Interlayer Mixture Design

Donald W. Christensen, P.E., PH.D.

Advanced Asphalt Technologies, LLC
40 Commerce Circle
Kearneysville, WV 25430

WisDOT ID no. 0092-21-04

January 2023

RESEARCH & LIBRARY UNIT

WISCONSIN HIGHWAY RESEARCH PROGRAM

WISCONSIN DOT
PUTTING RESEARCH TO WORK

DISCLAIMER

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project 0092-21-04. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers' names appear in this report only because they are considered essential to the object of the document.

TECHNICAL DOCUMENTATION PAGE

1. Report No. WHRP 0092-21-04	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Interlayer Mixture Design		5. Report Date January 2023
		6. Performing Organization Code
7. Author(s) Donald W. Christensen, P.E., Ph.D.		8. Performing Organization Report No. If applicable, enter any/all unique numbers assigned to the performing organization.
9. Performing Organization Name and Address Advanced Asphalt Technologies, LLC 40 Commerce Circle Kearneysville, WV 25430		10. Work Unit No.
		11. Contract or Grant No. **WHRP 0092-21-04**
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation Research & Library Unit 4822 Madison Yards Way Room 911 Madison, WI 53705		13. Type of Report and Period Covered Final Report Enter the month/year during which the work was performed (e.g., June 2012-June 2014). End date should reflect Report Date in box 5.
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The purpose of this research was to develop a simple alternative to flexural fatigue testing for ensuring the fatigue performance of Interlayer Mixture Designs (IMDs) in Wisconsin. The research approach involved producing 15 different mixtures and characterizing these mixtures using the CT index as determined from the ideal CT test, and characterizing the binders used in the mixtures with a variety of tests related to fatigue performance. Using the data produced with these tests, statistical analyses were performed to develop an accurate and simple model that could serve as a basis for a revised, simpler IMD fatigue specification. The final proposed IMD fatigue specification requires a minimum CT index of 140 at 20°C, a maximum binder low temperature grade of -34°C, and a minimum elastic recovery that depends on the non-recoverable creep compliance as determined in AASHTO M 332. The proposed IMD fatigue specification requires no new binder tests and replaces flexural fatigue testing with the much simpler and less expensive IDEAL-CT. There should be no major barriers to implementation.

17. Key Words Asphalt, asphalt pavement, interlayer mixture design, pavement performance, fatigue, mixture design, specification, CT index, modulus, DENT, LAS, modified binder, modified asphalt		18. Distribution Statement No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 50	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

The purpose of this report is to document the results of the WHRP research project *Interlayer Mixture Design*, as performed over the past several years by Advanced Asphalt Technologies, LLC. The purpose of this research is described in the RFP:

> *The objective of this research project is to develop an alternative method for accepting interlayer mixture designs without the bending beam fatigue test. Mixtures accepted that use other means are expected to maintain the same level of quality that the beam fatigue test provides. WisDOT will work with the research team to help communicate equipment restrictions for alternative acceptance testing.*

The problem addressed in this research is that the flexural fatigue testing currently used in accepting interlayer mixture designs (IMDs) is expensive and time-consuming. It would be very desirable if a simpler method for reliably ensuring the fatigue performance of IMDs could be developed and implemented in Wisconsin. The research described in this report was designed to address this problem and meet the objective described in the RFP.

The research approach involved producing 15 different mixtures, most meeting the basic binder and aggregate requirements of the IMD specification. However, a range in fatigue performance was needed to evaluate any method for predicting or controlling fatigue life. Some binders were therefore selected which would produce fatigue performance lower than needed for IMDs. Six different asphalt binders were used in the project—five of them were from Wisconsin and typical of modified binders used in the state. These binders were characterized with a range of tests that could potentially help to characterize fatigue performance, including dynamic modulus, double edge notched tension (DENT), elastic recovery from the multiple stress creep and recovery (MSCR) test, and the binder yield energy test. Mixture tests used in the project as surrogates for fatigue included the Texas Overlay Test and the Ideal Cracking Test (IDEAL-CT) procedure. It was however discovered early on the overlay test was unable to discriminate between the performance of the IMDs because they all passed the test with very little reduction in stiffness.

Using the data produced using these tests, statistical analyses were performed to develop an accurate and simple model that could serve as a basis for a revised, simpler IMD fatigue specification. This model predicts IMD cycles to failure based upon binder G* at 20ºC and mixture CT_{index} at 20ºC (from the IDEAL-CT). The r^2 for this model, at 95%, suggests the model is accurate enough to serve as the basis for an IMD fatigue specification. It was however found that binder low temperature grade was highly correlated to binder G* at 20°C. (r^2 = 92 %), so that IMD stiffness can be effectively controlled through the existing binder specification. The resulting recommended limits are a maximum binder low temperature grade of -34°C and a minimum mixture CT_{index} of 140 (after short-term oven aging). In addition to these requirements,

IMD binders should have a minimum elastic recovery (AASHTO M 332) given by the following equation:

$$Min. Elastic\ Recovery\ for\ IMDs = 25.0 + 29.4\, J_{nr3.2}^{-0.263}$$

Where $J_{nr3.2}$ is the non-recoverable creep compliance at a stress of 3.2 kPa, in units of 1/kPa. The IMD binder requirements will require no new tests or equipment. The IDEAL-CT mixture test is a simple procedure using a Marshall testing press to perform an indirect tension test at 20°C. The cost of this procedure is only about a quarter of that of the existing mixture test for IMDs—flexural fatigue testing. The proposed specification represents a savings of about $3,200 per IMD to producers, contractors, and the state of Wisconsin.

TABLE OF CONTENTS

DISCLAIMER i

TECHNICAL DOCUMENTATION PAGE ii

EXECUTIVE SUMMARY iii

LIST OF FIGURES vi

LIST OF TABLES viii

1. INTRODUCTION 1

2. LITERATURE REVIEW 3
- **2.1. Surrogate Tests for Flexural Fatigue Testing** 3
- **2.2. The NCHRP 9-59 Fatigue Model** 7
- **2.3. The Significance of WisDOT's IMD Fatigue Test** 8

3. RESEARCH APPROACH 9
- **3.1. Materials** 9
- **3.2. Methods** 10
- **3.3. Experimental Design and Analysis** 12

4. **RESULTS** 13

5. **ANALYSIS AND DISCUSSION** 19
- **5.1. Analysis** 19
- **5.2. Discussion** 38

6. **CONCLUSIONS AND RECOMMENDATIONS** 45
- **6.1. Conclusions** 45
- **6.2. Recommendations** 45
- **6.3. Implementation** 47

7. **REFERENCES** 48

LIST OF FIGURES

Figure 1. Typical Structure of a Wisconsin Pavement Including an IMD Layer. 3

Figure 2. Relationship Between Excess Elastic Recovery and δ_{10} for IMD Binders and Selected NCHRP 9-59 Binders. 21

Figure 3. Fatigue Life for Different Aggregate Blends, Averaged Over Binders from Supplier B 22

Figure 4. CT_{index} for Different Aggregate Blends, Averaged Over Binders from Supplier B. 23

Figure 5. Fatigue Life for Different Binders, Averaged Over Aggregate Blends 1 and 2. 23

Figure 6. CT_{index} for Different Binders, Averaged Over Aggregate Blends 1 and 2. 24

Figure 7. Predicted and Observed Values for Log CT_{index}. 27

Figure 8. Log Fatigue Life as a Function of Log Binder G*. 28

Figure 9. Log Fatigue Life as a Function of ΔTc. 28

Figure 10. Log Fatigue Life as a Function of Binder Yield Energy. 29

Figure 11. Log Fatigue Life as a Function of Excess Elastic Recovery 29

Figure 12. Log Fatigue Life as a Function of DENT Normalized Extension (NEXT75). 29

Figure 13. Log Fatigue Life as a Function of LAS Fracture/Fatigue Performance Ration (FFPR). 30

Figure 14. Log Fatigue Life as a Function of CT_{index}. 30

Figure 15. Observed and Predicted Fatigue Life Using Log G* Alone as a Predictor, with 26°C Data Point Omitted. 32

Figure 16. Observed and Predicted Fatigue Life Using Log G* Alone as a Predictor, with 26°C Data Point Omitted. 33

Figure 17. Observed and Predicted Fatigue Life Using Log G* and ΔTc as Predictors, with 26°C Data Point Omitted. 33

Figure 18. Observed and Predicted Fatigue Life Using Log G* and Binder Yield Energy as Predictors, with 26°C Data Point Omitted. 34

Figure 19. Observed and Predicted Fatigue Life Using Log G* and Excess Elastic Recovery as Predictors, with 26°C Data Point Omitted. 34

Figure 20. Observed and Predicted Fatigue Life Using Log G* and DENT Normalized Extension as Predictors, with 26°C Data Point Omitted. 35

Figure 21. Observed and Predicted Fatigue Life Using Log G* and LAS FFPR as Predictors, with 26°C Data Point Omitted. 35

