	16.5%	3.1	11.0%	3.1	2.7%
	HWTT CRD_{20k} (mm)	3.5	3.4%	4.3	3.3%	7.6	12.6%	3.1	8.7%	3.1	3.3%
	HWTT RRI	7412.8	1.0%	16275.6	1.4%	13574.8	7.8%	17523.6	1.6%	17559.1	0.4%
	HT-IDT Strength (psi)	36.4	10.7%	25.7	7.9%	21.3	14.0%	40.6	11.0%	42.9	15.1%
	HT-CS Peak Load (lbs.)	1251.8	4.9%	1007.6	3.7%	830.2	10.9%	1370.6	17.9%	1146.1	12.6%

In this study, data analyses were performed in three perspectives: firstly, to compare the performance test results between mix design and production; secondly, to evaluate the effect of mix reheating on performance test results; and finally, to assess the correlation between the candidate surrogate and mix design performance test results. Detailed analysis results are presented in the following sections.

4.1 Comparison of Performance Test Results between Mix Design and Production

Figure 5 presents the performance diagrams of the five BMD mixes evaluated in the study, where the rutting test results (expressed using the HWTT *RRI* parameter) are plotted on the x-axis against the cracking test results on the y-axis. In each figure, the blue circle marker presents the mix design results using LMLC specimens and the grey triangle marker represents the production results using RH-PMLC specimens. The two dashed lines represent the performance test criteria used in mix design. As discussed previously, Mix 1 and Mix 2 were designed using I-FIT as the cracking test, Mix 3 using OT, and Mix 4 and Mix 5 using IDEAL-CT.

As shown in Figure 5, all design mixes fell in the "sweet zone" of the performance diagram, which indicated that they passed the performance test requirements and were expected to have satisfactory rutting and cracking resistance. For Mix 1 and Mix 2, a significant change in the performance test results was observed from mix design to production. The production mix of Mix 1 showed significantly reduced rutting and cracking resistance than the design mix, as indicated by lower *RRI* and *FI* values. Although the production mix passed the I-FIT requirement, it failed the HWTT criterion of maximum 12.5 mm rut depth at 20,000 passes (or a minimum *RRI* of 10,000); as a result, it fell outside the "sweet zone" of the performance diagram. For Mix 2, the production mix had a higher *RRI* but a lower *FI* than the design mix, which was indicative of increased rutting resistance but reduced cracking resistance. The production mix failed the minimum *FI* threshold of 8.0, and thus, was outside the "sweet zone". For Mix 3 and Mix 4, despite the differences observed in the performance test results between mix design and production, both mixes passed the rutting and cracking test requirements and fell in the "sweet zone". For Mix 5, the production mix had a CT_{index} of 63.9, which barely failed the minimum threshold of 70. As a result, the production mix fell outside the "sweet zone" of the performance diagram. In summary, two out of the five BMD mixes (Mix 3 and Mix 4) remained "balanced" with satisfactory rutting and cracking resistance during production, while the other three mixes (Mix 1, Mix 2, and Mix 5) became "unbalanced" by failing either the rutting or cracking test requirement used in mix design.

