Crack Resistance and Durability of Ohio DOT Asphalt Mixtures Using I-FIT & IDEAL-CT: Phase 2

Prepared by:
Ala R. Abbas
Munir Nazzal
Tanvir Quasem
Mustafa Mansour
Syed Faizan Husain

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Prepared by:

Ala R. Abbas
Tanvir Quasem
Mustafa Mansour
Department of Civil Engineering
The University of Akron
Akron, Ohio 44325

Munir Nazzal
Syed Faizan Husain
Department of Civil and Architectural Engineering
and Construction Management
The University of Cincinnati
Cincinnati, OH 45221

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16. Abstract		

The primary objective of this research project was to assist the Ohio Department of Transportation (ODOT) in identifying a laboratory test that can be used to characterize the fracture behavior and cracking resistance of asphalt mixtures for potential incorporation into ODOT's mix design approval and quality control/quality assurance (QC/QA) process. Two laboratory tests were evaluated for this purpose, namely the Illinois flexibility index test (I-FIT) and indirect tensile asphalt cracking test (IDEAL-CT).

A laboratory testing plan was developed and implemented in this project that involved conducting both tests on a limited number of asphalt mixtures for screening purposes and selecting one of the two tests for full-scale evaluation using a larger number of asphalt mixtures representing the majority of asphalt mixtures used by ODOT. The screening evaluation revealed a high correlation between the I-FIT and IDEAL-CT test results. The I-FIT and IDEAL-CT test results also resulted in a similar ranking of asphalt mixtures in terms of resistance to cracking, which implies that each test can be used as a surrogate for the other. Several advantages were identified for the IDEAL-CT test that make it more favorable to use than the I-FIT test, including faster and easier sample preparation, applicability to asphalt mixtures containing larger aggregates, ability to achieve target air void level during compaction, availability of Excel spreadsheets to analyze test results, lower variation in test results, and familiarity of asphalt mix designers in Ohio with sample preparation and test procedure for conducting the IDEAL-CT test.

Therefore, it was recommended to select the IDEAL-CT test for the full-scale evaluation. The laboratory test results from the full-scale evaluation revealed that the total asphalt content (%), percentage of RAP, blend absorption (%), and aggregate gradation represented using the percent passing 3/4" sieve are the most significant parameters affecting the cracking parameter obtained using the IDEAL-CT test.

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1. Problem Statement

Asphalt binder is the most expensive component of asphalt mixtures that are used in flexible pavement construction. Over the last two decades, the price of liquid asphalt has risen significantly leading to substantial increases in the cost of asphalt pavements. This has led asphalt paving contractors and highway agencies to seek alternative techniques to reduce the amount of virgin asphalt used in asphalt mixtures and thereby lower the cost of pavement construction. Some of these techniques involved the use of recycled materials such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) in the production of asphalt mixtures. RAP is typically obtained from pavement resurfacing by surface milling or from pavement reconstruction activities that involve full-depth removal, while RAS is obtained from two sources: post-manufactured asphalt shingles (factory rejects and cut-outs that are discarded as scrap) and post-consumer asphalt shingles (weathered shingles that are removed when a new roof is installed on a building). The former is typically referred to as "manufacturer scrap," while the latter is generally referred to as "tear-offs."

While the potential benefits of incorporating higher percentages of RAP and RAS in asphalt mixtures are substantial, the use of these materials presents a concern that the resulting mixture may be more prone to load and non-load associated cracking and adhesion/cohesion failures during the service life of the pavement structure. This is due to the fact that the asphalt binder contained in the RAP and RAS is oxidized due to aging. Increased asphalt binder aging has been shown to contribute to the reduction of the adhesive and cohesive properties as well as the stress relaxation capacity of the binder, which are the root causes for the decreased cracking resistance of asphalt mixtures. This problem is magnified when RAS is used in conjunction with RAP in the preparation of asphalt mixtures.

The performance of asphalt mixtures containing RAP and RAS have generally been quantified by evaluating their rutting resistance, which is expected to improve by incorporating higher amounts of stiff aged binders and lower amounts of softer virgin binders. As the performance of RAP- and RAS-containing asphalt mixtures involves more than rutting, ODOT initiated a research study in 2016 entitled, "Crack Resistance and Durability of RAS Asphalt Mixtures," to address the need for a better method to predict durability performance of asphalt mixtures containing RAP and RAS (Rodezno et al. 2018). As part of the 2016 study, two test methods were proposed: the Texas overlay tester (Texas OT) and the Illinois semi-circular bend

(SCB) test, which is commonly referred to as the Illinois flexibility index test (I-FIT). After the completion of Phase 1, ODOT decided that the I-FIT was a better fit for ODOT's needs. However, a more user-friendly test method, the indirect tensile asphalt cracking test (IDEAL-CT), subsequently became available that may produce similar predictions for durability performance. To make an informed decision regarding the selection of an appropriate test method for the characterization of RAP- and RAS-containing asphalt mixtures and the adoption of standards for such method, ODOT modified the scope of the second phase of this research project to obtain additional test results using both test methods.

This research project aimed at evaluating a relatively large number of asphalt mixtures containing RAP and RAS using the I-FIT and IDEAL-CT tests in order to assist in the identification of an appropriate laboratory test that can be used by non-college educated technicians at ODOT and contractor labs to characterize the behavior of RAP- and RAS-containing asphalt mixtures. A standard test method was developed for the selected laboratory test to be used by ODOT and its contractors in mix design approval and QC/QA. In addition, recommendations were provided regarding the target performance criteria for asphalt mixtures containing RAP and RAS to ensure satisfactory field performance.

2. Research Background

2.1 Objectives of the Study

The primary objective of this research project is to assist ODOT in identifying a laboratory test that can be used to characterize the fracture behavior and cracking resistance of RAP- and RAS-containing asphalt mixtures for potential incorporation into ODOT's mix design approval and QC/QA process. The specific objectives of this project include:

- Develop a laboratory testing plan to evaluate the fracture behavior and cracking resistance of a relatively large number of surface, intermediate, and base course asphalt mixtures containing RAP and RAS.
- Evaluate the suitability of the I-FIT and IDEAL-CT tests and provide recommendations to ODOT for which testing equipment and methodology can be used to adequately test RAP/RAS mixtures for the desired properties. The recommended test equipment shall be appropriately sensitive, user-friendly, and can be operated efficiently by non-college educated technicians in the public and private sectors.

- Develop a test standard that includes target performance criteria to be used by ODOT and its contractors with the selected testing equipment and provide recommendations on how ODOT can best apply this test standard in its specifications to ensure satisfactory field performance for asphalt mixtures containing RAP and RAS.
- Suggest modifications to current ODOT RAP/RAS specifications based on the outcome of the laboratory testing conducted in this study.

2.2 Research Tasks

To achieve the previous objectives, this project included the following nine tasks:

- Task 1: Conduct Literature Review
- Task 2: Prepare Test Standards for the I-FIT and IDEAL-CT in ODOT Format
- Task 3: Develop a Laboratory Testing Plan for Screening and Full-Scale Evaluation of I-FIT and IDEAL-CT Tests
- Task 4: Conduct Testing for Screening Evaluation
- Task 5: Analyze Screening Test Results
- Task 6: Recommend a Test Method for Full-Scale Evaluation
- Task 7: Update Laboratory Testing Plan and Conduct Testing for Full-Scale Evaluation
- Task 8: Conduct Comprehensive Data Analysis
- Task 9: Prepare Final Report and Present Findings

2.3 Summary of Literature Review

Since the introduction of the I-FIT and IDEAL-CT in 2015 and 2017, respectively, several research studies were conducted to evaluate the fracture behavior and cracking resistance of asphalt mixtures using these two tests. These studies examined the effect of the testing equipment, specimen geometry, air void level, loading rate, testing temperature, aging level, mix design and composition on the I-FIT and IDEAL-CT test results. A thorough literature review of these studies was conducted as part of this research project (presented as Appendix A). Proposed performance criteria for both tests, repeatability of test results, correlation of laboratory test results to field performance, and efforts by state highway agencies to implement these tests in mix design approval and QC/QA were also covered in the literature review.

Below is a summary of the main findings from the literature review:

- Effect of testing equipment
  - Castillo-Camarena and Hall (2020) compared the loading rate obtained using a Pine Marshall testing platform that was equipped with a new load cell, a new linear variable differential transducer (LVDT), and new data acquisition system to the loading rate obtained using an asphalt mixture performance tester (AMPT). The loading rate obtained using the AMPT was found to be relatively constant and met the target specification loading rate of 50 ± 2 mm/minute, while the loading rate obtained using the Pine Marshall testing platform was inconsistent and did not meet the specified loading rate.
- Effect of specimen geometry
  - Al-Qadi et al. (2015) investigated the effect of specimen thickness on the I-FIT test results. The test results showed a relatively linear reduction in flexibility index (FI) with the increase in specimen thickness. Therefore, a linear equation was proposed to account for the effect of slice thickness on the FI value. The specimen thickness correction factor proposed by Al-Qadi et al. (2015) was evaluated and found to be reasonable by Rivera-Perez et al. (2018) and Kaseer et al. (2018).
  - Rivera-Perez et al. (2018) investigated the effect of the notch length in the I-FIT test results. The test results revealed a slight reduction in FI with the increase in notch length and a more obvious reduction in fracture energy (FE) and post-peak slope with the increase in notch length. The analysis of variance (ANOVA) was used to examine the effect of the notch length on FI, FE, and post-peak slope. The ANOVA results indicated a significant linear trend for both FE and post-peak slope, while the FI was not found to be significantly affected by the notch length.
  - Chen and Solaimanian (2020) compared the FI test results for top and bottom specimens obtained from 150-mm Superpave gyratory-compacted samples. No clear difference was observed between the top and bottom specimens.
- Effect of air void level
  - Several research studies were conducted to examine the effect of the specimen air void level on the I-FIT test results. It was generally observed that the FI increased with the increase in air void level (Barry 2016, Kaseer et al. 2018, Sreedhar and Coleri 2018, Rivera-

Perez et al. 2018, Batioja-Alvarez et al. 2019). Two equations were proposed by Barry (2016) and Kaseer et al. (2018) to correct for the effect of air void level on FI.

- Effect of loading rate
  - Rivera-Perez et al. (2018) and Haslett (2018) examined the effect of the loading rate on the I-FIT test results. No clear trend was observed between the FI and the loading rate.
- Effect of testing temperature
  - Haslett (2018) examined the effect of the testing temperature on the I-FIT test results. The FI was found to generally increase with the increase in testing temperature. However, the ranking of the asphalt mixtures was not the same at all temperatures, which was attributed to the variation in temperature sensitivity of the asphalt mixtures.
- Effect of asphalt mixture conditioning and aging
  - Asphalt mixture conditioning and aging have been found to be among the most significant factors affecting I-FIT and IDEAL-CT test results. Longer conditioning time was reported to result in lower FI values by Colas (2018). Lower FI values were also observed for long-term aged specimens than short-term aged specimens by Ling et al. (2017), Rodenza et al. (2018), Chen and Solaimanian (2019), and Zhu et al. (2019), and Zhang et al. (2019).
- Effect of mix design factors
  - The use of a stiffer asphalt binder (a binder with a higher high-temperature or a higher low-temperature PG grade), a larger nominal maximum aggregate size (NMAS), or higher percentages of RAP and/or RAS in the asphalt mixture generally resulted in lower cracking indices, while the incorporation of a higher asphalt binder content or a higher dose of a recycling agent (rejuvenator) in the asphalt mixture generally resulted in higher cracking indices (for more information, please refer to Tables A.3 and A.4).
- Laboratory-produced versus plant-produced asphalt mixtures
  - Some studies reported higher cracking indices for plant-produced asphalt mixtures than laboratory-produced mixtures (e.g., Batioja-Alvarez et al. (2019)), while others reported comparable cracking indices for both mixtures (e.g., Kaseer et al. (2018), Sreedhar et al. (2018), Sadek et al. (2019)).
  - It was suggested by Newcomb and Zhou (2019) to reheat plant-produced asphalt mixtures for 2 hours before compacting the IDEAL-CT specimens in order to obtain cracking tolerance indices (CT_{index}) comparable to short-term laboratory-produced mixtures.

- Repeatability of IDEAL-CT and I-FIT test results
  - The coefficients of variation (COVs) for FI generally ranged between 5% and 30%, while the COVs for the CT_{index} generally ranged between 5% and 25% (for more information, please refer to Tables A.5 and A.6).

3. Research Approach

Figure 1 presents a flow chart of the research approach that was followed in this research project. As can be noticed from this figure, a laboratory testing plan was developed and implemented in this project that involved conducting a preliminary evaluation to compare the performance of plant-produced versus laboratory-produced asphalt mixtures and to examine the effect of sample preparation on the I-FIT and IDEAL-CT test results. Based on the outcome of the preliminary evaluations, draft test methods were developed for both the I-FIT and IDEAL-CT tests that were used to conduct screening and full-scale evaluations of the I-FIT and IDEAL-CT tests to aid in identifying an appropriate laboratory test that can be used to characterize the cracking resistance and durability of RAP- and RAS-containing asphalt mixtures. In the screening evaluation, the I-FIT and IDEAL-CT tests were conducted on a limited number of asphalt mixtures. Based on the outcome of the screening evaluation, one of the tests was selected for further investigation in a full-scale evaluation using a larger number of asphalt mixtures representing the majority of asphalt mixtures used by ODOT.

Information about approved mix designs for surface, intermediate, and base course asphalt mixtures containing RAP and/or RAS was obtained from ODOT Asphalt Section and reviewed by the research team in order to select the asphalt mixtures that were included in the preliminary, screening, and full-scale evaluations. In addition, the research team contacted several asphalt paving contractors to inquire about the asphalt mixtures that would be used on ODOT construction projects and obtain the plant-produced asphalt mixtures for the laboratory testing. Detailed information about the asphalt mixtures that were included in the preliminary, screening, and full-scale evaluations is presented in the following subsections. The laboratory test results from these evaluations are presented in Appendices B, D, and E.

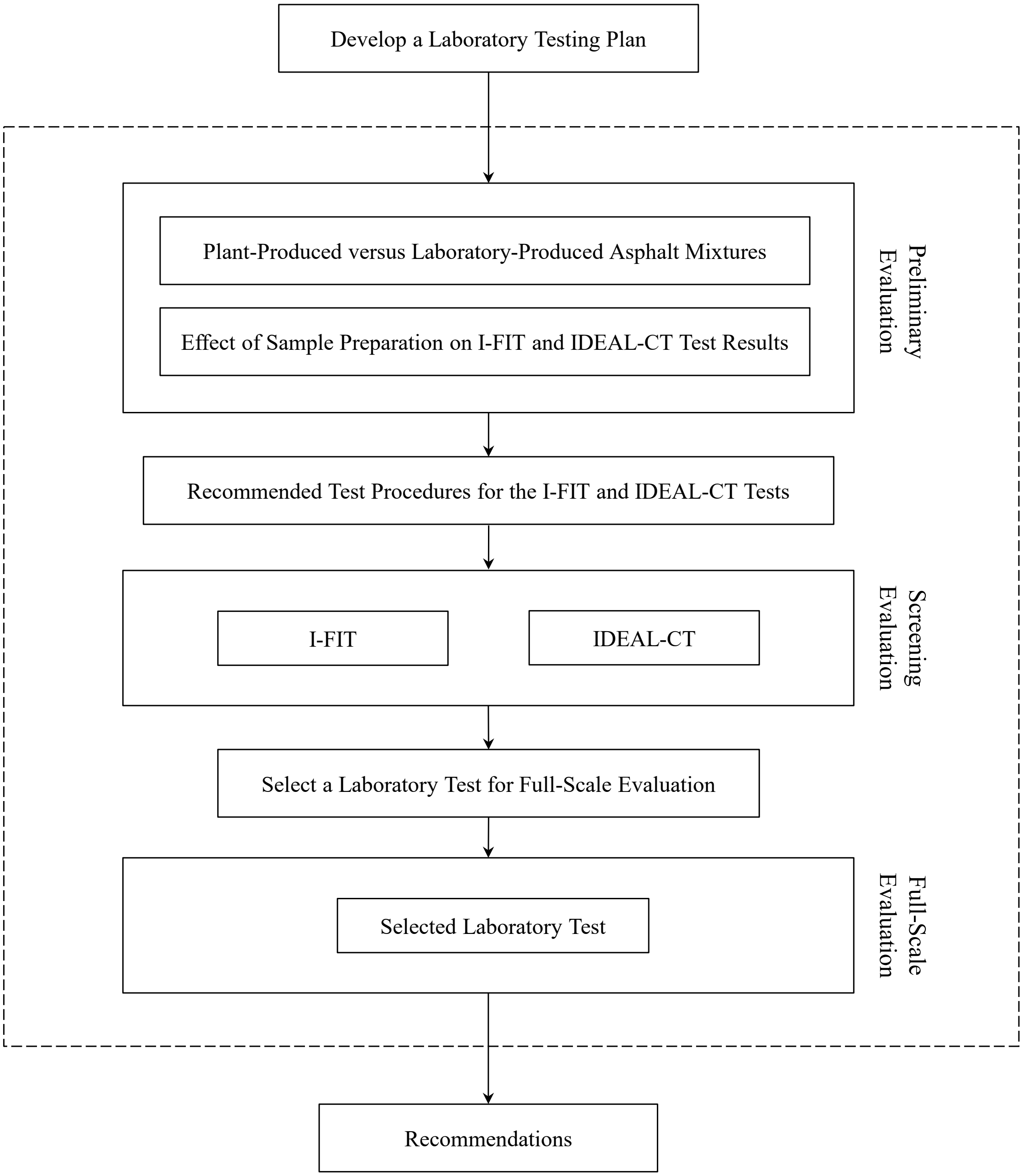

Figure 1. Flow Chart of Research Approach.

3.1 Preliminary Evaluation

The preliminary evaluation involved comparing the performance of plant-produced versus laboratory-produced asphalt mixtures, evaluating the effect of different aging protocols, examining the effect of air void level, investigating the effect of specimen dimensions, and examining the variability of the I-FIT and IDEAL-CT test results in order to determine the minimum number of specimens that are needed for each test. The laboratory testing matrices for the different parts of the preliminary evaluation are presented below.

Plant-Produced versus Laboratory-Produced Mixtures

Twenty-one asphalt mixtures were included in the comparison between plant-produced and laboratory-produced asphalt mixtures, representing six types of asphalt mixes used by ODOT: Item 442 (Superpave) 12.5 mm NMAS (Surface), Item 442 (Superpave) 19 mm NMAS (Intermediate), Item 441 (Marshall) Type 1 Surface, Item 441 (Marshall) Type 1 Intermediate, Item 441 (Marshall) Type 2 Intermediate, and Item 302 (Asphalt Concrete Base), as shown in Table 1. The plant-produced asphalt mixtures were obtained from asphalt plants and were compacted in the laboratory to prepare the I-FIT and IDEAL-CT specimens. In addition, laboratory-produced mixtures having the same composition as the plant-produced mixtures were prepared in the laboratory and were used to prepare the I-FIT and IDEAL-CT specimens for all twenty-one asphalt mixtures. The laboratory-produced asphalt mixtures were short-term aged according to AASHTO R 30 prior to compacting the I-FIT and IDEAL-CT specimens, while the plant-produced asphalt mixtures were reheated for 3 hours at the compaction temperature before compacting the specimens.

Table 1. Material Composition of Mixtures included in the Comparison between Plant-Produced and Laboratory-Produced Asphalt Mixtures.

Mix Type	Mix ID	Binder Type	AC (%)	RAP (%)	RAS (%)
Superpave 12.5 mm (Surface)	M1012	PG 70-22M	5.9%	15%	0%
	M1030	PG 70-22M	6.1%	15%	0%
	M1090	PG 76-22M	6.1%	15%	0%
	M1018	PG 76-22M	5.7%	15%	0%
	M0704	PG 76-22M	5.8%	15%	0%
Superpave 19 mm (Intermediate)	M0288	PG 64-28	4.7%	30%	0%
	M0981	PG 64-28	4.8%	25%	0%
	M0961	PG 64-28	4.9%	35%	0%
	M1028	PG 64-28	5.0%	40%	0%

Table 1. Material Composition of Mixtures included in the Comparison between Plant-Produced and Laboratory-Produced Asphalt Mixtures (Continued).

Mix Type	Mix ID	Binder Type	AC (%)	RAP (%)	RAS (%)
Marshall Type 1 Surface	M0992	PG 64-22	6.3%	25%	0%
	M0643	PG 70-22M	6.2%	25%	0%
Marshall Type 1 Intermediate	M0248	PG 64-22	6.0%	25%	0%
	M0586	PG 64-22	6.5%	25%	0%
	M0697	PG 58-28	5.5%	40%	0%
Marshall Type 2 Intermediate	M0962	PG 58-28	5.0%	30%	0%
	M1025	PG 58-28	4.9%	40%	0%
Item 302 Asphalt Concrete Base	M0919	PG 58-28	4.3%	40%	0%
	M0246	PG 58-28	4.2%	30%	0%
	M0971	PG 58-28	4.4%	30%	0%
	M1011	PG 64-22	4.1%	20%	0%
	M1032	PG 58-28	4.1%	45%	0%

Effect of Aging Protocols

Four asphalt mixtures were selected to evaluate the effect of different aging protocols on the I-FIT and IDEAL-CT test results, including one Superpave 12.5 mm (Surface) mix (M1030), one Superpave 19 mm (Intermediate) mix (M1028), one Marshall Type 1 Surface mix (M0992), and one Marshall Type 2 Intermediate mix (M0962). Plant-produced and laboratory-produced mixtures were used for all four asphalt mixtures. The following aging protocols were used to simulate the short-term and long-term aging of the I-FIT and IDEAL-CT specimens:

- Short-term oven aged (STOA):
    - Reheating of loose plant-produced asphalt mixtures for 3 hours at the compaction temperature.
    - Heating of loose laboratory-produced asphalt mixtures according to AASHTO R 30.
- Long-term oven aged (LTOA85):
    - Heating of compacted plant- or laboratory-produced samples for five days at 85°C.
- Long-term oven aged (LTOA95):
    - Heating of compacted plant- or laboratory-produced samples for three days at 95°C.

Effect of Air Void Level

One plant-produced asphalt mixture was used to examine the effect of the air void level on the I-FIT and IDEAL-CT test results. A Superpave 12.5 mm (Surface) mix (M1030) – prepared using PG 70-22, 5.9% asphalt binder content, and 15% RAP – was used for this purpose. The I-FIT and IDEAL-CT specimens were prepared using three different target air void levels of 5%, 7%, and 9%. Short-term aged specimens were used for this evaluation.

Effect of Specimen Dimensions

The research team evaluated the effect of the specimen dimensions on the I-FIT and IDEAL-CT test results by varying the specimen thickness. Four different thicknesses (25 mm, 38 mm, 50 mm (standard), and 62 mm) were used for the I-FIT specimens. All specimens were obtained from Superpave gyratory compacted samples measuring 150 mm in diameter and 160 mm in height. One mixture (Superpave 12.5 mm mix – M1012) was used for the preparation of the I-FIT test specimens. As for the IDEAL-CT test, two specimen thicknesses were considered in the evaluation (62 mm and 95 mm) using the standard specimen diameter of 150 mm. Nine asphalt mixtures (two Superpave 12.5 mm mixes (M0704 plant-produced and M1012 plant-produced), one Superpave 19 mm mix (M1028 plant-produced), three Marshall Type 1 surface mixes (M0992 plant-produced, M0992 laboratory-produced, and M0643 laboratory-produced), two Marshall Type 1 intermediate mixes (M0697 plant-produced and M0697 laboratory-produced), and one Marshall Type 2 intermediate mix (M0962 laboratory-produced)) were used for the preparation of the IDEAL-CT test specimens.

Variability of I-FIT and IDEAL-CT Test Results

The variability of the I-FIT and IDEAL-CT test results for all asphalt mixtures included in the preliminary evaluation was analyzed in order to determine the minimum number of test specimens required for each test.

3.2 Screening Evaluation

Based on the outcome of the preliminary evaluations (as detailed in Appendix B), draft test methods were developed for both the I-FIT and IDEAL-CT tests in ODOT standard format (Appendix C) that included detailed information about the requirements for the test apparatus (including the type of the load-support fixture), asphalt mixture preparation, aging protocol, fabrication of test specimens (including the target air void level), specimen dimensions, test temperature, loading rate, information collected during loading of test specimens, number of test replicates, and procedure for analyzing the test data to calculate the required performance parameter(s). The draft test method for the I-FIT test was primarily based on AASHTO TP 124-18 (Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index Test) and the draft test method for the IDEAL-CT test was primarily based on ASTM D8225-19 (Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature) with some modifications to achieve the objectives of this research project.

The preliminary evaluation results revealed comparable or higher cracking indices in the I-FIT and IDEAL-CT tests for plant-produced asphalt mixtures than for laboratory-produced mixtures. In addition, the preliminary evaluation results revealed lower cracking indices for LTOA specimens (for both LTOA85 and LTOA95) than STOA specimens. However, the ranking of the asphalt mixtures with regard to resistance to cracking was the same for all aging protocols. Therefore, to reduce the specimen preparation time for the I-FIT and IDEAL-CT tests, it was recommended to use STOA specimens for both tests. Specimen air void level had a significant effect on the I-FIT and IDEAL-CT cracking indices, with higher indices obtained at higher air void levels for both tests. An air void level of 7.0 ± 1.0% was recommended for the I-FIT test, as specified in AASHTO TP 124-18, and an air void level of 7.0 ± 0.5% was recommended for the IDEAL-CT test, as specified in ASTM D8225-19. The I-FIT test results were also found to be greatly affected by the specimen thickness. Therefore, it was recommended to conduct this test at the standard thickness of 50 ± 1 mm. As for the IDEAL-CT test, comparable results were obtained for 62-mm-thick and 95-mm-thick specimens, which was expected as the calculation procedure for the CT_{index} includes a correction factor for the effect of specimen thickness. Recommendations were made to use a specimen thickness of 62 ± 3 mm for Type 1 (Surface and Intermediate) mixes and use a specimen thickness of 95 ± 5 mm for Superpave (12.5 mm and 19 mm), Type 2 (Intermediate), and Item 302 mixes. The COV for the CT_{index} in the IDEAL-CT test averaged around 20% for surface mixes, 20% for intermediate mixes, and 25% for asphalt base mixes; while the COV for the FI in the I-FIT test averaged around 25% for surface mixes, 25% for intermediate mixes, and 35% for asphalt base mixes. Therefore, it was recommended to conduct both tests using a minimum of six specimens.

As part of the screening evaluation, the CT_{index} values from the IDEAL-CT test were compared to the FI values from the I-FIT test for all specimens that were included in the preliminary evaluation except those used to examine the effects of air void level and specimen thickness. The screening evaluation revealed a high correlation between the I-FIT and IDEAL-CT test results for all mixtures, with a coefficient of determination, R^2, of approximately 0.74. The I-FIT and IDEAL-CT test results also resulted in a similar ranking of asphalt mixtures in terms of resistance to cracking, which implies that each test can be used as a surrogate for the other.

In addition to the high correlation between the I-FIT and IDEAL-CT test results, several advantages were identified for the IDEAL-CT test that make it more favorable to use for routine purposes than the I-FIT test, including:

- Faster and easier sample preparation. As compared to the I-FIT test, no cutting, trimming, or notching is needed for the preparation of the IDEAL-CT test samples. As a result, less time is required for the sample preparation and no additional pieces of equipment (such as saws) are needed for the IDEAL-CT test. The I-FIT test also requires test specimens to be discarded if the notch terminates in an aggregate particle 9.5 mm or larger on both faces of the specimen. This requirement may result in several specimens being discarded, especially for mixtures with larger aggregates. Therefore, additional samples will need to be prepared to obtain a sufficient number of specimens for testing.
- Applicability to asphalt mixtures containing larger aggregate particles. The I-FIT test is limited to testing asphalt mixtures with a nominal maximum aggregate size (NMAS) of 19 mm or less, while the IDEAL-CT can accommodate asphalt mixtures containing larger aggregate particles such as asphalt base mixes by increasing the specimen thickness to 95 mm (from a standard thickness of 62 mm).
- Easier to achieve the target air void level during compaction. Even though a more strict air void requirement is specified for the IDEAL-CT test than the I-FIT test (7.0 ± 0.5% for the IDEAL-CT versus 7.0 ± 1% for the I-FIT), it is easier to the achieve the target air void level for the IDEAL-CT specimens than the I-FIT specimens as no cutting and trimming is needed for the IDEAL-CT test. This is especially the case for asphalt mixtures with larger aggregate sizes.

- Straightforward analysis of test results. An Excel spreadsheet is available for analyzing the IDEAL-CT test results, while a software developed by the University of Illinois at Urbana-Champagne (UIUC) is typically used to analyze the I-FIT test results. Even though the I-FIT software is relatively simple to use, it was not easy to verify the outcome of the data analysis when some of the test results did not make sense.
- Lower variation in test results. The coefficient of variation (CV) for the CT_{index} in the IDEAL-CT test averaged around 20% for surface mixes, 20% for intermediate mixes, and 25% for asphalt base mixes; while the CV for the FI in the I-FIT test averaged around 25% for surface mixes, 25% for intermediate mixes, and 35% for asphalt base mixes.
- Familiarity of asphalt mix designers in Ohio with the sample preparation and test procedure that are used in the IDEAL-CT test. Even though additional requirements are specified for the IDEAL-CT test regarding the testing equipment and the analysis of the test results, the sample preparation and test procedure used in the IDEAL-CT test are similar to those specified in ODOT Supplement 1051 (Resistance of Compacted Hot Mix Asphalt to Moisture-Induced Damage). Therefore, it should be easier to adopt the IDEAL-CT test as part of the asphalt mix design process in Ohio than the I-FIT test.
- Cost of test equipment. The IDEAL-CT test is conducted using an axial loading device capable of maintaining a constant deformation rate of 50 ± 2 mm/min that is equipped with a standard indirect tensile strength loading fixture similar to that specified in ODOT Supplement 1051. Some researchers informally indicated that the standard Pine loading frame that is widely available in Ohio can also be used for this purpose. If this is the case, no additional equipment cost will be required for the implementation of the IDEAL-CT as part of the asphalt mix design process in Ohio. Otherwise, an IDEAL-CT test setup that is also capable of performing the I-FIT can be purchased for around $12,000. The I-FIT test requires additional saws that cost around $6,000.

Based on the abovementioned advantages, it was recommended to conduct the full-scale evaluation using the IDEAL-CT test. For a more detailed discussion of the advantages of the IDEAL-CT test, please refer to Appendix D.

3.3 Full-Scale Evaluation

The laboratory testing plan was expanded in the full-scale evaluation using the IDEAL-CT test to include a larger number of asphalt mixtures representing the majority of mixtures used by ODOT. The cluster analysis method was used to group ODOT-approved asphalt mix designs for different mix types based on mix composition to aid in the selection of a representative sample of asphalt mixtures to be included in the full-scale evaluation. Clustering is basically a technique that groups data sets (in this case asphalt mix designs) into smaller groups of similar attributes called clusters. In this study, the asphalt mix designs were divided into clusters based on the composition of the mix blend, which was represented using the percentage of RAP (RAP%), percentage of RAS (RAS%), percentage of natural sand (NS%), percentage of natural gravel (NG%), percentage of crushed gravel (CG%), percentage of limestone (LS%), and percentage slag (Slag%). For more detailed information about the cluster analysis method and the selection of the optimum number of clusters, please refer to Appendix E.

The cluster analysis results for Superpave 12.5 mm mixes are presented in Table 2. As can be noticed from this table, a total of 1,379 mix designs were used for the cluster analysis for this mix type. It can also be noticed from this table that the largest cluster (Cluster 4) consisted of 531 mixes (representing ~39% of the Superpave 12.5 mm mixes) with a cluster mean of 14.8% RAP, 0.0% RAS, 14.5% natural sand, 0.1% natural gravel, 0.2% crushed gravel, 70.5% limestone, and 0.0% slag. In contrast, the smallest cluster (Cluster 5) consisted of 12 mixes (representing ~1% of the Superpave 12.5 mm mixes) with a cluster mean of 13.5% RAP, 0.0% RAS, 33.1% natural sand, 0.0% natural gravel, 0.0% crushed gravel, 53.4% limestone, and 0.0% slag.

Nine out of the twelve clusters (denoted with an asterisk next to the cluster number in Table 2) were selected for inclusion in the full-scale evaluation representing ~97% of the mix design of the Superpave 12.5 mm mixes. Table 3 presents the blend composition of the Superpave 12.5 mm mixes that were included in the full-scale evaluation to represent the nine clusters. As some of the Superpave 12.5 mm mixes in this table were already tested as part of the screening evaluation (shown in italics), there was no need to retest them as part of the full-scale evaluation.

Table 2. Cluster Analysis Results for Superpave 12.5 mm Mixes.

Cluster No.	Count	%	RAP	RAS	NS	NG	CG	LS	ACBF Slag
1*	207	15%	13.7	0.0	0.0	0.0	1.1	85.1	0.1
2*	182	13%	15.0	0.0	7.9	0.0	0.0	77.1	0.0
3*	52	4%	14.4	0.0	10.0	0.0	0.0	52.5	23.1
4*	531	39%	14.8	0.0	14.5	0.1	0.2	70.4	0.0
5	12	1%	13.5	0.0	33.1	0.0	0.0	53.4	0.0
6*	129	9%	10.0	0.0	12.0	0.0	0.0	78.0	0.0
7*	42	3%	0.0	0.0	12.6	0.6	3.0	83.8	0.0
8*	82	6%	13.4	0.0	12.5	1.7	60.6	7.8	4.0
9	25	2%	14.9	0.0	13.1	0.0	31.7	40.3	0.0
10*	48	3%	14.7	0.0	12.7	0.0	0.0	12.2	60.4
11*	47	3%	14.4	0.0	12.3	27.3	1.3	37.6	7.1
12	22	2%	12.0	0.0	12.7	54.7	0.0	9.3	11.3
Total	**1,379**	**100%**							

Note: Clusters with asterisks were selected for inclusion in the full-scale evaluation as they represented a larger percentage of asphalt mix designs.

Table 3. Mix Blend Composition of Selected Superpave 12.5 mm Mixes.

Cluster No.	Mix ID	%	RAP	RAS	NS	NG	CG	LS	ACBF Slag
1	M2719	15%	15.0	0.0	0.0	0.0	0.0	85.0	0.0
2	*M1012*	*13%*	*15.0*	*0.0*	*10.0*	*0.0*	*0.0*	*75.0*	*0.0*
2	*M0704*	*13%*	*15.0*	*0.0*	*8.0*	*0.0*	*0.0*	*77.0*	*0.0*
3	M2686	4%	15.0	0.0	13.0	0.0	0.0	57.0	15.0
4	*M1030*	*39%*	*15.0*	*0.0*	*15.0*	*0.0*	*0.0*	*70.0*	*0.0*
4	*M1090*	*39%*	*15.0*	*0.0*	*15.0*	*0.0*	*0.0*	*70.0*	*0.0*
6	M2367	9%	10.0	0.0	12.0	0.0	0.0	78.0	0.0
7	M2497	3%	0.0	0.0	11.5	0.0	0.0	88.5	0.0
8	M0888	6%	15.0	0.0	12.0	0.0	60.0	13.0	0.0
9	*M1018*	*2%*	*15.0*	*0.0*	*10.0*	*0.0*	*40.0*	*35.0*	*0.0*
10	M0676	3%	15.0	0.0	11.0	0.0	0.0	17.0	57.0
11	M2564	3%	15.0	0.0	10.0	31.0	16.0	28.0	0.0

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

A similar process was followed for selecting the asphalt mixtures for the other mix types (Superpave 19 mm, Type 1 Surface, Type 1 Intermediate, Type 2 Intermediate, and Item 302 mixes). A total of 1,102 mix designs were used in the cluster analysis for Superpave 19 mm mixes, 3,883 mix designs for Type 1 Surface mixes, 1,552 mix designs for Type 1 intermediate mixes, 2,930 mix designs for Type 2 Intermediate mixes, and 1,256 mix designs for Item 302 mixes. It is noted that some mix types such as Type 2 Intermediate showed higher variability in mix blend composition. Therefore, a larger number of clusters was needed to represent this mix type. In total, fifty-nine laboratory-produced asphalt mixtures were included in the full-scale evaluation. The test results for these asphalt mixtures are presented in Appendix E. As discussed in Appendix E, Superpave 12.5 mm and Type 1 Surface mixes exhibited the highest cracking resistance as measured using the CT_{index}, with an average CT_{index} of 101 and 111, respectively. Type 1 Intermediate and Item 302 mixes had an average CT_{index} of 98 and 87, respectively, while Type 2 Intermediate and Superpave 19 mm mixes had an average CT_{index} of 80 and 55, respectively. Additional specialty mixes (including mixes prepared RAS and mixes containing non-traditional binders such as PG 88-22M) were also tested as part of this research project.