Figure 22. Observed and Predicted Fatigue Life Using Log G* and CTindex at 20/26°C as Predictors, with 26°C Data Point Omitted. 36

Figure 23. Observed and Predicted Fatigue Life Using Log G* and CTindex at 5/11°C as Predictors, with 26°C Data Point Omitted. 36

Figure 24. Plot of Predicted vs Observed Fatigue Life—26ºC Data not included in model. 38

Figure 25. CT_{index} **at 20ºC as a Function of Binder G* at 20ºC and 10 Hz, Coded for Fatigue Life.** 39

Figure 26. Relationship between Binder G* at 20°C and 10 Hz (RT FOTR) and BBR Continuous Low Temperature Grade (RTFOT/PAV) for IMD Binders and Various Binders Tested at AAT's Laboratory. 40

Figure 27. Fatigue as a Function of BBR Continuous Low Temperature Grade, °C, Coded for CT_{index} **at 20°C.** 41

Figure 28. Fatigue Life as a Function of CT_{index} **at 20°C, for PG 58-34X Binders Only.** 41

Figure 29. Fatigue Life as a Function of Binder G* at 10 Hz, Coded for Excess Elastic Recovery. 43

Figure 30. Elastic Recovery Limit as Given in Appendix A of AASHTO M 332 for Elastomerically Modified Binders and Limit Proposed for IMD Binders in Wisconsin 44

LIST OF TABLES

Table 1. Summary Properties of IMD Mixes used in the Primary IMD Experiment. 9

Table 2. Summary Properties of Binder used in the Primary IMD Experiment. 10

Table 3. Mixture Performance Tests Used in Mixture Evaluation. 11

Table 4. Binder Tests Used in Mixture Evaluation. 12

Table 5. Asphalt Binder-Aggregate Blend Combinations for IMD Project. 12

Table 6. Fatigue Life of Interlayer Mixture Designs. 13

Table 7. Results of IDEAL CT Tests on IMDs at 20/26°C. 14

Table 8. Results of IDEAL CT Tests on IMDs at 5/11°C. 15

Table 9. Results of Binder Grading. 16

Table 10. Results of AASHTO M 332 MSCR Testing for IMD Binders. 16

Table 11. Results of AASHTO M 332 MSCR Testing for Selected NCHRP 9-59 Binders. 17

Table 12. Binder Modulus and Phase Angle Values at 10 Hz (63 rad/s). 17

Table 13. Results of Binder LAS, Yield Energy and DENT Tests. 18

Table 14. Potential Predictor Parameters in IMD Fatigue Model. 20

Table 15. Correlation Matrix for CT_{index} **Models.** 25

Table 16. Analysis of Variance for the CT_{index} **Model.** 25

Table 17. Model Parameters for the CT_{index} **Model.** 26

Table 18. R-squared Values Between Possible Predictors and Log N_f**.** 28

Table 19. R^2 **and MSE Values for Regression Models for Fatigue Life Using G* and One Other Predictor.** 31

Table 20. R^2 **and MSE Values for Regression Models for Fatigue Life Using G* and One Other Predictor, with 26°C Data Point Omitted.** 32

Table 21. Analysis of Variance for IMD Fatigue Model. 37

Table 22. Model Parameters for IMD Fatigue Model. 37

Table 23. Analysis of Variance for IMD Fatigue Model--26ºC Data Point Removed. 37

Table 24. Model Parameters for IMD Fatigue Model—26ºC Data Point Removed. 38

1. INTRODUCTION

The purpose of this report is to document the results of the WHRP research project *Interlayer Mixture Design*, as performed over the past several years by Advanced Asphalt Technologies, LLC. The purpose of this research is described in the RFP:

> *The objective of this research project is to develop an alternative method for accepting interlayer mixture designs without the bending beam fatigue test. Mixtures accepted that use other means are expected to maintain the same level of quality that the beam fatigue test provides. WisDOT will work with the research team to help communicate equipment restrictions for alternative acceptance testing.*

The problem addressed in this research is that the flexural fatigue testing currently used in accepting interlayer mixture design's (IMDs) is expensive and time-consuming. It would be very desirable if a simpler method for reliably ensuring the fatigue performance of IMDs could be developed and implemented in Wisconsin. The research described in this report was designed to address this problem and meet the objective described in the RFP.

The research approach involved producing 15 different mixtures, most meeting the basic binder and aggregate requirements of the IMD specification. However, a range in fatigue performance was needed to evaluate any method for predicting or controlling fatigue life. Some binders were therefore selected which would produce fatigue performance lower than needed for IMDs. Six different asphalt binders were used in the project—five of them were from Wisconsin and typical of modified binders used in the state. These binders were characterized with a range of tests that could potentially help to characterize fatigue performance, including dynamic modulus, double edge notched tension (DENT), elastic recovery from the multiple stress creep and recovery (MSCR) test, and the binder yield energy test. Mixture tests used in the project as surrogates for fatigue included the Texas Overlay Test and the IDEAL-CT procedure. It was however discovered early on the overlay test was unable to discriminate between the performance of the IMDs because they all passed the test with very little reduction in stiffness.

Using the data produced using these tests, statistical analyses were performed to develop an accurate and simple model that could serve as a basis for a revised, simpler IMD fatigue specification. The implications of this model are discussed as is the logic leading to the final revised specification for IMD fatigue performance. The report concludes with specific conclusions and recommendations dealing with this revised specification, along with suggested changes in the Wisconsin Special Provision for Interlayer Pavements and some simple steps for implementing this revised specification. The proposed recommended limits for IMDs in Wisconsin are a maximum binder low temperature grade of -34°C and a minimum mixture

CT_{index} of 140 (after short-term oven aging). In addition to these requirements, IMD binders should have a minimum elastic recovery (AASHTO M 332) given by the following equation:

$$Min. Elastic\ Recovery\ for\ IMDs = 25.0 + 29.4\, J_{nr3.2}^{-0.263}$$

Where $J_{nr3.2}$ is the non-recoverable creep compliance at a stress of 3.2 kPa, in units of 1/kPa. The IMD binder requirements will require no new tests or equipment. The IDEAL-CT mixture test is a simple procedure using a Marshall testing press to perform an indirect tension test at 20°C. The IDEAL-CT represents a significant savings compared to the current method of testing IMD mixtures, costing about a quarter of flexural fatigue testing.

2. LITERATURE REVIEW

Reflective cracking in asphalt concrete overlays is a common and serious problem, where cracking in an underlying pavement causes a crack to form and rapidly work through the asphalt concrete overlay. Wisconsin has developed a special interlayer mix design (IMD) that is placed in a thin layer between a PCC pavement and an asphalt concrete overlay that significantly improves the performance of the overlay. Figure 1 shows a typical pavement structure in Wisconsin using an IMD layer. Current WisDOT standards for IMDs require flexural fatigue testing at a strain of 2,000 µm/m; for approval, a fatigue life of 100,000 cycles is required. WisDOT has found that this requirement helps ensure that IMDs provide the superior fatigue resistance this mix type requires. However, WisDOT does not have the equipment to perform this test and it must be performed by outside contractors, making the testing time consuming and expensive. The objective of this research project is to develop a quicker, less expensive way of evaluating IMDs that can effectively replace flexural fatigue testing.

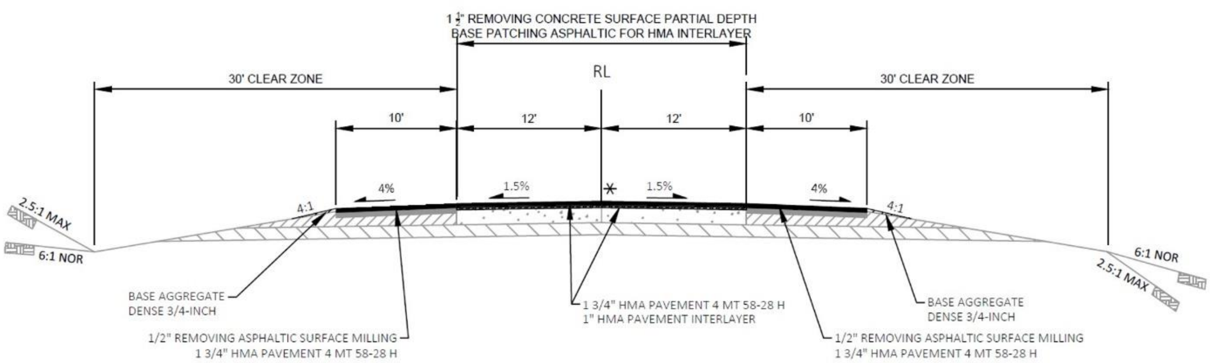

Figure 1. Typical Structure of a Wisconsin Pavement Including an IMD Layer.