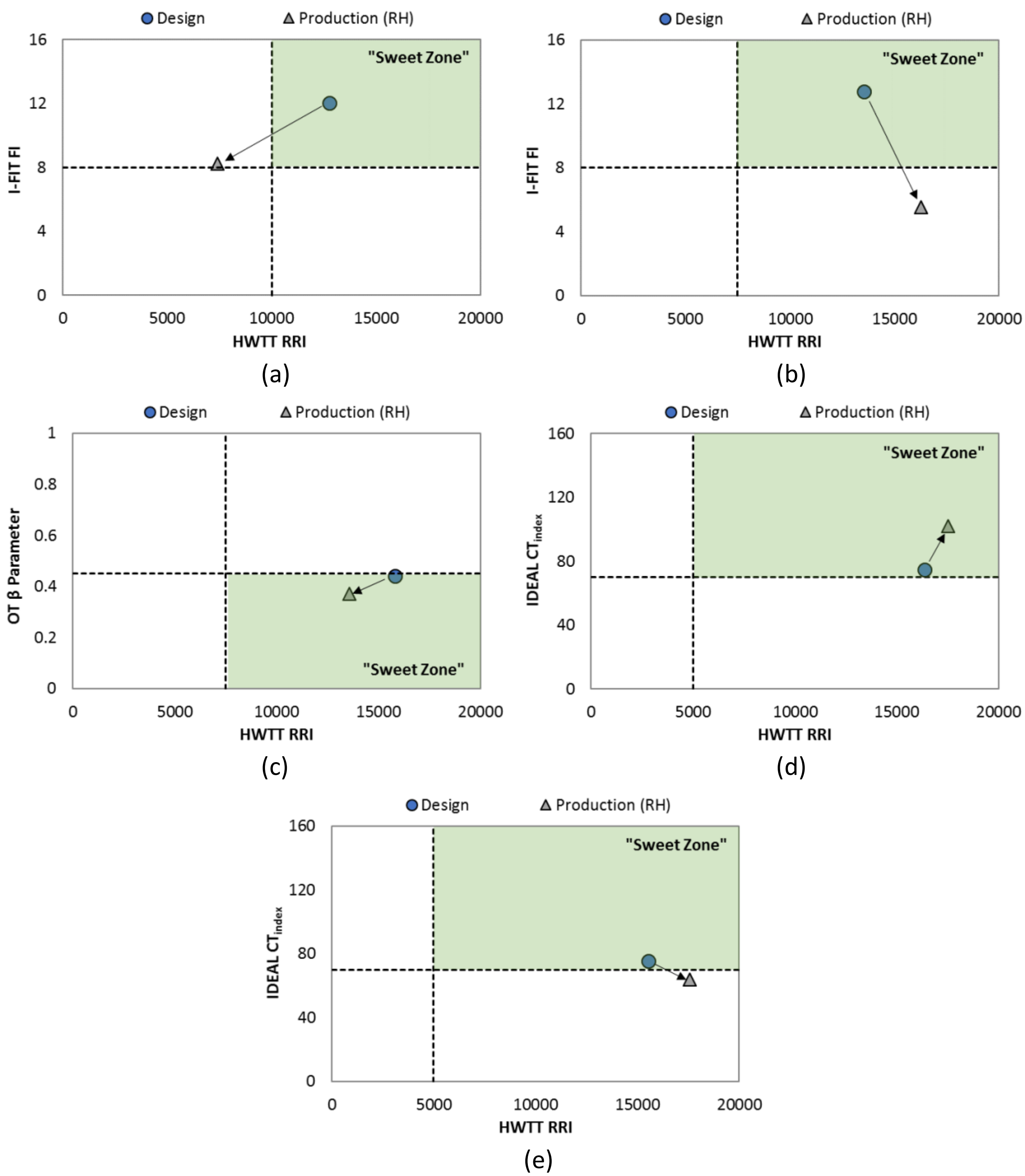


Figure 5. Performance Diagram for Mix Design versus Production; (a) Mix 1, (b) Mix 2, (c) Mix 3, (d) Mix 4, and (e) Mix 5

Figure 6 compares the I-FIT, OT, and IDEAL-CT results of LMLC versus RH-PMLC specimens. The bars represent the average *FI*, β parameter, and CT_{index} values, and the whiskers denote plus and minus one standard deviation among the replicate results. The numbers located on top of the figures are the p-values from the Student's t-test; a p-value less than 0.05 indicates that the cracking test results of LMLC and RH-PMLC specimens are statistically different for that specific mix. Note that the Student's t-test was conducted for each mix separately. In general, the comparison between the cracking test results of LMLC and RH-PMLC specimens varied from test to test. As shown in Figure 6(a), the LMLC specimens of Mix 1 through Mix 3 had statistically higher *FI* values than the corresponding RH-PMLC specimens, while the opposite trend was observed for Mix 4 and Mix 5. The OT results in Figure 6(b) showed a relatively consistent trend among all five BMD mixes, where the LMLC specimens had statistically equivalent or higher β parameter values than the RH-PMLC specimens. These OT results indicated that the production mixes had equivalent or better cracking resistance than the design mixes. For the IDEAL-CT results in Figure 6(c), the LMLC specimens of Mix 1, Mix 2, and Mix 5 had higher average CT_{index} values than the corresponding RH-PMLC specimens, while the opposite trend was observed for Mix 3 and Mix 4. According to the Student's t-test, the difference in the CT_{index} values between the two sets of specimens was not statistically significant for Mix 5. No strong correlation was observed for the change in V_{be} and the change in the cracking test results (except for I-FIT) from mix design to production (Figure 7). This indicated that there are other factors besides mix volumetrics that are accountable for the differences in the cracking test results between LMLC and RH-PMLC specimens. For example, these two sets of specimens were subjected to different levels of asphalt aging during production, which had an impact on mixture cracking test results.