The laboratory test results from the full-scale evaluation were analyzed to identify the most critical factors that should be considered in the design and evaluation of asphalt mixtures to ensure satisfactory resistance to cracking. Multi-linear regression analysis was conducted using the CT_{index} as the dependent variable and the following mix design parameters as the independent variables: total asphalt content (%), virgin asphalt content (%), RAP binder content (%), effective asphalt content (%), percentage of RAP, percentage of natural sand, percentage of natural gravel, percentage of crushed gravel, percentage of limestone, percentage of slag, fines to asphalt ratio (F/A), fifty to thirty ratio (F-T), asphalt binder film thickness (microns), blend absorption (%), percent passing 1.5” sieve, percent passing 1” sieve, percent passing 3/4” sieve, percent passing 1/2” sieve, percent passing 3/8” sieve, percent passing sieve #4, percent passing sieve #8, percent passing sieve #16, percent passing sieve #30, percent passing sieve #50, percent passing sieve #100, and percent passing sieve #200. The independent variables for all mixes were collected from job mix formula (JMF) packets provided by ODOT, with the exception of effective asphalt content (%), asphalt film thickness (microns), and blend absorption (%), which were estimated using information included in the JMF packets as well as ODOT aggregate specific gravity reports that include information about aggregate specific gravity and absorption for different ODOT-approved aggregate sources. The blend absorption (%) was estimated using the absorption and proportion of the various aggregates included in the asphalt mixture. For Item 302, several of the independent variables are not reported in the mix design packets. Therefore, the IDEAL-CT test results for this mix type were excluded from the regression analysis.

Forward and backward stepwise multi-linear regression analysis was performed to determine the optimum number of mix design variables to include in the regression model. The final CT_{index} model consisted of the following independent variables: total asphalt content (%), RAP binder content (%), percentage of natural gravel, percentage of slag, fifty to thirty ratio (F-T), blend absorption (%), percent passing 3/4” sieve, percent passing sieve #8, percent passing sieve #50, and percent passing sieve #100. From among these mix design parameters, the total asphalt content (%), percentage of RAP, blend absorption (%), and aggregate gradation represented using the percent passing 3/4” sieve were found to be the most significant parameters affecting the CT_{index}.

4. Research Findings and Conclusions

One of the objectives of this research project was to evaluate the suitability of the I-FIT and IDEAL-CT tests to characterize the fracture behavior and cracking resistance of asphalt mixtures in order to assist ODOT in identifying an appropriate laboratory test that can be used for routine purposes in mix design and QC/QA. A laboratory testing plan was developed and implemented in this project that involved conducting a preliminary evaluation to compare the performance of plant-produced versus laboratory-produced asphalt mixtures and to examine the effect of sample preparation on the I-FIT and IDEAL-CT test results. The laboratory testing plan also involved conducting both tests on a limited number of asphalt mixtures for screening purposes and selecting one of the two tests for full-scale evaluation using a larger number of asphalt mixtures representing the majority of asphalt mixtures used by ODOT. Below is a summary of the main findings and conclusions of the preliminary, screening, and full-scale evaluations:

- The preliminary evaluation results revealed comparable or higher cracking indices in the I-FIT and IDEAL-CT tests for plant-produced asphalt mixtures than for laboratory-produced mixtures. Higher cracking indices were also obtained for STOA specimens than for LTOA specimens (for both LTOA85 and LTOA95). However, the ranking of the asphalt mixtures with regard to resistance to cracking was the same for all aging protocols. Therefore, to reduce the specimen preparation time for the I-FIT and IDEAL-CT tests, it was recommended to use STOA specimens for both tests. Specimen air void level had a significant effect on the I-FIT and IDEAL-CT cracking indices, with higher indices obtained at higher air void levels for both tests. Therefore, to reduce the variability of the test results, it is recommended to maintain a tight control over the specimen air void level. The I-FIT test results were also found to be greatly affected by the specimen thickness, while comparable results were obtained for the IDEAL-CT test when using 62-mm-thick and 95-mm-thick specimens. The COV for the CT_{index} in the IDEAL-CT test averaged around 20% for surface mixes, 20% for intermediate mixes, and 25% for asphalt base mixes; while the COV for the FI in the I-FIT test averaged around 25% for surface mixes, 25% for intermediate mixes, and 35% for asphalt base mixes. Therefore, it was recommended to conduct both tests using a minimum of six specimens.

- The screening evaluation revealed a high correlation between the I-FIT and IDEAL-CT test results, with a coefficient of determination, R^2, of approximately 0.74. The I-FIT and IDEAL-CT test results also resulted in a similar ranking of asphalt mixtures in terms of resistance to cracking, which implies that each test can be used as a surrogate for the other. In addition, several advantages were identified for the IDEAL-CT test that make it more favorable to use than the I-FIT test, including faster and easier sample preparation, applicability to asphalt mixtures containing larger aggregate particles, ability to achieve the target air void level during compaction, availability of Excel spreadsheets to analyze the test results, lower variation in test results, and familiarity of asphalt mix designers in Ohio with the sample preparation and test procedure for conducting the IDEAL-CT test. Therefore, it was recommended to select the IDEAL-CT test for the full-scale evaluation.
- The laboratory test results from the full-scale evaluation were analyzed to identify the most critical factors that should be considered in the design and evaluation of asphalt mixtures to ensure satisfactory resistance to cracking, as measured using the IDEAL-CT test. Total asphalt content (%), percentage of RAP, blend absorption (%), and aggregate gradation represented using the percent passing 3/4” sieve were found to be the most significant parameters affecting the CT_{index}.
- A relatively large number of asphalt mixtures were evaluated in this study. These mixtures contained varying amounts of RAP to represent the mix designs commonly used in Ohio. A limited number of asphalt mixtures containing RAS were also included in the laboratory testing

plan even though RAS is rarely used in Ohio at the current time. In general, the IDEAL-CT test results showed relatively high CT_{index} values for virgin asphalt mixtures (containing no RAP and no RAS), indicating good resistance to cracking. In contrast, asphalt mixtures containing RAS showed poor resistance to cracking, as indicated by the low CT_{index} values obtained for these mixtures. The regression analysis results also showed a decrease in the CT_{index} with the increase in the amount of RAP incorporated into the asphalt mixture. However, other factors such as the total asphalt content (%), blend absorption (%), and percent passing 3/4" sieve were found to have a more significant effect than the amount of RAP on the CT_{index}.

5. Recommendations for Implementation

Based on the outcome of the preliminary, screening, and full-scale evaluations that were conducted as part of this research project, it is recommended for ODOT to use the IDEAL-CT test to characterize the fracture behavior and cracking resistance of asphalt mixtures. A draft test method detailing the requirements for the test device, fabrication of test specimens, specimen conditioning, IDEAL-CT test procedure, and reporting of the test results is presented in Appendix C in ODOT standard format. As can be noticed from this appendix, the draft test method for the IDEAL-CT test calls for using an axial loading device that is capable of applying an average constant deformation rate of 50 ± 2 mm/min. For asphalt mixtures prepared in the laboratory, it is recommended to short-term age the loose asphalt mixture according to AASHTO R 30, while for plant-produced mixtures, it is recommended to allow the loose asphalt mixture to cool to room temperature, then reheat the loose mixture at the compaction temperature for 2.5 to 3 hours prior to compaction. It is also recommended to compact the IDEAL-CT specimens to an air void level of 7.0 ± 0.5%, as specified in ASTM D8225-19, using a specimen thickness of 62 ± 3 mm for Type 1 (Surface and Intermediate) mixes and a specimen thickness of 95 ± 5 mm for Superpave (12.5 mm and 19 mm), Type 2 (Intermediate), and Item 302 mixes. Prior to testing, the IDEAL-CT specimens will need to be conditioned in a water bath or an environmental chamber at 25 ± 1°C for 2 hrs ± 10 minutes. A worksheet was also provided to summarize the IDEAL-CT test results.

Table 4 presents the minimum CT_{index} values that are recommended to be used by ODOT for the various mix types evaluated in this research project. It is suggested to use these threshold values as initial guidance by ODOT and to re-evaluate them and make adjustments if needed in the future. Even though a relatively large number of asphalt mixtures was included in the laboratory testing plan for this research project, caution should be used when applying the recommended threshold values to specialty mixes (such as mixes prepared using PG 88-22M), as the laboratory testing matrix included only a limited number of such mixes.

Table 4. Recommended Performance Criteria for the IDEAL-CT Test

Mix Type	**Minimum CT_{index}**
Item 442 (Superpave) 12.5 mm (Surface)	80
Item 442 (Superpave) 19 mm (Intermediate)	60
Item 441 (Marshall) Type 1 Surface Mixes	80
Item 441 (Marshall) Type 1 Intermediate Mixes	80
Item 441 (Marshall) Type 2 Intermediate Mixes	60
Item 302 (Marshall) Mixes	60

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Appendix A
Literature Review

A.1 Introduction

Over the last two decades, several laboratory tests and analysis procedures have been suggested to characterize the cracking resistance of asphalt mixtures, including the energy ratio (ER) test, the Texas overlay tester (Texas OT), the indirect tensile asphalt cracking test (IDEAL-CT), the indirect tensile strength using the N_{flex} approach, the Illinois semi-circular bend (SCB) test commonly referred to as the Illinois flexibility index test (I-FIT), the Louisiana Transportation Research Center semi-circular bend (SCB-LTRC) test, the Minnesota semi-circular bend (SCB-MN) test, and the disc-shaped compact tension (DCT) test. Among these tests, the I-FIT and IDEAL-CT tests have received more attention in recent years because they require a relatively inexpensive testing device and can be conducted within a reasonably short period of time making them easier to implement into mix design approval and quality control and quality assurance (QC/QA). The following subsections provide an overview of both test methods along with a summary of recent research studies that were conducted using these tests. The literature search in Phase 2 focused on updating the literature review that was conducted in Phase 1 of this research project (Crack Resistance and Durability of RAS Asphalt Mixtures – Phase 1) and was summarized in Rodenzo et al. (2018).

A.2 Illinois Flexibility Index Test

The Illinois flexibility index test (I-FIT) was developed as part of a research study for the Illinois Department of Transportation (IDOT) to evaluate the fatigue cracking resistance of asphalt mixtures containing reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) (Al-Qadi et al. 2015). The I-FIT is performed at an intermediate temperature of 25ºC according to AASHTO TP 124. The most recent version of this test standard is AASHTO TP 124-18 (Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using the Flexibility Index Test (FIT)), which is an updated version of AASHTO TP 124-16 (Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperatures). In this test, an asphalt mixture sample is compacted in a Superpave gyratory mold measuring 150 mm in diameter to a height of 160 mm. The compacted sample is then cut and trimmed into two cylindrical samples measuring 150 mm in diameter and 50 ± 1 mm in thickness. Each 50-mm thick sample is then sliced vertically to produce two semi-circular specimens. A notch with a depth of 15 mm and a width of less than 2.25 mm is then made at the center of the flat edge of the specimen.

The I-FIT is performed by loading the semi-circular specimens monotonically to failure at a constant cross-head deformation rate of 50 mm/min. Load and vertical deformation are recorded until the specimen breaks and the load reading drops to zero. The load and vertical deformation data is analyzed to calculate two cracking parameters, namely the fracture energy (FE) and the flexibility index (FI), which are calculated according to Equations A.1 and A.2, respectively. The FE represents the energy needed to propagate a crack through a pavement layer, whereas FI can be used to identify brittle mixes that are prone to premature cracking. Since FE is a function of the peak load and the corresponding displacement, Nazzal et al. (2017) recommended normalizing the FE values with respect to the peak strength obtained for each specimen, as shown in Equation A.3. A cracking parameter that is similar to the NFE was suggested by Batioja-Alvarez et al. (2019). This cracking parameter, referred to as the cracking resistance index (CRI), was also calculated by dividing the fracture energy by the peak load.

$$G_F = \frac{W_F}{Area_{lig}} \times 10^6 \tag{A.1}$$

$$FI = \frac{G_F}{|m|} \times A \tag{A.2}$$

$$NFE = \frac{G_F}{\sigma_{peak}} \tag{A.3}$$

where,

G_F = fracture energy (Joules/m^2)

W_f = work of fracture, or area beneath load vs. displacement curve (Joules)

$Area_{lig}$ = ligament area, ligament thickness × length (mm^2)

$|m|$ = absolute value of slope at inflection point

A = unit conversion (0.01)

σ_{peak} = peak stress

A.3 Indirect Tensile Asphalt Cracking Test

The indirect tensile asphalt cracking test (IDEAL-CT) was developed by Zhou et al. (2017, 2019) as a potential test for incorporation into mix design and QA/QC testing to evaluate the cracking resistance of asphalt mixtures. This test procedure is similar to the conventional indirect tensile (IDT) strength test. However, a different approach is used to analyze the load and displacement data based on crack propagation laws proposed by Paris and Erdogan (1963) and Bazant and Prat (1998). A new parameter called the cracking test index (CT_{index}) is proposed for evaluating the cracking resistance of the asphalt mixtures. Zhou et al. (2017, 2019) suggested using a cylindrical specimen measuring 150 mm in diameter and 62 mm in thickness that is compacted to an air voids level of 7 ± 0.5% for this test. Equations A.4 and A.5 were proposed to calculate the CT_{index} at the standard thickness of 62 mm and for non-standard thicknesses, respectively.

For 62-mm-thick samples:
$$CT_{index} = \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{d} \tag{A.4}$$

For non 62-mm-thick samples:
$$CT_{index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{d} \tag{A.5}$$

where,

G_f = work of fracture which is the total area under load versus displacement curve

D = sample diameter (mm)

l_{75} = displacement corresponding to the 75 percent of the peak load in the post-peak stage

m_{75} = slope in the post-peak stage calculated as follows:

$$m_{75} = \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \tag{A.6}$$

where,

P_{85} = 85 percent of the peak load in the post-peak stage

P_{65} = 65 percent of the peak load in the post-peak stage

l_{85} = displacement corresponding to 85 percent of the peak load in the post-peak stage

l_{65} = displacement corresponding to 65 percent of the peak load in the post-peak stage

A.4 Summary of Previous Studies

Several research studies have been conducted to examine the effect of testing equipment, specimen geometry, air void level, loading rate, testing temperature, aging level, mix design and composition on the I-FIT and IDEAL-CT test results since the introduction of these tests in 2015 and 2017, respectively. This section provides a summary of these studies. Proposed performance criteria for both tests, repeatability of test results, correlation of laboratory test results to field performance, and efforts by state highway agencies to implement these tests in mix design approval and QC/QA are also covered in this section.

A.4.1 Effect of Testing Equipment

Barber et al. (2018) examined the impact of machine compliance on I-FIT test results obtained using four different devices (Figure A.1). A procedure was developed to estimate the machine compliance by testing a standard reference material as well as simulating the mechanical behavior of the reference material in the I-FIT test using the finite element model (FEM). Machine compliance was reported to have an insignificant effect on the test results. Therefore, it was concluded that none of the four loading systems had an impact on the test results.

Haslett (2018) examined the effects of using a line-load displacement (LLD) test setup – similar to that used in the conventional I-FIT test – and a crack mouth opening displacement (CMOD) test setup – similar to that used in the low-temperature semi-circular bending (SCB) test (Figure A.2) – on the fracture properties of asphalt mixtures. The test results revealed significantly higher FI values for the CMOD setup than the LLD setup. However, similar ranking of the asphalt mixtures was obtained using the two setups.

Nsengiyumva and Kim (2019) utilized six different load-support fixtures (Figure A.3) to investigate the effect of these fixtures on the I-FIT test results and variability. Several cracking parameters were considered in the analysis, including the fracture energy (FE), flexibility index (FI), peak load, and the coefficient of the cracking index (CRI). It was reported that the I-FIT test results were generally repeatable; however, the type of load-support fixture affected the test results and repeatability. In addition, it was reported that the use of curved rolling surfaces improved the repeatability of the test results in comparison to flat surfaces, while the addition of roller springs generally increased the variability of the test results. The use of a mid-span jig was also found to

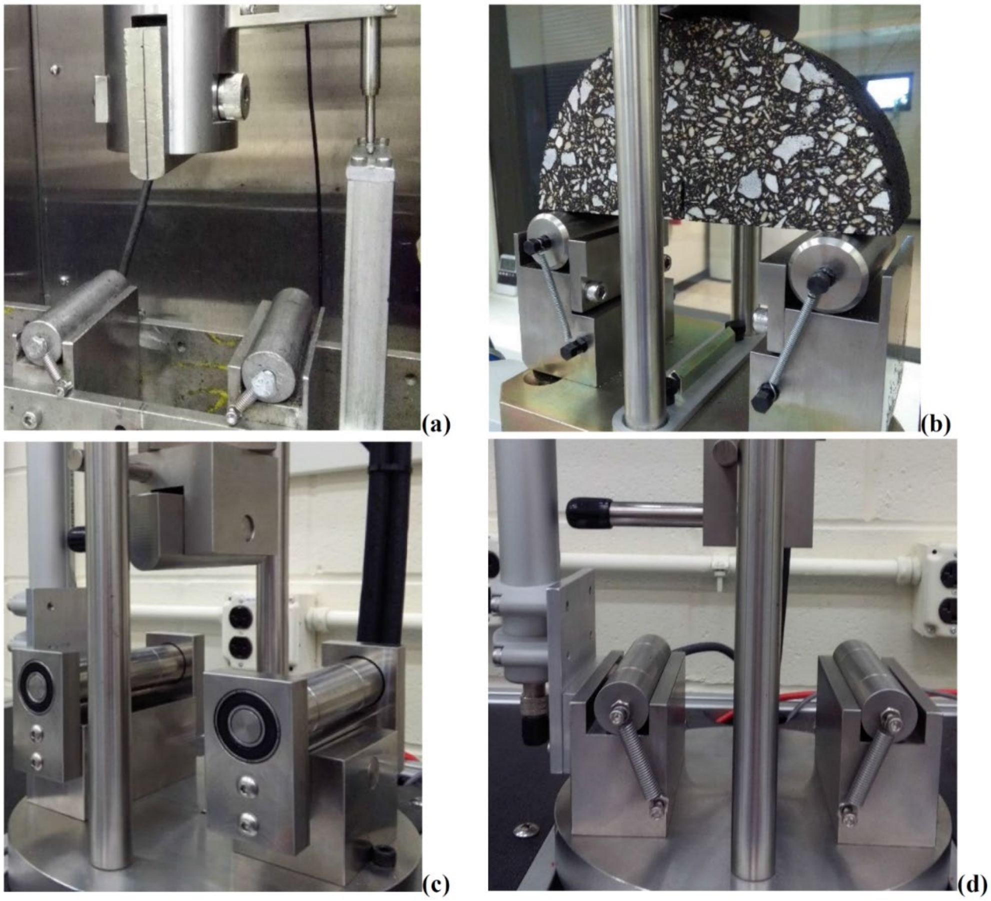


Figure A.1. Load-Support Fixtures Investigated by Barber et al. (2018).

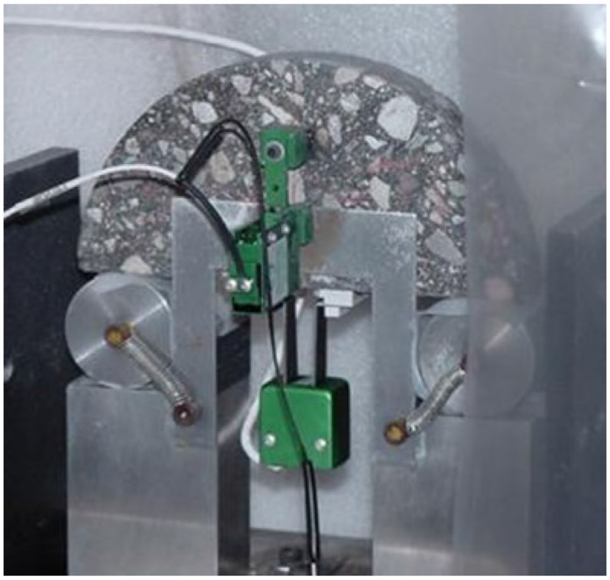
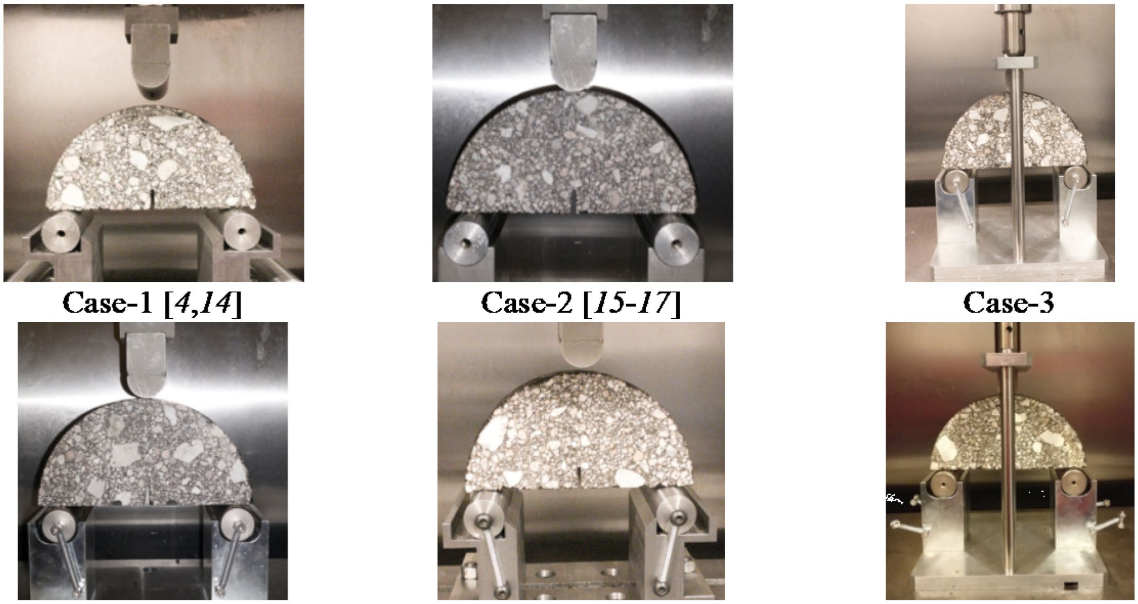


Figure A.2. Semi-Circular Bending (SCB) with a Crack Mouth Opening Displacement (CMOD) Test Setup (Marasteanu et al. 2012).

be detrimental to testing repeatability. The authors recommended to avoid friction at the support because it can erroneously increase fracture resistance with a higher variability. It is noted that a loading rate of 3 mm/minute was used in this study. Therefore, these results cannot be directly related to test results obtained at the standard loading rate of 50 mm/minute for the I-FIT test.



Case-1 [4,14] **Case-2 [15-17]** **Case-3**

Case-4 **Case-5** **Case-6**

Figure A.3. Load-Support Fixtures Investigated by Nsengiyumva and Kim (2019).

Preliminary results from an ongoing research study sponsored by the Arkansas Department of Transportation to develop a balanced mix design approach were presented by Castillo-Camarena and Hall (2020) in the Transportation Research Board (TRB) 99th Annual Meeting. In that study, a Pine Marshall testing platform equipped with a new load cell, a new linear variable differential transducer (LVDT), and new data acquisition system (Figure A.4) was utilized to conduct IDEAL-CT testing on five different asphalt mixtures. The IDEAL-CT test results were compared to I-FIT test results obtained using an asphalt mixture performance tester (AMPT) on the same asphalt mixtures. Figure A.5 presents the displacement versus time and loading rate versus time measurements obtained using the Pine Marshall testing platform and the AMPT device. As can be noticed from this figure, the loading rate obtained using the AMPT was relatively constant and met the target specification loading rate of 50 mm/minute, while the loading rate

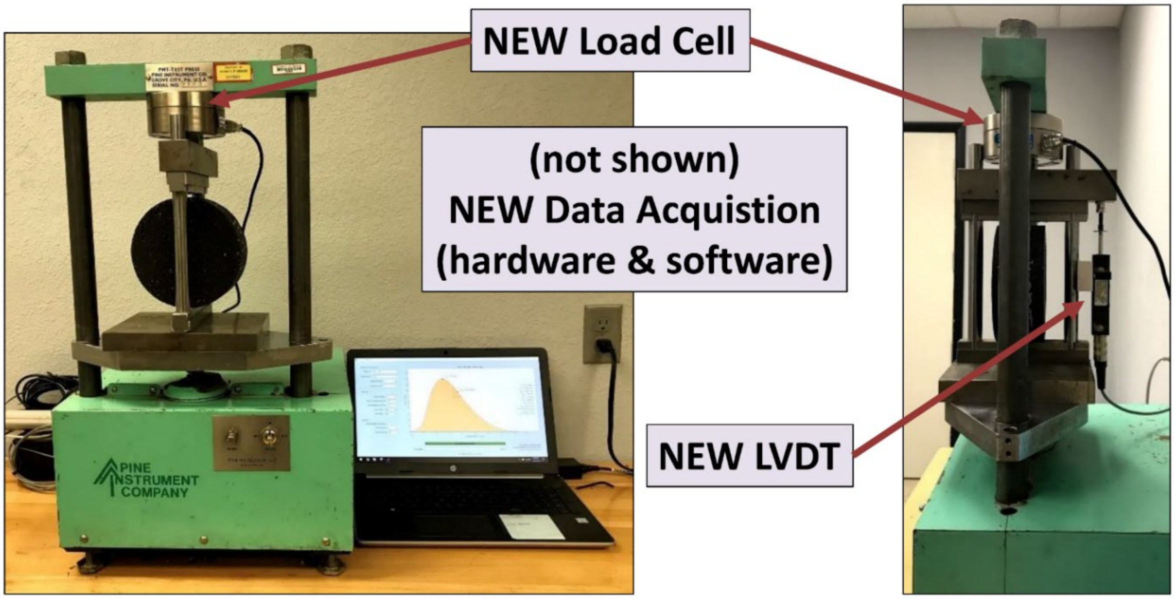


Figure A.4. Pine Marshall Testing Platform used by Castillo-Camarena and Hall (2020).

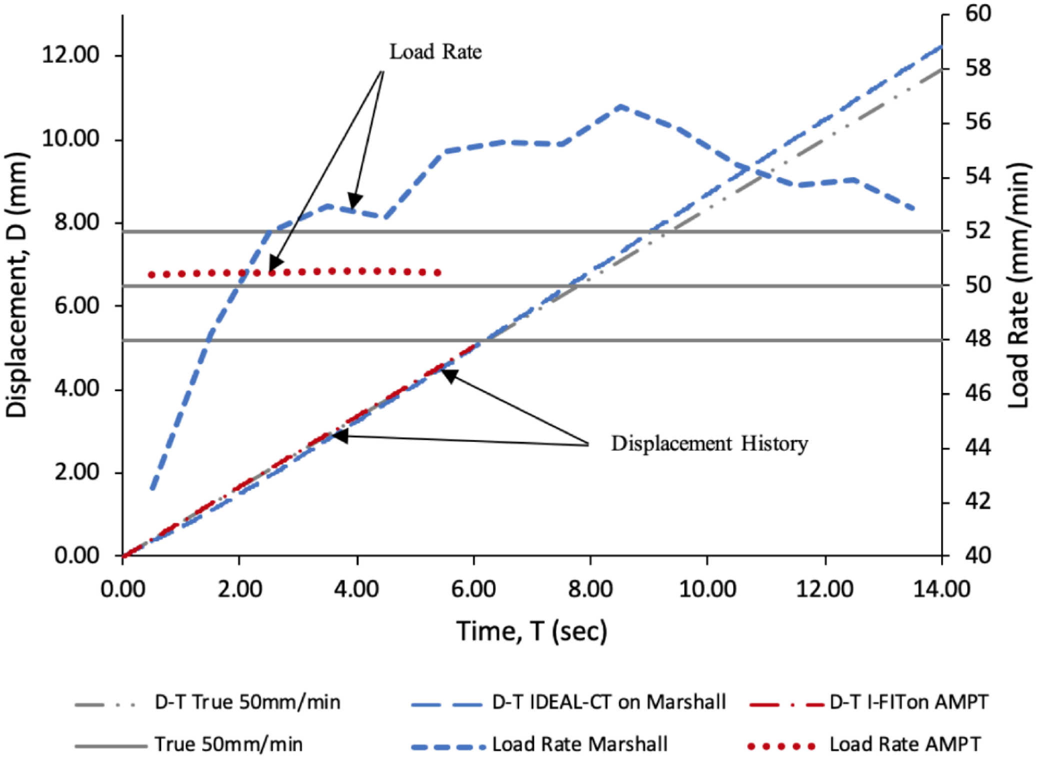


Figure A.5. Displacement versus Time and Loading Rate versus Time Measurements Obtained by Castillo-Camarena and Hall (2020).

obtained using the Pine Marshall testing platform was inconsistent and did not meet the specified loading rate. It was reported that despite the non-constant loading rate obtained using the Marshall loading frame, the IDEAL-CT test results compared favorably to the I-FIT test results, with generally less variability observed for the CT_{index} from the IDEAL-CT test than the FI from the I-FIT test. The researchers suggested to conduct additional IDEAL-CT testing using different Marshall loading frames and compare the test results to results that meet the loading rate specification to verify if a Marshall loading frame can be used for IDEAL-CT testing.

A.4.2 Effect of Specimen Geometry

Al-Qadi et al. (2015) investigated the effect of specimen thickness on the I-FIT test results. Specimens were prepared using a slice thickness ranging between 25 mm and 62.5 mm. The test results for a plant-produced and a laboratory-produced asphalt mixtures are presented in Figures A.6 and A.7, respectively. These figures show a relatively linear reduction in FI with the increase in specimen thickness. Therefore, the following equation was proposed to account for the effect of slice thickness on the FI value:

$$FI_{50} = FI_t \times \frac{t}{50} \tag{A.7}$$

where,

FI_{50} = corrected FI (using a reference slice thickness of 50 mm)
FI_t = measured FI at a non-standard slice thickness
t = slice thickness (mm)

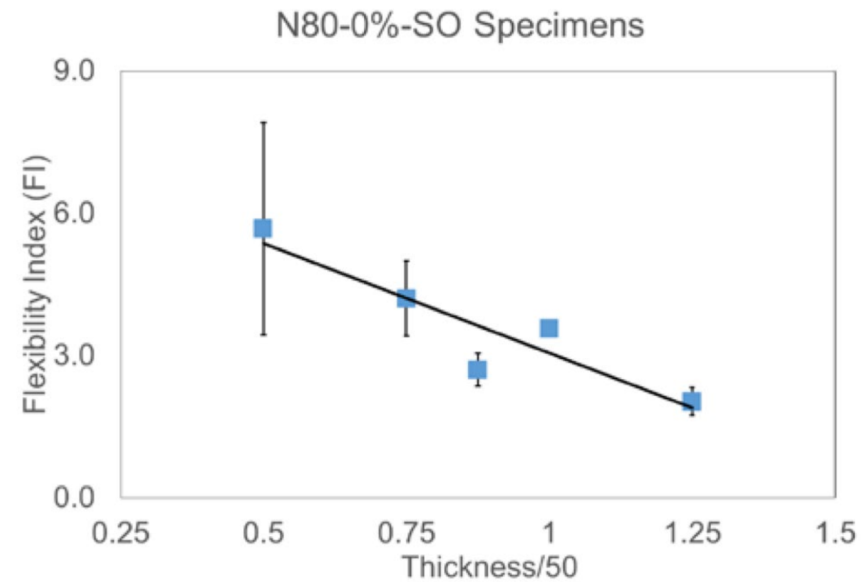


Figure A.6. Effect of Slice Thickness on FI for
a Plant-Produced Asphalt Mixture (Al-Qadi et al. 2015).

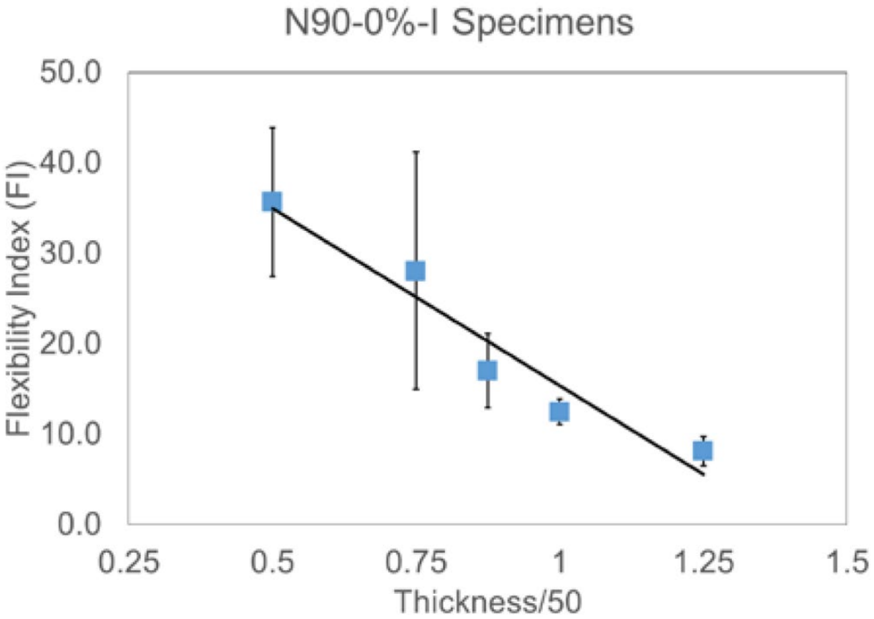


Figure A.7. Effect of Slice Thickness on FI for
a Laboratory-Produced Asphalt Mixture (Al-Qadi et al. 2015).

The specimen thickness correction factor proposed by Al-Qadi et al. (2015) was evaluated and found to be reasonable by Rivera-Perez et al. (2018) and Kaseer et al. (2018), as shown in Figures A.8 and A.9, respectively.

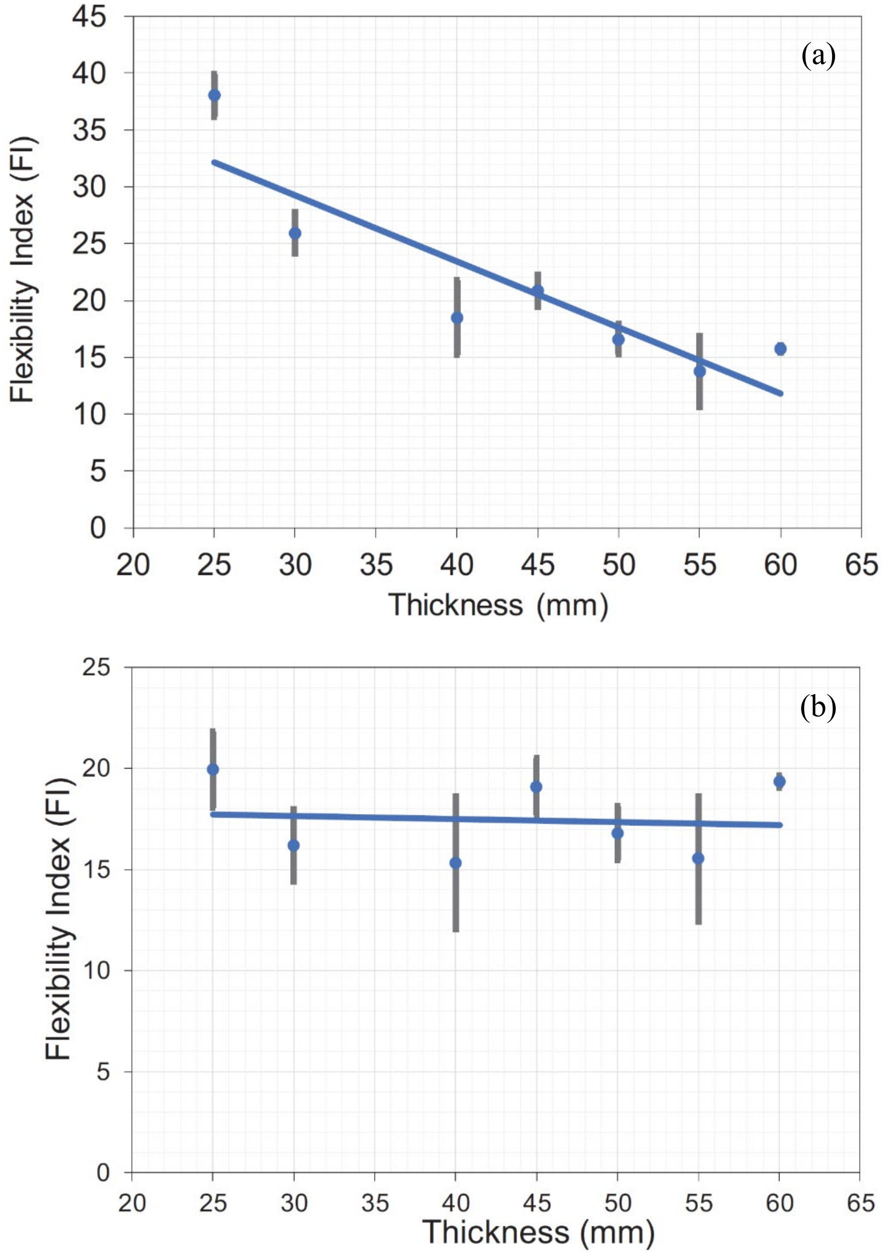


Figure A.8. (a) Uncorrected and (b) Corrected FI Values Obtained by Rivera-Perez et al. (2018) for the Effect of Slice Thickness.