2.1. Surrogate Tests for Flexural Fatigue Testing

There are several mixture and binder tests that have been proposed as surrogates for mixture flexural fatigue testing; among the most widely used are several versions of the semi-circular bending (SCB) test [1, 2, 3, 4], the Texas Overlay Test [5, 6, 7, 8, 9, 10, 11], and the IDEAL CT Test [12, 13]. Binder parameters calculated from dynamic shear rheometer (DSR) test data that have been promoted as indicators of fatigue performance include $|G^*| \sin \delta$, the Glover-Rowe parameter (GRP), the R-parameter from the Christensen-Anderson rheological model, fatigue life predictions calculated from the linear amplitude sweep (LAS) test, and ΔTc [14, 15, 16, 17, 18, 19]. The parameter $G^* \sin \delta$, also called G” or the dynamic loss modulus in shear, is the current intermediate temperature DSR specification parameter, and is often thought of as the binder fatigue parameter. It has come under substantial criticism lately, primarily because it does not appear to accurately characterize the improved fatigue performance of many polymer-modified binders [20]. The Glover-Rowe parameter has been criticized for similar reasons [14, 15, 20]. The ΔTc parameter is calculated by subtracting the critical bending beam rheometer

(BBR) temperature based on m-value from that based on stiffness: $\Delta Tc = Tc(S) - Tc(M)$ [19]. This parameter has been widely used over the past 10 years or so to characterize the durability and fatigue resistance of asphalt binders. As ΔTc increases (becomes more positive), the durability and fatigue performance of the binder in general should increase. It is a promising binder parameter for an improved method of evaluating the fatigue performance of IMDs.

The LAS test is in essence a binder fatigue test performed using a DSR to load a binder specimen in rotational shear [17, 18]. In the standard version of this test, the results are analyzed using continuum damage theory to produce estimated fatigue life values at difference shear strains. In a simpler alternative analysis developed by Christensen and Tran, the test is analyzed using the NCHRP 9-59 fatigue model (described below) to estimate the fracture/fatigue performance ratio (FFPR), which is an indicator of overall fracture and fatigue performance. An FFPR value close to 1 indicates average performance, while values above 1 suggest superior performance and values significantly below 1 suggest poor fracture/fatigue performance [21, 22]. The LAS is a good potential candidate for evaluating IMDs because it is a quick and inexpensive test, although there is little or no data correlating LAS data to field performance.

The binder yield energy test is a binder strength test performed using the DSR. In this test, the energy required to cause yielding in an asphalt binder specimen is measured. The test uses 8-mm parallel plates with a 2-mm gap and a strain rate of 1% per second [25]. This test correlated very well to the observed fatigue performance of mixes in the 2012 FHWA ALF experiment and can probably be performed over a wide range of intermediate temperatures [24]. In addition to the observed correlation to mixture fatigue performance, this test is promising because it uses the DSR and standard test fixtures, and it could be easily implemented. Non-uniform distribution of stresses and strains is a drawback of this test, as well as relatively slow loading, which is important and is a problem with many strength tests.

The double edge-notched tension (DENT) test has been used successfully to characterize the fracture properties of both asphalt binders and HMA mixes [26]. In this test, a rectangular test specimen resembling that used in a force-ductility test is prepared with 45° notches on both sides at the center of the specimen. The specimen is loaded at a constant deformation rate until failure, and the load and energy to failure are measured. Generally, three sets of specimens are prepared with different ligament lengths (the ligament length is the distance between the notches at the midpoint of the specimen). Total energy to failure is plotted as a function of ligament length; the intercept gives essential work of fracture, an indication of the inherent fracture toughness of the material. The slope of the plot gives the plastic work of fracture. The critical crack tip opening displacement (CTOD) is calculated by dividing the essential work of fracture by the maximum stress [26]. As with the yield energy test, CTOD showed a good correlation to cracking in the 2012 FHWA ALF experiment [24].

The DENT test is promising to characterize fatigue performance, but it is not a standard method, has not been widely used and would be more difficult to implement than the tests based on DSR testing. Christensen and Tran have developed a simplified version of this test, which only requires testing of two specimens instead of six and uses an alternative analysis using normalized extension (NEXT) [21, 22]. Extension to failure in a DENT test using the largest specimen notches is highly correlated to CTOD used in the standard analysis and should correlate well to cracking. However, a problem with DENT extension to failure (or CTOD) is that it is sensitive to binder stiffness and so could provide misleading results for very stiff or very soft binders. A solution to this is to use normalized extension (NEXT) which is DENT extension to failure normalized to a standard stiffness. Another issue in the DENT test is how to define failure. If failure is defined as the extension at maximum load, then post-peak behavior is ignored and the benefits of polymer modification—often most clear in post-peak extension—may not be seen in the DENT results. Defining failure at a very large post peak extension, for instance to 10 % of the maximum load, post-peak, can also be misleading because some binders can exhibit extreme post-peak extension at loads so low that it has no practical effect on fracture and fatigue properties. For the purposes of the IMD project, the DENT test was included using the simplified version developed by Christensen and Tran, and normalized extension to 75 % of the maximum load, post-peak (NEXT75). The load used for the normalization was 20 kN.

There are two recent projects that have examined binder tests and specifications for evaluating fatigue resistance: NCHRP 9-59, which is now complete, and NCHRP 9-60, which is ongoing [20, 21, 22]. NCHRP 9-59 recommended the use of GRP and ΔTc (or similar indicators of binder rheologic type), with a caveat that additional testing of polymer modified binders—especially without the severe aging used in NCHRP 9-59—is needed to refine these recommendations [21, 22]. NCHRP 9-60 has focused more on low-temperature cracking than fatigue cracking but has been critical of the use of both loss modulus (G”) and GRP for evaluating the fatigue performance of polymer-modified binders [20]. Binder testing with the DSR—combined with volumetrics—is an attractive, economical approach to evaluating the fatigue resistance of asphalt mixtures, but it is not clear that any of the currently available alternatives are suitable for a wide range of binders, especially those that have been substantially modified with elastomeric polymers.

In the SCB test, three semi-circular specimens are sawn from a gyratory compactor specimen. A notch is sawn in the middle of the flat side of the SCB specimen, which is then tested in a flexural strength test, typically using a Marshall press or similar inexpensive testing machine [1, 2, 3, 4]. There are at least two versions of the SCB test. In its original form, as developed by Al Qadi and his associates at the University of Illinois, the test is performed at 20ºC and 50 mm/min [1]. The developers of the test called the test the “IFIT” test, standing for Illinois Flexibility Index Test. The analysis of IFIT data involves calculation of the flexibility index (FI) from the load-displacement curve. The developers of this test showed that surface cracking in pavements tends to increase as FI decreases and recommended a minimum FI of 8 to ensure adequate cracking resistance in asphalt pavements [1]. The IFIT test has been evaluated by numerous other researchers and has been adopted by several agencies.

A second version of the SCB test has been developed at the Louisiana State University (LSU) by Mohammed and associates [3, 4]. This version of the test uses the same sample geometry, but testing is performed at a much slower rate. The analysis is also quite different, requiring testing of specimens with three different notch depths and the calculation of fracture-mechanics based parameters [3, 4]. This version of the SCB test has not been as widely adopted as the Illinois. As pointed out later in this report, the slow loading rates used in monotonic tests of HMA are a significant problem when using such tests to characterize fatigue resistance, since traffic fatigue loading (and laboratory fatigue loading) are done at much higher loading rates. Errors due to slow loading rate are especially severe in the Louisiana version of the SCB test, because it is done at a loading rate even slower than the IFIT test and most other monotonic mixture tests. Although the IFIT test does appear promising, it was decided not to include this test in the IMD study, because there was more interest in the IDEAL-CT (discussed below), which appears to provide results highly correlated to those of the IFIT and is simpler to perform.

The Texas overlay test was developed at Texas A & M University and is now a standard test method in Texas (Tex-248-F). The test was originally developed in 1979 but did not wee widespread use for many years [5, 6]. The test was modified and refined by several researchers starting in 2003 [7, 8, 9, 10, 11]. In this test, a roughly rectangular specimen is sawn from a gyratory specimen and notched through its center. The specimen is then mounted to two separate steel blocks, one stationary and one that moves through a servo-hydraulic loading system. The specimen is loaded in displacement control, using a triangular loading function with a maximum displacement of 0.64 mm [5]. One cycle of loading is completed every 10 seconds, with no rest periods between cycles. The test is continued until the load drops to 93% of its initial value, or until 1,200 cycles are reached (TX-248-F). Zhou and Scullion have proposed that mixes that can sustain 300 or more cycles in the overlay test without a stiffness reduction of 93% can be considered crack resistant [8]. The overlay test showed excellent correlation to the fatigue performance of the ALF II sections, but modest correlations to fatigue performance in the ALF Sustainability Study [24, 27]. Correlation between the overlay test and the observed fatigue performance of pavements are limited. The overlay test has a theoretical advantage over static tests such as the SCB and IDEAL-CT in that it is a fatigue test. However, the loading rate in the overlay test is much slower than in flexural fatigue tests or in pavement subjected to traffic loading, so like the SCB test and IDEAL-CT, the slow loading rate may cause problems when correlating results to laboratory fatigue and field performance data. The overlay test is also more complicated than the SCB test or IDEAL-CT—requiring more complicated specimen preparation, and some type of programmable, servo-mechanical test machine. The overlay test was initially included in the IMD study, primarily because it was the only cracking test which used repeated loading, and it was felt this might help improve the accuracy of the overlay test compared to other tests. Unfortunately, as discussed later in this report, the overlay test was found early on to be unsuitable for evaluating the fatigue performance of IMDs because their fatigue resistance was so high that they showed little degradation during the test and the mixtures could not be differentiated. It is possible that the overlay test could be modified for use in evaluating IMDs, for instance by using higher displacements and/or more loading cycles. However, such an effort was beyond the scope of this project.