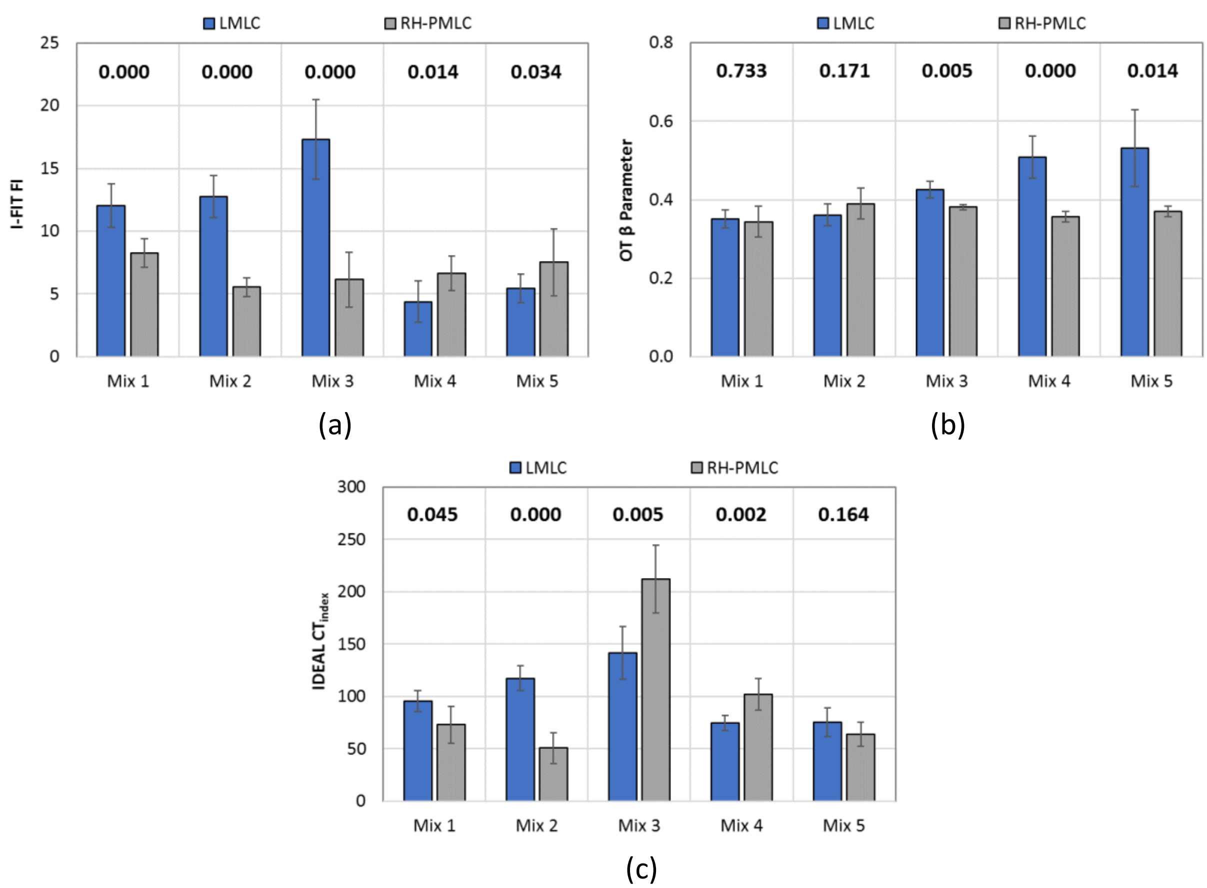
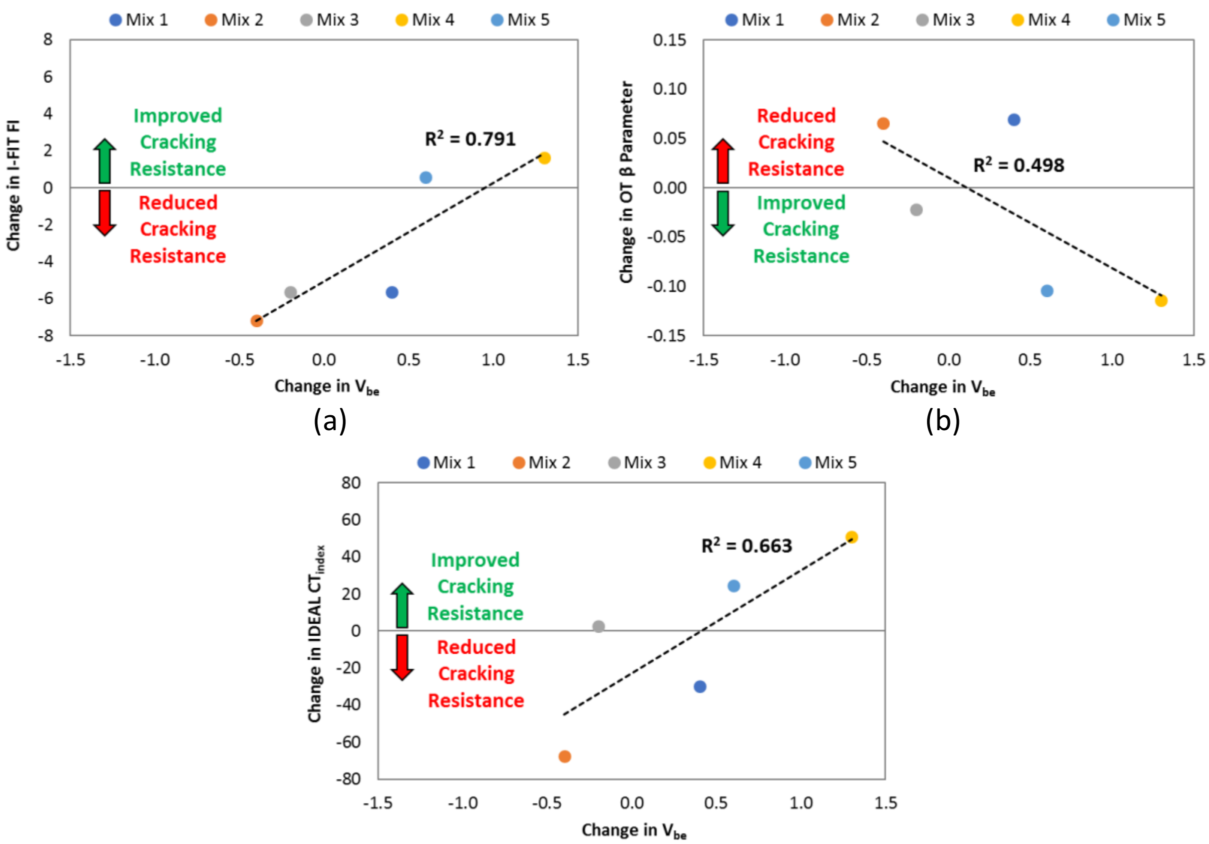


Figure 6. Cracking Test Results of LMLC versus RH-PMLC Specimens; (a) I-FIT *FI*, (b) OT β Parameter, (c) IDEAL CT_{index}



(a) (b) (c)

Figure 7. Correlation between Changes in V_{be} and Changes in the Cracking Test Results from Mix Design to Production; (a) I-FIT *FI*, (b) OT β Parameter, (c) IDEAL CT_{index}

Figure 8 presents the percent difference in the average cracking test results between LMLC and RH-PMLC specimens (calculated using Equation 2). Note that for the I-FIT and IDEAL-CT results, a positive value is indicative of better cracking results for RH-PMLC specimens relative to LMLC specimens, while a negative value is expected for such a trend in the OT results. As shown, the percent difference values varied from approximately -60% to 50% for the I-FIT and IDEAL-CT results. Relatively speaking, the differences in the OT results between LMLC and RH-PMLC specimens were less significant. The percent difference in the average β parameter varied from approximately -30% to 10% among the five mixes.

$$\% \text{ Difference} = \left(\frac{Performance\ Index_{RH-PMLC}}{Performance\ Index_{LMLC}} - 1\right) * 100\% \tag{2}$$

Where,

Performance Index $_{RH\text{-}PMLC}$ = performance index parameter of RH-PMLC specimen; and
Performance Index $_{LMLC}$ = performance index parameter of LMLC specimen.

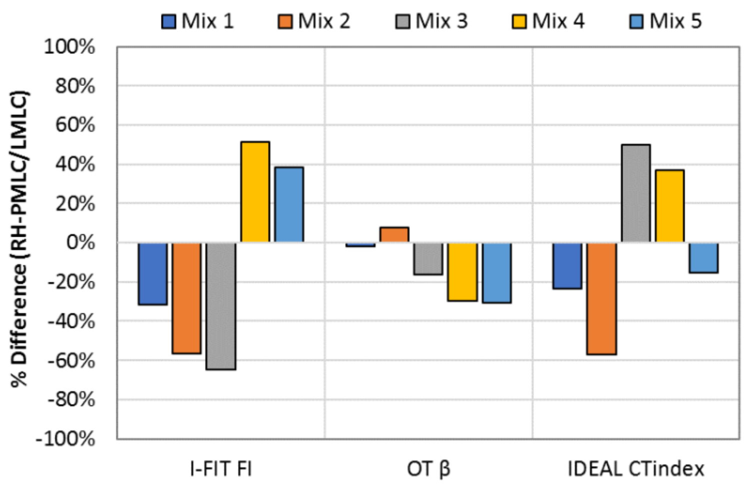


Figure 8. Percent Difference in the Average Cracking Test Results between LMLC and RH-PMLC Specimens