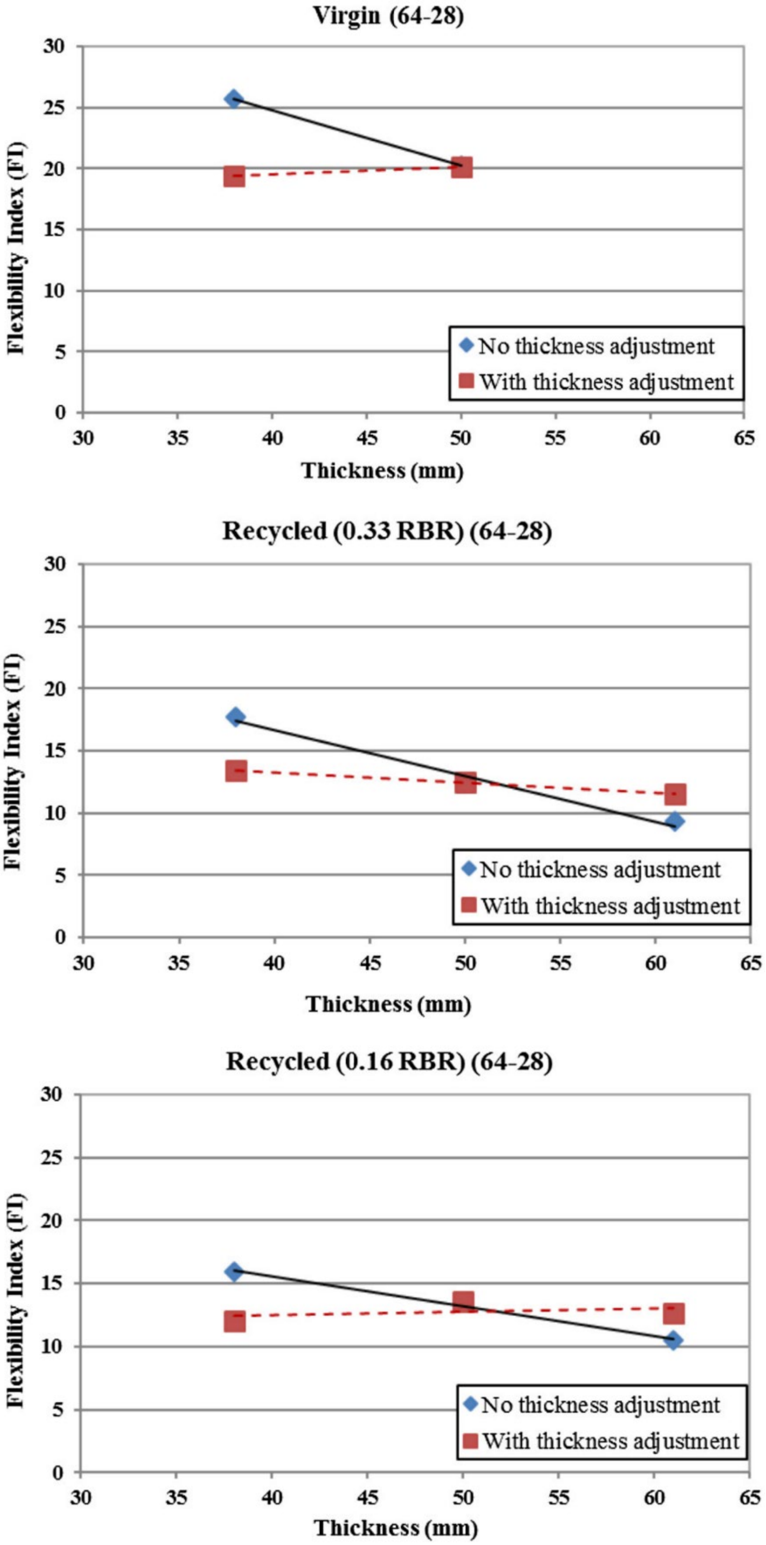


Figure A.9. Uncorrected and Corrected FI Values Obtained for Different Asphalt Mixtures by Kaseer et al. (2018) for the Effect of Slice Thickness.

Rivera-Perez et al. (2018) investigated the effect of the notch length in the I-FIT test on the FI, post-peak slope, and FE. As can be noticed from Figure A.10, the test results revealed a slight reduction in FI with the increase in notch length and a more obvious reduction in FE and post-peak slope with the increase in notch length. The analysis of variance (ANOVA) was used to examine the effect of the notch length on the three parameters. The ANOVA results indicated a significant linear trend for both FE and post-peak slope, with an r^2 of 0.767 for FE and an r^2 of 0.613 for the post-peak slope. On the other hand, the one-way ANOVA analysis for FI resulted in a p-value of 0.03 (< 0.05), which implies that the FI is not significantly affected by the notch length.

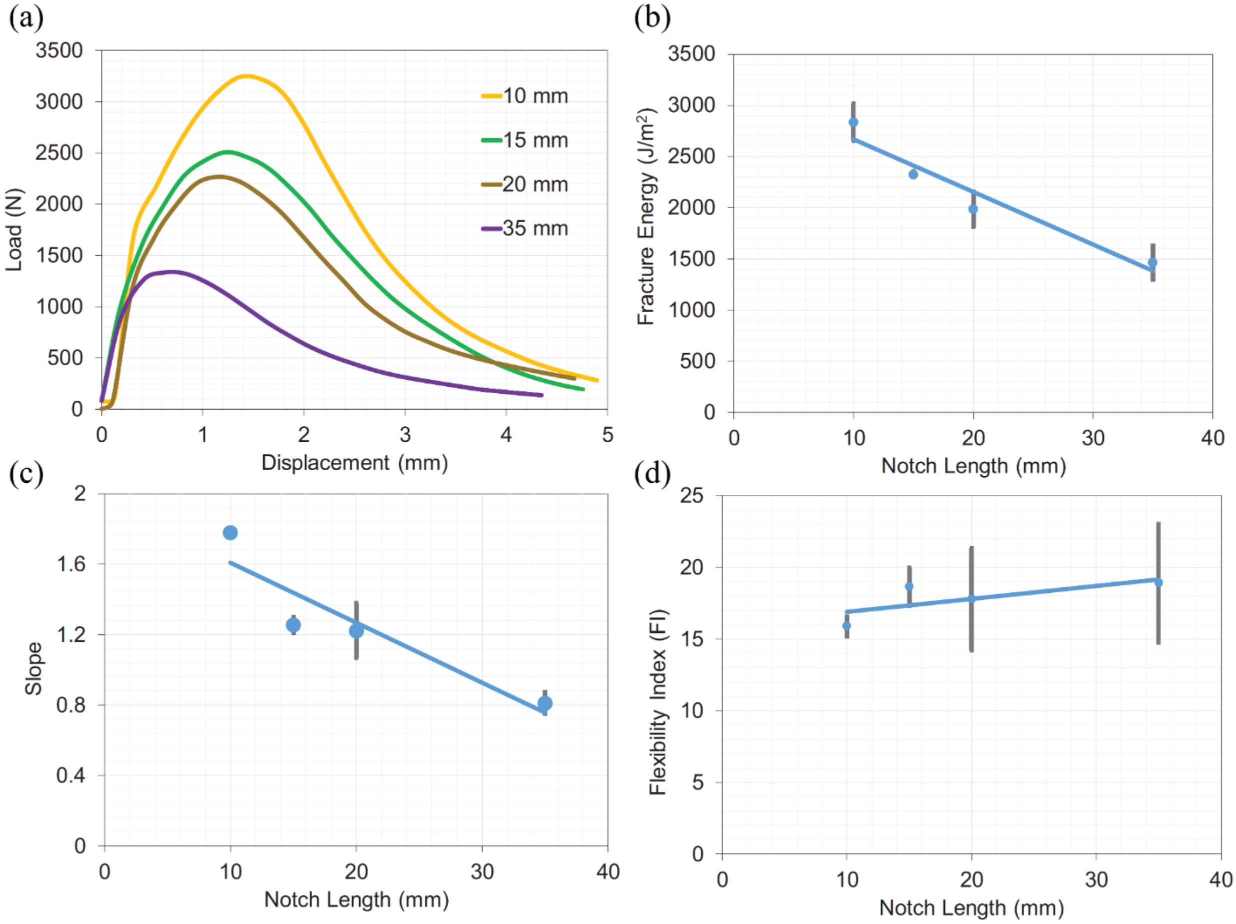


Figure A.10. Effect of Notch Length on T-FIT Test Results (Rivera-Perez et al. 2019).

Chen and Solaimanian (2020) compared the FI test results for top and bottom specimens obtained from 150-mm Superpave gyratory-compacted samples (Figure A.11). As can be noticed from Figure A.12, no clear difference was observed between the top and bottom specimens.

Statistical analysis further confirmed this observation in that a p-value greater than 0.05 (no significant difference) was obtained when the FI values for the top specimens were compared to those of the bottom specimens.

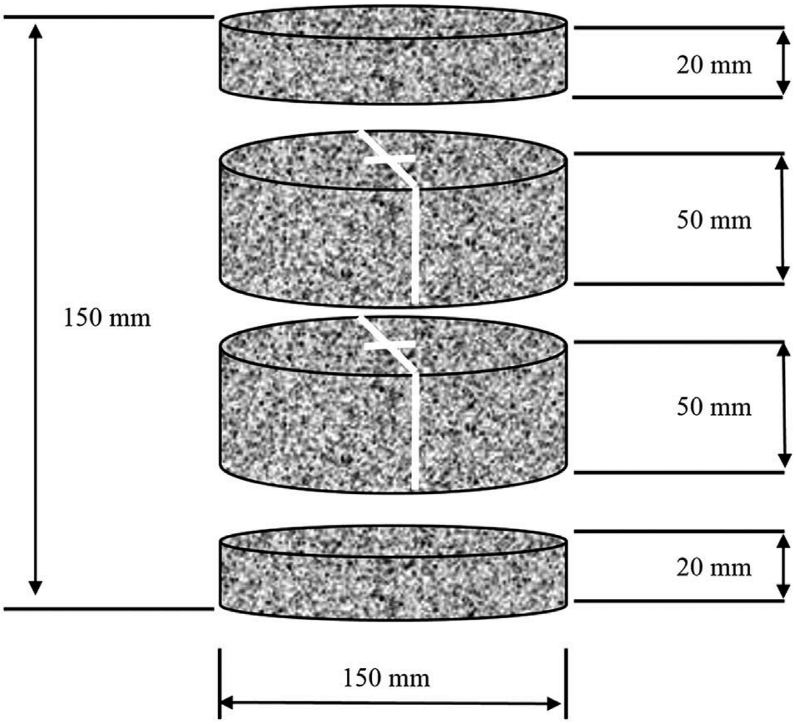


Figure A.11. Cutting, Trimming, and Notching of FI Specimens by Chen and Solaimanian (2020).

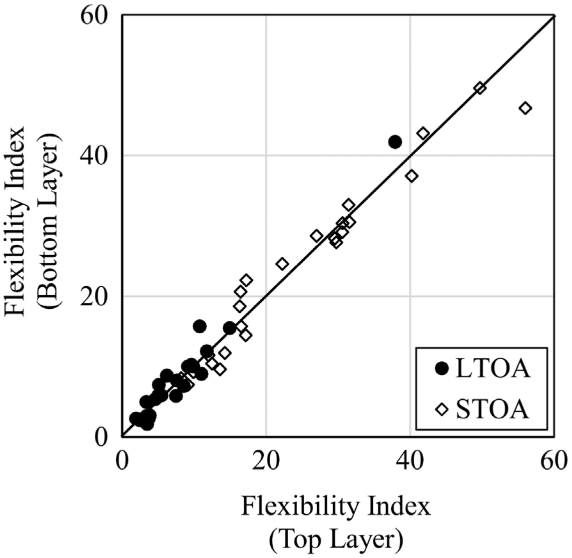


Figure A.12. Comparison of FI for Top and Bottom Specimens (Chen and Solaimanian 2020).

As mentioned earlier, the standard sample diameter for the I-FIT test is 150 mm. A study was conducted by Lu and Saleh (2017) that suggested that the I-FIT test can be conducted using 100-mm-diameter specimens for asphalt mixtures with a nominal maximum aggregate size (NMAS) of 10 mm or smaller. A minimum specimen thickness of 30 mm and a notch length ranging between 10 and 15 mm was recommended by Lu and Saleh (2017) for the 100-mm-diameter specimens to minimize the effect of the specimen dimensions on the test results.

A.4.3 Effect of Air Void Level

Several research studies have been conducted to examine the effect of the specimen air void level on the I-FIT test results. It was generally observed that the FI increased with the increase in air void level (Barry 2016, Kaseer et al. 2018, Sreedhar and Coleri 2018, Rivera-Perez et al. 2018, Batioja-Alvarez et al. 2019). Equation A.8 was proposed by Barry (2016) and Equation A.9 was proposed by Kaseer et al. (2018) to correct for the effect of air void level on FI. The uncorrected and corrected FI values obtained in both studies are presented in Figures A.13 and A.14, respectively.

$$FI_{AV-Corrected} = FI \times \frac{0.0651}{AV-AV^2} \tag{A.8}$$

$$FI_{AV-Corrected} = FI \times \frac{7}{AV} \tag{A.9}$$

where,

$FI_{AV\text{-}Corrected}$ = corrected FI using a reference air void level of 7%

FI = measured FI at a non-standard air void level

AV = specimen air void level

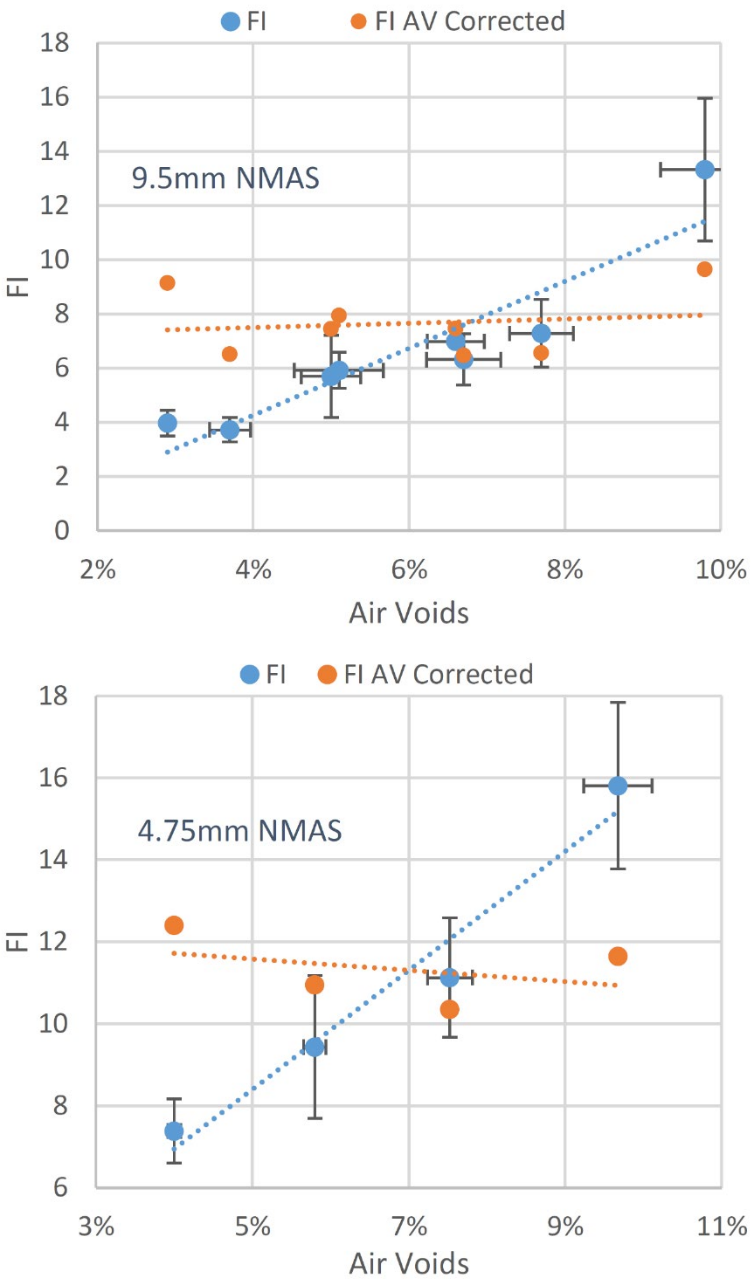


Figure A.13. Uncorrected and Corrected FI Values Obtained by Barry (2016) for the Effect of Air Void Level for Two Asphalt Mixtures.

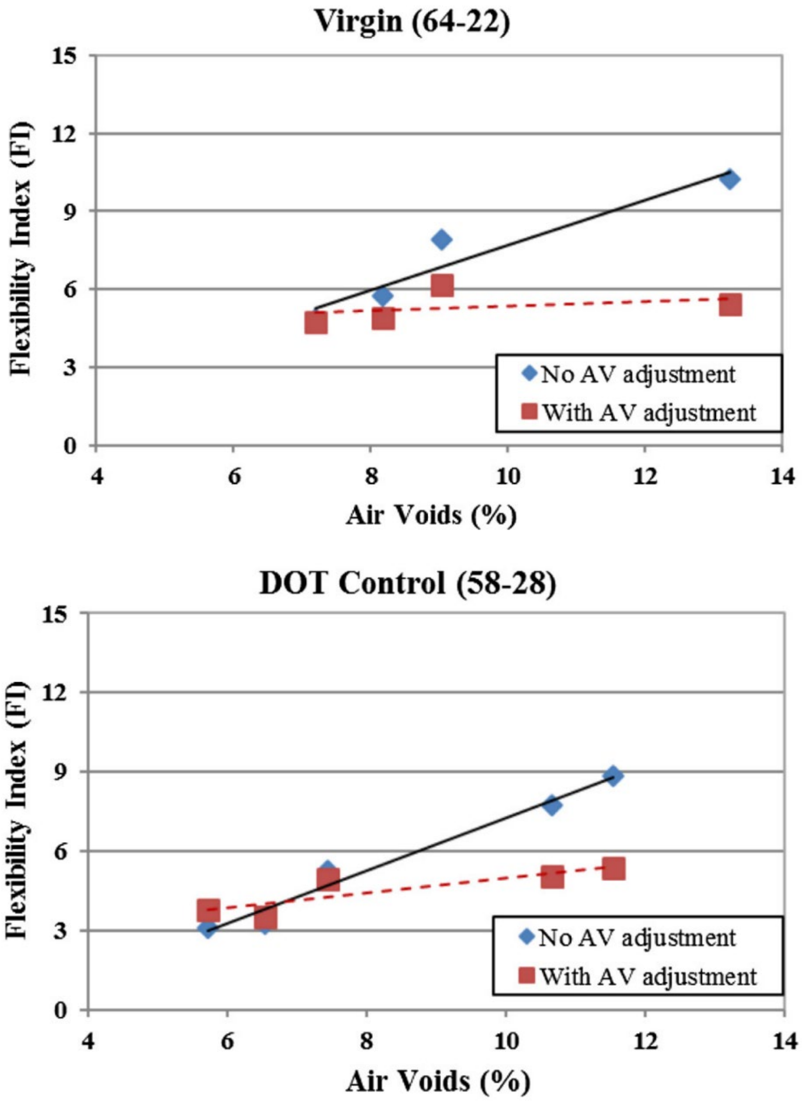


Figure A.14. Uncorrected and Corrected FI Values Obtained
by Kaseer et al. (2018) for the Effect of Air Void Level for Two Asphalt Mixes.

A.4.4 Effect of Loading Rate

Several research studies examined the effect of the loading rate on the I-FIT test results (Rivera-Perez et al. 2018, Haslett 2018). As can be noticed from Figure A.15 and Table A.1, no clear trend was observed between the FI and the loading rate. Therefore, care should be taken when comparing test results obtained at different loading rates.

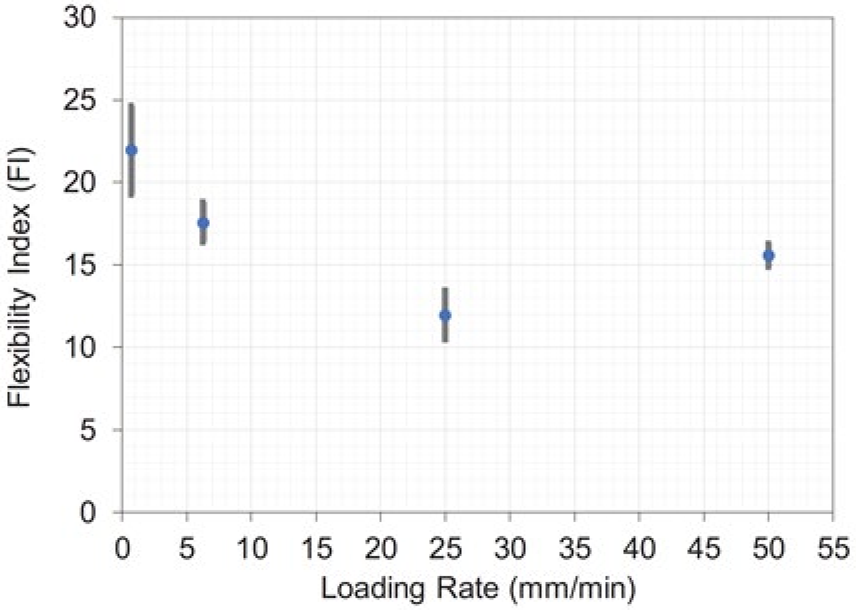


Figure A.15. Effect of Loading Rate on I-FIT Test Results (Rivera-Perez et al. 2018).

Table A.1. Effect of Loading Rate on I-FIT Test Results (Haslett 2018).

Testing Condition	**Mixture**	**G_f**	**FI**
		J/m^2	
13°C & 50mm/min	VT 20% RAP	2964	26.48
	VT 40% RAP	2610	8.62
	VA 0% RAP	2272	1.78
	VA 20% RAP	1397	1.79
	VA 40% RAP	1113	1.18
13°C & 10 mm/min	VA 0% RAP	3256	7.50
	VA 20% RAP	2001	4.58
	VA 40% RAP	1211	1.00
13°C & 1.86mm/min	VA 0% RAP	**2370**	15.22
	VA 20% RAP	1643	7.35
	VA 40% RAP	**2194**	5.42

A.4.5 Effect of Testing Temperature

The effect of the testing temperature on the I-FIT test results was examined by Haslett (2018). As can be noticed from Table A.2, the FI generally increased with the increase in testing temperature. However, the ranking of the asphalt mixtures was not the same at all temperatures, which can be attributed to variations in the temperature sensitivity of the asphalt mixtures.

Table A.2. Effect of Testing Temperature on I-FIT Test Results (Haslett 2018).

Testing Condition	Mixture	G_f J/m^2	FI
25°C & 50mm/min	VT 20% RAP	1692	34.60
	VT 40% RAP	1419	54.43
	VA 0% RAP	3855	29.40
	VA 20% RAP	2888	16.41
	VA 40% RAP	2384	6.62
13°C & 50mm/min	VT 20% RAP	2964	26.48
	VT 40% RAP	2610	8.62
	VA 0% RAP	2272	1.78
	VA 20% RAP	1397	1.79
	VA 40% RAP	1113	1.18
1°C & 50mm/min	VT 20% RAP	1590	2.38
	VT 40% RAP	1138	1.29

A.4.7 Effect of Asphalt Mixture Conditioning and Aging

Asphalt mixture conditioning and aging have been found to be among the most significant factors affecting I-FIT and IDEAL-CT test results. Colas (2018) examined the effect of conditioning time on FI. As can be noticed in Figure A.16, a pronounced drop in FI was observed with the increase in number of hours of conditioning.

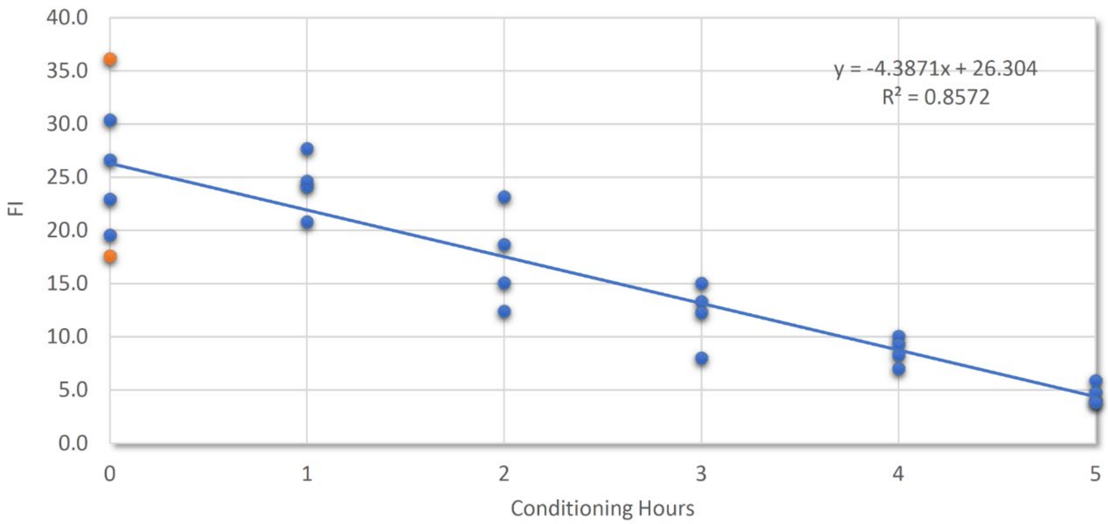


Figure A.16. Effect of Conditioning Time on FI (Colas 2018).

Ling et al. (2017) examined the effect of several factors including short-term (SL) and long-term (LT) aging on the cracking resistance of asphalt mixtures in Wisconsin. A summary of the test results is presented in Figure A.17. The short-term aging was conducted according to AASHTO R 30 (4 hours at 135ºC on a loose asphalt mixture) and the long-term aging was conducted for 12 hours at 135ºC on a loose asphalt mixture. As can be noticed from Figure A.17, lower FI values were obtained for the long-term aged specimens than the short-term aged specimens, which was mainly attributed to a reduction in the post-peak slope.

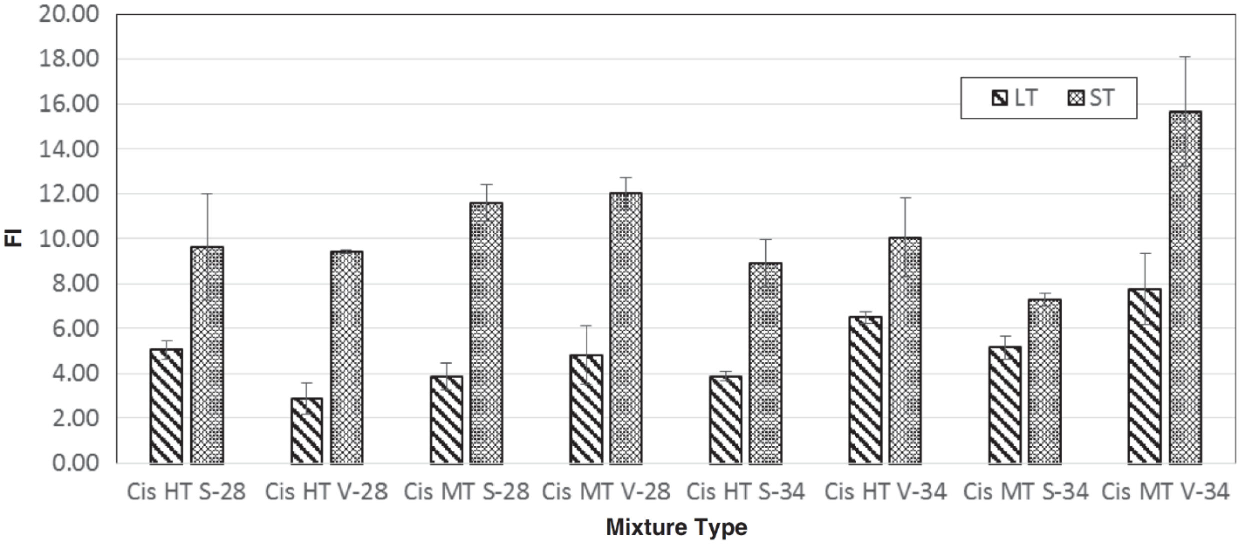


Figure A.17. Effect of Short-Term and Long-Term Aging on FI (Ling et al. 2017).

In Phase 1 of this research project, Rodenza et al. (2018) utilized the I-FIT test to evaluate the cracking resistance of eight asphalt mixtures containing RAP and/or RAS using short-term oven-aged (STOA; 4 hours at 135ºC) and long-term oven-aged (LTOA; 5 days at 85ºC) specimens according to AASHTO R 30. Figure A.18 presents the FI test results for the STOA and LTOA specimens. The letters above each bar represent the ranking of the asphalt mixtures with regard to FI. As can be noticed from this figure, the FI values obtained for the LTOA specimens were smaller than those obtained for the STOA specimens. However, the ranking of the asphalt mixtures did not significantly change upon aging.

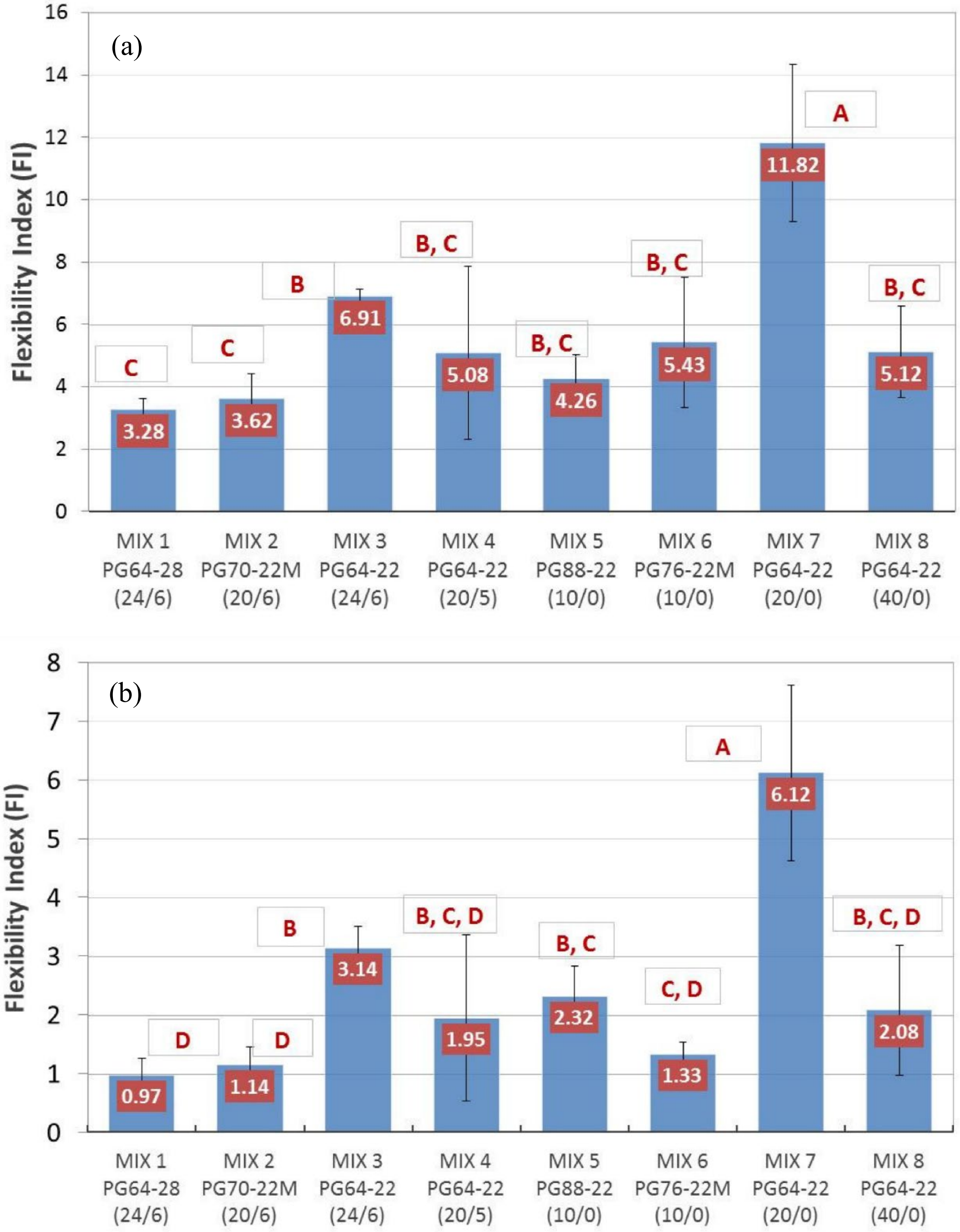


Figure A.18. Effect of (a) Short-Term and (b) Long-Term Aging on FI (Rodenza et al. 2018).

Chen and Solaimanian (2019) compared the I-FIT test results for STOA and LTOA asphalt mixtures prepared with and without RAP and RAS. Short-term aging was achieved by heating the asphalt mixtures for 2 hours at 150°C prior to compaction, while long-term aging was achieved by maintaining the loose asphalt mixtures at 85°C for 5 days. Figure A.19 presents the test results obtained by Chen and Solaimanian (2019) for these mixtures. As can be noticed from this figure, a linear trend (with an R^2 value of 0.67) was observed between the results for the LTOA and STOA specimens. By comparing the FI values for the two specimen types, it can be noticed that the FI values for the STOA specimens are generally three to four times those for the LTOA specimens.

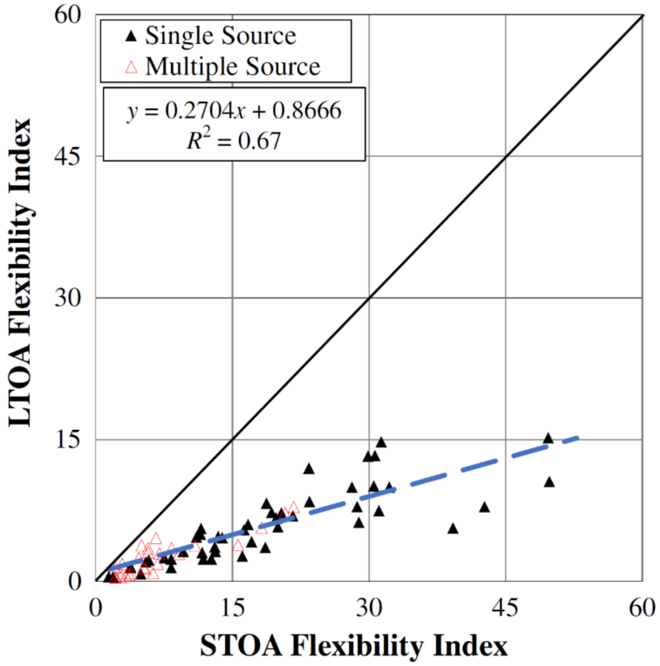


Figure A.19. Effect of Short-Term and Long-Term Aging on FI (Chen and Solaimanian 2019).