The IDEAL-CT is a simple indirect tension test in which load and displacement are measured. It was developed at Texas A & M University by Zhou, Im, Sun, and Scullion [12, 13]. The standard loading rate for the test is 50 mm/min, and it can be performed on a Marshall press using gyratory specimens [12, 13]. Zhou and his associates developed a parameter from the IDEAL-CT data call the CT-index (CTI), which is based on fracture mechanics principals and proposed as characteristic of cracking resistance. In this paper the authors demonstrated that CTI is sensitive to RAP and RAS content, binder grade, binder content, laboratory aging and air void content. They also showed that the CTI is reasonably repeatable [12, 13]. Zhou and his associates compared CTI to the results of both the IFIT test and the overlay test and found good correlations among the three tests. The also showed a good correlation between CTI and fatigue performance of the mixes in the ALF Sustainability Study [12, 13]. The IDEAL-CT is well suited to routine use in evaluating mix designs—it is simple, does not require any new equipment or special training to perform, and to date correlates well to other cracking tests and fatigue performance in the ALF Sustainability study. It was one of two cracking tests included in a recent report on Implementing balanced mix design (BMD) in Wisconsin [28]. For these reasons, the IDEAL-CT was selected for inclusion in the IMD study.

2.2. The NCHRP 9-59 Fatigue Model

The recently completed project NCHRP 9-59 has presented a new and unique model for characterizing fatigue performance in asphalt mixtures [21, 22]. Some of the features of this model are directly applicable to the problem of predicting IMD fatigue performance. Christensen and Tran proposed that the fatigue life of an asphalt mixture is a function of the binder fatigue strain capacity, the binder fatigue exponent, the applied strain, and the binder content of the mixture [21, 22]:

$$N_f = \left(\frac{FSC}{\varepsilon}\right)^{180/\delta} \tag{1}$$

Where

N_f	=	cycles to failure
FSC	=	fatigue strain capacity of the binder, %
ε	=	applied strain in binder, %
	=	$\varepsilon_{mix}/(VBE/100)$
ε_{mix}	=	*applied strain in mixture, %*
VBE	=	binder content, volume %
δ	=	binder phase angle at 20°C and 10 Hz, degrees

In Equation 1, FSC is a function of binder modulus and a factor called the fatigue/fracture performance ratio (FFPR):

$$FSC = FFPR\left(\frac{4.45\times10^6}{|G^*|}\right)^{0.806} \tag{2}$$

Where

|G^*| = dynamic complex shear modulus of the binder at desired temperature and loading frequency, Pa

FFPR values typically range from about 0.50 to 2.00 [21, 22]. The understanding of how different factors affect FFPR has improved since the NCHRP 9-59 research was completed. There are three factors that primarily affect FFPR in asphalt mixtures:

- Asphalt rheologic type, as indicated by ΔTc and related parameters
- The effectiveness of any polymer modification in the binder
- Asphalt-aggregate interactions that significantly alter mixture strength and/or stiffness

It should be noted that the mixtures Christensen and Tran used in their study were heavily aged—five days of loose mix aging at 95ºC. About half of the mixtures were polymer modified, using a variety of polymer types and concentrations. However, most of the binders were not as heavily modified as a typical IMD binder [21, 22]. For this reason, and because of the heavy aging, the results of NCHRP 9-59, although providing some insight into IMD fatigue performance, are not necessarily directly applicable to this research.

The critical question in predicting the fatigue performance of IMDs is what test or tests will accurately reflect the various factors affecting mixture fatigue performance and provide good estimates of IMD performance? It was believed that the overlay test or IDEAL-CT might effectively address all these factors, so that they would by themselves provide a good indication of fatigue performance. However, it also seemed possible that these mixture tests might not fully reflect one or more of the factors affecting mixture fatigue performance, such as binder rheologic type or polymer modification. In this case, an accurate prediction of IMD fatigue life might require both a mixture test, such as IDEAL-CT, along with one or more binder parameters (hopefully ones that are provided in routine specification tests). Thus, the experimental plan for the IMD study included both mixture and binder tests.

2.3. The significance of Wisconsin's IMD Fatigue Test

An important issue in the IMD project is the unusual conditions used in the IMD fatigue test, which requires a minimum fatigue life of 100,000 cycles at 2,000 microstrain. These harsh test conditions are necessary to reflect the conditions within the pavement interlayer and the desire for a reasonable service life. Very few tests in the literature are run at such a high strain, which brings up the question of whether existing fatigue data and models—gathered at much lower strains—are applicable to the IMD fatigue test. An additional complication is that most of the mixtures meeting the IMD fatigue requirements will be heavily polymer modified, with significantly greater polymer content than many currently used polymer-modified asphalt paving mixtures. This also potentially creates a problem in applying existing fatigue data and models to predicting IMD fatigue tests. For these reasons, existing data and fatigue models should only be considered to provide general guidance as to the fatigue performance of Wisconsin's IMDs.

3. RESEARCH APPROACH

3.1. Materials

Four aggregate blends/mix designs and six binders were used in performing the primary experiment in this research. All aggregate blends met Wisconsin IMD specifications and were recommended by the POC. Four of the binders were polymer modified binders regularly used in Wisconsin and potentially suitable for use in IMDs. One of the binders was selected from the NCHRP 9-59 binders and was strongly polymer modified, but its rheologic type did not appear as suitable for use in IMDs as the Wisconsin binders. This binder was included in the study to help separate the effects of polymer modification and rheologic type on the fatigue life of IMDs. The sixth binder was a non-modified binder from Wisconsin, included to ensure that any predictive method developed in this project would soundly reject non-modified binders.

The aggregate blends used in this research are summarized in Table 1. Mixes 1 through 3 met the IMD specifications for VMA (16.0% minimum) and were very close to the target air voids of 2.0%. The VMA for mix 4, at 15.9%, was slightly below the minimum of 16.0%, and had a somewhat low air void content of 1.0% at the design asphalt content. There were no volumetrics available from the supplier for this mix design. Given the typical variability of volumetric parameters and the lack of information from the supplier, it was decided that further refinements in mix 4 would not be productive. The amount of mineral dust (passing the #200 sieve, or 0.074 mm) in the aggregates was nearly identical for mixes 1 through 3, ranging from 6.2 to 7.0 %. The mineral dust in mixture 4, however, was significantly higher at 9.0 %. A detailed evaluation of the effects of mineral dust on fatigue performance is beyond the scope of this project, and in any case, would not be possible because of the narrow range in mineral dust content and the lack of other important information on the nature of these fines, such as surface area. It is possible that the high dust content for mixture 4 might have some effect on the fatigue properties of aggregate blend 4—this topic will be addressed later in this report.

Table 1. Summary Properties of IMD Mixes used in the Primary IMD Experiment.

No.	WisDOT Grad.	NMAS[A]	JMF Passing #200	Design Asphalt Content, %		VMA, %		Air Voids, %	
				Supplier	AAT	Supplier	AAT	Supplier	AAT
1	No. 5	9.5 mm	6.2	7.3	7.3	17.6	17.8	1.5	2.1
2	No. 5	9.5 mm	7.0	7.4	7.7	17.2	17.9	2.0	2.1
3	No. 6	4.75 mm	6.6	8.8	8.6	20.5	20.6	1.0	2.0
4	No. 6	4.75 mm	9.0	N/A	8.5	N/A	15.9	N/A	1.0

Note A: nominal maximum aggregate size, defined as one sieve size larger than the first sieve to retain 10 % or more of the aggregate blend.

Summary properties for the binders are given in Table 2. The δ_{10} parameter has been proposed by Bennert as an alternative to ΔTc and is easier to determine since it is a simple calculation made from frequency sweep data [27]. It represents the phase angle when the binder modulus is 10 MPa. Like ΔT values, lower δ_{10} values generally indicate poorer fatigue performance. The MSCR excess recovery is the elastic recovery determined in the MSCR test, minus the minimum elastic recovery given in the Appendix of AASHTO M 332. This was found to be the best indicator of the effectiveness of polymer modification in improving fatigue resistance. Other binder properties are given later in this report.

Table 2. Summary Properties of Binder used in the Primary IMD Experiment.
Letters in parentheses after binder grade denote different suppliers.