Figure 9 compares the HWTT results of LMLC versus RH-PMLC specimens for the five BMD mixes. Considering that HWTT was used as a mixture rutting test in this study, test results were discussed using CRD_{20K} instead of TRD_{20k} and *RRI* to avoid the confounding effect of moisture damage (stripping) on HWTT rut depth measurements. Note that because HWTT results only included two replicates, statistical analysis could not be conducted. As shown, all five BMD mixes except Mix 3 had reasonably similar CRD_{20K} values between the two sets of specimens. For Mix 3, LMLC specimens had a significantly lower CRD_{20K} than the RH-PMLC specimens, indicating better rutting resistance for mix design in comparison to production. The percent difference in the HWTT *Corrected* RD_{20K} results between LMLC and RH-PMLC specimens, calculated using Equation 2, varied by up to 50% among the five BMD mixes (Figure 10).

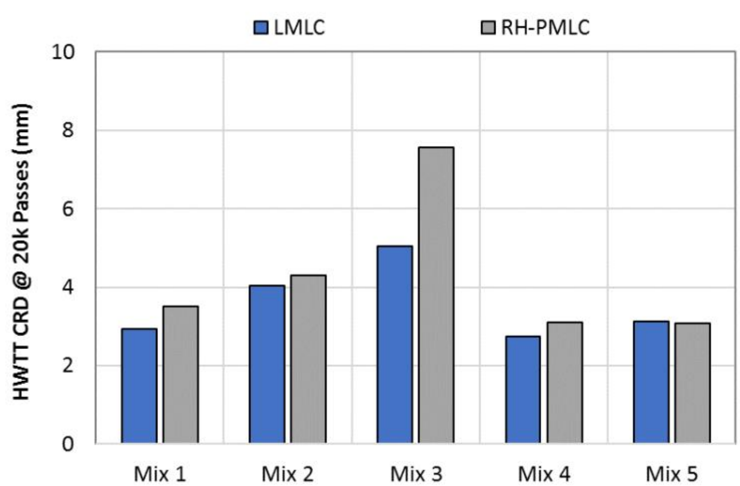


Figure 9. HWTT *Corrected* RD_{20K} Results of LMLC versus RH-PMLC Specimens

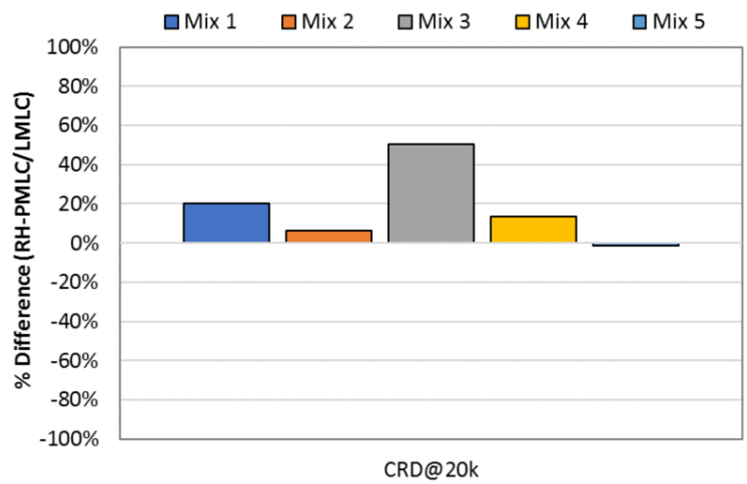


Figure 10. Percent Difference in the Average HWTT *Corrected* RD_{20K} Results between LMLC and RH-PMLC Specimens

4.2 Effect of Mix Reheating on Performance Test Results

Figure 11 presents the comparison of I-FIT, OT, and IDEAL-CT results for HC-PMLC versus RH-PMLC specimens. In general, no consistent trend was observed among the cracking test results. For Mix 2, Mix 4, and Mix 5, the HC-PMLC and RH-PMLC specimens had statistically equivalent *FI* values in Figure 11(a), indicating no significant difference in the cracking resistance between design and production mixes. For Mix 1, the HC-PMLC specimens had a lower *FI* value, and thus, reduced cracking resistance than the RH-PMLC specimens. However, the opposite trend was observed for Mix 3. For the OT results in Figure 11(b), the HC-PMLC specimens had consistently higher β parameter values than the RH-PMLC specimens, which was indicative of reduced cracking resistance. These results contradicted the common expectation that mix reheating would have a detrimental impact on mixture cracking resistance as a result of asphalt aging occurring during the reheating process. However, it should be noted that due to the large number of HC-PMLC specimens fabricated and the fact that the mix was sampled at the Test Track but compacted off-site at the NCAT's research lab, the preparation of HC-PMLC specimens in this study was much more time consuming than in normal production scenarios where contractors only need to compact a limited number of specimens at their on-site QC labs. Therefore, caution should be exercised when interpreting the difference in the cracking test results between HC-PMLC and RH-PMLC specimens in Figure 6. For the IDEAL-CT results in Figure 11(c), Mix 1, Mix 2, and Mix 5 showed statistically equivalent CT_{index} values between the two sets of PMLC specimens. For Mix 3, the RH-PMLC specimens had a higher CT_{index} value, and thus, better cracking resistance than the HC-PMLC specimens, while the opposite trend was observed for Mix 5.