Zhu et al. (2019) examined the effect of aging time and aging temperature on the I-FIT test results for two asphalt mixtures. A total of twelve aging protocols were considered in this study: four aging durations (1, 3, 5, and 7 days) and three aging temperatures (75, 85, and 95ºC). Figure A.20 presents the FI decay curves for the two asphalt mixtures. As can be noticed from this figure, the FI decreased when asphalt mixtures were exposed to a higher temperature and/or a longer aging duration, with the most significant drop in FI taking place in the first three days. Interestingly, even though the two asphalt mixtures (PM2 and PM3) had similar characteristics (9.5 mm nominal maximum aggregate size (NMAS), an N_{design} of 90, 6.2% asphalt content, PG 70-22, and a RAP content of 11.1% and 12.2%, respectively), the two mixtures exhibited different aging rates, especially during the first three days.

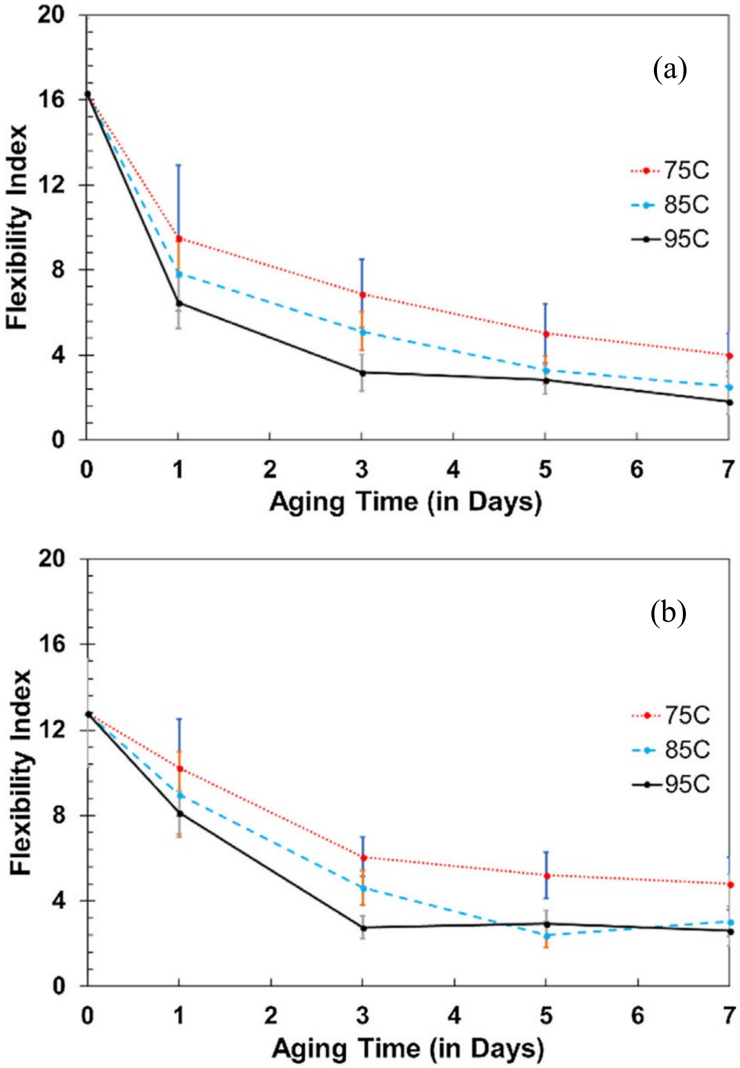


Figure A.20. Effect of Aging Duration and Aging Temperature on FI: (a) PM2 and (b) PM3 (Zhu et al. 2019).

Zhang et al. (2019) examined the effect of different aging protocols on the I-FIT test results for eleven plant-produced laboratory-compacted asphalt mixtures. The FI test results for the short-term and long-term oven-aged specimens are presented in Figure A.21. It was assumed that the short-term aging took place during production, while three protocols were used for long-term aging

(1 day at 135ºC, 5 days at 95ºC, and 12 days at 95ºC). During long-term aging, loose asphalt mixtures were spread in steel pans at an approximate depth of 25 mm. The mixtures were stirred every other day and the pans were rotated around the oven. After aging, the asphalt mixtures were cooled and then reheated at 135ºC for 2 hours prior to compaction to a target air voids level of 6 ± 0.5%. As can be noticed from Figure A.21, the FI values obtained for the LTOA specimens were lower than those obtained for the STOA specimens. For the LTOA specimens, it can be observed that FI decreased with the increase in aging duration and/or aging temperature, with the largest drop in FI obtained for specimens aged for 1 day at 135ºC (FI ratio ranging between approximately 0.05 and 0.2) and the smallest drop in FI obtained for specimens aged for 5 days at 95ºC (FI ratio ranging between 0.2 and 0.35).

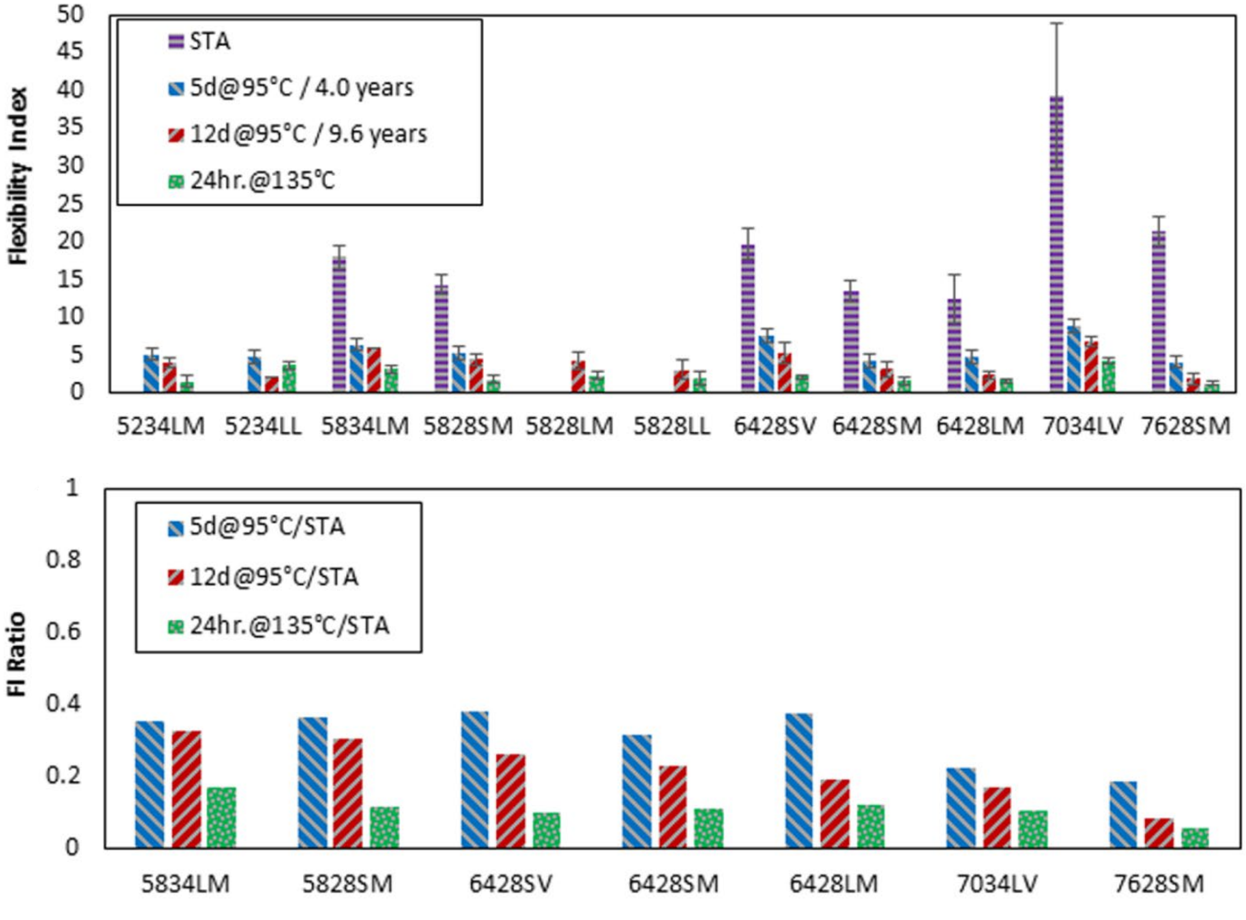


Figure A.21. Effect of Short-Term and Long-Term Aging on FI (Zhang et al. 2019).

A.4.6 Effect of Mix Design Factors

Several research studies have been conducted to examine the effect of different mix design factors on the I-FIT and IDEAL-CT test results. A summary of the outcome of these studies is presented in Tables A.3 and A.4. As can be noticed from these tables, asphalt mixtures prepared using a stiffer asphalt binder (a binder with a higher high-temperature or a higher low-temperature PG grade), a larger nominal maximum aggregate size (NMAS), or higher percentages of RAP and/or RAS generally resulted in lower cracking indices, while mixtures containing a higher asphalt binder content or a higher dose of a recycling agent (rejuvenator) generally resulted in higher cracking indices.

Table A.3. Effect of Different Mix Design Factors on FI.

Mix Design Factor	Effect on FI	Reference	Comments
Binder content ↑	FI ↑	Barry (2016)	Figure 4.5
	FI ↑	Colas (2018)	Slide 13/28
	FI ↑	Sreedhar and Coleri (2018)	Page 04018298-7
	FI ↑	Kaseer et al. (2018)	Figure 4
	FI ↑	Newcomb and Zhou (2018)	Figures 4.1, 4.5, 4.9, and 4.13
	FI ↑	Chen and Solaimanian (2019)	Page 538
	FI ↑	Sharifi et al. (2019)	Figure 6
	FI ↑	Zaumanis et al. (2019)	Figure 12
	FI ↑	Nemati et al. (20(20)	Table 5
	FI ↑	Chen and Solaimanian (2020)	Equations 2 and 4
Binder stiffness ↑	FI ↔	Bahia et al. (2016)	Figure 29
	FI ↓	Im and Zhou (2017)	Figures 5 and 6
	FI ↓	Colas (2018)	Slide 22/28
	FI ↓	Rodezno et al. (2018)	Figures 12 and 13 (Mix 5 and Mix 6)
	FI ↓	Kaseer et al. (2018)	Figure 4
	FI ↓	Chen and Solaimanian (2019)	Page 538
	FI ↓	Nemati et al. (2020)	Table 5
	FI ↓	Chen and Solaimanian (2020)	Equations 2 and 4

Table A.3. Effect of Different Mix Design Factors on FI (Continued).

Mix Design Factor	Effect on FI	Reference	Comments
NMAS ↑	FI ↓	Ling et al. (2017)	Equation 1
	FI ↓	Colas (2018)	Slide 15/28
	FI ↓	Rodezno et al. (2018)	Figures 12 and 13 (Mix 3 and Mix 4)
RAP% ↑	FI ↓	Bahia et al. (2016)	Figure 29
	FI ↓	Elkhatib (2016)	Figure 30
	FI ↓	Ozer et al. (2016)	Figure 6
	FI ↓	Ling et al. (2017)	Equation 1
	FI ↓	Fakhri and Ahmadi (2017)	Figure 5
	FI ↓	Xie et al. (2017)	Table 7
	FI ↓	Im and Zhou (2017)	Figure 4
	FI ↓	Colas (2018)	Slide 25/28
	FI ↓	Haslett (2018)	Table 2
	FI ↓	Rodezno et al. (2018)	Figures 12 and 13 (Mix 3 and Mix 7)
	FI ↓	Kaseer et al. (2018)	Figure 15
	FI ↓	Chen and Solaimanian (2019)	Figures 6 and 7
	FI ↓	Zaumanis et al. (2019)	Figure 12
	FI ↓	Nazzal et al. (2019)	Figures D.5 and D.12
	FI ↓	Nemati et al. (20(20)	Table 5
RAS% ↑	FI ↓	Moore (2016)	Table 14
	FI ↓	Xie et al. (2017)	Table 7
	FI ↓	Im and Zhou (2017)	Figure 4
	FI ↓	Rodezno et al. (2018)	Figures 12 and 13 (Mix 3 and Mix 7)
	FI ↓	Kaseer et al. (2018)	Figure 15
	FI ↓	Chen and Solaimanian (2019)	Figures 6 and 7
	FI ↓	Sharifi et al. (2019)	Figure 6
Recycling agent (rejuvenator) dose ↑	FI ↑	Barry (2016)	Figures 4.5 and 4.6
	FI ↑	Wielinski et (2018)	Abstract
	FI ↑	Espinoza-Luque et al. (2018)	Table 2
	FI ↑	Kaseer et al. (2018)	Figures 11 and 12
	FI ↑	Chen and Solaimanian (2019)	Figure 8
	FI ↑	Nazzal et al. (2019)	Figure D.5

Table A.4. Effect of Different Mix Design Factors on CT_{index}.

Mix Design Factor	Effect on CT_{index}	Reference	Comments
Binder content ↑	CT_{index} ↑	Zhou et al. (2017)	Figures 6 and 11
	CT_{index} ↑	Newcomb and Zhou (2018)	Figures 4.2, 4.6, 4.10, and 4.14
	CT_{index} ↑	Zhou (2019)	Figures 8 and 17
Binder stiffness ↑	CT_{index} ↓	Zhou et al. (2017)	Figure 5
	CT_{index} ↓	Im and Zhou (2017)	Figures 5 and 6
	CT_{index} ↓	Zhou (2019)	Figure 7
RAP% ↑	CT_{index} ↓	Zhou et al. (2017)	Figures 4 and 13
	CT_{index} ↓	Im and Zhou (2017)	Figure 4
	CT_{index} ↓	Zhou (2019)	Figures 6 and 23
	CT_{index} ↓	Zalghout (2019)	Figure 31
RAS% ↑	CT_{index} ↓	Zhou et al. (2017)	Figures 4 and 13
	CT_{index} ↓	Im and Zhou (2017)	Figure 4
	CT_{index} ↓	Zhou (2019)	Figures 6 and 23
Recycling agent (rejuvenator) dose ↑	CT_{index} ↑	Lee et al. (2019)	Figure 12

A.4.8 Test Results for Laboratory-Produced and Plant-Produced Asphalt Mixtures

Several research studies have compared the I-FIT and IDEAL-CT test results for laboratory-produced and plant-produced asphalt mixtures. Some of these studies reported higher FI and CT_{index} values for the plant-produced mixtures than the laboratory-produced mixtures (e.g., Batioja-Alvarez et al. (2019)), while others reported comparable FI and CT_{index} values for both mixtures (e.g., Kaseer et al. (2018), Sreedhar et al. (2018), Sadek et al. (2019)). One main factor that has been reported to result in differences between plant-produced and laboratory-produced asphalt mixtures is whether the plant-produced mixture is reheated or not before compaction and the reheating time needed to reach the compaction temperature. To obtain comparable CT_{index} values to short-term laboratory-produced asphalt mixtures, it was suggested by Newcomb and Zhou (2019) to reheat the plant-produced asphalt mixtures for 2 hours before compacting the IDEAL-CT specimens.

A.4.9 Repeatability of IDEAL-CT and I-FIT Test Results

Tables A.5 and A.6 present a summary of the coefficients of variation (COVs) reported by different studies for FI and CT_{index}, respectively. In some cases, the average COV was reported in the publication, while in other cases the minimum and maximum COVs were reported and are included in these tables as a range. The source of this information along with a brief commentary for each study is included in the comments column. As can be noticed from these tables, the COVs for FI generally ranged between 5% and 30% and those for the CT_{index} generally ranged between 5% and 25% for most mixtures.

Table A.5. Reported Coefficients of Variation for FI.

Reference	FI COV	Comments
Al-Qadi at al. (2015)	4.3% to 20.3%	Figure 5.11 (Laboratory mixes)
	4.2% to 21.3%	Figure 5.11 (Plant mixes)
	6% to 20%	Table 6.2 (Plant mixes)
Moore (2016)	6% to 42%	Table 14
	18%	Page 61
Bahia at al. (2016)	8% to 20%	Page 52
Barry (2016)	9% to 27%	Table 4.2 (Non-rejuvenated mix)
	13% to 28%	Table 4.2 (Rejuvenated mix)
Elkhatib (2016)	4.2% to 49.2%	Tables 37 and 38 (Plant mixes)
	4.9% to 20.3%	Table 41 (Laboratory mixes)
Ozer at al. (2016)	6% to 20%	Table 6 (ALF mixes)
	1.5% to 21.1%	Table C1 (Short-term aged/ with and without ReOB)
	14.9% to 30.7%	Table C2 (Long-term aged/ with and without ReOB)
Ling at al. (2017)	8% to 20%	Page 155
Bennert at al. (2017)	15%	Page 124 (Field cores)
Fakhri and Ahmadi (2017)	5% to 15%	Figure 6 (No freezing and thawing)
Wu at al. (2017)	4.5% to 35.8%	Figure 5
Im and Zhou (2017)	7.8% to 28.5%	Table 1
Bennert at al. (2018)	24.4%	Page 400

Table A.5. Reported Coefficients of Variation for FI (Continued).

Reference	FI COV	Comments
Colas (2018)	19.5%	Slide 19/28 (Laboratory mix - based on 4 out of 4 samples)
	10.5%	Slide 19/28 (Laboratory mix - based on 3 out of 4 samples)
	22.4%	Slide 19/28 (Field mix - based on 4 out of 4 samples)
	12.6%	Slide 19/28 (Field mix - based on 3 out of 4 samples)
Newcomb and Zhou (2018)	7% to 26%	Table 4.1
Rodezno at al. (2018)	24.7%	Page 29, Table 10
	32.0%	Page 29, Table 10
Espinoza-Luque at al. (2018)	13.8% to 30.8%	Table 2 (Mixes with and without rejuvenators)
Kaseer at al. (2018)	3% to 48%	Figure 17
Sreedhar at al. (2018)	16.5%	Table 4
Newcomb and Zhou (2018)	7% to 26%	Table 4.1
Chen and Solaimanian (2019)	15.2%	Table 3 (Single source STOA)
	17.5%	Table 3 (Single source LTOA)
	18.4%	Table 3 (Multiple source STOA)
	22.1%	Table 3 (Multiple source LTOA)
Julian at al. (2019)	7.7% to 31.9%	Table 15 (HMA and WMA mixes with RAS)
Nsengiyumva and Kim (2019)	15.7% to 37.8%	Table 2 (Using a loading rate of 3 mm/minute)
Jahangiri at al. (2019)	23.5% to 80.7%	Table 2
West at al. (2019)	10% to 20%	Table 6
Buttlar et al. (2019)	43.7% (Avg.)	Table 5-3 (Field cores)
Yan et al. (2020)	23.2% (Avg.)	Table 3 (Notched specimens)
Buttlar et al. (2021)	9.6% to 46.1%	Figure 3-5 (Four replicates)

Table A.6. Reported Coefficients of Variation for CT_{index}.

Reference	CT_{index} COV	Comments
Zhou et al. (2017)	1.7% to 23.5%	Table 2 (Laboratory mixes)
	12.1% to 20.0%	Table 2 (Plant mixes)
Im and Zhou (2017)	1.8% to 24.9%	Table 1
	5.6% to 23.9%	Table 2

Table A.6. Reported Coefficients of Variation for CT_{index} (Continued).

Reference	CT_{index} COV	Comments
Bennert et al. (2018)	16.5% (Avg)	Page 399
Newcomb and Zhou (2018)	5% to 17%	Table 4.1
	5% to 17%	Table 4.1
Zhou (2019)	1.7% to 23.5%	Table 2 (Laboratory mixes)
	12.1% to 20.0%	Table 2 (Plant mixes)
West et al. (2019)	Less than 20%	Table 6
Buttlar et al. (2019)	11.1% to 72.6%	Table 5-4 (Plant-produced laboratory-compacted)
Yan et al. (2020)	7.0% (Avg.)	Table 4
Buttlar et al. (2021)	8% to 51.8%	Figure 3-8

A.4.10 Proposed Performance Criteria

Tables A.7 and A.8 present the minimum threshold values used in different research studies for the FI and the CT_{index}, respectively. As can be noticed from these tables, a minimum threshold value of 8 has been commonly used for the FI and a minimum threshold value of 80 has been generally used for the CT_{index}, as suggested by Al-Qadi et al. (2015) and Zhou et al. (2017), respectively, for use in balanced mix design. Several research studies indicated that the minimum FI requirement might be too strict for some asphalt mixtures (e.g., West at al. 2019). Therefore, research is currently underway in a number of states to recommend target performance criteria for these tests that better reflect the susceptibility of the asphalt mixtures to cracking.

Table A.7. Minimum Threshold Value Used or Proposed in Different Studies for FI.

Reference	Threshold Value	Comments
Bahia et al. (2016)	6.5	Table 26 (Light traffic – STOA mixes)
	2.5	Table 26 (Light traffic – LTOA mixes)
	12.0	Table 26 (Medium traffic – STOA mixes)
	5.0	Table 26 (Medium traffic – LTOA mixes)
	18.0	Table 26 (Heavy traffic – STOA mixes)
	7.5	Table 26 (Heavy traffic – LTOA mixes)
Ozer et al. (2016)	10	Table 2 (High performance)
	6	Table 2 (Acceptable)

Table A.7. Minimum Threshold Value Used or Proposed in Different Studies for FI (Continued).

Reference	Threshold Value	Comments
Bennert et al. (2017)	7	Page 126
Wu et al. (2017)	8	Page 124 (HMA)
Bennert et al. (2018)	18	Table 5 (High-performance thin overlay)
	18	Table 5 (Bituminous-rich inter course)
	13	Table 5 (High RAP – surface course)
	11	Table 5 (High RAP – inter/base course)
Espinoza-Luque et al. (2018)	8	Page 646
Newcomb and Zhou (2018)	8	Table 3.3
Al-Qadi et al. (2019)	8	Figure 6.1 (Laboratory-produced STOA)
	6	Figure 6.1 (Laboratory-produced LTOA 3 Days at 95°C)
	8	Figure 6.1 (Plant-produced STOA)
	4	Figure 6.1 (Plant-produced LTOA 3 Days at 95°C)
Batioja-Alvarez et al. (2019)	5.8	Page 344 (30th FI percentile for interstate highways)
	5.1	Page 344 (20th FI percentile for non-interstate highways)
Jahangiri et al. (2019)	8	Page 397
Parnell (2019)	8	Figure 1
Safi et al. (2019)	8	Page 157
Nazzal et al. (2019)	2	Table E.2
West et al. (2019)	8	Page 120
Leiva-Villacorta and Julian (2020)	8	Page 41
Coleri et al. (2020)	6	Page 88 (Level 3 mixes)
	8	Page 88 (Level 4 mixes)

Table A.8. Minimum Threshold Value Used or Proposed in Different Studies for CT_{index}.

Reference	Threshold Value	Comments
Bennert et al. (2018)	245	Table 4 (High-performance thin overlay)
	245	Table 4 (Bituminous-rich inter course)
	180	Table 4 (High RAP – surface course)
	140	Table 4 (High RAP – inter/base course)
Newcomb and Zhou (2018)	80	Table 3.3

Table A.8. Minimum Threshold Value Used
or Proposed in Different Studies for CT_{index} (Continued).

Reference	Threshold Value	Comments
Diefenderfer and Bowers (2019)	80	Table 5
Buttlar et al. (2020)	150	Table 6-2 (High criticality surface lift)
	100	Table 6-2 (Medium criticality surface lift)
	55	Table 6-2 (Low criticality surface lift)
	100	Table 6-2 (High criticality non-surface lift)
	70	Table 6-2 (Medium criticality non-surface lift)
	35	Table 6-2 (Low criticality non-surface lift)
Zhou et al. (2020)	55	Table 3 (TxDOT dense graded mixes)
	90	Table 3 (Superpave mixes)
	135	Table 3 (Stone matrix asphalt)
	180	Table 3 (Thin overlay mix)
	400	Table 3 (Crack attenuating mix)
Alkuime et al. (2021)	80	Table 5
Diefenderfer et al. (2021)	70	Page 46

A.4.11 Use of IDEAL-CT and I-FIT Test Results in Mix Design and QC/QA

Bahia et al. (2016) conducted a study for the Wisconsin DOT to evaluate the performance of asphalt mixtures containing varying amounts of RAP using the I-FIT test. A statistical approach was used to differentiate between mixtures based on mix composition and aging. For short-term aging, the asphalt mixtures were aged for 4 hours at 135°C and for long-term aging, the asphalt mixtures were aged at the same temperature for 12 hours. It was concluded in that study that the I-FIT test is ready for implementation in Wisconsin as a reliable monotonic fracture test to identify the cracking potential of asphalt mixtures. Based on the experimental test results, a threshold value of 8.0 was suggested for FI. However, further investigation of the FI limit was recommended using field performance data.

Bennert et al. (2018) conducted a study to identify a fatigue cracking test that can be used as guidance for quality control purposes by contractors in New Jersey. A good correlation was reported between the IDEAL-CT and the Texas OT test results. However, the IDEAL-CT test was reported to be more practical than the Texas OT and I-FIT tests for this purpose as it requires a relatively inexpensive testing device and a shorter time to prepare and test the asphalt mixture specimen (as no gluing, sawing, or notching is required). Minimum CT_{index} values of 150, 120, and 245 were recommended for surface courses that contain high RAP content, intermediate or base courses that contain high RAP content, and high-performance thin overlays (HPTO), respectively.

A research study was conducted by Newcomb and Zhou (2018) for Minnesota DOT to evaluate the potential use of the IDEAL-CT and I-FIT tests in balanced-mix-design (BMD). In that study, samples were compacted to achieve a target air void content of 7% ± 0.5% after aging at the suggested compaction temperature for 4 hours. A minimum CT_{index} value of 80 was recommended for the IDEAL-CT and a minimum FI value of 8.0 was recommended for the I-FIT to ensure satisfactory mix performance. This study recommended using the IDEAL-CT test for QC/QA purposes due to its simplicity and good repeatability.

Diefenderfer and Bowers (2019) evaluated several laboratory tests for potential incorporation into a balanced-mix design approach to be used by Virginia DOT. These tests included the Cantabro test, Asphalt Pavement Analyzer (APA), overlay tester, I-FIT, N_{flex} indirect tensile strength, and the IDEAL-CT. Upon further review, three tests were selected for in-depth investigation, namely the Cantabro test for durability, the APA test for rutting susceptibility, and the IDEAL-CT test for cracking resistance. Three methods were considered for establishing the threshold criteria for these tests: conservative application, average, and average ± standard deviation. The merits for each method were discussed. However, due to the relatively small number of mixtures included in this study (five mixes only), the authors suggested incorporating additional asphalt mixtures into the test plan before making any final recommendations regarding the threshold values for these tests.

Batioja-Alvarez et al. (2019) evaluate the potential use of the I-FIT test as a performance-related quality control (QC/QA) test by Indiana DOT. The test results obtained in that study showed that the FI values for field-compacted samples were consistently higher than those for laboratory-compacted samples. It was indicated that aging might be a contributing factor to the difference between these samples. Based on the test results, it was concluded that the I-FIT cracking parameters could be used as a tool to validate the quality of asphalt mixtures. However, further investigations is need to better understand the effects of the interaction between the various factors that affect these parameters. Threshold criteria were also recommended based on the cumulative distribution function for the FI values using data for the entire population of asphalt mixtures (Figure 2). The 30th percentile (FI = 5.8), and the 20th percentile (FI = 5.1) were suggested to be used as a limiting threshold for interstate and non-interstate highways, respectively.

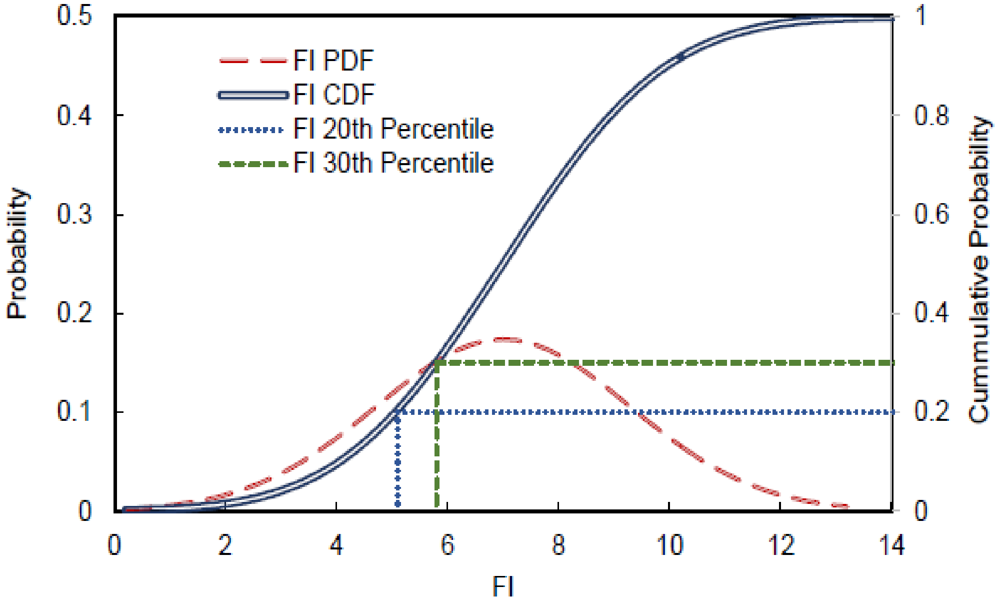


Figure A.22. Cumulative Distribution of FI Values (Batioja-Alvarez et al. 2019).

A.4.12 Correlation between I-FIT and IDEAL-CT Test Results with Field Performance

Al-Qadi et al. (2015) evaluated the correlation between the I-FIT test results and field performance data using the Federal Highway Administration (FHWA) Accelerated Loading Facility (ALF) in McLean, Virginia as well as 35 pavement sections in the state of Illinois. As can be noticed from Figure A.23, higher FI values corresponded to better cracking performance in the FHWA ALF. Different performance categories for FI were identified in that research study based on the ALF performance data. An FI value lower than approximately 2.0 was reported for poor-performing sections, and an FI value greater than approximately 6.0 was associated with good-performing sections.

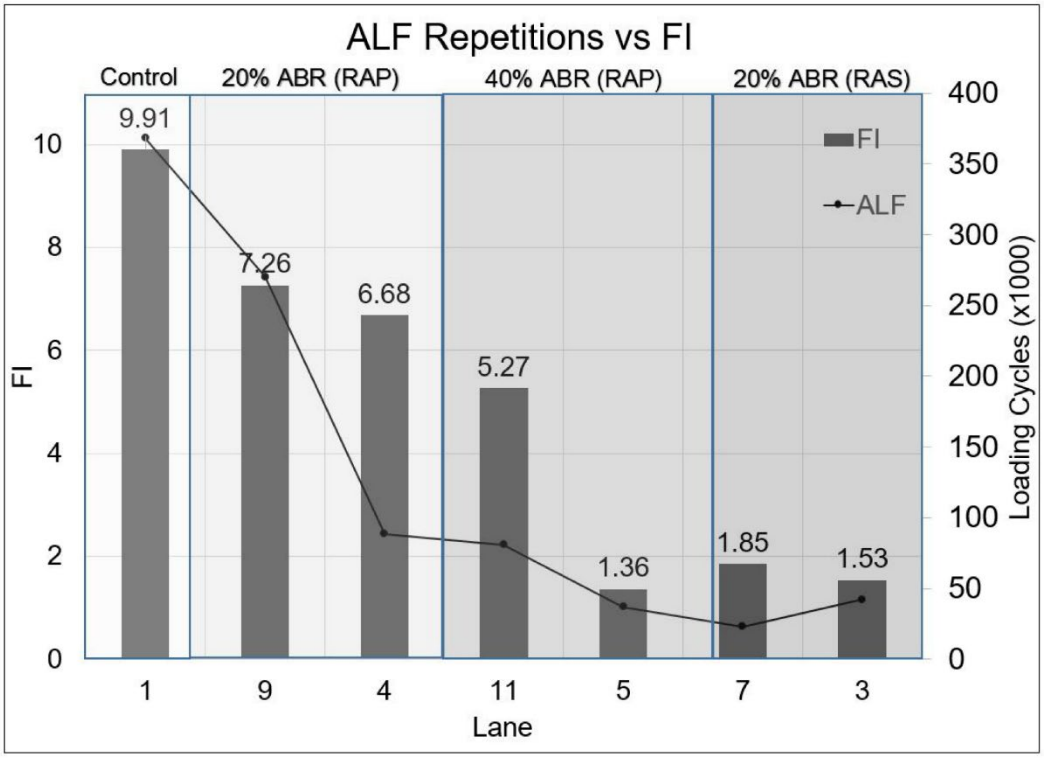


Figure A.22. Correlation between FI and Results from FHWA ALF (Al-Qadi et al. 2015).

Zhou (2019) evaluated the correlation between the IDEAL-CT test results and field performance data from the FHWA ALF as well as Long-Term Pavement Performance (LTPP) test sections for warm mix asphalt overlays in Oklahoma. It was observed in that study that higher CT_{index} values corresponded to better cracking performance. In addition, a high correlation was reported between the CT_{index} and the number of passes applied until the appearance of the first crack in the FHWA ALF test sections (Figure A.23) as well as field reflective cracking rate for in-service roads in Texas.

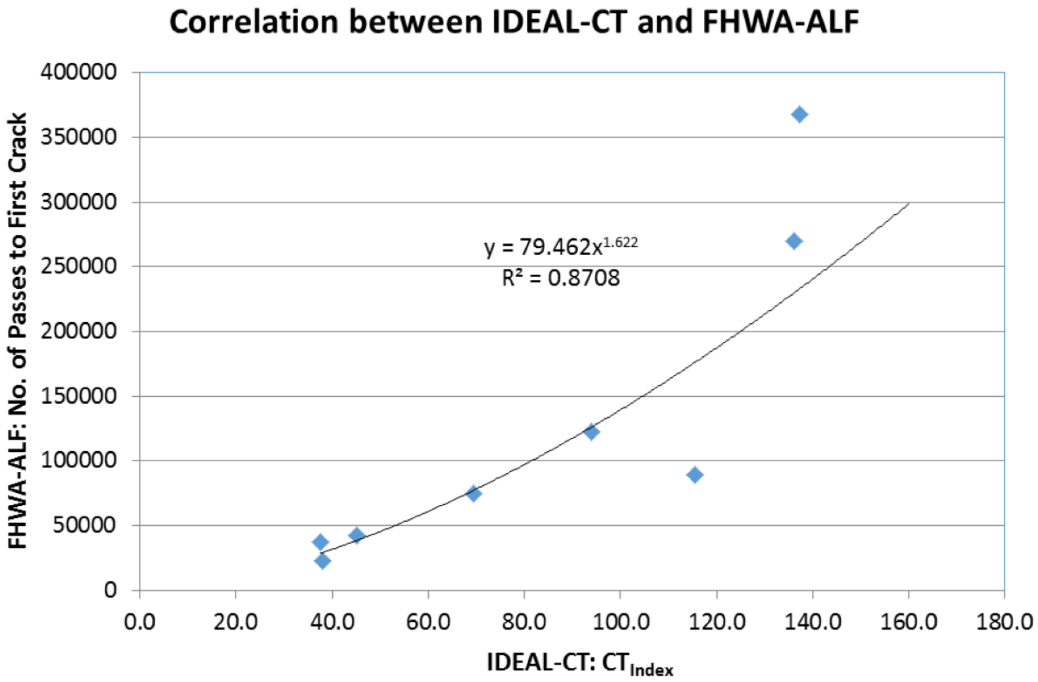


Figure A.23. Correlation between CT$_{index}$ and Results from FHWA ALF (Zhou 2019).

Appendix B
Preliminary Evaluation Results

B.1 Introduction

The preliminary evaluation involved comparing the performance of plant-produced versus laboratory-produced asphalt mixtures, evaluating the effect of different aging protocols, examining the effect of air void level, investigating the effect of specimen dimensions, and examining the variability of the I-FIT and IDEAL-CT test results to determine the minimum number of specimens that are needed for each test. A summary of the laboratory test results for the different parts of the preliminary evaluation is presented in the following subsections.