Binder Grade	Source Project	Polymer Modified	ΔTc PAV *ºC*	δ_{10} RTFOT *ºC*	MSCR Elastic Recovery *%*	MSCR Excess Recovery *%*
58-34 E(a)	WHRP IMD	Yes	1.45	49.2	89.0	30.2
58-28 E(a)	WHRP IMD	Yes	1.34	49.5	55.6	17.8
58-34 V(b)	WHRP IMD	Yes	2.49	49.7	61.2	26.5
58-28 E(b)	WHRP IMD	Yes	0.53	44.3	87.5	23.3
58-28 S(a)	WHRP Other	No	1.11	48.9	0.6	0.0
70-28 E(c)	NCHRP 9-59	Yes	0.61	46.5	79.4	32.8

3.2. Methods

Aggregates for the four mixtures were shipped to AAT's laboratory in Kearneysville, WV by the various suppliers. These aggregates were blended to meet the JMF provided by the supplier. AAT then verified the mixture by mixing the selected asphalt binder and aggregate blend to several asphalt contents bracketing the reported design value. After determining the theoretical maximum specific gravity and the bulk specific gravity the volumetric composition for the mix was calculated and compared with the suppliers JMF. From this data, the design asphalt content for the mixture was selected. As discussed above, the design asphalt content for mixture 4 was not available, and so a reasonable assumption was made concerning the asphalt contents for the initial trials.

A variety of binder and mixture tests were used to characterize the materials used in the IMD study. The most important of these tests was the flexural fatigue test used to characterize the cracking performance of the IMDs. Other mixture tests used in the study included the Texas overlay test and the IDEAL-CT [5, 6, 7, 8, 9, 10, 11, 12, 13]. Specimens for flexural fatigue testing were compacted in a slab using a roller, and specimens for testing were sawn from this slab after verifying the proper air void content (nominally 2.0%). Specimens for the overlay test and the IDEAL-CT were sawn from gyratory compacted specimens. Mixture performance tests used in the IMD project are listed in Table 3. Most of the mixture tests were performed at a temperature of 20ºC. As discussed later in this report, for one mix, tests were also performed at 26ºC to help differentiate the effects of binder stiffness and polymer modification. Additional testing at temperatures other than 20ºC would have provided additional information on this topic but was not possible within the budget and time limits for the project. IDEAL-CTs were performed 20/26ºC and 5/11ºC. The lower temperature tests were performed because data collected as part of NCHRP 9-59 suggested that static tests such as the IDEAL-CT and SCB correlate better to fatigue test results when they are run at significantly lower temperatures than the fatigue tests.

The overlay test was only performed on four mixtures. When results from these tests were analyzed, it was found that there was almost no loss in modulus for any of the mixtures, and as a result, their performance could not be differentiated. It was concluded that the overlay test, in its standard form, is unsuitable for characterizing the fatigue performance of IMDs. It is possible that the overlay test could be modified for use on IMDs, by increasing the displacement used in the test, the number of loading cycles, or both. However, such modifications would likely consume significant time and funding and were beyond the scope of this project. Therefore, the overlay test was abandoned after these initial four tests.

Table 3. Mixture Performance Tests Used in Mixture Evaluation.

Test	Standard	Temperature ºC	Specimens
Flexural Fatigue	AASHTO T 321	20 and 26	4 beams sawn from slab
Texas Overlay Test	TEX-248-F	20	3 sawn from gyratory specimens
IDEAL-CT Test	Zhou, 2019	Varies	3 gyratory specimens

Tests conducted on the IMD asphalt binders are listed in Table 4. All binders were graded according to both AASHTO M 320 and M 332 (MSCR test). The binder yield energy test was performed at 20ºC for all binders, and 26ºC for the binder used in the mixture tested at this temperature. The test temperatures used for the LAS and DENT tests varied from binder to binder, because both tests provide good data only over a narrow range of binder stiffness; test temperatures for each binder were selected to provide optimum data quality. For grading, binders were aged as required in the two standards (AASHTO M 320 and 332). For the LAS, yield energy and DENT tests, binders were aged in the RTFOT to approximate the condition of the mixture performance specimens, which were subject only to short-term oven aging.

Table 4. Binder Tests Used in Mixture Evaluation.

Test	Standard	Temperature °C	Aging
Binder Grading	AASHTO M 320	N/A	Varies
	AASHTO M 332	N/A	Varies
Linear Amplitude Sweep (LAS)	AASHTO TP 101	Varies	RTFOT
Binder Yield Energy Test	AASHTO TP 123	20/26°C	RTFOT
Simplified Double Edge Notched Tension Test (DENT)	NCHRP 9-59	Varies	RTFOT

3.3. Experimental Design and Analysis

The experiment design can be considered an unbalanced partial factorial, to be analyzed using multiple regression techniques. The dependent variable is fatigue life, Nf. The log transform of Nf was used as this provides better correlations and residual distributions in statistical models for this variable. Predictor variables were various properties calculated from the mixture and binder tests described above. As with fatigue life, log transforms were used for the predictor variables when appropriate. The testing matrix used in the primary experiment is shown in Table 5; a total of 15 mixtures were used in this part of the project. The open cells in Table 5 represent mixes that were produced and tested, while blacked out cells represent mixes that were not included in the study.

Table 5. Asphalt Binder-Aggregate Blend Combinations for IMD Project.
Open cells represent mixes produced and tested, while blacked out cells represent mixes not included in the study.

			Aggregate Blend			
Grade	**Supplier**	**Temp., °C**	**1**	**2**	**3**	**4**
58-34 E	**Mathy**	**20**			■	■
58-28 E	**Mathy**	**20**			■	■
58-28 E	**Mathy**	**26**		■	■	■
58-34 V	**P&D**	**20**				
58-28 E	**P&D**	**20**				
58-28 S	**Mathy**	**20**		■	■	■
70-28 E	**9-59**	**20**	■	■		■

4. RESULTS

Basic results of the various mixture and binder tests are summarized in the Tables 6 through 13 below. Table 6 summarizes the results of flexural fatigue testing for the 15 IMD mixtures. The table includes binder grade, aggregate blend, test temperature, initial stiffness (at cycle 200), standard error for initial stiffness, fatigue life, and standard error for fatigue life. Standard error in this and the other tables in Chapter 4 is a measure of the variability of the mean test value, in this case a coefficient of variation for the average of four fatigue tests.

Table 6. Fatigue Life of Interlayer Mixture Designs.

Binder[A]	**Aggregate Blend**	**Temp.** *°C*	**Initial Stiffness** *MPa*	**Standard Error**[B] *%*	**Fatigue Life**[C]	**Standard Error**[D] *%*
58-34 E (a)	2	20	7.00	1.80	127,059	25.7
58-28 E (a)	2	20	11.37	2.16	12,261	3.2
58-34 V (b)	3	20	5.38	1.66	334,637	15.4
58-28 E (b)	3	20	8.98	0.58	13,195	4.4
58-34 E (a)	1	20	5.85	1.58	444,540	9.8
58-28 E (a)	1	20	10.45	0.32	8,647	7.6
58-34 V (b)	1	20	5.30	1.34	358,916	22.1
58-28 E (b)	1	20	8.41	0.73	23,482	4.8
58-34 V (b)	2	20	5.61	1.51	253,850	6.8
58-28 E (b)	2	20	9.49	1.71	13,708	7.7
58 -28 E (a)	1	26	6.19	2.71	66,319	13.0
58-28 S (a)	1	20	10.31	0.75	4,482	3.5
70-28 E (c)	3	20	8.12	2.80	20,927	14.3
58-34 V (b)	4	20	5.14	0.50	839,779	13.1
58-28 E (b)	4	20	8.24	0.56	33,661	40.3

Note A: letters a, b, and c at the end of the binder grade refer to different suppliers.

Note B: Calculated as = std. dev. Initial stiffness / [average (S_0) × [$\sqrt{n}$]

Note C: Calculated as = $10^{\text{average (log Nf)}}$

Note D: Calculated as = {$10^{\text{std. dev. (log Nf) /n0.5}}$-1} × 100%

Table 7 is a summary of the results of the IDEAL CT for the 15 IMD mixtures at 20 and 26°C. Besides binder, aggregate blend and test temperature, this table includes CT_{indes}, standard error for CT_{index}, fracture energy, and standard error for fracture energy.

Table 7. Results of IDEAL CT Tests on IMDs at 20/26°C.

Binder[A]	**Aggregate Blend**	**Temp.** *°C*	CT_{index}	**Standard Error**[B] *%*	**IDEAL-CT Fracture Energy** *J/m^2*	**Standard Error**[C] *%*
58-34 E (a)	2	20	154	4.16	10,781	1.54
58-28 E (a)	2	20	118	4.81	12,535	1.27
58-34 V (b)	3	20	247	9.52	8,787	1.48
58-28 E (b)	3	20	130	4.37	12,299	2.80
58-34 E (a)	1	20	187	1.72	10,584	1.48
58-28 E (a)	1	20	156	14.65	12,158	1.62
58-34 V (b)	1	20	246	10.94	9,343	0.89
58-28 E (b)	1	20	198	9.34	11,917	3.95
58-34 V (b)	2	20	171	12.49	9,030	4.65
58-28 E (b)	2	20	135	10.85	12,132	2.37
58 -28 E (a)	1	26	166	5.49	8,531	2.03
58-28 S (a)	1	20	126	2.68	10,532	1.13
70-28 E (c)	3	20	299	13.98	15,542	3.15
58-34 V (b)	4	20	461	7.88	8,887	1.49
58-28 E (b)	4	20	310	8.68	13,087	0.71

Note A: letters a, b, and c at the end of the binder grade refer to different suppliers.