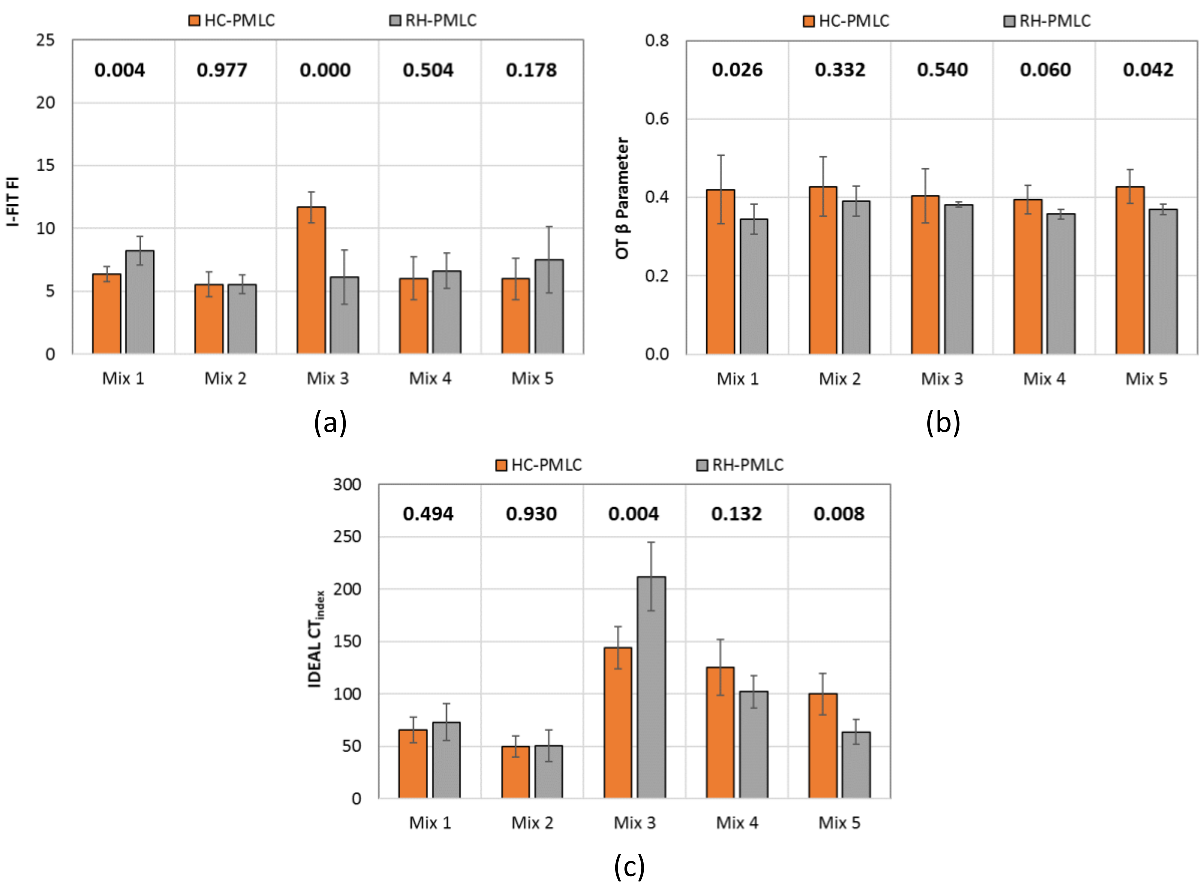


Figure 11. Cracking Test Results of HC-PMLC versus RH-PMLC Specimens; (a) I-FIT *FI*, (b) OT β Parameter, (c) IDEAL CT_{index}

Figure 12 presents the percent difference in the average cracking test results between HC-PMLC and RH-PMLC specimens. Note that a negative value for the I-FIT and IDEAL-CT results and a positive value for the OT results indicates that mix reheating has a negative impact on the mixture cracking resistance. In most cases, mix reheating did not have a negative impact on the cracking test results. The only three exceptions were the I-FIT result of Mix 3 and the IDEAL-CT results of Mix 4 and Mix 5. The percent difference between the two sets of PMLC specimens varied from -50% to 30% for the I-FIT results and varied from -40% to 50% for the IDEAL-CT results, respectively, among the five mixes. Relatively speaking, the variations in the OT results between HC-PMLC and RH-PMLC specimens were less significant, with the percent difference in the average β parameter varying between -20% and -5%. These results indicated that the I-FIT and IDEAL-CT results were more sensitive to the impact of mix reheating than the OT results.

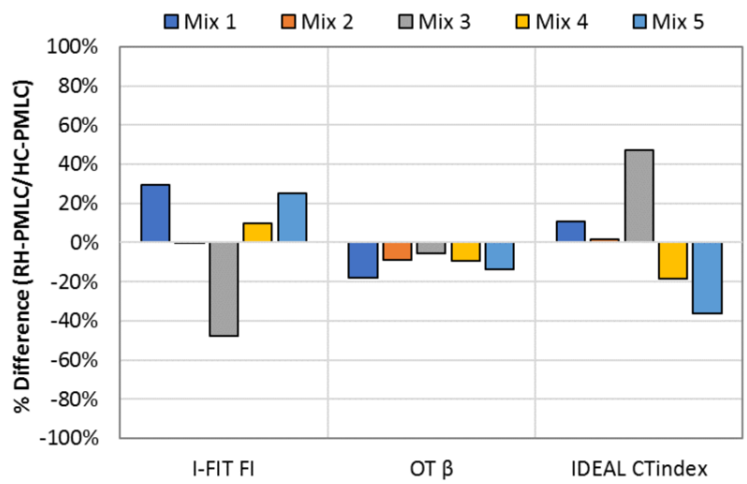


Figure 12. Percent Difference in the Average Cracking Test Results between HC-PMLC and RH-PMLC Specimens

Figure 13 presents the comparison of HWTT results for HC-PMLC and RH-PMLC specimens. In general, there was no consistent trend on the impact of mix reheating on mixture rutting resistance. For Mix 1 through Mix 3, the HC-PMLC specimens had lower CRD_{20k} values than the corresponding RH-PMLC specimens, while the opposite trend was observed for Mix 5. For Mix 4, the two sets of PMLC specimens had almost identical CRD_{20k} values. The percent difference in HWTT results of HC-PMLC and RH-PMLC specimens varied between -25% and 20% among the five BMD mixes (Figure 14).