B.2 Plant-Produced versus Laboratory-Produced Mixtures

Twenty-one asphalt mixtures were selected for the comparison between plant-produced and laboratory-produced asphalt mixtures, representing six types of asphalt mixes used by ODOT: Item 442 (Superpave) 12.5 mm NMAS (Surface), Item 442 (Superpave) 19 mm NMAS (Intermediate), Item 441 (Marshall) Type 1 Surface, Item 441 (Marshall) Type 1 Intermediate, Item 441 (Marshall) Type 2 Intermediate, and Item 302 (Asphalt Concrete Base), as shown in Table B.1. The plant-produced asphalt mixtures were obtained from asphalt plants and were compacted in the laboratory to prepare the I-FIT and IDEAL-CT specimens. In addition, laboratory-produced mixtures having the same composition as the plant-produced mixtures were prepared in the laboratory and were used to prepare the I-FIT and IDEAL-CT specimens for all twenty-one asphalt mixtures. The laboratory-produced asphalt mixtures were short-term aged according to AASHTO R 30 prior to compacting the I-FIT and IDEAL-CT specimens, while the plant-produced asphalt mixtures were reheated for 3 hours at the compaction temperature before compacting the specimens.

Table B.1. Material Composition of Mixtures included in the Comparison between Plant-Produced and Laboratory-Produced Asphalt Mixtures.

Mix Type	Mix ID	Binder Type	AC (%)	RAP (%)	RAS (%)
Superpave 12.5 mm (Surface)	M1012	PG 70-22M	5.9%	15%	0%
	M1030	PG 70-22M	6.1%	15%	0%
	M1090	PG 76-22M	6.1%	15%	0%
	M1018	PG 76-22M	5.7%	15%	0%
	M0704	PG 76-22M	5.8%	15%	0%
Superpave 19 mm (Intermediate)	M0288	PG 64-28	4.7%	30%	0%
	M0981	PG 64-28	4.8%	25%	0%
	M0961	PG 64-28	4.9%	35%	0%
	M1028	PG 64-28	5.0%	40%	0%
Marshall Type 1 Surface	M0992	PG 64-22	6.3%	25%	0%
	M0643	PG 70-22M	6.2%	25%	0%
Marshall Type 1 Intermediate	M0248	PG 64-22	6.0%	25%	0%
	M0586	PG 64-22	6.5%	25%	0%
	M0697	PG 58-28	5.5%	40%	0%
Marshall Type 2 Intermediate	M0962	PG 58-28	5.0%	30%	0%
	M1025	PG 58-28	4.9%	40%	0%
Item 302 Asphalt Concrete Base	M0919	PG 58-28	4.3%	40%	0%
	M0246	PG 58-28	4.2%	30%	0%
	M0971	PG 58-28	4.4%	30%	0%
	M1011	PG 64-22	4.1%	20%	0%
	M1032	PG 58-28	4.1%	45%	0%

Figures B.1 and B.2 present a comparison between the I-FIT and IDEAL-CT test results, respectively, for the plant-produced and laboratory-produced asphalt mixtures using a 45-degree line of equality. A point falling on the line of equality in these figures indicates that the cracking indices are equivalent for both mixtures. A data point falling above the line of equality indicates a higher value for the cracking index for the laboratory-produced asphalt mixture, while a data point falling below the line of equality indicates a higher value for the cracking index for the plant-produced asphalt mixture. As can be noticed from both figures, comparable cracking indices were obtained for plant-produced and laboratory-produced asphalt mixtures, except for Superpave 12.5 mm and Type 1 Surface mixtures, which exhibited comparable or higher cracking indices for the plant-produced asphalt mixtures. This observation is consistent with results reported by other studies in the literature.

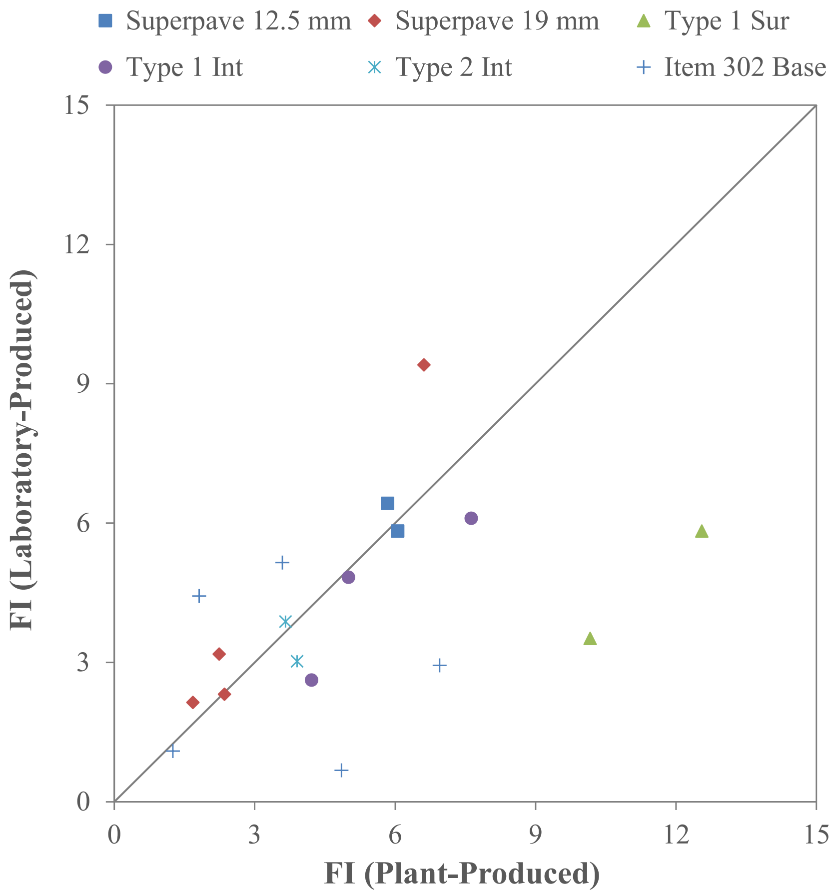


Figure B.1. I-FIT Results for Laboratory- versus Plant-Produced Asphalt Mixtures.

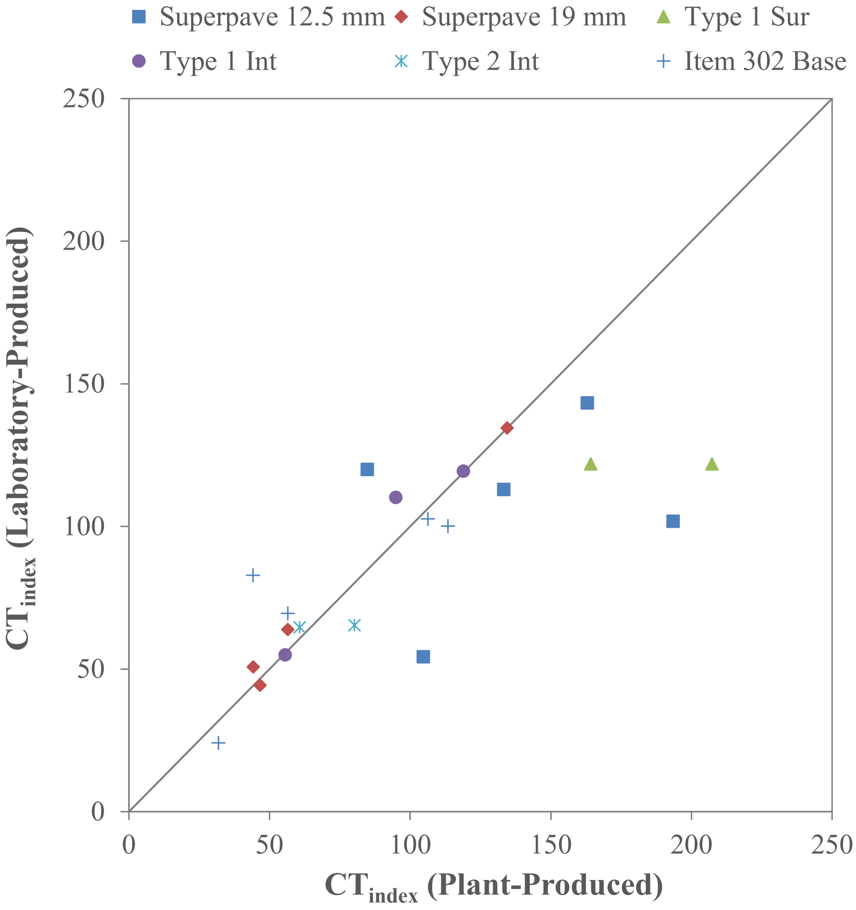


Figure B.2. IDEAL-CT Results for Laboratory- versus Laboratory-Produced Asphalt Mixtures.

B.3 Effect of Aging Protocols

Four asphalt mixtures were selected to evaluate the effect of different aging protocols on the I-FIT and IDEAL-CT test results, including one Superpave 12.5 mm (Surface) mix (M1030), one Superpave 19 mm (Intermediate) mix (M1028), one Marshall Type 1 Surface mix (M0992), and one Marshall Type 2 Intermediate mix (M0962). Plant-produced and laboratory-produced asphalt mixtures were used for the evaluation of the effect of aging. The following aging protocols were used to simulate the short-term and long-term aging of the I-FIT and IDEAL-CT specimens:

- Short-term oven aged (STOA):
  - Reheating of loose plant-produced asphalt mixtures for 3 hours at the compaction temperature.
  - Heating of loose laboratory-produced asphalt mixtures according to AASHTO R 30.

- Long-term oven aged (LTOA85):
  - Heating of compacted plant- or laboratory-produced samples for five days at 85°C.
- Long-term oven aged (LTOA95):
  - Heating of compacted plant- or laboratory-produced samples for three days at 95°C.

The effect of the different aging protocols on the I-FIT and IDEAL-CT test results for the four asphalt mixtures (Superpave 12.5 mm Surface, Superpave 19 mm Intermediate, Type 1 Surface, and Type 2 Intermediate) is presented in Figures B.3 to B.14. Figures B.3 to B.10 present the I-FIT and IDEAL-CT test results obtained for each asphalt mixture using the three aging protocols. Figures B.11 and B.12 present a comparison between the I-FIT and IDEAL-CT test results for the STOA and LTOA specimens, while Figures B.13 and B.14 present a comparison between the I-FIT and IDEAL-CT test results for the LTOA95 and LTOA85 specimens.

As can be noticed from Figures B.11 and B.12, lower cracking indices were obtained for LTOA specimens than for STOA specimens using both the I-FIT and IDEAL-CT tests. However, by comparing the distance between the data points and line of equality in both figures, it can be noticed that the effect of aging is more pronounced on the FI than the CT_{index}. These figures show that the FI for the LTOA specimens is approximately 1/3 that of the STOA specimens, while the CT_{index} for the LTOA specimens is approximately 1/2 that of the STOA specimens. This was the case for both LTOA95 and LTOA85 aging protocols, which resulted in comparable cracking indices, as shown in Figures B.13 and B.14.

The previous figures also show that the four asphalt mixtures had the same ranking with regard to resistance to cracking regardless of the protocol used to age the I-FIT and IDEAL-CT specimens. Therefore, to reduce the specimen preparation time for both tests, it was recommended to use STOA specimens.

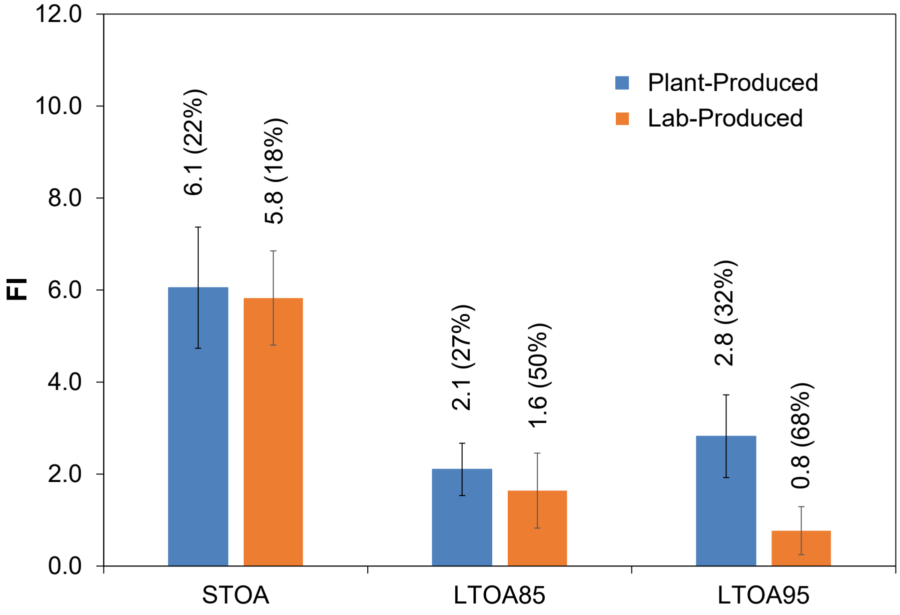


Figure B.3. Effect of Aging on the I-FIT Test Results for a Superpave 12.5 mm Mixture.

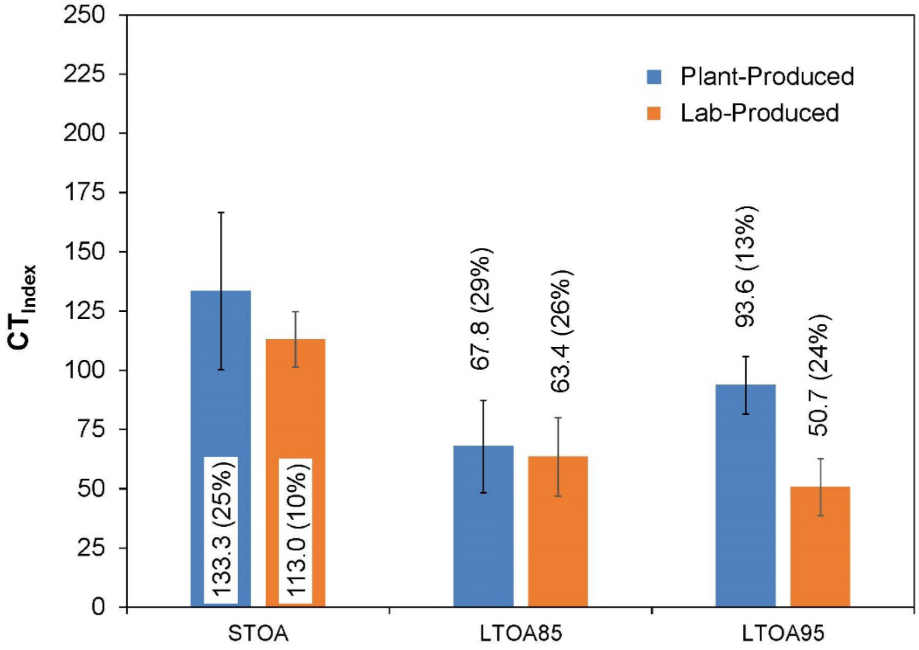


Figure B.4. Effect of Aging on the IDEAL-CT Test Results for a Superpave 12.5 mm Mixture.

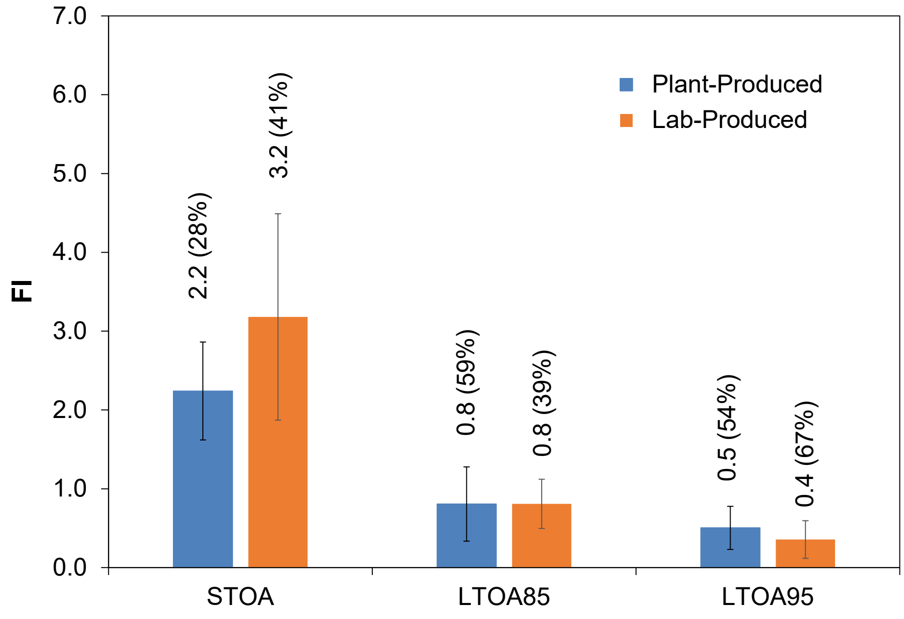


Figure B.5. Effect of Aging on the I-FIT Test Results for a Superpave 19 mm Mixture.

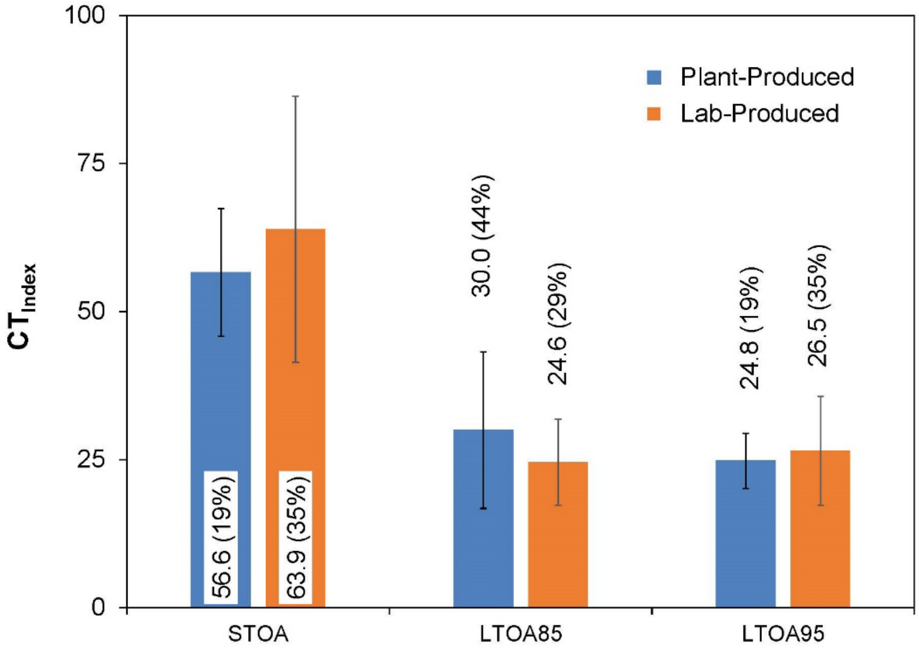


Figure B.6. Effect of Aging on the IDEAL-CT Test Results for a Superpave 19 mm Mixture.

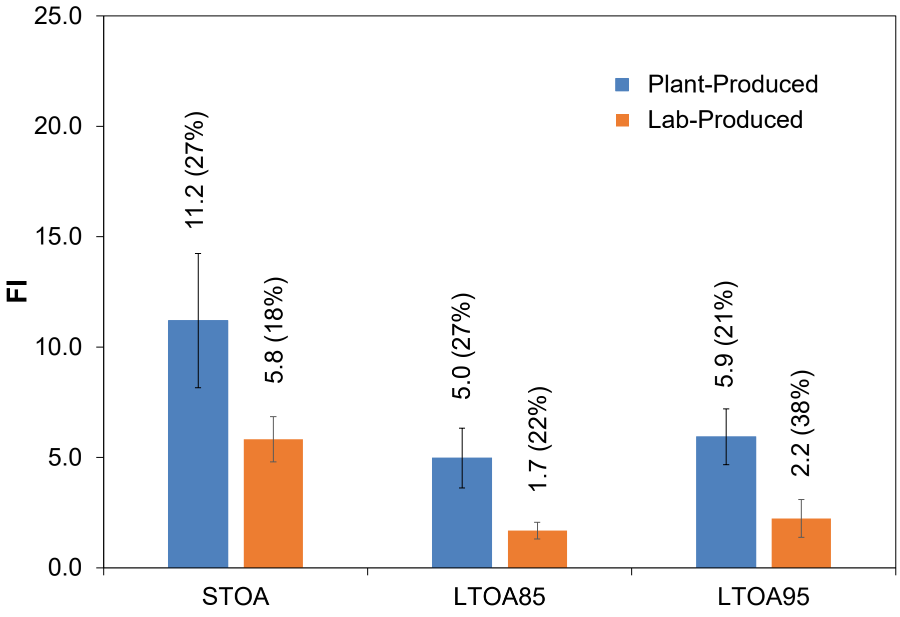


Figure B.7. Effect of Aging on the I-FIT Test Results for a Type 1 Surface Mixture.

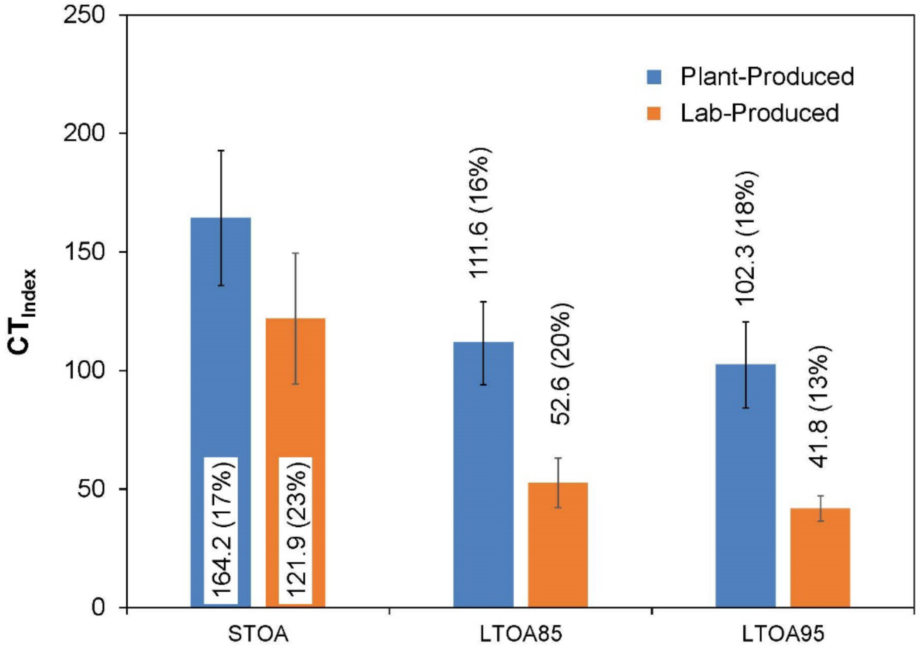


Figure B.8. Effect of Aging on the IDEAL-CT Test Results for a Type 1 Surface Mixture.

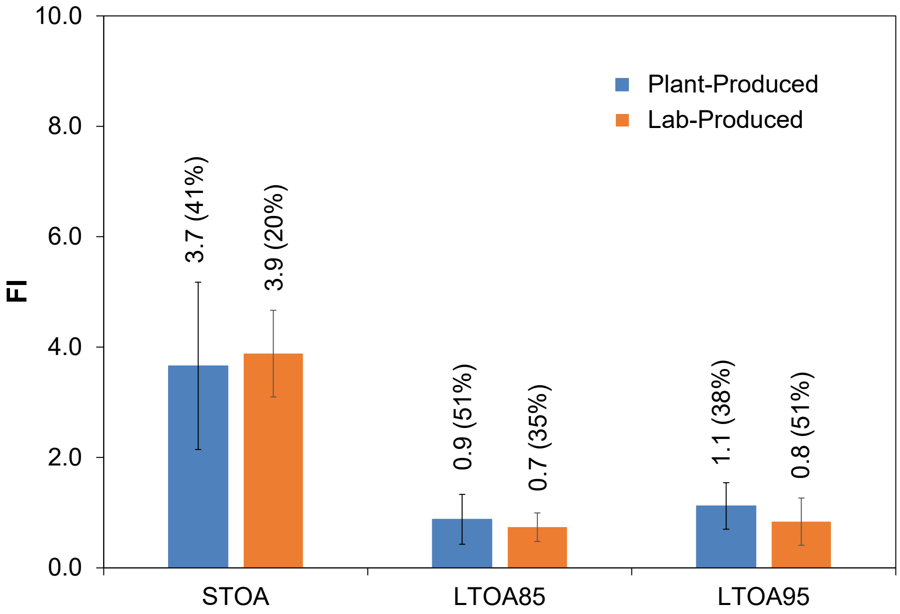


Figure B.9. Effect of Aging on the I-FIT Test Results for a Type 2 Intermediate Mixture.

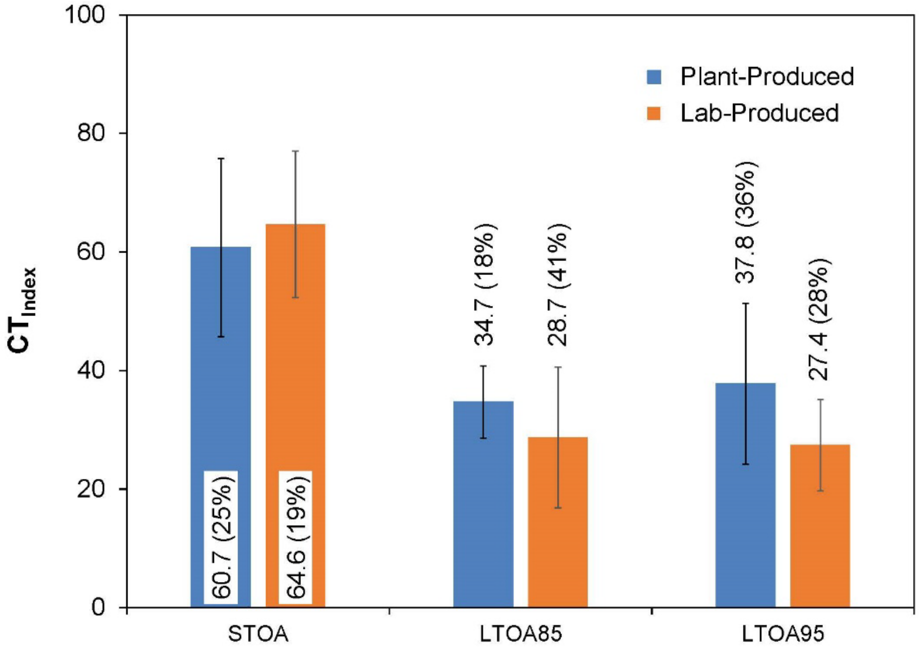


Figure B.10. Effect of Aging on the IDEAL-CT Test Results for a Type 2 Intermediate Mixture.

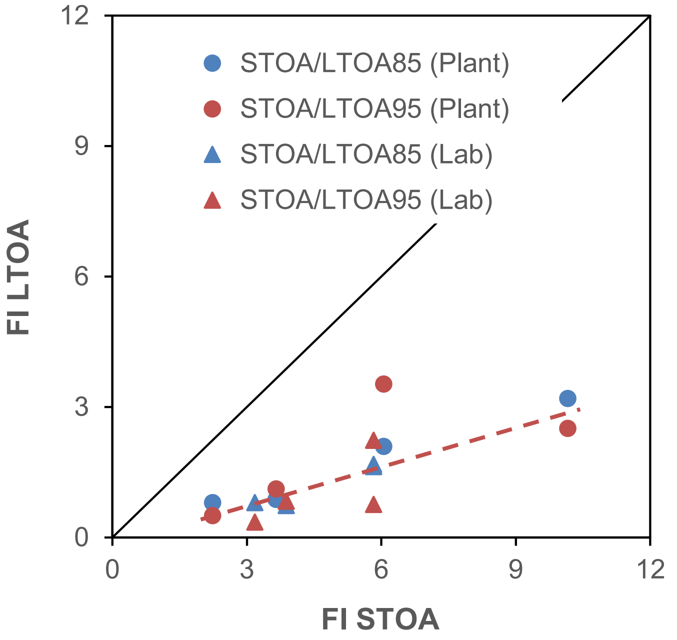


Figure B.11. Comparison between I-FIT Test Results for LTOA and STOA Specimens.

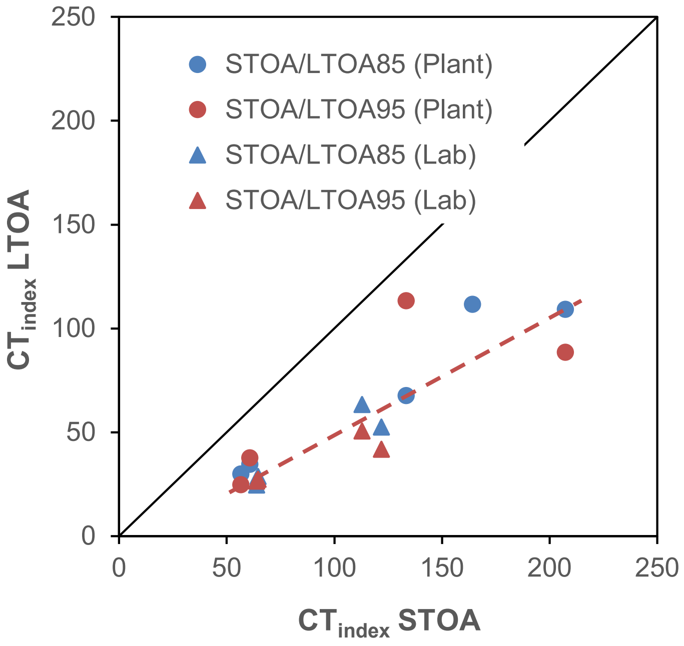


Figure B.12. Comparison between IDEAL-CT Test Results for LTOA and STOA Specimens.

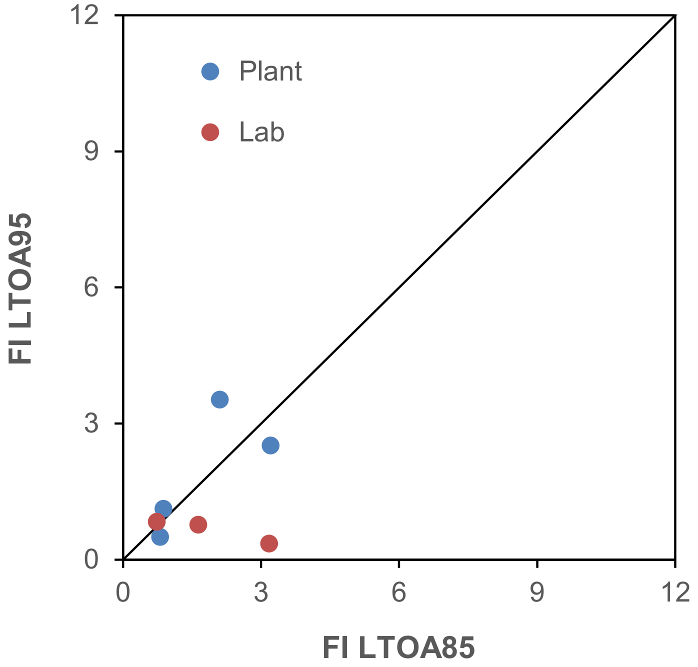


Figure B.13. Comparison between I-FIT Test Results for LTOA95 and LTOA85 Specimens.

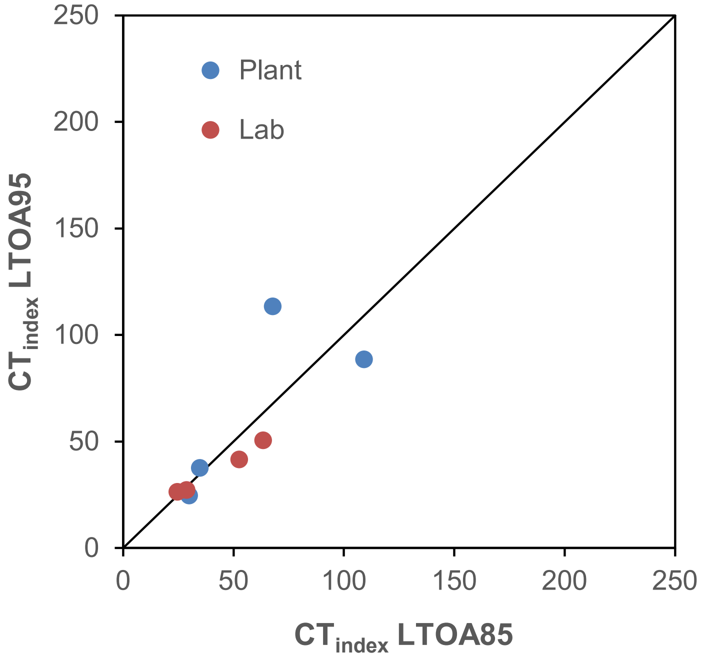


Figure B.14. Comparison between IDEAL-CT Test Results for LTOA95 and LTOA85 Specimens.

B.5 Effect of Air Void Level

A target air void level of 7.0 ± 1.0% is specified in AASHTO TP 124-18 for I-FIT specimens, while a target air void of 7.0 ± 0.5% is specified in ASTM D8225-19 for IDEAL-CT specimens. To examine the effect of the air void level on the I-FIT and IDEAL-CT test results, specimens were prepared for both tests using three different target air void levels of 5%, 7%, and 9%. One plant-produced asphalt mixture meeting ODOT specifications for Superpave 12.5 mm (Surface) mix (M1030) was used for this purpose. The asphalt mixture was produced using PG 70-22, 5.9% asphalt binder content, and 15% RAP. Short-term aged specimens were used for this evaluation.

The I-FIT and IDEAL-CT test results at the three different air void levels (5%, 7%, and 9%) are presented in Figures B.15 and B.16, respectively. As can be noticed from both figures, higher cracking indices were obtained at higher air void levels for both I-FIT and IDEAL-CT tests. However, the effect of the air void level was more pronounced on the FI than the CT_{index}. As the I-FIT test specification also allows for a wider range of target air void levels (7.0 ± 1.0%) than the IDEAL-CT test specification (7.0 ± 0.5%), higher variability is expected in the I-FIT test results. The test results in Figures B.15 and B.16 suggest that air void level has a significant effect on the I-FIT and IDEAL-CT cracking indices. Therefore, it should be strictly controlled during sample preparation for each test.

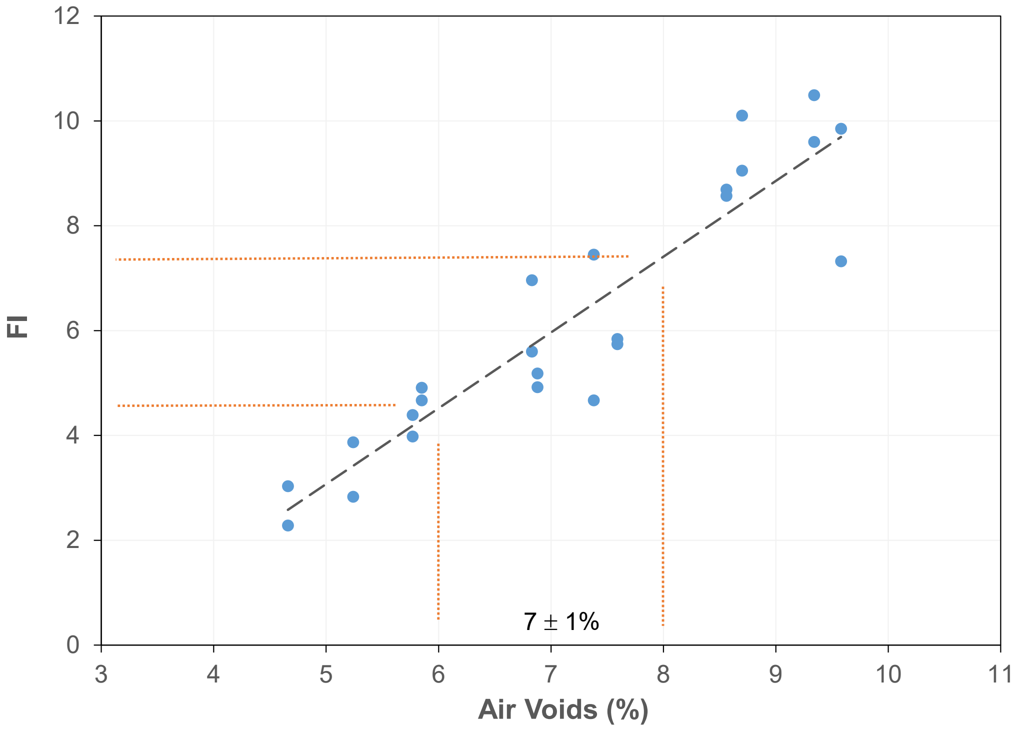


Figure B.15. Effect of Air Void Level on I-FIT Test Results.