Note B: Calculated as = std. dev. (CT_{index})/ [average (CT_{index}) × [$\sqrt{n}$]×100%

Note C: Calculated as = std. dev. (FE)/ [average (FE) × [$\sqrt{n}$]×100%

Table 8 is a summary of the results of the IDEAL CT for the 15 IMD mixtures at 5 and 1°C--15° lower than for the test results given in Table 7. These tests were performed because SCB data from NCHRP 9-59 suggested that static tests such as the SCB and IDEAL-CT might correlate better to fatigue tests when performed at a significantly lower temperature. Besides binder, aggregate blend and test temperature, this table includes CT_{indes}, standard error for CT_{index}, fracture energy, and standard error for fracture energy.

Table 8. Results of IDEAL CT Tests on IMDs at 5/11°C.

Binder^{A}	**Aggregate Blend**	**Temp.** *°C*	CT_{index}	**Standard Error**^{B} *%*	**IDEAL-CT Fracture Energy** *J/m²*	**Standard Error**^{C} *%*
58-34 E (a)	2	5	74.7	12.09	21,270	1.35
58-28 E (a)	2	5	27.7	6.38	20,106	2.97
58-34 V (b)	3	5	144.7	10.26	21,528	0.24
58-28 E (b)	3	5	66.3	18.12	22,562	2.45
58-34 E (a)	1	5	88.0	3.99	20,972	1.11
58-28 E (a)	1	5	31.5	7.94	21,823	1.58
58-34 V (b)	1	5	121.0	9.10	21,256	1.88
58-28 E (b)	1	5	59.3	8.39	22,331	2.59
58-34 V (b)	2	5	82.3	6.52	19,533	0.80
58-28 E (b)	2	5	41.0	8.57	20,441	1.60
58 -28 E (a)	1	11	77.7	3.51	18,717	2.65
58-28 S (a)	1	5	39.0	6.45	19,812	0.62
70-28 E (c)	3	5	95.7	9.28	26,263	2.88
58-34 V (b)	4	5	216.7	8.03	21,908	0.82
58-28 E (b)	4	5	141.3	7.54	25,864	1.23

Note A: letters a, b, and c at the end of the binder grade refer to different suppliers.

Note B: Calculated as = std. dev. (CT_{index}*)/ [average (*CT_{index}*)* $\times [\sqrt{n}]\times 100\%$

Note C: Calculated as = std. dev. (S_0)*/ [average* $(S_0) \times [\sqrt{n}]\times 100\%$

Tables 9 and 10 show the results of binder grading for the six binders used in the 15 IMD mixtures. Table 9 shows the results of AASHTO M 320 grading, while Table 10 is for AASHTO T 332 grading, using the multiple stress creep and recovery (MSCR) procedure.

Table 9. Results of Binder Grading.

Binder[A]	AASHTO M 320			Rheologic Type Indicators	
	T_c(high) *°C*	T_c(low) *°C*	T_c(intermediate) *°C*	ΔTc *°C*	δ_{10}[B] *degrees*
58-34 E	72.8	-35.0	10.5	1.45	49.2
58-28 E	69.1	-29.1	17.4	1.34	49.5
58-34 V	63.4	-35.3	11.0	2.49	49.7
58-28 E	73.1	-32.0	14.9	0.53	44.3
58-28 S	61.7	-29.6	17.3	1.11	48.9
70-28 E	71.0	-32.6	15.5	0.61	46.0

Note A: letters a, b, and c at the end of the binder grade refer to different suppliers.
Note B: binder phase angle (degrees) at G = 10 MPa at 4°C (frequency varies).*

Table 10. Results of AASHTO M 332 MSCR Testing for IMD Binders.

Binder[A]	$J_{nr3.2}$ *1/kPa*	$R_{3.2}$ *%*	Min. $R_{3.2}$[B] *%*	Excess Elastic Recovery[C] *%*
58-34 E	.072	89.0	58.7	30.3
58-28 E	.386	55.6	37.8	17.8
58-34 V	.531	61.2	34.7	26.5
58-28 E	.051	87.5	64.3	23.2
58-28 S	2.683	0.6	22.7	0.0
70-28 E	.174	79.4	46.6	32.8

Note A: letters a, b, and c at the end of the binder grade refer to different suppliers.

Note B: Min. $R_{3.2} = 29.4\, J_{nr3.2}^{-0.263}$

Note C: excess elastic recovery = if($R_{3.2}$>Min. $R_{3.2}$), $R_{3.2}$ – Min. $R_{3.2}$, otherwise 0.

Additional binder data is summarized in Table 11 and 12. Table 11 lists the details of the MSCR tests performed as part of the AASHTO M 332 grading, while Table 12 gives binder modulus (G*) and phase angle at 20°C and 10 Hz.

Table 11. Results of AASHTO M 332 MSCR Testing for Selected NCHRP 9-59 Binders.

Binder[A]	$J_{nr3.2}$ *1/kPa*	$R_{3.2}$ *%*	**Min.** $R_{3.2}$[B] *%*	**Excess Elastic Recovery**[C] *%*
O	0.0235	82.0	78.8	3.2
N	0.0035	92.4	100.0	0.0
E	0.0079	83.0	100.0	0.0
G	0.0329	81.7	72.2	9.5
J	0.0326	80.0	72.3	7.7
M	0.0020	96.5	100.0	0.0
C	0.0735	75.3	58.4	16.9

Note A: letters a, b, and c at the end of the binder grade refer to different suppliers.
Note A: Min. $R_{3.2} = 29.4\, J_{nr3.2}^{-0.263,}$ *but not to exceed 100%.*
Note B: excess elastic recovery = if ($R_{3.2}$*>Min.* $R_{3.2}$*),* $R_{3.2}$ *– Min.* $R_{3.2}$*,otherwise 0.*

Table 12. Binder Modulus and Phase Angle Values at 10 Hz (63 rad/s).

Binder[A]	**Temp.** *°C*	**G*** *MPa*	**Phase Angle** *deg*
58-34 E (a)	20	2.58	57.5
58-28 E (a)	20	6.51	54.9
58-28 E (a)	26	2.45	58.8
58-34 V (b)	20	2.29	59.5
58-28 E (b)	20	5.33	51.0
58-28 S (a)	20	7.35	53.0
70-28 E (c)	20	4.55	53.1

Note A: letters a, b, and c at the end of the binder grade refer to different suppliers.

Table 13—the last table in Chapter 4—is a summary of the other binder tests performed as part of this project. These include the values for LAS FFPR, binder yield energy, and DENT normalized extension. Yield energy tests were performed at the same temperature as the corresponding mixture fatigue test. This protocol could not be followed for the LAS and DENT tests, because these tests can only be performed over a narrow range of binder stiffness, and so the test temperature must vary for each binder.

Table 13. Results of Binder LAS, Yield Energy and DENT Tests.

Binder[A]	**LAS FFPR**	**Yield Energy at 20°C** *kPa*	**Yield Energy at 26°C** *kPa*	**DENT Normalized Extension** *mm*
58-34 E	2.03	1,518	N/A	36.0
58-28 E	1.55	1,403	418	18.8
58-34 V	2.01	439	N/A	34.9
58-28 E	1.92	1,146	N/A	14.0
58-28 S	1.00	48	N/A	12.5
70-28 E	2.14	548	N/A	15.2

Note A: letters a, b, and c at the end of the binder grade refer to different suppliers.

5. ANALYSIS AND DISCUSSION

5.1. Analysis

The purpose of this research is to develop a method for accurately predicting the fatigue performance of IMDs, using simple tests and calculations—as opposed to the flexural fatigue testing now used. Statistical methods are useful in addressing this sort of problem, but caution is needed in this case because of the small sample size. This means that any statistical model developed should probably be limited to two predictors, otherwise it will likely be overparameterized and unreliable when extended to new observations. To provide additional confidence in any model developed, possible predictor parameters must be selected before the analysis, with a good idea of how and why they might help predict fatigue performance. The potential predictor parameters, their effect on fatigue performance and the rational for this effect are listed in Table 14. The relationship between modulus and fatigue life—at least for strain-controlled fatigue—is well known and was explained in NCHRP 9-59 in terms of the strong decrease in strain capacity associated with increased modulus. This is possibly the single most important factor affecting the fatigue life of asphalt concrete mixtures. The effect of binder phase angle and rheologic type on fatigue performance was shown in NCHPR 9-59. Increasing phase angle decreases the fatigue exponent, which tends to decrease fatigue life. However, for a given asphalt binder an increase in phase angle is usually going to be accompanied by a decrease in modulus and an increase in strain capacity, which will increase fatigue life. Therefore, the effect of phase angle on fatigue life tends to be offset by the effect of modulus, and as a result the observed relationship between phase angle and fatigue life tends to be relatively weak. Binder rheologic type has a moderate to strong effect on fatigue life—as ΔTc or δ_{10} increase, strain capacity increases resulting in an increase in fatigue life. This was one of the findings of NCHRP 9-59 but has also been widely accepted that increasing ΔTc is generally associated with improved fatigue performance and durability.