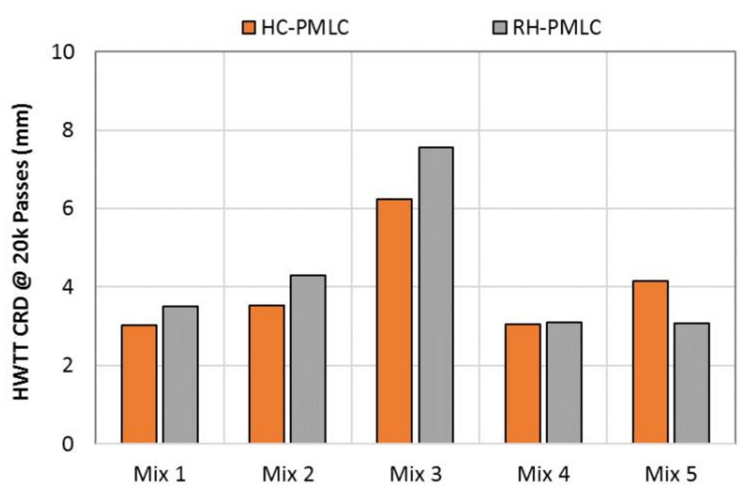


Figure 13. HWTT CRD_{20K} Results of HC-PMLC versus RH-PMLC Specimens

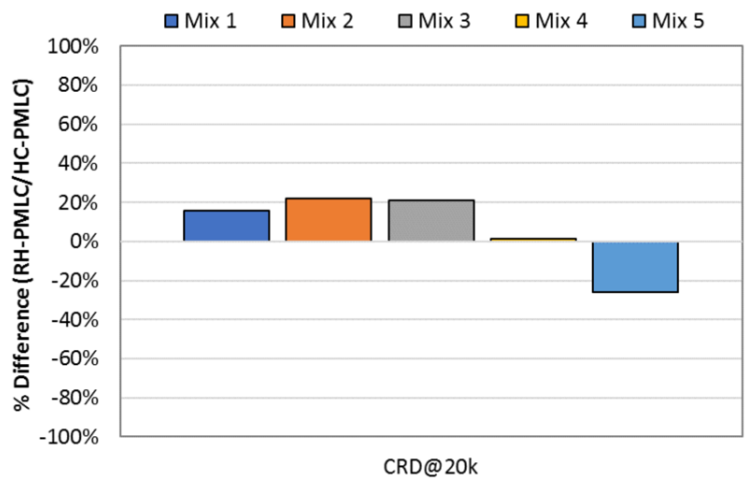
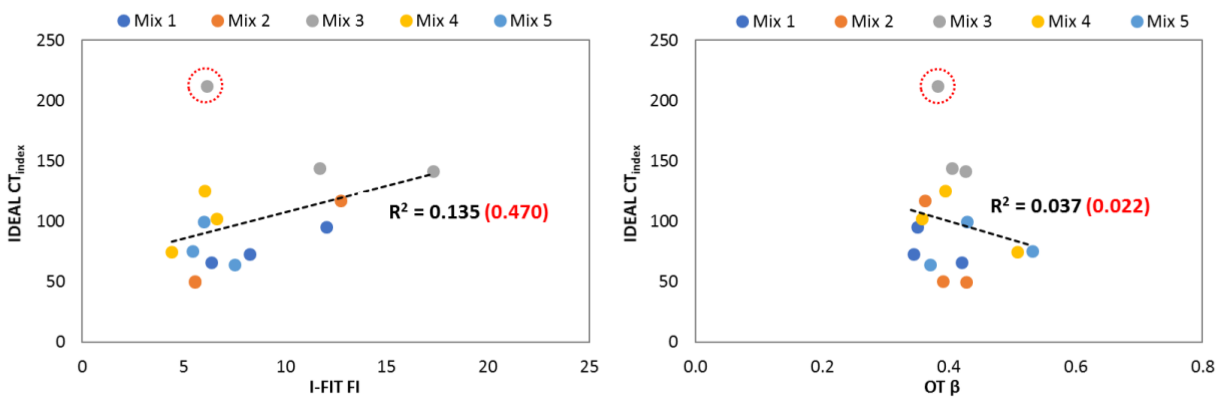


Figure 14. Percent Difference in the Average HWTT CRD_{20K} Results between HC-PMLC and RH-PMLC Specimens

4.3 Correlation between Surrogate and Mix Design Performance Test Results

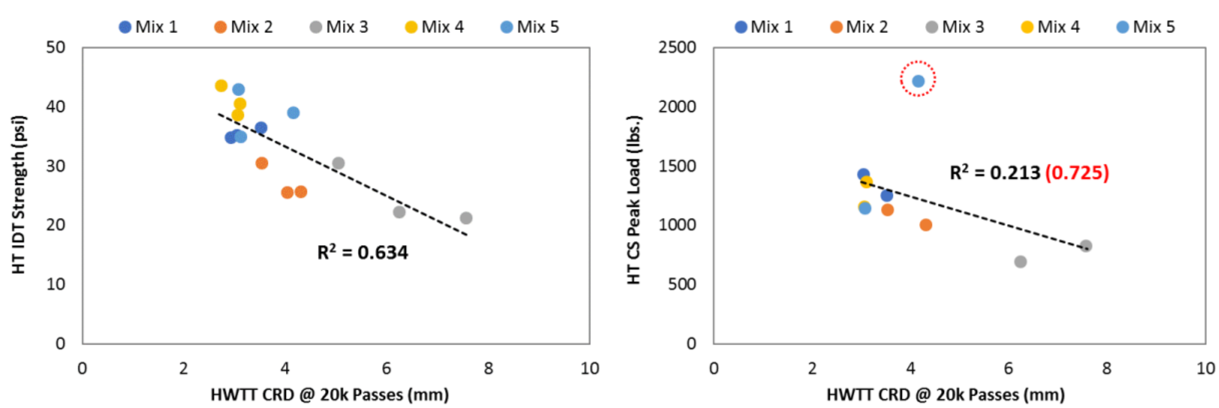
Figure 15 presents the correlation between the IDEAL-CT versus I-FIT and OT test results collected in the study. Note that the IDEAL-CT was evaluated as a candidate surrogate cracking test to I-FIT and OT for BMD production testing. Each correlation analysis includes 15 data points as a combination of five mixes and three specimen types. As shown in Figure 15(a), a general positive relationship was observed between the IDEAL-CT and I-FIT results, where CT_{index} increased as *FI* increased. However, the correlation between the two sets of test results was not strong with a correlation coefficient (r) of 0.367 and a resultant coefficient of determination (R^2) of 0.135. Among all the data points included, the one located most far away from the best-fit trendline had an abnormally high CT_{index} value of 212.1, which corresponded to the RH-PMLC specimens of Mix 3. If this data point was excluded from the correlation analysis, the R^2 value improved to 0.470 (r = 0.686); nevertheless, the correlation between IDEAL-CT and I-FIT results was not robust. Although the IDEAL-CT and OT results showed a general negative relationship where CT_{index} increased as the β parameter decreased [Figure 15(b)], the correlation was very weak with a R^2 value of 0.037 (r = 0.192). Excluding the data point with an extremely high CT_{index} did not improve the correlation between the IDEAL-CT and OT results. In summary, no strong correlation between the IDEAL-CT versus I-FIT and OT results was found in Figure 15. Therefore, it is not recommended for transportation agencies to utilize a "universal" correlation to determine a production criterion for IDEAL-CT based on the mix design criteria using I-FIT or OT. Mix-specific correlations, however, may exist among the three cracking tests and need further investigation.