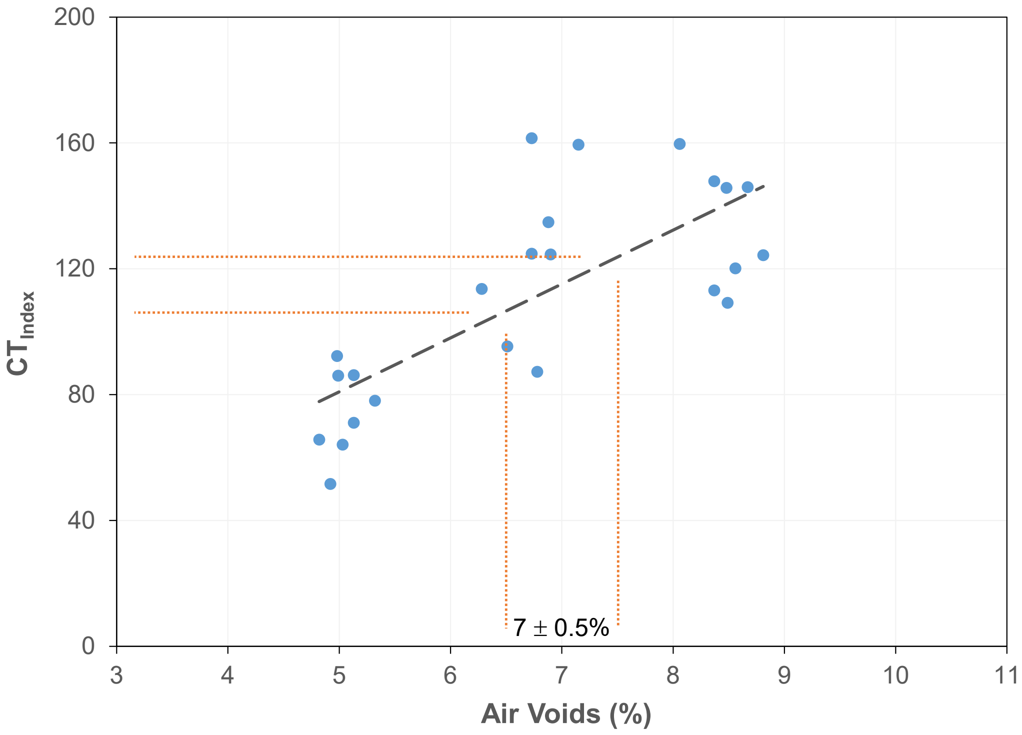


Figure B.16. Effect of Air Void Level on IDEAL-CT Test Results.

B.6 Effect of Specimen Dimension

The research team evaluated the effect of the specimen dimensions on the I-FIT and IDEAL-CT test results by varying the specimen thickness. Four different thicknesses (25 mm, 38 mm, 50 mm (standard), and 62 mm) were used for the I-FIT specimens. All specimens were obtained from Superpave gyratory compacted samples measuring 150 mm in diameter and 160 mm in height. One mixture (Superpave 12.5 mm mix – M1012) was used for the preparation of the I-FIT test specimens. As for the IDEAL-CT test, two specimen thicknesses were considered in the evaluation (62 mm and 95 mm) using the standard specimen diameter of 150 mm. Nine asphalt mixtures (two Superpave 12.5 mm mixes (M0704 plant-produced and M1012 plant-produced), one Superpave 19 mm mix (M1028 plant-produced), three Marshall Type 1 surface mixes (M0992 plant-produced, M0992 laboratory-produced, and M0643 laboratory-produced), two Marshall Type 1 intermediate mixes (M0697 plant-produced and M0697 laboratory-produced), and one Marshall Type 2 intermediate mix (M0962 laboratory-produced)) were used for the preparation of the IDEAL-CT test specimens.

Figure B.17 presents the effect of the specimen thickness on the I-FIT test results. As can be noticed from this figure, thinner I-FIT specimens, such as 25-mm-thick specimens, resulted in higher FI values with higher variability. The FI decreased with the increase in specimen thickness and became consistent at a thickness of 50 mm. Therefore, it was recommended to conduct the I-FIT test at the standard thickness of 50 ± 1 mm.

Figures B.18 and B.19 present the effect of the specimen thickness on the IDEAL-CT test results. As can be noticed from these figures, comparable CT_{index} values were obtained for the 95-mm and the 62-mm-thick specimens. This is expected as the CT_{index} includes a correction factor for specimen thickness. It is recommended to use a specimen thickness of 62 ± 3 mm for Type 1 (Surface and Intermediate) mixes and use a specimen thickness of 95 ± 5 mm for Superpave (12.5 mm and 19 mm), Type 2 (Intermediate), and Item 302 mixes for the IDEAL-CT test.

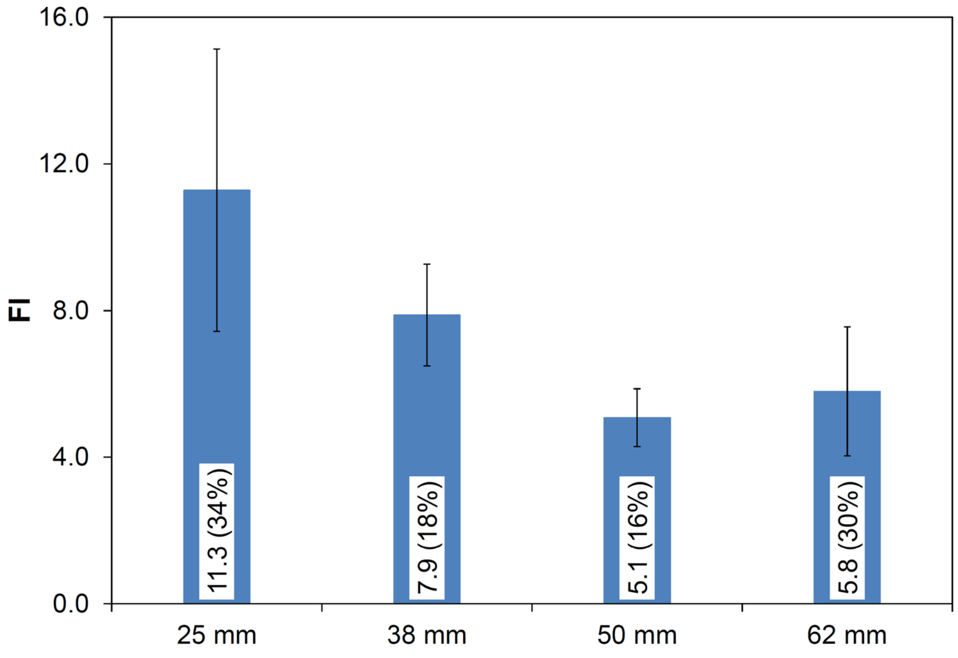


Figure B.17. Effect of Specimen Thickness on I-FIT Test Results.

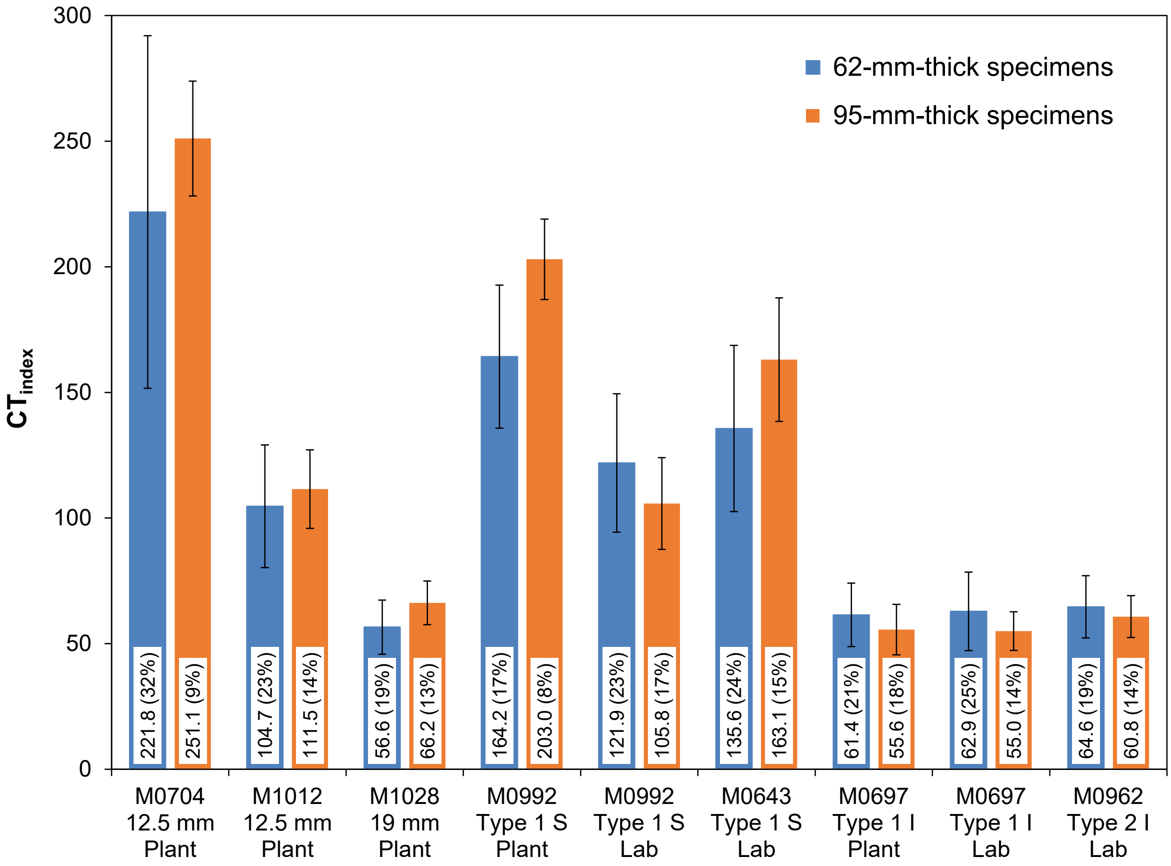


Figure B.18. Effect of Specimen Thickness on IDEAL-CT Test Results.

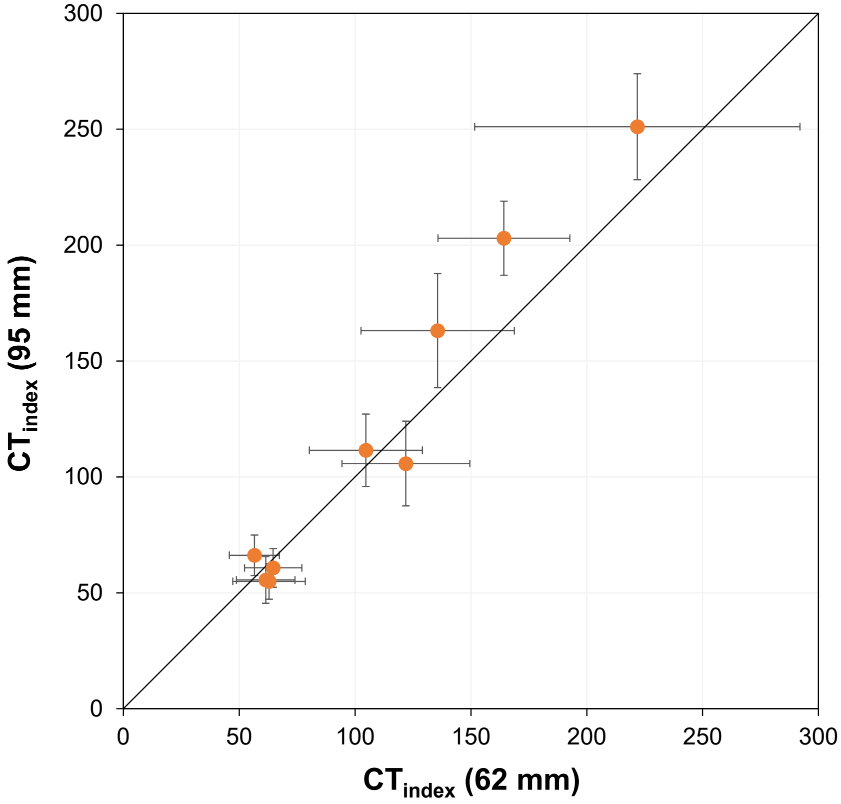


Figure B.19. Comparison between CT$_{\text{index}}$ Values of 95-mm and 62-mm-Thick Specimens.

B.7 Variability of I-FIT and IDEAL-CT Test Results

The coefficient of variation (COV) for the CT$_{\text{index}}$ in the IDEAL-CT test averaged around 20% for surface mixes, 20% for intermediate mixes, and 25% for asphalt base mixes; while the COV for the FI in the I-FIT test averaged around 25% for surface mixes, 25% for intermediate mixes, and 35% for asphalt base mixes. Therefore, it was recommended to conduct both tests using a minimum of six specimens.

Appendix C
Draft Test Methods for the I-FIT and IDEAL-CT Tests

C.1 Introduction

This appendix presents draft test methods for the I-FIT and IDEAL-CT tests in ODOT standard format. The test methods include detailed information about the requirements for the test apparatus (including the type of the load-support fixture), asphalt mixture preparation, aging protocol, fabrication of test specimens (including the target air void level), specimen dimensions, test temperature, loading rate, information collected during loading of test specimens, number of test replicates, and procedure for analyzing the test data to calculate the required performance parameter(s). The draft test method for the I-FIT test was primarily based on AASHTO TP 124-18 (Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index Test) and the draft test method for the IDEAL-CT test was primarily based on ASTM D8225-19 (Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature) with some modifications to achieve the objectives of this research project.

STATE OF OHIO
DEPARTMENT OF TRANSPORTAION

SUPPLEMENT XXXX
DETERMINING THE CRACKING RESISTANCE OF ASPHALT MIXTURES USING THE ILLINOIS FLEXIBILITY INDEX TEST (I-FIT)

January X, 2020

XXXX.01 Description. This test method is used to determine the cracking resistance properties of asphalt mixtures at intermediate temperatures. In this test, a semi-circular specimen with a notch in the center of the flat edge is loaded to failure using a test fixture with semi-circular bend (SCB) geometry. The fracture parameters obtained from this test (fracture energy, G_f, and post peak slope, *m*, of the load–displacement curve) are used to calculate the Flexibility Index (FI), which can be used to identify brittle asphalt mixtures that may be prone to premature cracking. This procedure is applicable to laboratory-compacted specimens as well as field cores with a nominal maximum aggregate size (NMAS) of 19 mm or less. This supplement is based on the most recent AASHTO standard test method for the Illinois flexibility index test (I-FIT), as documented in AASHTO TP 124-18 (2019).

XXXX.02 Testing Device. An I-FIT test system consisting of an axial loading device (capable of applying a constant deformation rate of 50 ± 1 mm/min), a load measuring device (with a resolution of 10 N or lower and a capacity of at least 10 kN), a bend test fixture (conforming to AASHTO test method TP 124-18 Method A or Method B, with a total distance of 120 ± 0.1 mm between the two steel rollers), specimen deformation measurement devices (with a resolution of 0.01 mm or lower), and a control and data acquisition system (capable of collecting load and displacement test data at a minimum sampling frequency of 20 Hz) are used for this test.

XXXX.03 Fabrication of Test Specimens. The I-FIT test specimens can be obtained from Superpave gyratory compacted (SGC) cylinders or from field cores. The preparation procedure for both types of specimens is discussed below.

SGC Specimens: To fabricate the I-FIT test specimens in the laboratory, place the asphalt mixture in a 150-mm Superpave gyratory mold and compact the mixture to a height of 160 ± 1 mm in accordance with AASHTO T 312. Prior to testing, pour the asphalt mixture onto a tray and place it in an oven for short-term aging as per AASHTO R 30. When conducting tests to determine the effects of long-term aging, use the procedure specified in AASHTO R 30. Obtain two 50 ± 1 mm thick discs with smooth and parallel faces from the middle of the 160 ± 1 mm tall specimen, as shown in Figure 1. Measure the bulk density of each disc according to ODOT Supplement 1036 and use it to confirm that the air void level for each disc is 7.0 ± 1%. Cut each disc into two identical halves to create four individual I-FIT specimens, as shown in Figure 1. Prepare a minimum of six individual test specimens for each I-FIT test.

For test specimen preparation, a typical laboratory saw can be used to obtain the cylindrical discs with smooth parallel surfaces from the SGC specimen. Diamond-impregnated cutting faces and water cooling are recommended to minimize damage to the specimen. When cutting the specimens, take care to avoid pushing the two halves against each other because this may create an uneven base surface of the test specimen that will affect the test results. After obtaining the semicircular specimen, use a tile saw to create a notch with a depth of 15 ± 1 mm and a width of less than or equal to 2.25 mm. The dimensions for the final notched semicircular test specimen are shown in Figure 2.

Discard any specimen having a notch that terminates in an aggregate particle 9.5 mm or larger on both faces of the specimen. For the remaining specimens, measure the notch depth on both faces of the specimen and record the average value to the nearest 0.1 mm. Measure and record the notch width at two locations along the notch and record the average to the nearest 0.1 mm. Measure and record the ligament length on both faces of the specimen and record the average value to the nearest 0.1 mm. Measure and record the thickness of each specimen at three locations (two locations approximately 19.0 mm on each side of the notch and a third location on the curved edge directly across from the notch) and record the average thickness to the nearest 0.1 mm.

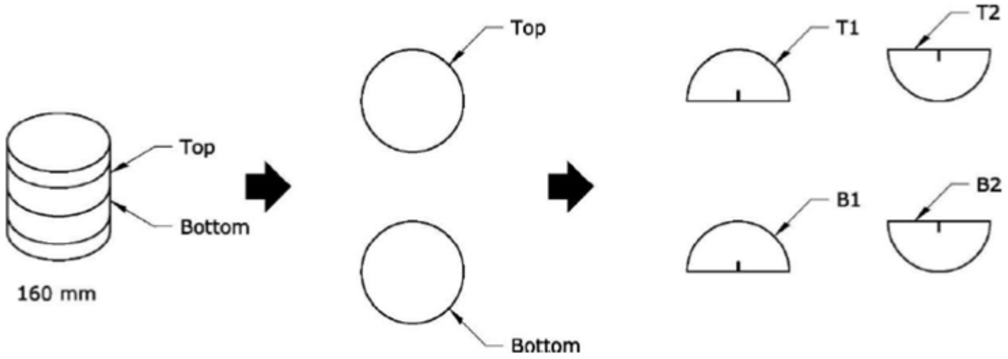


Figure 1: Laboratory Fabrication of I-FIT Specimens.

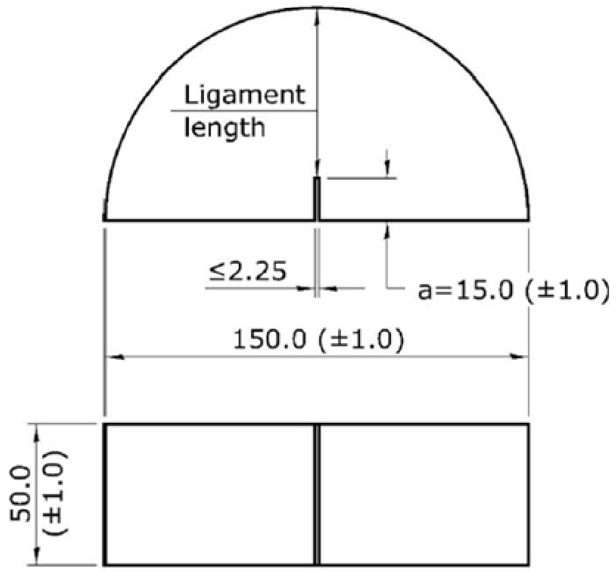


Figure 2: Final Dimensions of an I-FIT Specimen (All dimensions are in mm).

Field Core Specimens: I-FIT test specimens can also be obtained from field cores having a diameter of 150 ± 8 mm. The thickness of the field cored test specimens may vary from 25 to 50 ± 1 mm. To preserve the core thickness, the as-compacted face of the field core can be left intact (there is no need to trim this face). If the lift thickness in the field is less than 50 ± 1 mm, prepare the I-FIT specimens so that they are as thick as possible; the specimen thickness must be two times the nominal maximum aggregate size (NMAS) of the mixture or 25 ± 1 mm, whichever is greater. If the lift thickness is greater than 50 ± 1 mm, prepare a 50 ± 1 mm disc in a manner that is similar to that for the SGC samples. Cores from pavements with lifts greater than 75 ± 1 mm may be cut to provide two cylindrical specimens of equal thickness. Therefore, to obtain four I-FIT replicates from field cores, as specified in AASHTO TP 124-18, one 150-mm-diameter field core is required if the lift thickness is greater than or equal to 100 mm, and two 150-mm-diameter field cores are required if the lift thickness is less than 100 mm. It is noted that the air void requirement does not apply to specimens prepared from field cores. However, it is necessary to measure the air void content of each disc in accordance with AASHTO T 269.

XXXX.04 Sample Conditioning and I-FIT Test Procedure. Prior to testing, condition the I-FIT test specimens in a water bath or an environmental chamber at 25 ± 0.5 °C for 2 hours ± 10 minutes. Be sure to complete the positioning and testing of each I-FIT specimen within 5 ± 1 minutes after conditioning in the environmental chamber or water bath.

Position the conditioned test specimen on the loading frame so that it is symmetrical in every direction with respect to the roller supports. Ensure that the specimen is perpendicular to the roller supports in both the horizontal plane and the vertical plane and that the line of the force applied by the loading head passes vertically through the center of the specimen and through the sawed notch.

Apply a small contact load of 0.1 ± 0.01 kN at a loading rate of 0.05 kN/s. Subtract the weight of the loading head from the contact load to obtain the actual contact load on the specimen. Record the weight of the loading head, the applied contact load, and the actual contact load to the nearest 0.01 kN.

Conduct the I-FIT test at a rate of 50 ± 1 mm/min. During the test, collect the load and line load displacement data at a minimum sampling frequency of 20 Hz in order to obtain a smooth load–load line displacement curve. Stop the I-FIT test when the load drops below 0.1 kN.

XXXX.05 Test Parameters. Several test parameters are obtained from the load versus displacement curve in the I-FIT test, including the work of fracture (W_f), fracture energy (G_f), secant stiffness (S), post-peak slope (m), displacement at peak load (u_0), and critical displacement (u_1), as illustrated in Figure 3. These parameters can be used to calculate the flexibility index (FI) using Equations 1 and 2:

$$G_F = \frac{W_F}{Area_{lig}} \times 10^6 \quad (1)$$

$$FI = \frac{G_F}{|m|} \times A \quad (2)$$

where,

$Area_{lig}$ = ligament area = ligament thickness × length
A = a unit conversion factor (0.01)

Use the I-FIT software and the accompanying Matlab compiler that is available on the Illinois Center for Transportation (ICT) website to analyze the load versus displacement data. More information about the required software is available at: https://apps.ict.illinois.edu/.

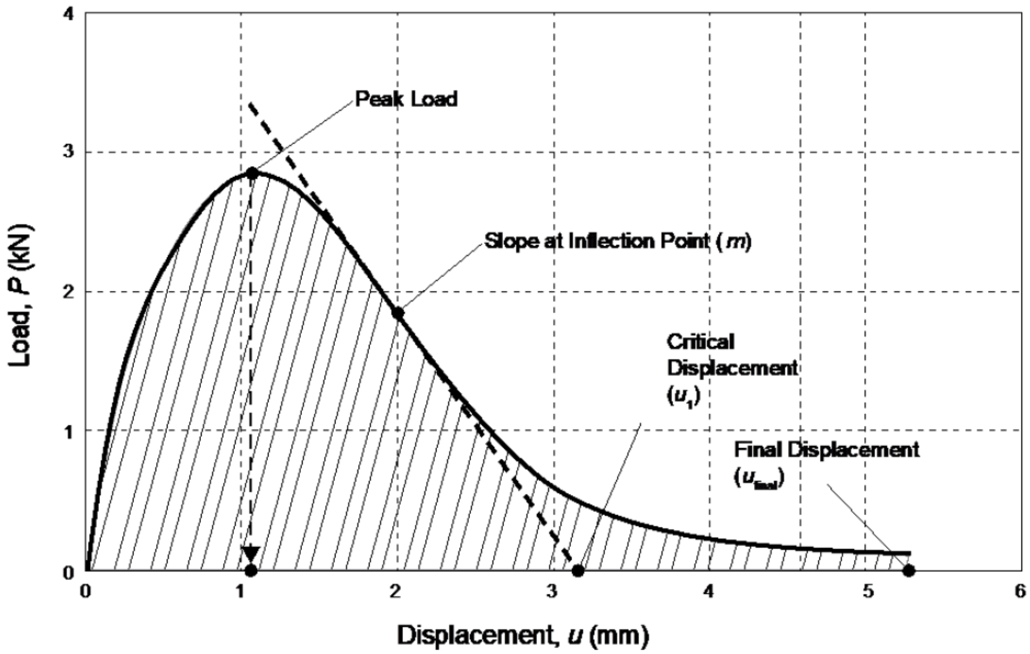


Figure 3: Typical Load versus Displacement Curve.

XXXX.06 Report. The information to be reported for the I-FIT test includes the following:

- Bulk specific gravity of specimen for each disc (nearest 0.001)
- Maximum theoretical specific gravity of asphalt mixture (nearest 0.001)
- Air void content for each specimen (nearest 0.1%)
- Number of cut faces for each specimen (if pavement cores were used)
- Average notch depth for each specimen (nearest 0.1 mm)
- Average notch width for each specimen (nearest 0.1 mm)
- Average ligament length for each specimen (nearest 0.1 mm)
- Average specimen thickness for each specimen (nearest 0.1 mm)
- Average and coefficient of variation (COV) of peak load (nearest 0.1 kN)
- Average and COV of recorded time at peak load (nearest 0.1 s)
- Average and COV of displacement at the peak load, u_0 (nearest 0.1 mm)
- Average and COV of critical displacement, u_1 (nearest 0.1 mm)
- Average and COV of post-peak slope, m (nearest 0.1 kN/mm)
- Average and COV of fracture energy, G_f (nearest 1 J/m^2)
- Average and COV of flexibility index, FI (nearest 0.1)

Use the attached worksheet to summarize your results.

STATE OF OHIO
DEPARTMENT OF TRANSPORTAION

SUPPLEMENT XXXX
DETERMINING THE CRACKING RESISTANCE OF ASPHALT MIXTURES USING THE INDIRECT TENSILE ASPHALT CRACKING TEST

November X, 2021

XXXX.01 Description. This test method is used to determine the cracking resistance properties of asphalt mixtures at intermediate temperatures. In this test, a cylindrical specimen is vertically loaded along its diameter until the specimen breaks and the measured load drops to nearly zero. The cracking parameter obtained from this test is called the cracking tolerance index (CT_{index}), which can be used to identify brittle asphalt mixtures that may be prone to premature cracking.

This supplement is based on the most recent ASTM standard test method for the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) as documented in ASTM D8225−19 with some modifications.

XXXX.02 Testing Device. To conduct the test, use an indirect tensile cracking test system consisting of the following:

- An axial loading device that is capable of applying an average constant deformation rate of 50 ± 2 mm/min. A hydraulic, electromechanical, screw-driven, or pneumatic frame may be used if the frame is able to maintain the specified average constant deformation rate.
- A load measurement device with a resolution of 10 N or lower and a capacity of at least 25 kN.
- A loading strip that has a width of 19.05 ± 0.3-mm; conforms to Option A, Option B, or Option C in Section 6 of ASTM D8225−19; and has a concave surface with a radius of curvature that is equal to the radius of the test specimen.
- Specimen deformation measurement devices with a resolution of 0.01 mm or lower.
- A control and data acquisition system that is capable of collecting load and displacement test data at a sampling frequency of at least 40 Hz.

XXXX.03 Fabrication of Test Specimens. Both field cores and Superpave gyratory compacted (SGC) cylinders can be used as IDEAL-CT test specimens. The preparation procedure for both types of specimens is discussed below.

SGC Specimens Prepared from Loose Mixtures: For asphalt mixtures prepared in the laboratory, pour the asphalt mixture into a tray and place the tray in an oven for short-term aging (according to AASHTO R 30) prior to compaction. For asphalt mixtures produced at an asphalt plant and compacted in the laboratory, allow the loose asphalt mixture to cool to room temperature, then reheat the loose mixture at the compaction temperature for 2.5 to 3 hours prior to compaction.

To fabricate IDEAL-CT test specimens in the laboratory from a loose asphalt mixture, place the asphalt mixture in a 150-mm Superpave gyratory mold and compact the mixture to the target height shown in the table below in accordance with AASHTO T 312.

Mix Type	Target Height
Item 301 Mixes	95 mm ± 5 mm
Item 302 Mixes	95 mm ± 5 mm
Item 424A Mixes	62 mm ± 3 mm
Item 424B (Smoothseal) Mixes	62 mm ± 3 mm
Item 441 Type 1 Surface Mixes	62 mm ± 3 mm
Item 441 Type 1 Intermediate Mixes	62 mm ± 3 mm
Item 441 Type 2 Intermediate Mixes	95 mm ± 5 mm
Item 442 Mixes	95 mm ± 5 mm
Item 443 Mixes	95 mm ± 5 mm
SS-823 Type 1 Surface Mixes	62 mm ± 3 mm
SS-823 Type 1 Intermediate Mixes	62 mm ± 3 mm
SS-823 Type 2 Intermediate Mixes	95 mm ± 5 mm
SS-860 (Thinlays) Mixes	62 mm ± 3 mm

Measure the specimen diameter at three locations along the height of the specimen to the nearest 0.1 mm (using a caliper) and record the average diameter to the nearest 0.1 mm. Measure the specimen thickness at three locations along the circumference of the specimen to the nearest 0.1 mm (using a caliper) and record the average to the nearest 0.1 mm.

Measure the bulk density of the compacted specimen according to ODOT Supplement 1036 and use it to calculate the air void level for each specimen to ensure that a target air void level of 7.0 ± 0.5% is achieved. Test a minimum of six specimens for each IDEAL-CT test.

Field Core Specimens: Field cores with a diameter of 150 ± 2 mm and a thickness of at least 38 mm can be used as IDEAL-CT test specimens. To preserve the core thickness, leave the as-compacted face of the field core intact (in other words, do not trim the as-compacted face). Measure the air void content of each disc in accordance with AASHTO T 269. It is noted that the air void requirement does not apply to the field cores.

XXXX.04 Sample Conditioning and IDEAL-CT Test Procedure. After measuring the bulk density of the compacted specimen, thoroughly dry the specimen on all sides using a portable fan that is at least 12 inches (305 mm) in diameter for a minimum of 4 hours. This can be achieved by placing the specimen on a metal rack similar to an oven rack and directing the fan toward the specimen to allow airflow from all directions during this time. Allow for a minimum of 16 hours after measuring the bulk density before beginning to condition the specimen for IDEAL-CT testing (i.e., do not test the specimen until the following day after the bulk density is measured), and maintain the specimens at a temperature ranging between 68 °F and 86 °F (20 °C and 30 °C) prior to conditioning. Condition the IDEAL-CT test specimens in a water bath or an environmental chamber at 25 ± 1°C for 2 hrs ± 10 minutes before testing. For each specimen, position the sample and complete the IDEAL-CT test within 4 minutes of removing the specimen from the environmental chamber or the water bath.

Position the conditioned test specimen on the loading frame so that it is centered and makes uniform contact with the loading fixture. Conduct the IDEAL-CT test at a loading rate of 50 ± 2 mm/min. During the test, collect the load and displacement data at a minimum sampling frequency of 40 Hz in order to obtain a smooth load-displacement curve. Stop the IDEAL-CT test when the load drops below 0.1 kN.

XXXX.05 Test Parameters. Several test parameters are obtained from the load versus displacement curve in the IDEAL-CT test. These test parameters include the work of fracture (G_f), secant stiffness (S), displacement corresponding to the 75 percent of the peak load in the post-peak stage (l_{75}), and post-peak slope (m_{75}), as illustrated in Figure 1. These parameters can be used to calculate the cracking tolerance index (CT_{index}) using Equations 1 and 2:

$$CT_{index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{D} \tag{1}$$

where,

t = specimen thickness (mm)
D = sample diameter (mm)

$$m_{75} = \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \tag{2}$$

where,

P_{85} = 85 percent of the peak load in the post-peak stage (kN)

P_{65} = 65 percent of the peak load in the post-peak stage (kN)
l_{85} = displacement corresponding to 85 percent of the peak load in the post-peak stage (mm)
l_{65} = displacement corresponding to 65 percent of the peak load in the post-peak stage (mm)

Contact the manufacturer of your axial loading device or smart jig for additional information on how to analyze the load versus displacement data to obtain the CT_{index}.

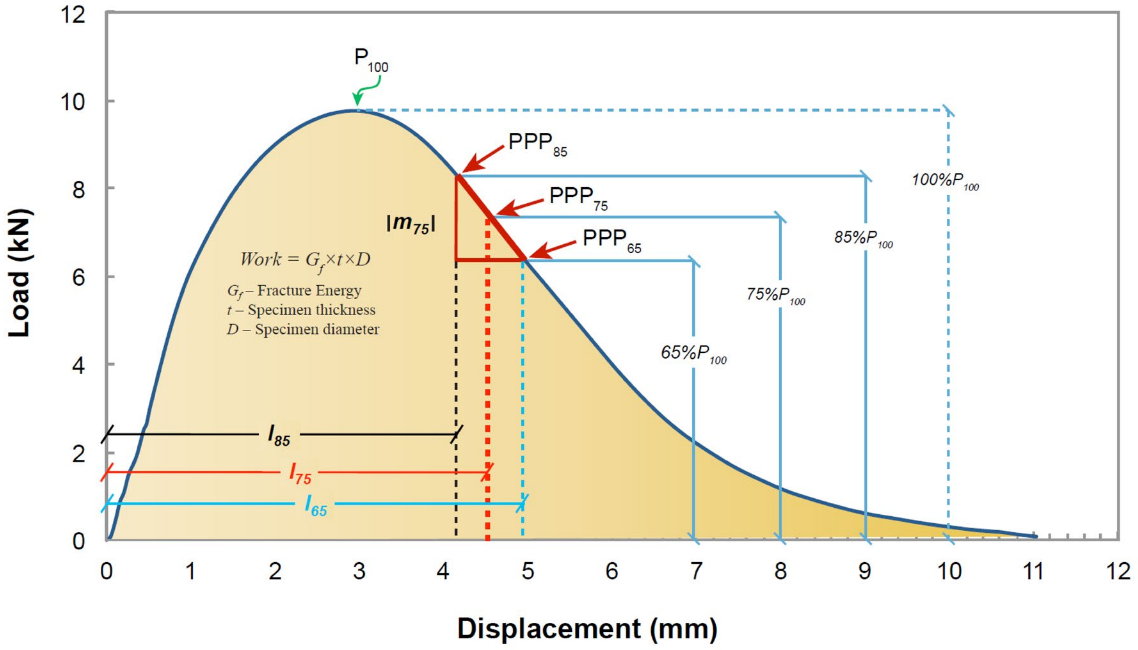


Figure 1: Typical Load versus Displacement Curve.

XXXX.06 Acceptance. The minimum performance criteria for this test is presented in the table below.

Mix Type	Minimum CT_{index}
Item 442 (Superpave) 12.5 mm (Surface)	80
Item 442 (Superpave) 19 mm (Intermediate)	60
Item 441 (Marshall) Type 1 Surface Mixes	80
Item 441 (Marshall) Type 1 Intermediate Mixes	80
Item 441 (Marshall) Type 2 Intermediate Mixes	60
Item 302 (Marshall) Mixes	60

XXXX.07 Report. Report the following information:

- Mix producer.
- Project identification number (ID).