Table 14. Potential Predictor Parameters in IMD Fatigue Model.

Parameter	Effect on Fatigue Life	Expected Strength of Relationship	Rationale
Binder G*	Decrease	Very strong	Increasing modulus leads to lower strain capacity, decreasing fatigue life.
Binder phase angle	Decrease	Weak	Increasing phase angle decreases fatigue exponent, decreasing fatigue life. Opposite in effect from G*, so effect is muted. No effect on monotonic tests.
Binder rheologic type (ΔTc, δ_{10})	Increase	Moderate	All else being equal, increasing ΔTc or δ_{10} increases strain capacity and increases fatigue life.
Indicators of polymer modifier effectiveness (excess elastic recovery, DENT normalized extension, binder yield energy, LAS FFPR)	Increase	Moderate to strong	Increasing polymer modification increases strain capacity and fatigue life. This effect can be difficult to separate from that of rheologic type, which can also affect these parameters.
CT_{index}	Increase	Uncertain	IDEAL-CT theoretically should reflect binder strain capacity as affected by the factors listed above, and by specific asphalt-aggregate interactions.

One of the most difficult aspects of HMA fatigue performance to address is the effect of polymer modification. As explained earlier in this report, several candidate tests/parameters have been included in the IMD project as possible predictors of fatigue life: excess elastic recovery, DENT normalized extension (NEXT 75), binder yield energy test and LAS fracture/fatigue performance ratio (FFPR). One of the complicating factors in characterizing the effect of polymer modification on the fatigue and fracture properties of asphalt binders and mixtures is that as seen in Table 14, there are at least three factors that will affect the failure and fatigue properties of an asphalt binder: modulus, rheologic type and polymer modification. It can be difficult to separate these. If a binder exhibits good fracture and fatigue properties, is it because it has a low modulus, or a favorable rheologic type or perhaps because it has been effectively polymer modified? Three of the parameters for evaluating polymer modification listed in Table 14 have been normalized for the effect of binder stiffness on fracture properties: excess elastic recovery, DENT normalized extension and LAS FFPR. However, these parameters will still be affected by rheologic type, along with polymer modification. This is an important complication for these tests, since it appears that rheologic type can alter the effectiveness of polymer modification as measured by these tests. As an example, Figure 2 shows excess elastic recovery as a function of δ_{10} for the IMD asphalt binders and for seven NCHRP 9-59 binders. All of these except one were polymer modified; the NCHRP 9-59 binders were aged in the RTFOT followed by 40 hours in the PAV, while the IMD binders were subjected to RTFOT aging only. It appears that as δ_{10} increases, the effect of polymer modification on excess elastic recovery increases—at δ_{10} values below about 33 degrees, excess elastic recovery is zero, and these are polymer modified binders. Binder yield energy has not been normalized and so should be expected to be affected by modulus, along with rheologic type and polymer modification.

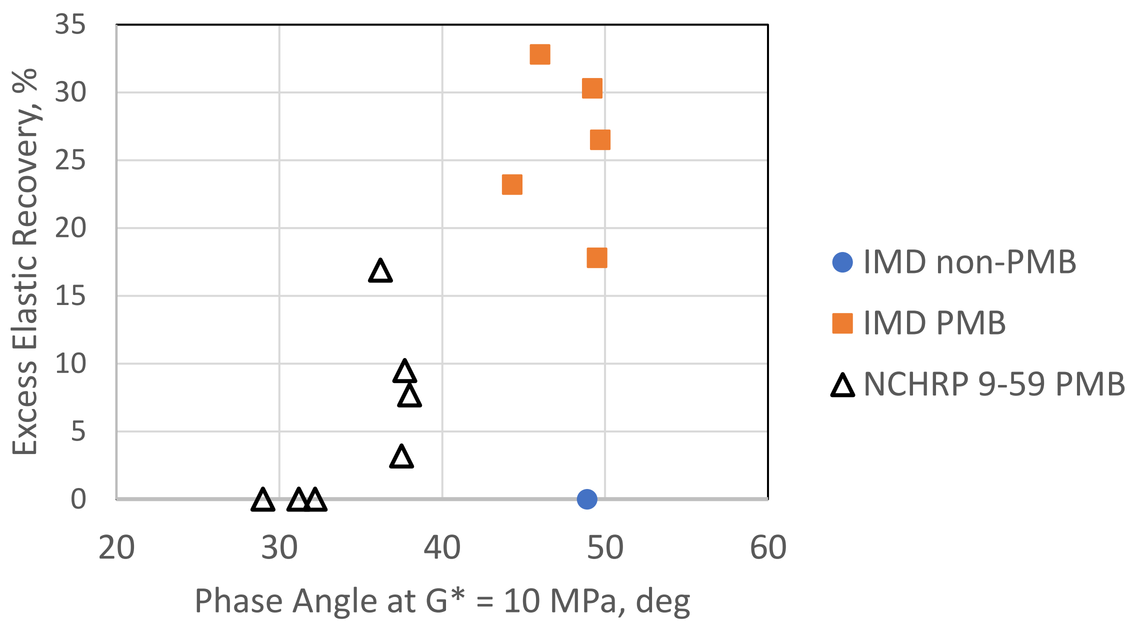

Figure 2. Relationship Between Excess Elastic Recovery and δ_{10} for IMD Binders and Selected NCHRP 9-59 Binders.

Because the overlay test was unable to differentiate the performance of the IMDs, the only mixture test included in the IMD study was the IDEAL-CT; the parameter used for characterizing the fatigue performance using this method was the CT_{index}. As discussed above, this test has been related to laboratory fatigue tests and to a lesser extent field performance, although its relative sensitivity to the specific factors affecting fatigue life is not clear. It seems likely that CT_{index} is affected by modulus, rheologic type and polymer modification, but not necessarily in the same way as fatigue life. Perhaps the most useful aspect of the CT_{index} is that it potentially can characterize the effect of specific asphalt-aggregate interactions on fatigue life. Binder tests alone will not account for this affect. For this reason, it is desirable to include the

CT_{index} in any approach to predicting IMD fatigue performance. It is however important before proceeding with in-depth analysis to understand what properties affect CT_{index}.

A useful initial step in analyzing the IMD data is to look broadly at the effect of aggregates and binders on the two mixture tests used in the study—fatigue life and CT_{index}—by calculating average values and comparing them for different materials. Because the experiment design was not a full factorial, average values for each aggregate can only be calculated using the binders from supplier (b). Similarly, average values for each of the four IMD binders can only be calculated using aggregate blends 1 and 2. Figure 3 shows fatigue life for the four aggregate blends, averaged over binder from supplier (b); Figure 4 shows CT_{index} (both at 20 and 5°C) for the four blends, averaged over supplier (b) binders. The trend is the same for all three measurements—from best to worst performance: aggregate blend 4, 1, 3, and 2. It is encouraging that both CT_{index} values and fatigue life all show the same trend for the effect of aggregate, since this suggests that CT_{index} might be an effective surrogate for flexural fatigue life. Figure 5 shows fatigue life for the four IMD binders, averaged over aggregate blends 1 and 2. Figure 6 shows CT_{index} for the IMD binders averaged over aggregate blends 1 and 2. As with the previous two plots, the trend for binder effect is the same for fatigue life and CT_{index} at 20 and 5°C. The binders from supplier (b) show slightly better performance compared to those from supplier (a), while the PG 58-34 binders show much better fatigue life compared to the PG 58-28 binders. This suggests that binder low-temperature grade might be a significant factor in determining the fatigue performance of IMDs.