(a) (b)

Figure 15. Correlation between Surrogate versus Mix Design Cracking Test Results; (a) IDEAL-CT vs. I-FIT, (b) IDEAL-CT vs. OT

Figure 16 presents the correlation between the HT-IDT and HT-CS results versus HWTT CRD_{20k} results. Note that the HT-IDT and HT-CS tests were evaluated as two candidate surrogate rutting tests to HWTT for BMD production testing. As shown in Figure 16(a), a reasonable negative relationship was found between the HT-IDT and HWTT results, where the HT-IDT strength increased as CRD_{20k} decreased. The correlation between the two sets of rutting results had a R^2 value of 0.634 (r = 0.796). However, no correlation was found between the HT-CS test and HWTT results in Figure 16(b). It should be noted that due to the availability constraint of the HT-CS shear fixture [Figure 4(a)], the HT-CS test was not conducted on LMLC specimens. Among the ten data points (for HC-PMLC and RH-PMLC specimens only) included in Figure 16(b), the one located most far away from the best-fit trendline had an abnormally high HT-CS peak load of 2,219.7 lbs., which corresponded to the HC-PMLC specimens of Mix 5. If this data point was excluded from the correlation analysis, the R^2 value improved significantly to 0.725 (i.e., r = 0.851). In summary, test results in Figure 16 demonstrated the potential of using the HT-IDT and HT-CS tests as two candidate surrogate rutting tests to HWTT for BMD production testing.



(a) (b)

Figure 16. Correlation between Surrogate versus Mix Design Rutting Test Results; (a) HT-IDT Test vs. HWTT, (b) HT-CS Test vs. HWTT

5 CONCLUSIONS AND RECOMMENDATIONS

Based on the test results and data analyses of this study, the following conclusions are made:

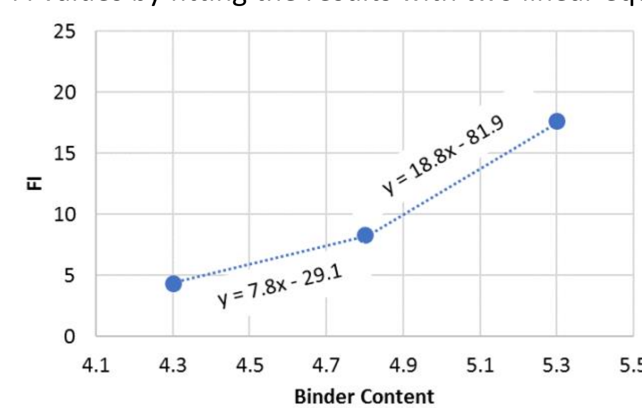
- Notable differences were found in the performance test results of the five BMD mixes between mix design and production. Three production mixes failed the rutting or cracking test requirement used for mix design approval, and thus, fell outside the performance “sweet zone.”
- There was no consistent trend in the comparison of cracking test results between mix design (LMLC specimens) and production (RH-PMLC specimens). The percent difference varied from approximately -60% to 50% for I-FIT and IDEAL-CT. As compared to I-FIT and IDEAL-CT, the differences in the OT results were less significant; the percent difference varied from -30% to 10%.
- The impact of mix reheating on the performance test results was mixed among the five BMD mixes and varied from test to test. The percent difference in the cracking test results between HC-PMLC and RH-PMLC specimens varied from -50% to 30% for I-FIT, -40% to 50% for IDEAL-CT, and -20% to -5% for OT. The percent difference in the HWTT results between the two sets of PMLC specimens varied between -25% and 20%.
- No correlation was found between IDEAL-CT versus I-FIT and OT results. Therefore, it is not recommended for transportation agencies to utilize a “universal” correlation to determine a production criterion for IDEAL-CT based on the mix design criteria using I-FIT or OT. Mix-specific correlations, however, may exist among these cracking tests and need further investigation.
- The HT-IDT and HT-CS tests showed reasonable correlations to HWTT, and thus, have the potential of being used as a surrogate rutting test to HWTT for BMD production testing.

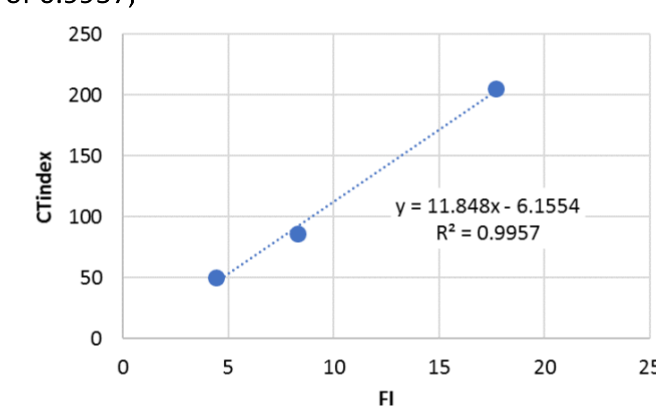
Based on the findings of this study, a draft outline of procedure for QC and acceptance testing of BMD is developed and discussed as follows. For ease of explanation, two illustrative examples with actual performance testing data are provided. In Example 1, I-FIT was used as the cracking test for both mix design and production testing. In Example 2, IDEAL-CT was used as surrogate cracking test to I-FIT for production testing, where the production criterion was determined based on the mix-specific correlation between the I-FIT and IDEAL-CT results at multiple asphalt binder contents.