- Job mix formula (JMF) number.
- Mix type.
- Test date.
- Test temperature, °C (to the nearest 0.1 °C).
- Specimen identification number.
- Specimen air voids, % (to the nearest 0.1%).
- Specimen diameter, mm (to the nearest 0.1 mm).
- Specimen thickness, mm (to the nearest 0.1 mm).
- Peak load, kN (to the nearest 0.1 kN).
- Indirect tensile strength, kPa (to the nearest 0.1 kPa).
- Displacement, l_{75}, mm (to the nearest 0.1 mm).
- Failure energy, G_f, Joules/mm^2 (to the nearest 0.1 Joule/mm^2).
- Post-peak slope, $|m_{75}|$, N/mm (to the nearest 0.1 N/mm).
- Cracking tolerance index, CT_{index} (to the nearest 0.1).
- Load versus displacement curves for all specimens.

Summarize the test results on the attached worksheet. Provide the load versus deformation data and graphs for all specimens including the outliers to ODOT Asphalt Section.

STATE OF OHIO
DEPARTMENT OF TRANSPORTATION

Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

MIX PRODUCER:
PROJECT ID:
JMF #:
MIX TYPE:

TEST DATE:
TEST TEMPERATURE (°C):

Load drop from (%)	85	to (%)	65

Specimen ID	Specimen Diameter (mm)	Specimen Thickness (mm)	Air Voids (%)	Peak Load (kN)	Tensile Strength (kPa)	Displacement l_{75} (mm)	Fracture Energy G_f (J/m^2)	Post-Peak Slope S	CT_{index} (t/62) $*(G_f/S)$ *(L/D)
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Average	0.0	0.0	0.0	0.0	0.0	0.0
Standard Deviation	0.0	0.0	0.0	0.0	0.0	0.0
COV	0.0	0.0	0.0	0.0	0.0	0.0

Last Modified: 12/21/2020

Appendix D
Screening Evaluation Results

D.1 Introduction

As part of the screening evaluation, the CT_{index} values from the IDEAL-CT test were compared to the FI values from the I-FIT test for all specimens included in the preliminary evaluation except those used to examine the effects of air void level and specimen thickness. This included specimens prepared using both plant-produced and laboratory-produced asphalt mixtures as well as STOA and LTOA-specimens. The comparison between the CT_{index} and the FI values is presented in Figure D.1. As can be noticed from this figure, a relatively high correlation – with a coefficient of determination, R^2, of approximately 0.74 – was obtained between the CT_{index} and the FI. Both laboratory tests also resulted in a similar ranking of asphalt mixtures with regard to cracking resistance, which implies that each test can be used as a surrogate for the other.

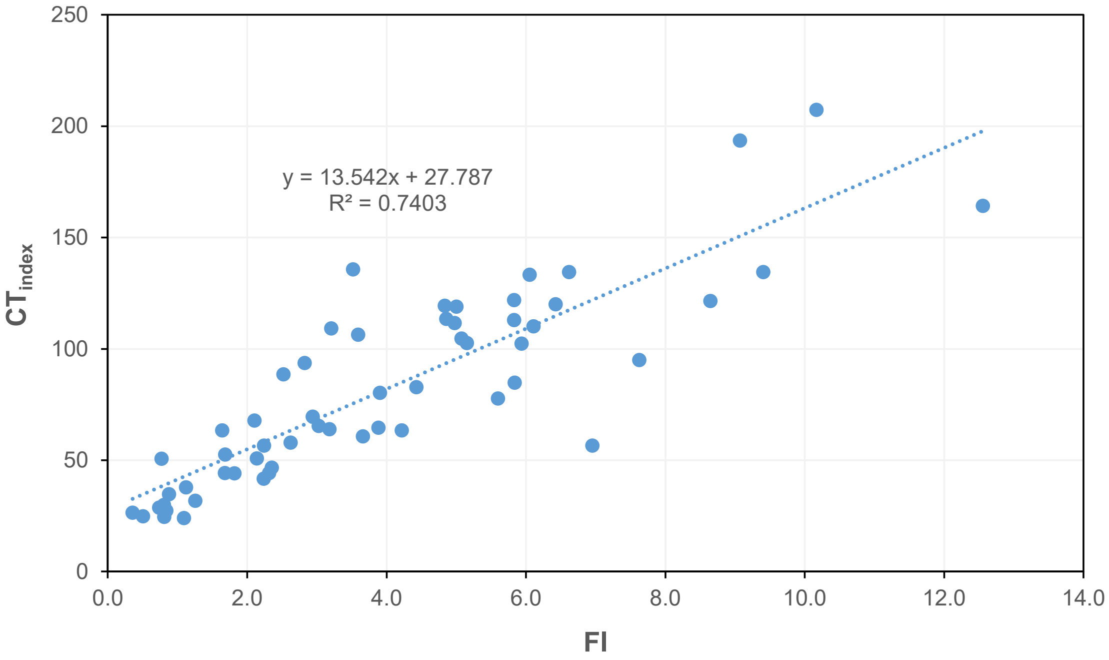


Figure D.1. Comparison between CT_{index} and FI Values.

D.2 Selection of a Laboratory Test for Full-Scale Evaluation

In addition to the high correlation between the I-FIT and IDEAL-CT test results, several advantages were observed for the IDEAL-CT test that make it more favorable to use for routine purposes than the I-FIT test, including:

- Faster and easier sample preparation. As compared to the I-FIT test, no cutting, trimming, or notching is needed for the preparation of the IDEAL-CT test samples. As a result, less time is required for the sample preparation and no additional pieces of equipment (such as saws) are needed for the IDEAL-CT test. The I-FIT test also requires test specimens to be discarded if the notch terminates in an aggregate particle 9.5 mm or larger on both faces of the specimen. This requirement may result in several specimens being discarded, especially for mixtures with larger aggregates. Therefore, additional samples will need to be prepared to obtain a sufficient number of specimens for testing.
- Applicability to asphalt mixtures containing larger aggregate particles. The I-FIT test is limited to testing asphalt mixtures with a nominal maximum aggregate size (NMAS) of 19 mm or less, while the IDEAL-CT can accommodate asphalt mixtures containing larger aggregate particles such as asphalt base mixes by increasing the specimen thickness to 95 mm (from a standard thickness of 62 mm).
- Easier to achieve the target air void level during compaction. Even though a more strict air void requirement is specified for the IDEAL-CT test than the I-FIT test (7.0 ± 0.5% for the IDEAL-CT versus 7.0 ± 1% for the I-FIT), it is easier to the achieve the target air void level for the IDEAL-CT specimens than the I-FIT specimens as no cutting and trimming is needed for the IDEAL-CT test. This is especially the case for asphalt mixtures with larger aggregate sizes.
- Straightforward analysis of test results. An Excel spreadsheet is available for analyzing the IDEAL-CT test results, while a software developed by the University of Illinois at Urbana-Champagne (UIUC) is typically used to analyze the I-FIT test results. Even though the I-FIT software is relatively simple to use, it was not easy to verify the outcome of the data analysis when some of the test results did not make sense.
- Lower variation in test results. The coefficient of variation (CV) for the CT_{index} in the IDEAL-CT test averaged around 20% for surface mixes, 20% for intermediate mixes, and 25% for

asphalt base mixes; while the CV for the FI in the I-FIT test averaged around 25% for surface mixes, 25% for intermediate mixes, and 35% for asphalt base mixes.

- Familiarity of asphalt mix designers in Ohio with the sample preparation and test procedure that are used in the IDEAL-CT test. Even though additional requirements are specified for the IDEAL-CT test regarding the testing equipment and the analysis of the test results, the sample preparation and test procedure used in the IDEAL-CT test are similar to those specified in ODOT Supplement 1051 (Resistance of Compacted Hot Mix Asphalt to Moisture-Induced Damage). Therefore, it should be easier to adopt the IDEAL-CT test as part of the asphalt mix design process in Ohio than the I-FIT test.
- Cost of test equipment. The IDEAL-CT test is conducted using an axial loading device capable of maintaining a constant deformation rate of 50 ± 2 mm/min that is equipped with a standard indirect tensile strength loading fixture similar to that specified in ODOT Supplement 1051. Some researchers informally indicated that the standard Pine loading frame that is widely available in Ohio can also be used for this purpose. If this is the case, no additional equipment cost will be required for the implementation of the IDEAL-CT as part of the asphalt mix design process in Ohio. Otherwise, an IDEAL-CT test setup that is also capable of performing the I-FIT can be purchased for around $12,000. The I-FIT test requires additional saws that cost around $6,000.

Table D.1 presents a comparison between the IDEAL-CT and I-FIT tests in terms of equipment cost, sample preparation effort, sample preparation time, analysis complexity of test data, repeatability of test results, viability for routine use, and current level of experience for implementation. A ranking scale of 1 to 5 is used in this table, where 1 represents the least favorable and 5 represents the most favorable for each category. On the basis of this comparison, it is recommended to use the IDEAL-CT test for the full-scale evaluation in this research project.

Table D.1. Comparison between IDEAL-CT and I-FIT Tests.

Rank Scale 1-5 **(1 for Least Favorable and 5 for Most Favorable)**	**IDEAL-CT**	**I-FIT**
Equipment Cost	5	4
Sample Preparation Effort	4	2
- Trimming?	No	Yes
- Cutting?	No	Yes
- Notching?	No	Yes
Sample Preparation Time	4	2
- Sample Preparation Time in days	~ 4	~ 6
Sample Testing Time	5	5
- Pre-Conditioning of Test Specimen Needed?	Yes	Yes
- Pre-Conditioning Time in hours	2	2
- Sample Setup and Loading Time in minutes	< 5	< 5
Analysis Complexity of Test Data	5	4
Repeatability of Test Results	3	2
Viability for Routine Use		
- Mix Design	4	2
- QC/QA	3	1
Current Level of Experience for Implementation	5	4
Total (Out of 45)	**38**	**26**

Appendix E

Full-Scale Evaluation Results

E.1 Introduction

The laboratory testing plan was expanded in the full-scale evaluation using the IDEAL-CT test to include a larger number of asphalt mixtures representing the majority of mixtures used by ODOT. The cluster analysis method was used to group ODOT-approved asphalt mix designs for different mix types based on mix composition to aid in the selection of a representative sample of asphalt mixtures to be included in the full-scale evaluation. Clustering is basically a technique that groups data sets (in this case asphalt mix designs) into smaller groups of similar attributes called clusters. In this study, the asphalt mix designs were divided into clusters based on the composition of the mix blend, which was represented using the percentage of RAP (RAP%), percentage of RAS (RAS%), percentage of natural sand (NS%), percentage of natural gravel (NG%), percentage of crushed gravel (CG%), percentage of limestone (LS%), and percentage slag (Slag%).

E.2 Selection of Asphalt Mixtures using the Cluster Analysis Method

JMP Pro software (version 14) was used to perform the cluster analysis. Several clustering techniques are available in JMP Pro including hierarchical clustering, centroid based clustering (k-means), distribution-based clustering, density-based clustering, fuzzy clustering, and constraint-based clustering. For this research study, hierarchical clustering (with Ward minimum variance) was used to group the data into clusters. In this method, each data point is initially considered as an individual cluster. In subsequent iterations, similar data points are merged to form larger clusters. A summary of the cluster analysis results is presented in Figures E.1 and E.2 and Table E.1 for Superpave 12.5 mm mixes. A total of 1,379 Superpave 12.5 mm mix designs were used in the analysis. Figure E.1 presents a comparison between the cluster distance and the corresponding number of clusters. This figure shows a significant drop in cluster distance until the number of clusters reached twelve, followed by a more gradual drop in cluster distance with the increase in the number of clusters. This indicates that twelve clusters are sufficient to represent Superpave 12.5 mm mixes. Figure E.2 presents a dendogram showing the cluster tree for the 1,379 Superpave 12.5 mm mixes, with the horizontal dotted blue line representing the cut-off point for twelve clusters.

Table E.1 presents the cluster means for the twelve Superpave 12.5 mm mix design clusters. As can be noticed from this table, the largest cluster (Cluster 4) consisted of 531 mixes (representing ~39% of the Superpave 12.5 mm mixes) with a cluster mean of 14.8% RAP, 0.0% RAS, 14.5% natural sand, 0.1% natural gravel, 0.2% crushed gravel, 70.5% limestone, and 0.0% slag. In contrast, the smallest cluster (Cluster 5) consisted of 12 mixes (representing ~1% of the Superpave 12.5 mm mixes) with a cluster mean of 13.5% RAP, 0.0% RAS, 33.1% natural sand, 0.0% natural gravel, 0.0% crushed gravel, 53.4% limestone, and 0.0% slag.

Nine out of the twelve clusters (denoted with an asterisk next to the cluster number in Table E.1) were selected for inclusion in the full-scale evaluation representing ~97% of the mix design of the Superpave 12.5 mm mixes. Table E.2 presents the blend composition of the Superpave 12.5 mm mixes that were included in the full-scale evaluation to represent the nine clusters. As some of the Superpave 12.5 mm mixes in this table were already tested as part of the screening evaluation (shown in italics), there was no need to retest them as part of the full-scale evaluation.

A similar process was followed for selecting the asphalt mixtures for the other mix types (Superpave 19 mm, Type 1 Surface, Type 1 Intermediate, Type 2 Intermediate, and Item 302 mixes). A total of 1,102 mix designs were used in the cluster analysis for Superpave 19 mm mixes, 3,883 mix designs for Type 1 Surface mixes, 1,552 mix designs for Type 1 intermediate mixes, 2,930 mix designs for Type 2 Intermediate mixes, and 1,256 mix designs for Item 302 mixes. It is noted that some mix types such as Type 2 Intermediate showed higher variability in mix blend composition. Therefore, a larger number of clusters was needed to represent this mix type. The blend composition for the selected Superpave 19 mm, Type 1 Surface, Type 1 Intermediate, Type 2 Intermediate, and Item 302 mixes is presented in Tables E.3 to E.7. In total, fifty-nine laboratory-produced asphalt mixtures were included in the full-scale evaluation. Asphalt mixtures tested as part of the screening evaluation are denoted in these tables using italics. A summary of the IDEAL-CT test results for the fifty-nine asphalt mixtures is presented in Section E.3. Additional specialty mixes (including mixes prepared RAS and mixes containing non-traditional binders such as PG 88-22M) were also tested as part of this research project. The test results for these asphalt mixtures is presented in Section E.5.

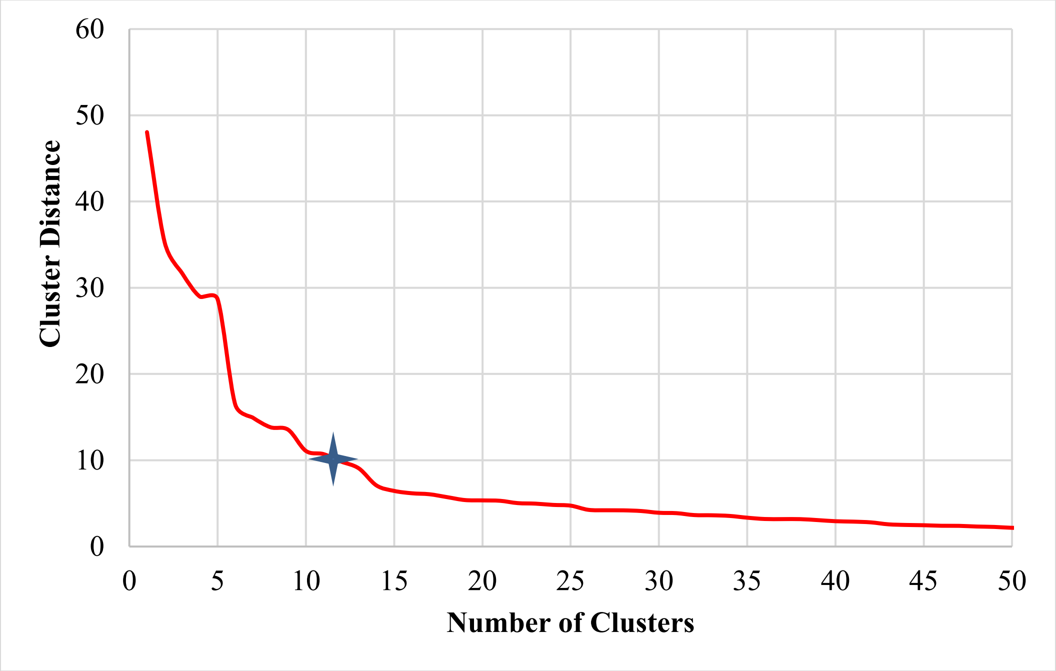


Figure E.1. Cluster Distance versus Number of Clusters for Superpave 12.5 mm Mixes.

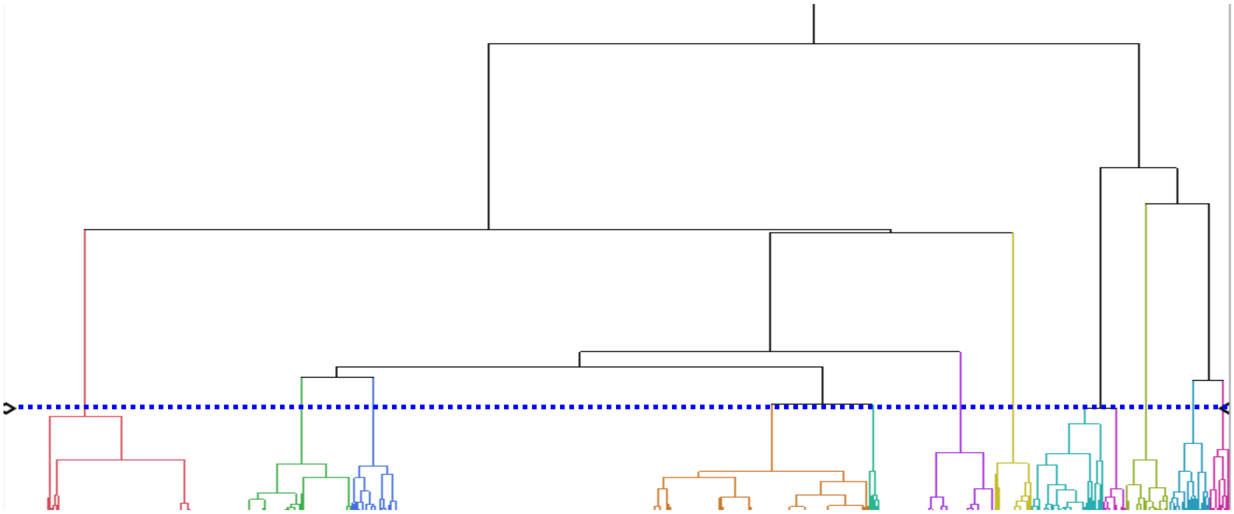


Figure E.2. Dendogram Showing Cluster Tree for the 1,379 Superpave 12.5 mm Mixes.

Table E.1. Cluster Means for the Twelve Superpave 12.5 mm Mix Clusters.

Cluster No.	Count	%	RAP	RAS	NS	NG	CG	LS	ACBF Slag
1*	207	15%	13.7	0.0	0.0	0.0	1.1	85.1	0.1
2*	182	13%	15.0	0.0	7.9	0.0	0.0	77.1	0.0
3*	52	4%	14.4	0.0	10.0	0.0	0.0	52.5	23.1
4*	531	39%	14.8	0.0	14.5	0.1	0.2	70.4	0.0
5	12	1%	13.5	0.0	33.1	0.0	0.0	53.4	0.0
6*	129	9%	10.0	0.0	12.0	0.0	0.0	78.0	0.0
7*	42	3%	0.0	0.0	12.6	0.6	3.0	83.8	0.0
8*	82	6%	13.4	0.0	12.5	1.7	60.6	7.8	4.0
9*	25	2%	14.9	0.0	13.1	0.0	31.7	40.3	0.0
10*	48	3%	14.7	0.0	12.7	0.0	0.0	12.2	60.4
11*	47	3%	14.4	0.0	12.3	27.3	1.3	37.6	7.1
12	22	2%	12.0	0.0	12.7	54.7	0.0	9.3	11.3
Total	**1,379**	**100%**							

Note: Clusters with asterisks were selected for inclusion in the full-scale evaluation as they represented a larger percentage of asphalt mix designs.

Table E.2. Blend Composition of Selected Superpave 12.5 mm Mixes.

Cluster No.	Mix ID	%	RAP	RAS	NS	NG	CG	LS	ACBF Slag
1	M2719	15%	15.0	0.0	0.0	0.0	0.0	85.0	0.0
2	*M1012*	*13%*	*15.0*	*0.0*	*10.0*	*0.0*	*0.0*	*75.0*	*0.0*
2	*M0704*	*13%*	*15.0*	*0.0*	*8.0*	*0.0*	*0.0*	*77.0*	*0.0*
3	M2686	4%	15.0	0.0	13.0	0.0	0.0	57.0	15.0
4	*M1030*	*39%*	*15.0*	*0.0*	*15.0*	*0.0*	*0.0*	*70.0*	*0.0*
4	*M1090*	*39%*	*15.0*	*0.0*	*15.0*	*0.0*	*0.0*	*70.0*	*0.0*
6	M2367	9%	10.0	0.0	12.0	0.0	0.0	78.0	0.0
7	M2497	3%	0.0	0.0	11.5	0.0	0.0	88.5	0.0
8	M0888	6%	15.0	0.0	12.0	0.0	60.0	13.0	0.0
9	*M1018*	*2%*	*15.0*	*0.0*	*10.0*	*0.0*	*40.0*	*35.0*	*0.0*
10	M0676	3%	15.0	0.0	11.0	0.0	0.0	17.0	57.0
11	M2564	3%	15.0	0.0	10.0	31.0	16.0	28.0	0.0

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

Table E.3. Blend Composition of Selected Superpave 19 mm Mixes.

Mix ID	**RAP**	**RAS**	**NS**	**NG**	**CG**	**LS**	**ACBF Slag**
M2370	25.0	0.0	10.0	0.0	0.0	65.0	0.0
M0981	*25.0*	*0.0*	*14.0*	*0.0*	*0.0*	*61.0*	*0.0*
M0288	*30.0*	*0.0*	*10.0*	*0.0*	*0.0*	*60.0*	*0.0*
M2636	0.0	0.0	23.0	0.0	25.0	52.0	0.0
M1005	25.0	0.0	0.0	0.0	0.0	75.0	0.0
M0961	*35.0*	*0.0*	*0.0*	*0.0*	*0.0*	*65.0*	*0.0*
M2146	40.0	0.0	8.0	25.0	0.0	27.0	0.0
M2311	35.0	0.0	0.0	0.0	0.0	48.0	17.0
M1028	*40.0*	*0.0*	*10.0*	*0.0*	*10.0*	*40.0*	*0.0*

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

Table E.4. Blend Composition of Selected Type 1 Surface Mixtures.

Mix ID	**RAP**	**RAS**	**NS**	**NG**	**CG**	**LS**	**ACBF Slag**
M0202	0.0	0.0	30.0	54.0	0.0	16.0	0.0
M2568	0.0	0.0	24.0	0.0	0.0	76.0	0.0
M0678	20.0	0.0	24.0	0.0	0.0	46.0	10.0
M2276	20.0	0.0	32.0	0.0	0.0	48.0	0.0
M2555	20.0	0.0	0.0	0.0	0.0	80.0	0.0
M2197	20.0	0.0	15.0	0.0	0.0	65.0	0.0
M2075	20.0	0.0	30.0	50.0	0.0	0.0	0.0
M0643	*25.0*	*0.0*	*0.0*	*58.0*	*0.0*	*17.0*	*0.0*
M0992	*25.0*	*0.0*	*25.0*	*40.0*	*0.0*	*10.0*	*0.0*
M2304	20.0	0.0	20.0	45.0	0.0	0.0	15.0

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

Table E.5. Blend Composition of Selected Type 1 Intermediate Mixes.

Mix ID	RAP	RAS	NS	NG	CG	LS	ACBF Slag
M2073	40.0	0.0	27.0	0.0	0.0	33.0	0.0
M1105	20.0	0.0	20.0	0.0	0.0	60.0	0.0
M0586	*25.0*	*0.0*	*0.0*	*0.0*	*0.0*	*75.0*	*0.0*
M2449	30.0	0.0	0.0	0.0	0.0	70.0	0.0
M0560	0.0	0.0	26.0	0.0	0.0	74.0	0.0
M2246	35.0	0.0	33.0	32.0	0.0	0.0	0.0
M0248	*25.0*	*0.0*	*20.0*	*40.0*	*0.0*	*15.0*	*0.0*
M0697	*40.0*	*0.0*	*20.0*	*40.0*	*0.0*	*0.0*	*0.0*
M2452	25.0	0.0	15.0	60.0	0.0	0.0	0.0

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

Table E.6. Blend Composition of Selected Type 2 Intermediate Mixes.

Mix ID	RAP	RAS	NS	NG	CG	LS	ACBF Slag
M2086	40.0	0.0	10.0	50.0	0.0	0.0	0.0
M2180	25.0	0.0	10.0	50.0	0.0	15.0	0.0
M2167	0.0	0.0	18.0	60.0	0.0	22.0	0.0
M2303	35.0	0.0	20.0	0.0	0.0	45.0	0.0
M0962	*30.0*	*0.0*	*27.0*	*0.0*	*0.0*	*43.0*	*0.0*
M2481	25.0	0.0	27.0	0.0	0.0	48.0	0.0
M1025	*40.0*	*0.0*	*10.0*	*0.0*	*0.0*	*50.0*	*0.0*
M2181	20.0	0.0	20.0	0.0	0.0	60.0	0.0
M2093	25.0	0.0	0.0	0.0	0.0	75.0	0.0
M2094	40.0	0.0	0.0	0.0	0.0	60.0	0.0

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

Table E.7. Blend Composition of Selected Item 302 Mixes.

Mix ID	RAP	RAS	NS	NG	CG	LS	ACBF Slag
M2234	40.0	0.0	8.0	52.0	0.0	0.0	0.0
M2198	25.0	0.0	14.0	27.0	0.0	34.0	0.0
M2028	45.0	0.0	10.0	20.0	0.0	25.0	0.0
M1032	*45.0*	*0.0*	*4.0*	*6.0*	*0.0*	*45.0*	*0.0*
M0919	*40.0*	*0.0*	*10.0*	*0.0*	*0.0*	*50.0*	*0.0*
M0246	*30.0*	*0.0*	*15.0*	*0.0*	*0.0*	*55.0*	*0.0*
M1011	*20.0*	*0.0*	*20.0*	*0.0*	*0.0*	*60.0*	*0.0*
M0971	*30.0*	*0.0*	*10.0*	*30.0*	*0.0*	*30.0*	*0.0*
M2687	0.0	0.0	0.0	0.0	0.0	100.0	0.0

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

E.3 Full-Scale Evaluation Test Results

The IDEAL-CT test results for the selected Superpave 12.5 mm, Superpave 19 mm, Type 1 Surface, Type 1 Intermediate, Type 2 Intermediate, and Item 302 mixes are presented in Tables E.8 to E.13 and Figures E.3 to E.8. A comparison between the IDEAL-CT test results for all mixes is presented in the form of boxplots in Figure E.9 and cumulative probability distribution plots in Figure E.10. As can be noticed from this figure, surface mixes, including Superpave 12.5 mm and Type 1 Surface mixes, exhibited the highest cracking resistance as measured using the CT_{index}, with an average CT_{index} of 101 and 111, respectively. Type 1 Intermediate and Item 302 mixes had an average CT_{index} of 98 and 87, respectively, while Type 2 Intermediate and Superpave 19 mm mixes had an average CT_{index} of 80 and 55, respectively.

Table E.8. IDEAL-CT Test Results for Superpave 12.5 mm Mixes.

Mix ID	**Binder Type**	**AC (%)**	**RAP (%)**	**RAS (%)**	**Avg. CT_{index}**	**COV of CT_{index} (%)**
M2686	PG 70-22M	5.7	15.0	0.0	70	20
M1018	*PG 76-22M*	*5.7*	*15.0*	*0.0*	*120*	*8*
M2719	PG 70-22M	5.8	15.0	0.0	76	15
M0704	*PG 70-22M*	*5.8*	*15.0*	*0.0*	*102*	*12*
M2367	PG 70-22M	5.8	10.0	0.0	151	9
M0888	PG 70-22M	5.8	15.0	0.0	102	14
M1012	*PG 70-22M*	*5.9*	*15.0*	*0.0*	*54*	*17*
M2564	PG 70-22M	5.9	15.0	0.0	51	16
M2497	PG 70-22M	6.0	0.0	0.0	171	21
M1030	*PG 70-22M*	*6.1*	*15.0*	*0.0*	*113*	*10*
M1090	*PG 76-22M*	*6.1*	*15.0*	*0.0*	*143*	*20*
M0676	PG 70-22M	6.2	15.0	0.0	53	12

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

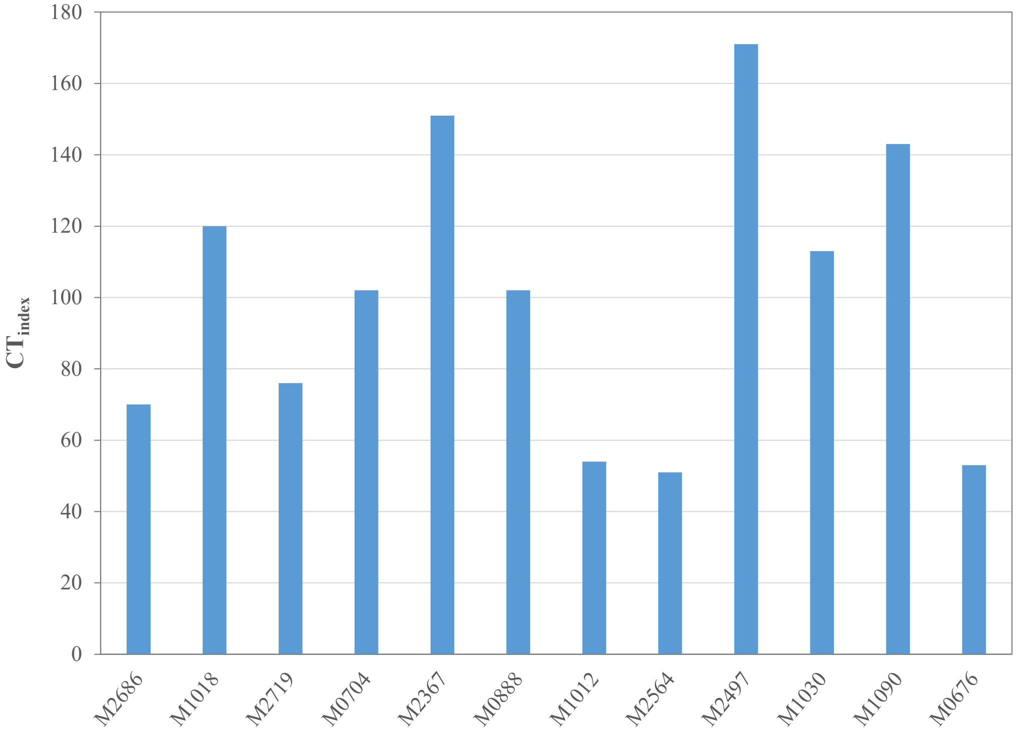


Figure E.3. IDEAL-CT Test Results for Superpave 12.5 mm Mixes.

Table E.9. IDEAL-CT Test Results for Superpave 19 mm Mixes.

Mix ID	**Binder Type**	**AC (%)**	**RAP (%)**	**RAS (%)**	**Avg. CT_{index}**	**COV for CT_{index} (%)**
M2370	PG 64-28	4.6	25.0	0.0	51	10
M1005	PG 64-28	4.6	25.0	0.0	43	9
M0288	*PG 64-28*	*4.7*	*30.0*	*0.0*	*134*	*16*
M2636	PG 64-28	4.7	0.0	0.0	19	16
M2311	PG 64-28	4.7	35.0	0.0	44	17
M0981	*PG 64-28*	*4.8*	*25.0*	*0.0*	*44*	*6*
M0961	*PG 64-28*	*4.9*	*35.0*	*0.0*	*51*	*24*
M2146	PG 64-28	4.9	40.0	0.0	41	37
M1028	*PG 64-28*	*5.0*	*40.0*	*0.0*	*64*	*35*

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

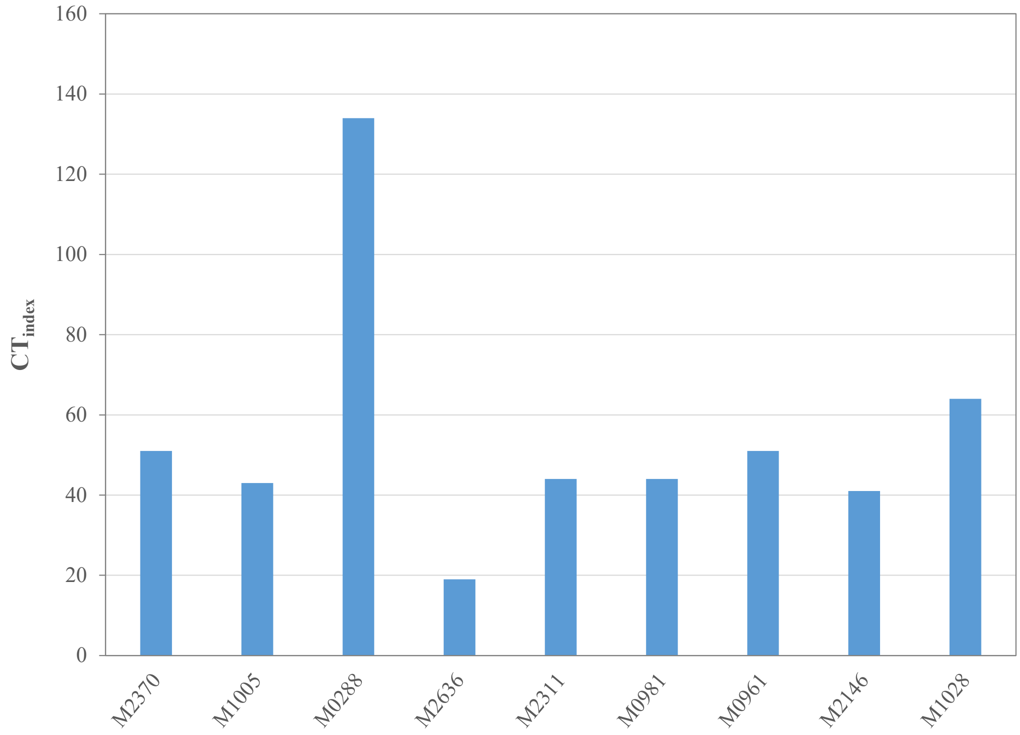


Figure E.4. IDEAL-CT Test Results for Superpave 19 mm Mixes.

Table E.10. IDEAL-CT Test Results for Type 1 Surface Mixes.