5.1 Draft Outline of Procedure for Quality Control and Acceptance Testing of BMD

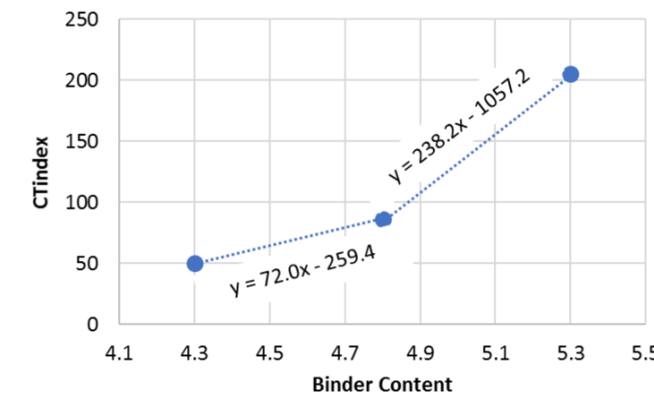
<table>
<tr><th>Step</th><th>Activity</th><th>Example 1</th><th>Example 2</th></tr>
<tr><td>1</td><td>Establish a BMD job mix formula per AASHTO Rxx, Balanced Asphalt Mixture Design, or Agency Specification</td><td>• Design a 35% RAP mix (with rejuvenator) following Oklahoma DOT’s 2018 provisional specification on BMD;
  o HWTT criterion: rut depth (RD) < 12.5mm at 20,000 passes, 50°C;
  o I-FIT criterion: flexibility index (FI) > 8.0 at 25°C.
• Select OBC of 4.8% based on the following design performance results.
<table><tr><th>Binder Content</th><th>I-FIT FI</th><th>HWTT RD (mm)</th></tr><tr><td>4.3%</td><td>4.4</td><td>3.0</td></tr><tr><td>4.8% (OBC)</td><td>8.3</td><td>4.0</td></tr><tr><td>5.3%</td><td>17.7</td><td>4.7</td></tr></table></td><td>Same as Example 1.</td></tr>
<tr><td>2</td><td>Select mixture performance test(s) for QC and acceptance testing [1].

Note 1: The selected production test(s) may differ from those used in mix design.</td><td>• Select I-FIT as the production cracking testing (in this example, rutting test is not required for production testing).</td><td>• Select IDEAL-CT as a surrogate production cracking test to I-FIT (in this example, rutting test is not required for production testing).</td></tr>
<tr><td>3</td><td>Establish mix-specific sensitivity relationships between asphalt binder content (and possibly minus #200) and performance test results [2].
• In cases where the mix design test(s) is to be used for production, use the original BMD design curve(s).
• Otherwise, conduct the selected production test(s) at the optimum binder content (OBC), OBC plus 0.5%, and OBC minus 0.5%, and verify the correlation between the mix design and production test results (preferably with a R^2 value of 0.8 or higher). If a correlation does not exist, it would necessitate not using the selected surrogate test in a production setting.
Estimate the changes in production test results for every 0.1% decrease and increase in binder content from OBC.

Note 2: The developed relationships can assist in the control of the mixture during production.</td><td>• Establish a sensitivity relationship between asphalt binder contents and I-FIT FI values by fitting the results with two linear equations.


  o For every 0.1% decrease in asphalt binder content from OBC, FI is expected to decrease by 0.78 from the target value of 8.3;
  o For every 0.1% increase in asphalt binder content from OBC, FI is expected to increase by 1.88 from the target value of 8.3.</td><td>• Conduct IDEAL-CT at OBC, OBC - 0.5%, and OBC + 0.5%;
<table><tr><th>Binder Content</th><th>IDEAL CT_{index}</th></tr><tr><td>4.3%</td><td>50.2</td></tr><tr><td>4.8% (OBC)</td><td>86.2</td></tr><tr><td>5.3%</td><td>205.3</td></tr></table>
• Verify the mix-specific correlation between IDEAL-CT and I-FIT results with a R^2 of 0.9957;


• Establish a sensitivity relationship between asphalt binder contents and IDEAL CT_{index} values by fitting the results with two linear equations;</td></tr>
</table>

			 ○ For every 0.1% decrease in asphalt binder content from OBC, CT_{index} is expected to decrease by 7.2 from the target value of 86.2; ○ For every 0.1% increase in asphalt binder content from OBC, CT_{index} is expected to increase by 23.8 from the target value of 86.2.
4	Establish the production criterion based on the agency specified production tolerance for asphalt binder content.	• If the agency currently allows ±0.3% in asphalt binder content for production tolerance, the minimum production FI criterion would be selected as 6.0 (8.3 - 3 * 0.78 = 5.96, rounding up to 6.0).	• If the agency currently allows ±0.3% in asphalt binder content for production tolerance, the minimum production CT_{index} criterion would be selected as 65 (86.2 - 3 * 7.2 = 64.6, rounding up to 65).
5	Conduct the selected production test(s) on plant produced mix at the agency specified testing frequency [3]. Measure and report volumetric properties as typically required (for information only). **Note 3**: The testing frequency should be selected by considering the time associated with the total test tie required for the selected production test(s).	• Conduct I-FIT for every 2,000 tons of production mix.	• Conduct IDEAL-CT for every 2,000 tons of production mix.
6	Compare the production test results versus the criteria established in Step 5. Accept or reject the mix based on the "Go" vs. "No-Go" option or using pay factor adjustments by including softer boundaries such as bonus, full pay, penalty, and removal. **Note 4:** The criteria used for pay factor adjustments should be selected by considering the test method variability and their correlation to actual field performance.	• Follow the "Go" versus "No-Go" option. ○ If FI ≥ 6.0, accept the mix; ○ If FI < 6.0, reject the mix.	• Follow the "Go" versus "No-Go" option. ○ If CT_{index} ≥ 65, accept the mix; ○ If CT_{index} < 65, reject the mix.

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