Mix ID	**Binder Type**	**AC (%)**	**RAP (%)**	**RAS (%)**	**Avg. CT_{index}**	**COV for CT_{index} (%)**
M0202	PG 64-22	6.0	0.0	0.0	112	21
M0678	PG 64-22	6.0	20.0	0.0	101	13
M2568	PG 64-22	6.1	0.0	0.0	224	14
M2197	PG 64-22	6.1	20.0	0.0	91	10
M2075	PG 64-22	6.1	20.0	0.0	136	6
M2304	PG 64-22	6.1	20.0	0.0	71	5
M2276	PG 64-22	6.2	20.0	0.0	53	18
M2555	PG 64-22	6.2	20.0	0.0	68	12
M0643	*PG 70-22M*	*6.2*	*25.0*	*0.0*	*136*	*24*
M0992	*PG 64-22*	*6.3*	*25.0*	*0.0*	*122*	*23*

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

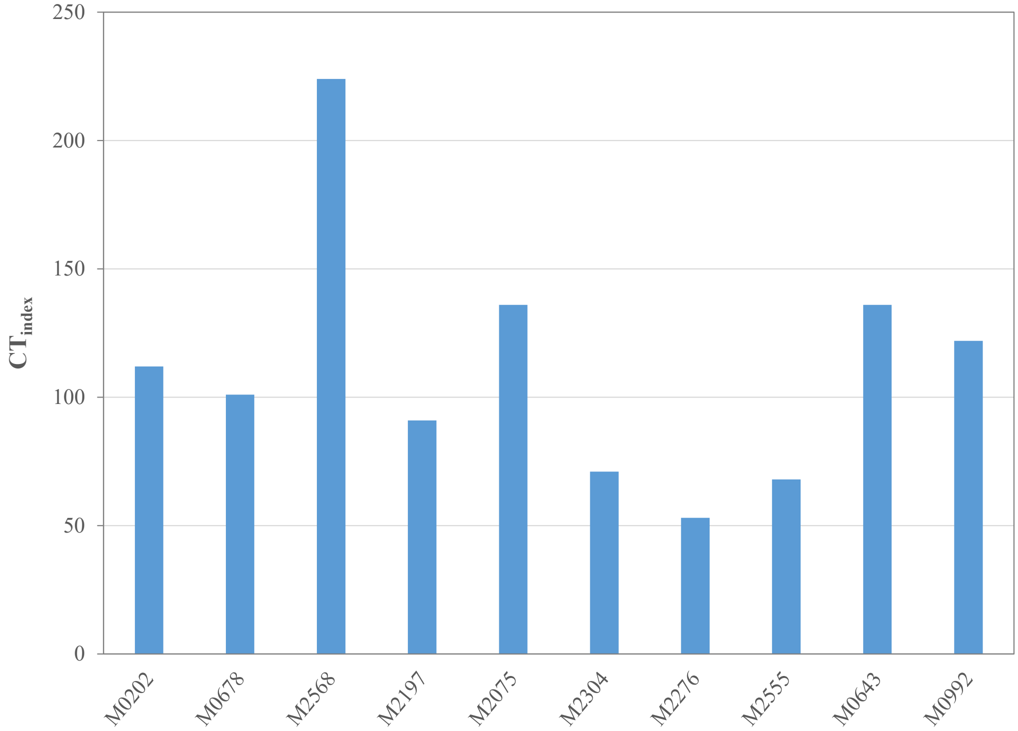


Figure E.5. IDEAL-CT Test Results for Type 1 Surface Mixes.

Table E.11. IDEAL-CT Test Results for Type 1 Intermediate Mixes.

Mix ID	**Binder Type**	**AC (%)**	**RAP (%)**	**RAS (%)**	**Avg. CT$_{index}$**	**COV for CT$_{index}$ (%)**
M0697	*PG 58-28*	*5.5*	*40.0*	*0.0*	*55*	*14*
M2449	PG 58-28	5.9	30.0	0.0	59	10
M2073	PG 58-28	6.0	8.0	0.0	84	12
M0560	PG 64-22	6.0	0.0	0.0	88	19
M2246	PG 58-28	6.0	35.0	0.0	104	13
M0248	*PG 64-22*	*6.0*	*25.0*	*0.0*	*110*	*20*
M1105	PG 64-22	6.2	20.0	0.0	92	16
M2452	PG 64-22	6.2	25.0	0.0	125	32
M0586	*PG 64-22*	*6.5*	*25.0*	*0.0*	*119*	*8*

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

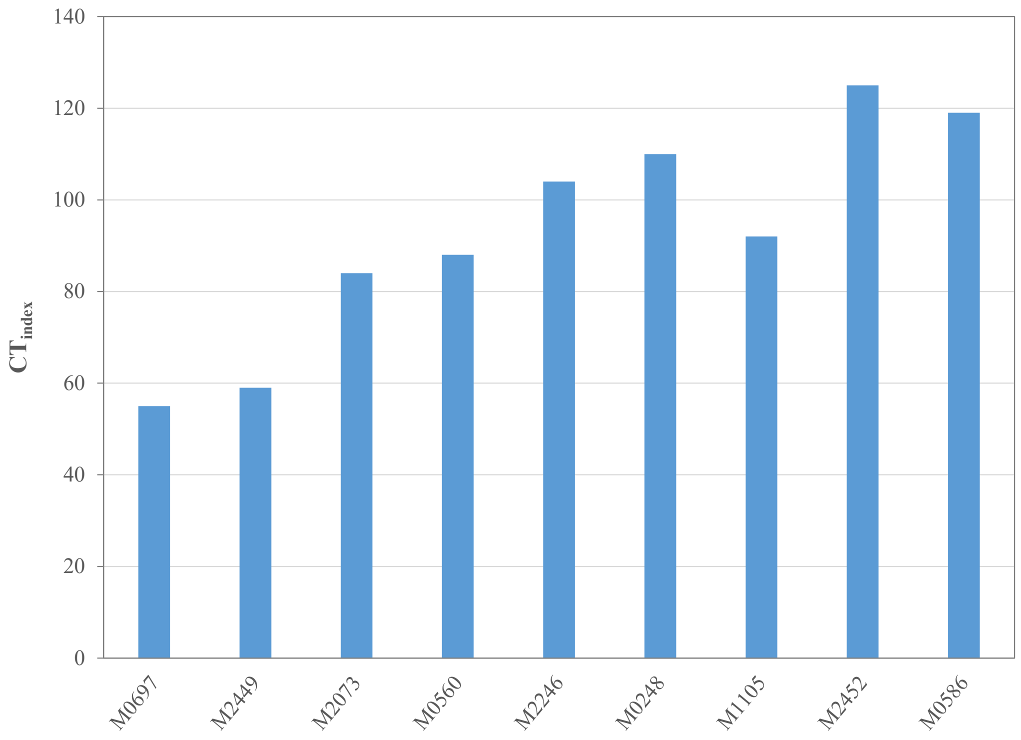


Figure E.6. IDEAL-CT Test Results for Type 1 Intermediate Mixes.

Table E.12. IDEAL-CT Test Results for Type 2 Intermediate Mixes.

Mix ID	**Binder Type**	**AC (%)**	**RAP (%)**	**RAS (%)**	**Avg. $\mathbf{CT_{index}}$**	**COV for $\mathbf{CT_{index}}$ (%)**
M2086	PG 58-28	4.8	40.0	0.0	67	29
M2180	PG 64-22	4.9	25.0	0.0	88	14
M2167	PG 64-22	4.9	0.0	0.0	160	29
M2303	PG 58-28	4.9	35.0	0.0	120	15
M1025	*PG 58-28*	*4.9*	*40.0*	*0.0*	*65*	*16*
M2181	PG 64-22	4.9	20.0	0.0	105	28
M2093	PG 64-22	4.9	25.0	0.0	39	14
M2094	PG 58-28	4.9	40.0	0.0	37	38
M0962	*PG 58-28*	*5.0*	*30.0*	*0.0*	*65*	*19*
M2481	PG 64-22	5.0	25.0	0.0	59	29

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

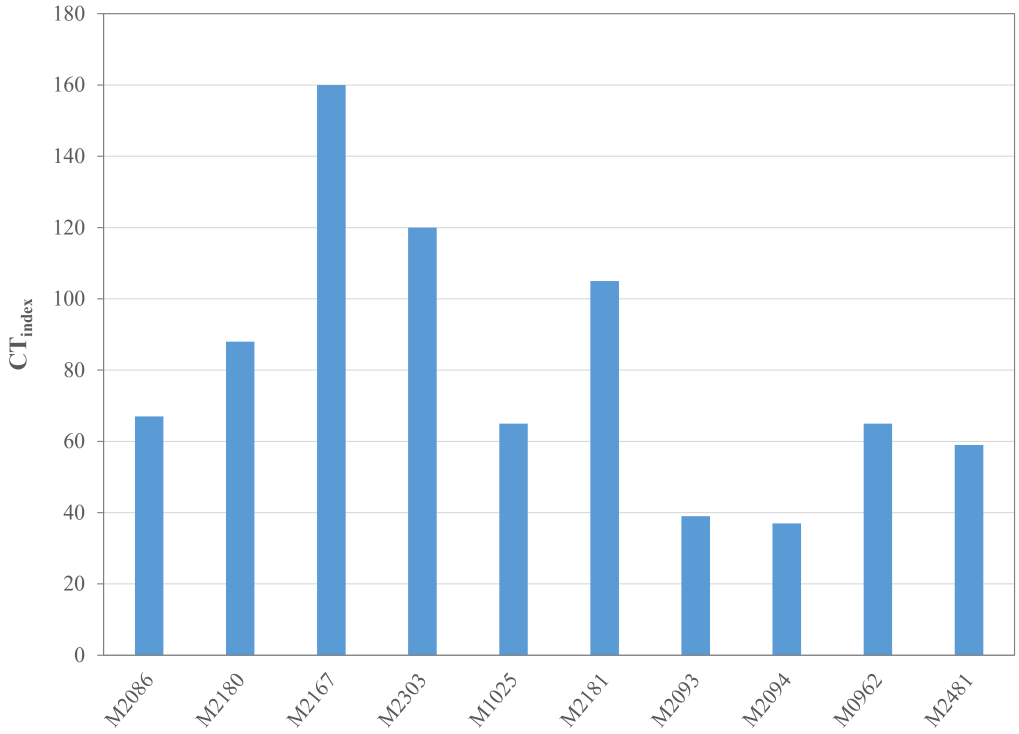


Figure E.7. IDEAL-CT Test Results for Type 2 Intermediate Mixes.

Table E.13. IDEAL-CT Test Results for Item 302 Mixes.

Mix ID	**Binder Type**	**AC (%)**	**RAP (%)**	**RAS (%)**	**Avg. $\mathrm{CT}_{\mathrm{index}}$**	**COV for $\mathrm{CT}_{\mathrm{index}}$ (%)**
M2234	PG 58-28	3.8	40.0	0.0	80	23
M2198	PG 64-22	4.1	25.0	0.0	138	21
M1032	*PG 58-28*	*4.1*	*45.0*	*0.0*	*83*	*28*
M1011	*PG 64-22*	*4.1*	*20.0*	*0.0*	*80*	*25*
M2028	PG 58-28	4.2	45.0	0.0	47	21
M0246	*PG 58-28*	*4.2*	*30.0*	*0.0*	*102*	*17*
M0919	*PG 58-28*	*4.3*	*40.0*	*0.0*	*24*	*23*
M0971	*PG 58-28*	*4.4*	*30.0*	*0.0*	*100*	*5*
M2687	PG 64-22	4.4	0.0	0.0	131	38

Note: Mixes shown in italics were already tested as part of the screening evaluation. Therefore, there was no need to retest them as part of the full-scale evaluation.

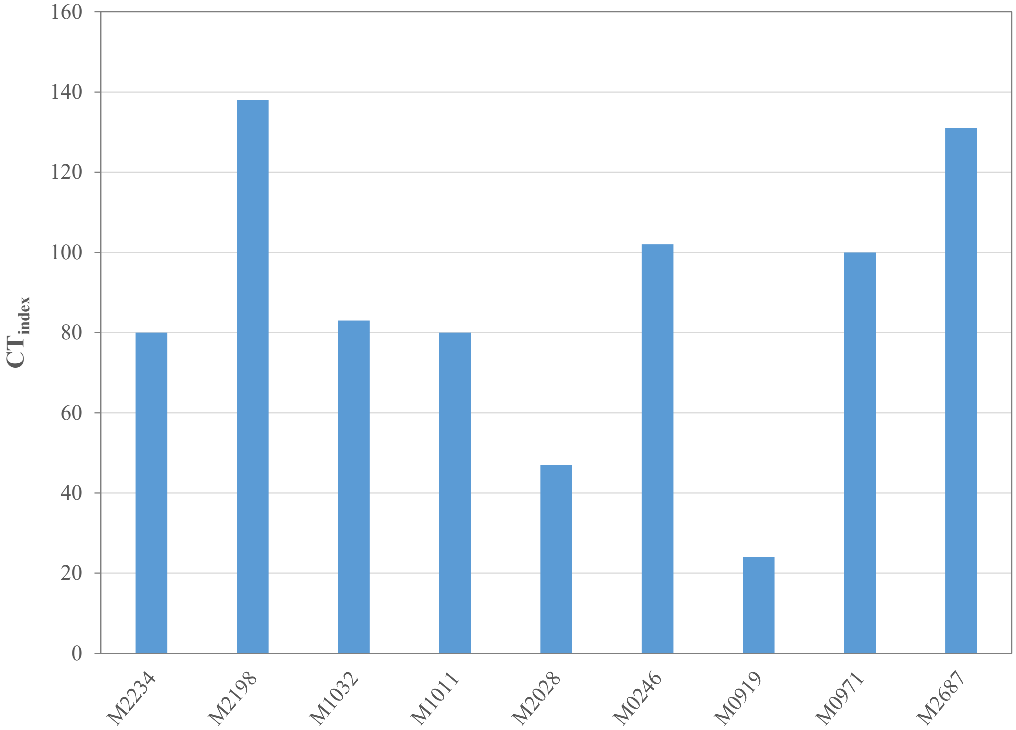


Figure E.8. IDEAL-CT Test Results for Item 302 Mixes.

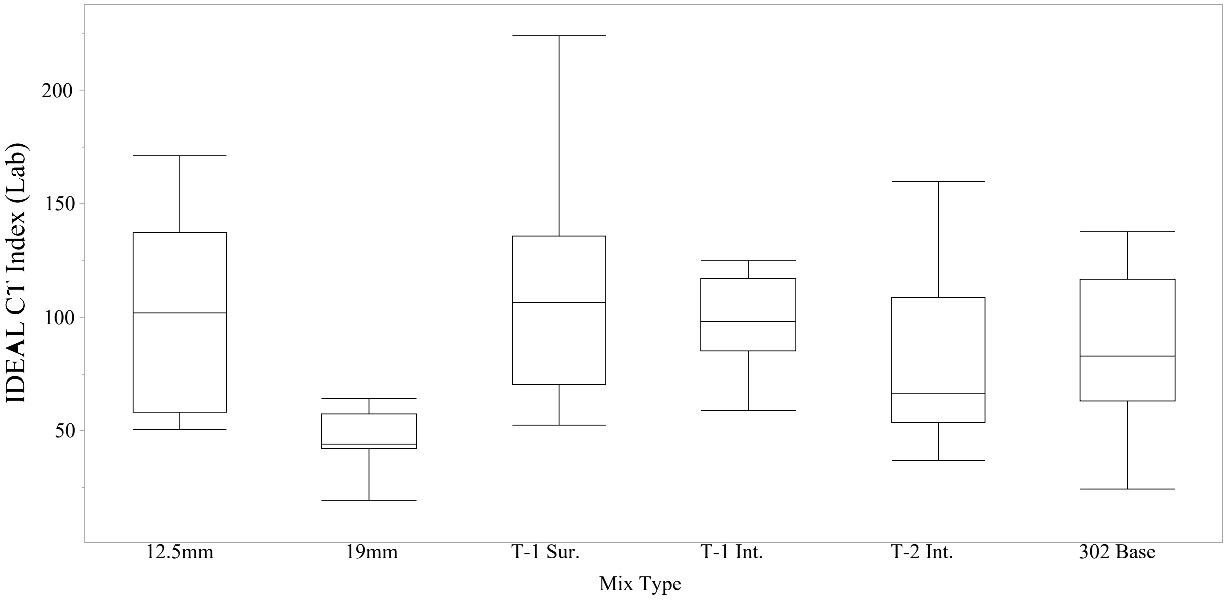


Figure E.9. Comparison of IDEAL-CT Test Results for Different Mix Types.

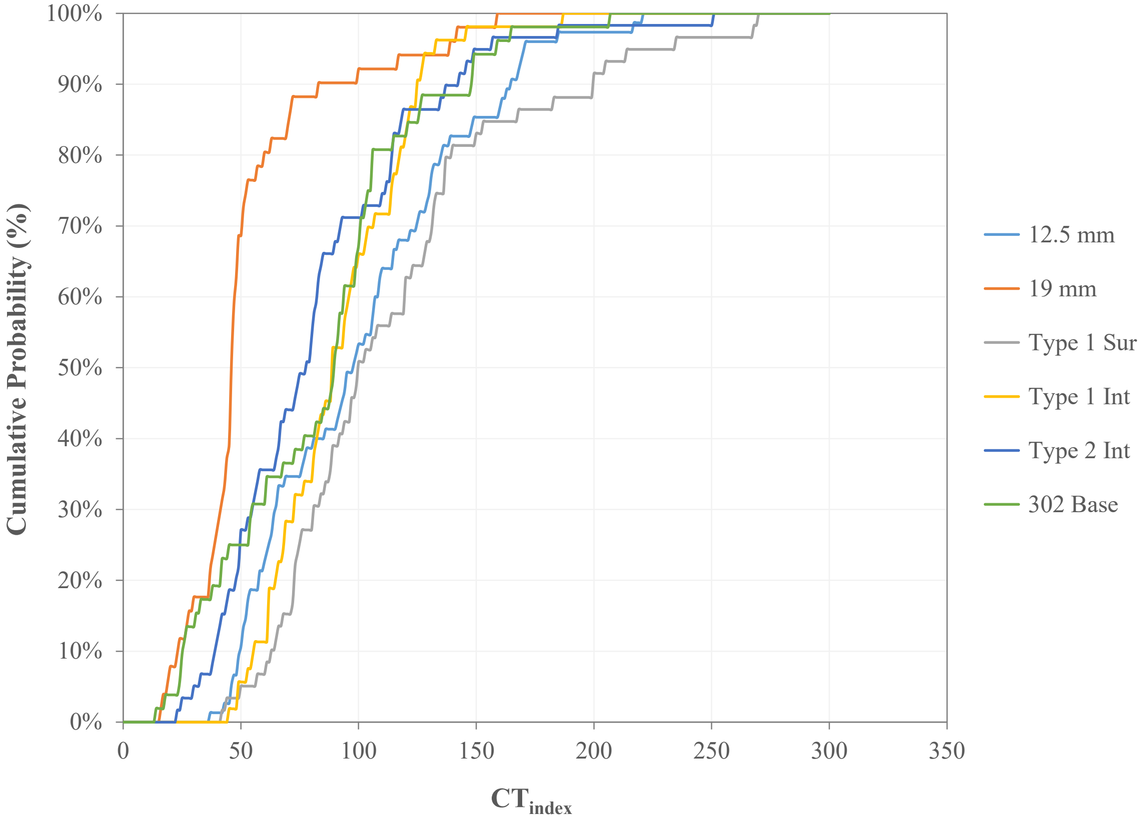


Figure E.10. Cumulative Probability Distribution of $\mathrm{CT_{index}}$ Values for Different Mixes.

E.4 Modeling of IDEAL-CT Test Results

The laboratory test results from the full-scale evaluation were analyzed to identify the most critical factors that should be considered in the design and evaluation of asphalt mixtures to ensure satisfactory resistance to cracking. Multi-linear regression analysis was conducted using the CT_{index} as the dependent variable and the following mix design parameters as the independent variables: total asphalt content (%), virgin asphalt content (%), RAP binder content (%), effective asphalt content (%), percentage of RAP, percentage of natural sand, percentage of natural gravel, percentage of crushed gravel, percentage of limestone, percentage of slag, fines to asphalt ratio (F/A), fifty to thirty ratio (F-T), asphalt binder film thickness (microns), blend absorption (%), percent passing 1.5" sieve, percent passing 1" sieve, percent passing 3/4" sieve, percent passing 1/2" sieve, percent passing 3/8" sieve, percent passing sieve #4, percent passing sieve #8, percent passing sieve #16, percent passing sieve #30, percent passing sieve #50, percent passing sieve #100, and percent passing sieve #200. The independent variables for all mixes were collected from job mix formula (JMF) packets provided by ODOT, with the exception of effective asphalt content (%), asphalt film thickness (microns), and blend absorption (%), which estimated using information included in the JMF packets as well as ODOT aggregate specific gravity reports. For Item 302, several of the independent variables are not reported in the mix design packets. Therefore, the IDEAL-CT test results for this mix type were excluded from the regression analysis.

The regression analysis was conducted using JMP Pro software (version 14). To identify the optimum number of mix design variables to include in the regression model, stepwise multi-linear regression was first performed using all independent variables. This analysis provided a set of possible models with different combinations of independent variables and the corresponding root mean square errors (RMSE) that can be used to select the number of independent variables to include in the final model. The stepwise multi-linear regression analysis results for the full-scale evaluation data is presented in Figure E.11. As can be observed from this figure, the RMSE dropped significantly with the increase in the number of independent variables until the number of variables reached ten, followed by a more gradual decrease in RMSE. Therefore, it was decided to use ten independent variables in the final model.

The resulting CT_{index} model and the corresponding model coefficients are presented in Figure E.12. A summary of the p-values for the different independent variables (at a confidence level of 95%, i.e., $\alpha = 5\%$) is presented in Figure E.13. A comparison between the measured versus predicted CT_{index} values is presented in Figure E.14 for all mixes. The quality of fit of the CT_{index} model for the different mix types is presented in Figures E.15 through E.19.

As can be noticed from Figure E.11, the final CT_{index} model consisted of the following independent variables: total asphalt content (%), RAP binder content (%), percentage of natural gravel, percentage of slag, fifty to thirty ratio (F-T), blend absorption (%), percent passing 3/4" sieve, percent passing sieve #8, percent passing sieve #50, and percent passing sieve #100. From among these parameters, the following parameters had the most significant effect on the CT_{index} based on the p-values (Figure E.13). $p\text{-value} < 0.05$: total asphalt content (%), RAP binder content (%), blend absorption (%), and percent passing 3/4" sieve.

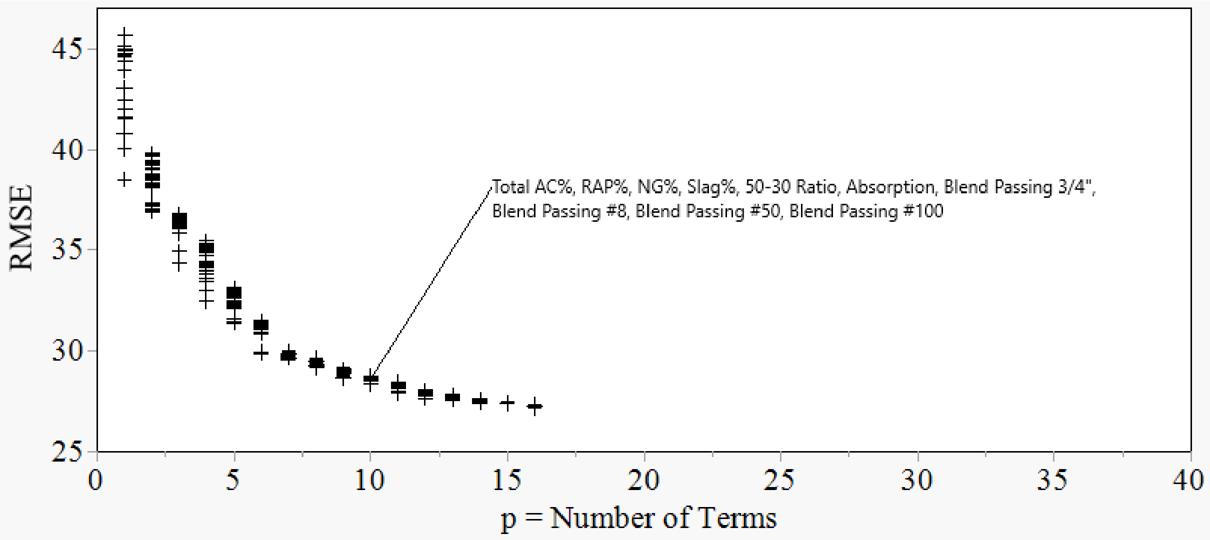
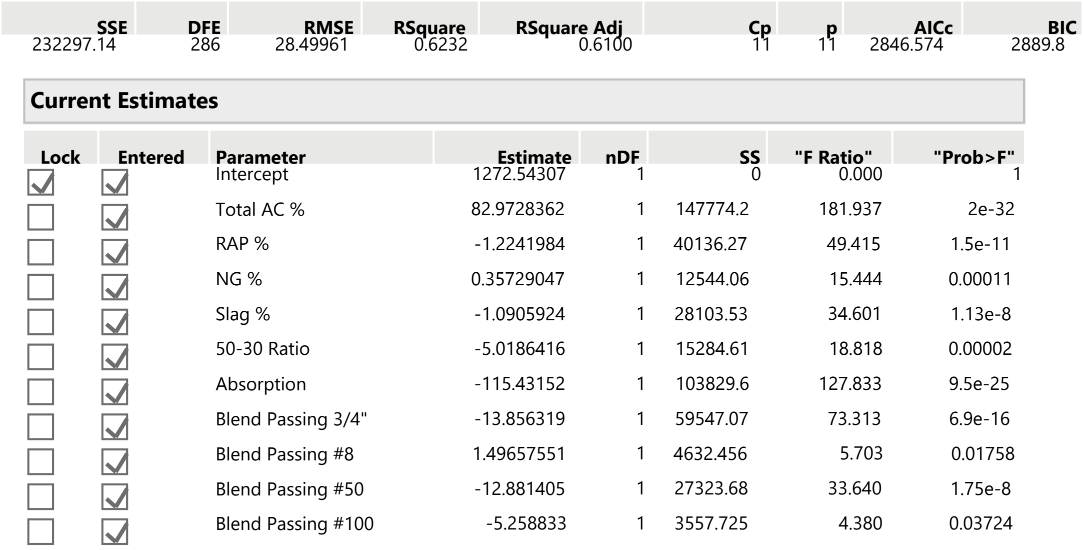


Figure E.11. RMSE versus Number of Independent Variables.

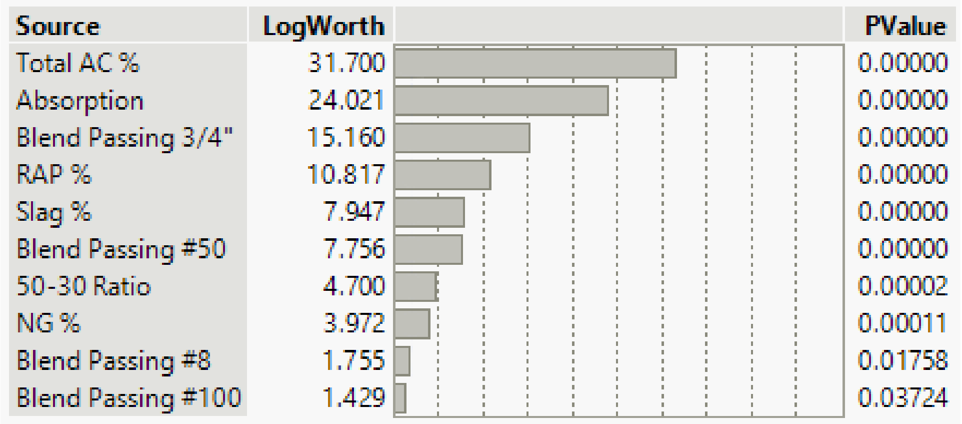


SSE	DFE	RMSE	RSquare	RSquare Adj	Cp	p	AICc	BIC
232297.14	286	28.49961	0.6232	0.6100	11	11	2846.574	2889.8

Current Estimates

Lock	Entered	Parameter	Estimate	nDF	SS	"F Ratio"	"Prob>F"
☑	☑	Intercept	1272.54307	1	0	0.000	1
☐	☑	Total AC %	82.9728362	1	147774.2	181.937	2e-32
☐	☑	RAP %	-1.2241984	1	40136.27	49.415	1.5e-11
☐	☑	NG %	0.35729047	1	12544.06	15.444	0.00011
☐	☑	Slag %	-1.0905924	1	28103.53	34.601	1.13e-8
☐	☑	50-30 Ratio	-5.0186416	1	15284.61	18.818	0.00002
☐	☑	Absorption	-115.43152	1	103829.6	127.833	9.5e-25
☐	☑	Blend Passing 3/4"	-13.856319	1	59547.07	73.313	6.9e-16
☐	☑	Blend Passing #8	1.49657551	1	4632.456	5.703	0.01758
☐	☑	Blend Passing #50	-12.881405	1	27323.68	33.640	1.75e-8
☐	☑	Blend Passing #100	-5.258833	1	3557.725	4.380	0.03724

Figure E.12. Parameter Estimates for CT$_{index}$ Model.



Source	LogWorth	PValue
Total AC %	31.700	0.00000
Absorption	24.021	0.00000
Blend Passing 3/4"	15.160	0.00000
RAP %	10.817	0.00000
Slag %	7.947	0.00000
Blend Passing #50	7.756	0.00000
50-30 Ratio	4.700	0.00002
NG %	3.972	0.00011
Blend Passing #8	1.755	0.01758
Blend Passing #100	1.429	0.03724

Figure E.13. p-value for different variables of the CT$_{index}$ Model.

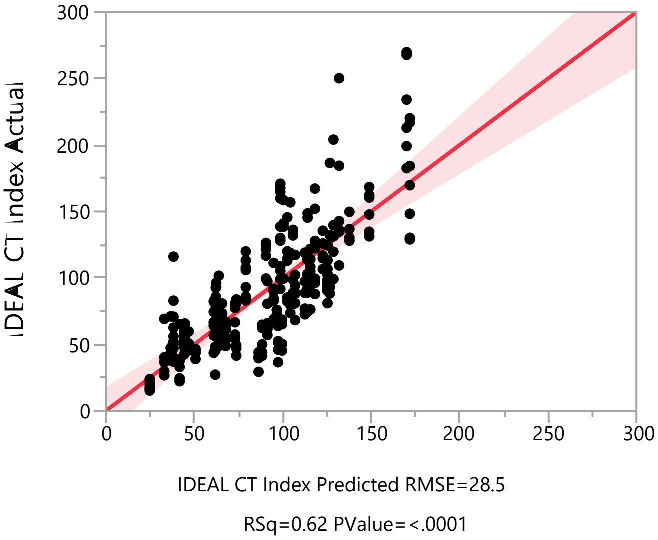


Figure E.14. Measured versus Predicted CT_{index} for All Mix Types.

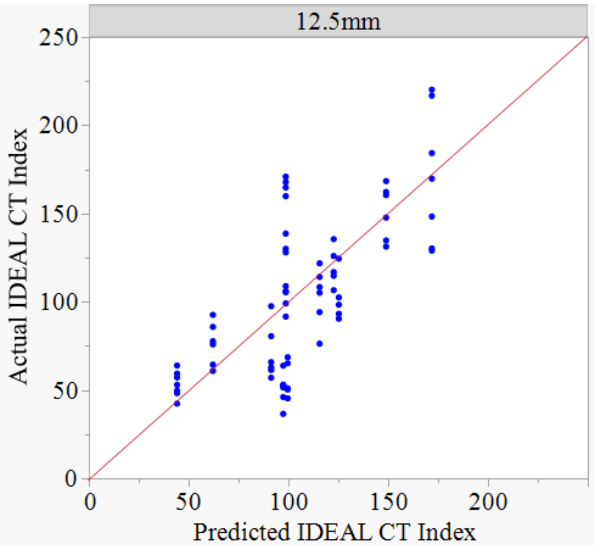


Figure E.15. Measured versus Predicted CT_{index} for Superpave 12.5 mm Mixes.

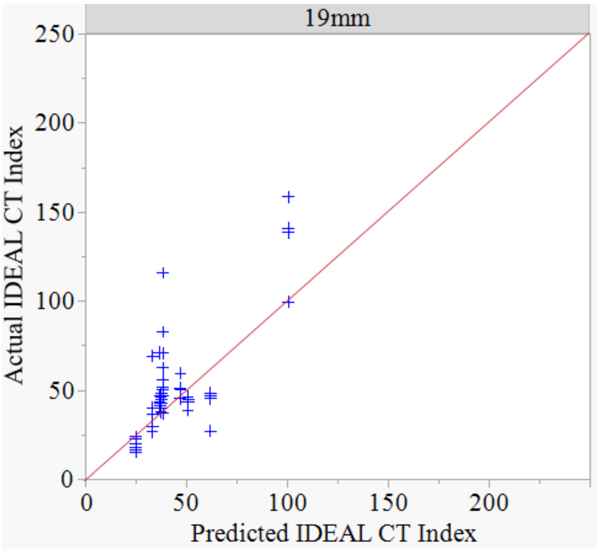


Figure E.16. Measured versus Predicted CT_{index} for Superpave 19 mm Mixes.

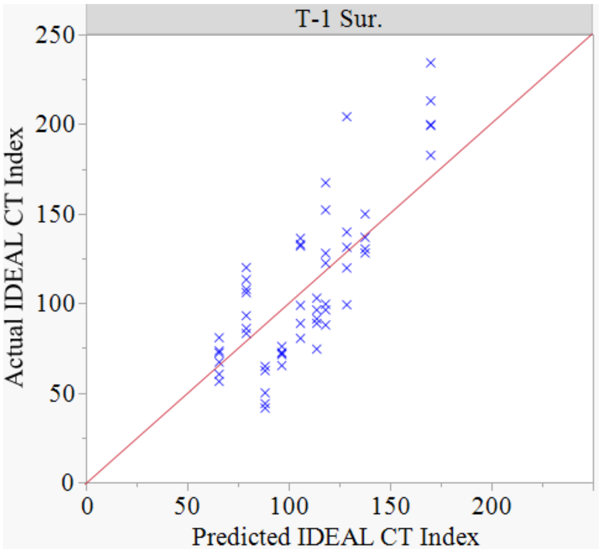


Figure E.17. Measured versus Predicted CT_{index} for Type 1 Surface Mixes.

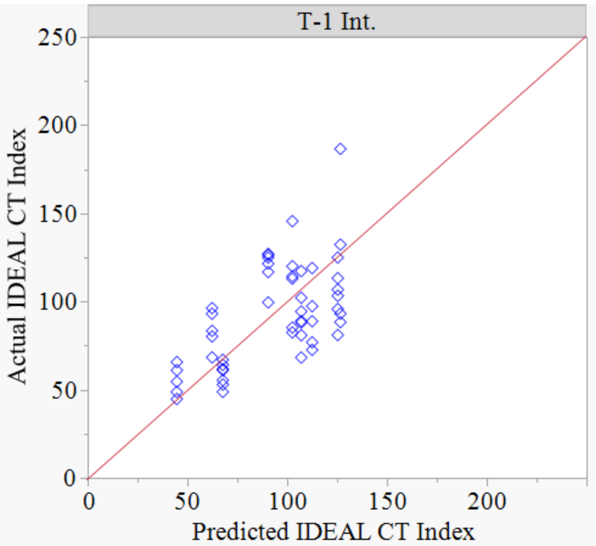


Figure E.18. Measured versus Predicted CT_{index} for Type 1 Intermediate Mixes.

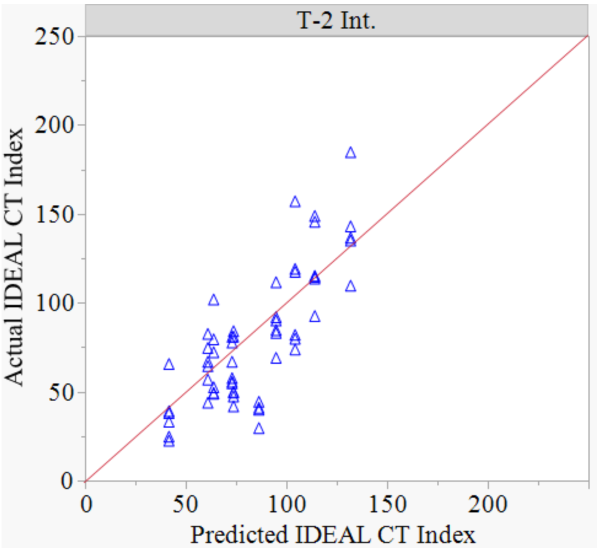


Figure E.19. Measured versus Predicted CT_{index} for Type 2 Intermediate Mixes.

E.5 Testing of Additional Asphalt Mixtures

Four specialty mixtures were tested to evaluate their cracking performance in this study. They included two asphalt mixtures prepared with non-traditional PG 88-22M asphalt binder (Superpave 12.5 mm surface mix M2855 and Superpave 19 mm intermediate mix M2854) and two asphalt mixtures containing RAS (Marshall Type 1 Surface mix M0095 and Marshall Type 2 Intermediate mix M0094). The asphalt mixture composition and average CT_{index} values for these mixes are presented in Table E.14.

Table E.14. Mixture Composition and Average CT_{index} for Specialty Mixes.

Mix Type	**Mix ID**	**Binder Type**	**AC (%)**	**RAP (%)**	**RAS (%)**	**Avg. CT_{index}**	**COV for CT_{index} (%)**
12.5 mm	M2855	PG 88-22M	6.3	10.0	0.0	57	18
19 mm	M2854	PG 88-22M	5.3	10.0	0.0	36	31
T1 Sur.	M0095	PG 64-22	6.2	0.0	5.0	51	25
T2 Int.	M0094	PG 64-22	5.1	0.0	5.0	32	35