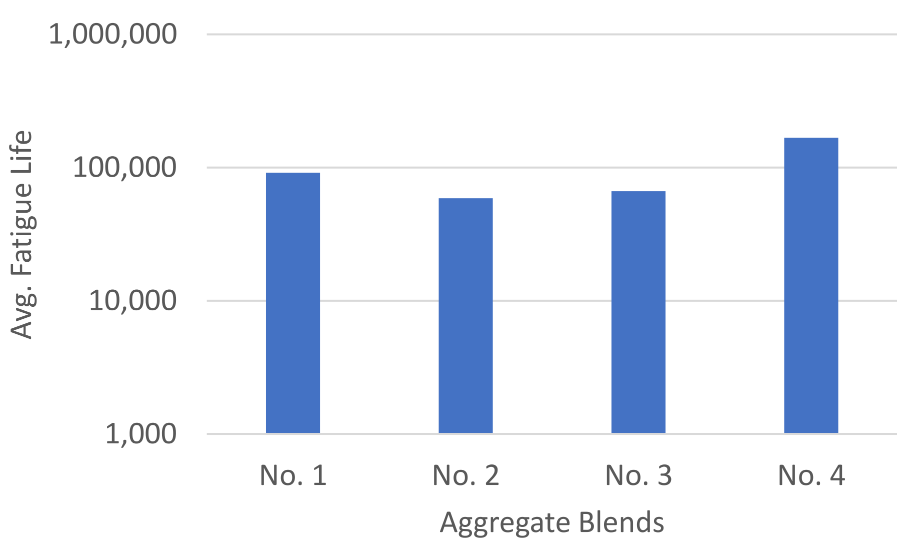

Figure 3. Fatigue Life for Different Aggregate Blends, Averaged Over Binders from Supplier B.

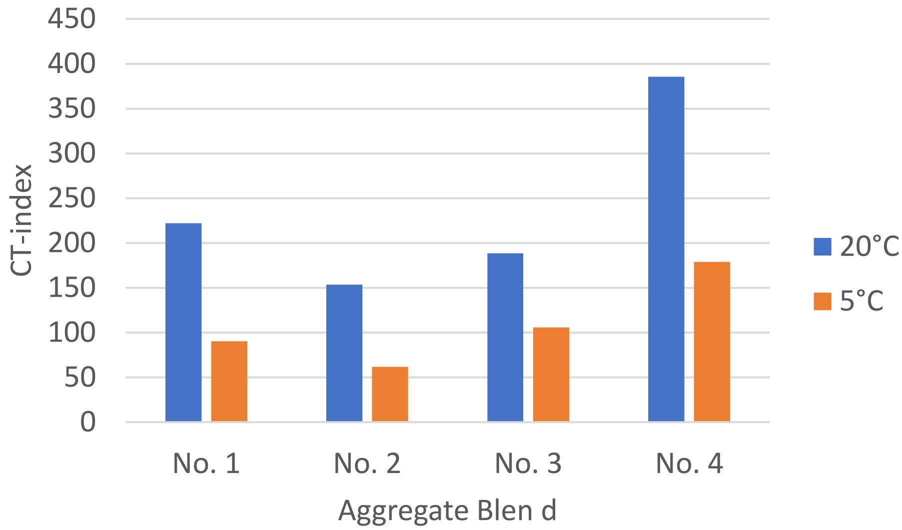

Figure 4. CT_{index} for Different Aggregate Blends, Averaged Over Binders from Supplier B.

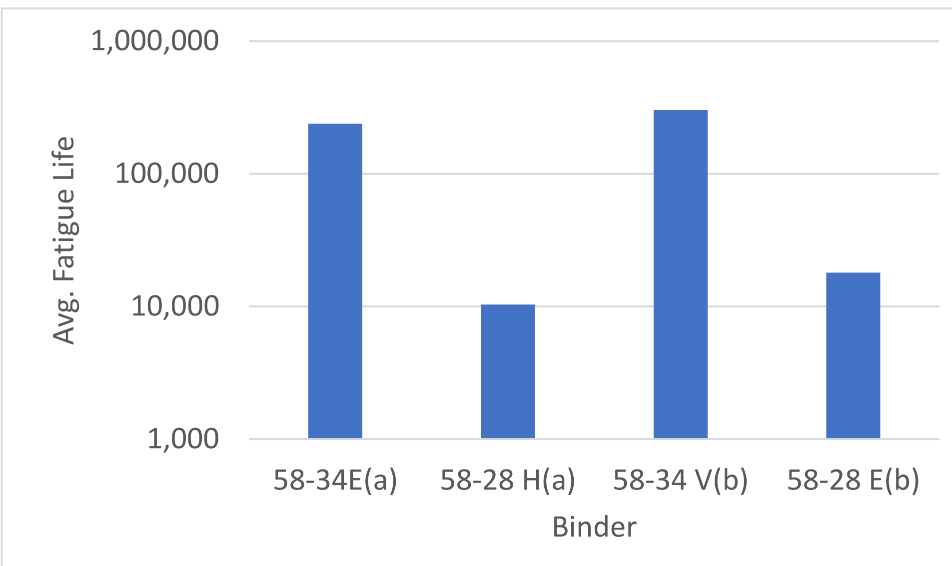

Figure 5. Fatigue Life for Different Binders, Averaged Over Aggregate Blends 1 and 2.

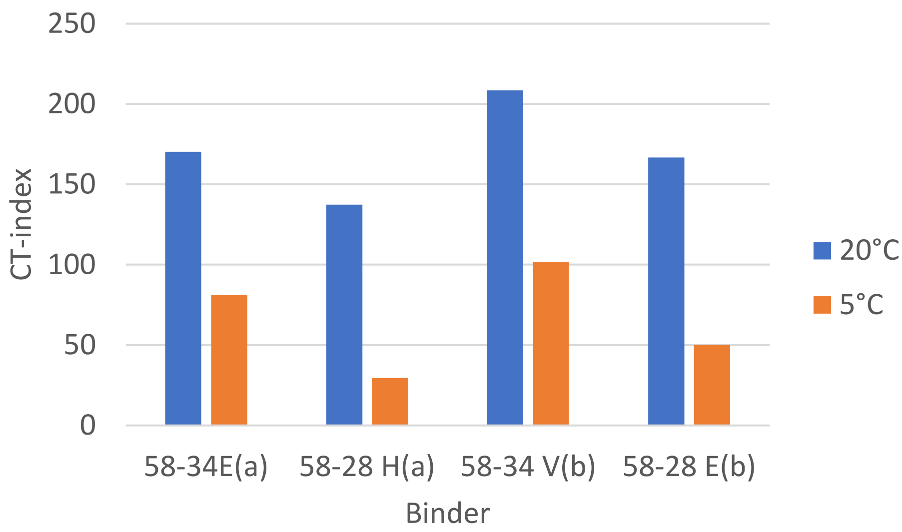

Figure 6. CT_{index} for Different Binders, Averaged Over Aggregate Blends 1 and 2.

The next step in the data analysis for this project is to determine if CTindex is a suitable surrogate for fatigue life, based on its sensitivity to factors known to effect fatigue life, the most important of these being binder modulus, aggregate type and gradation and the presence of polymer modifiers in the binder. Table 15 is the correlation matrix for CT_{index} and likely predictor variables. The correlation matrix shows the linear correlation coefficients between possible two-way combinations of predictor variables. This is useful in identifying highly correlated predictor variables; if potential predictor variables are highly correlated, models using both predictors should be avoided because it can produce misleading results. There appear to be no highly correlated predictors among the candidates shown in Table 15. The variables aggregate blend 2, aggregate blend 3 and aggregate blend 4 are indicator variables for the aggregate blends—the effect of aggregate blend 1 is zero, and the values for these three parameters represent the difference in log CT_{index} for each of the remaining 3 blends. For the purposes of modeling CT_{index}, binder modulus values were determined at a frequency of 0.1 rad/s, corresponding approximately to a loading time of 5 seconds. When running the full model, it was found that ΔTc was not a significant predictor ($p = 0.985$); the model was run again after eliminating this predictor. Note that the low significance of ΔTc does not necessarily mean that this variable does not affect CT_{index}. As mentioned above, the range in ΔTc values for this data set is relatively narrow and for this reason does not appear to have a significant effect on CT_{index}. A data set with a wider range in ΔTc values might increase the significance of this predictor. The resulting model is summarized in Table 16 (analysis of variance) and Table 17 (model parameters). The R^2 value of 91.4% is high. All predictors except for aggregate blend 3 are highly significant; aggregate blend 3 was not eliminated from the model so that the effect of aggregate blend 3 relative to blend 1 is clear. This model parameter in Table 17 lead to the following equation for predicting CT_{index}:

$$CT_{index} = 473G^{*-0.346}10^{0.00749EER}AGG \quad (1)$$

Where:

CT_{index} = mixture CT_{index} at temperature T
G^* = binder complex modulus at temperature T and 10 Hz, MPa
EER = binder excess elastic recovery, %
AGG = variable for aggregate effect
= 1.00 for aggregate blend 1
= 0.75 for aggregate blend 2
= 1.22 for aggregate blend 3
= 2.20 for aggregate blend 4

Note that the purpose of this analysis was not to develop a method for predicting CT_{index} but determine the sensitivity of CT_{index} to different mixture and binder properties. Equation 1 is not recommended for predicting CT_{index} for purposes of evaluating or accepting asphalt concrete mixtures.

Table 15. Correlation Matrix for CT_{index} Models.

	Log G*	Excess Elastic Recovery	ΔTc	Agg. Blend 2	Agg. Blend 3	Agg. Blend 4	Log CT_{index}
Log G*	**1**	-0.164	-0.320	-0.002	0.022	-0.013	-0.798
Excess elastic recovery		**1**	0.176	0.112	0.295	0.093	0.369
ΔTc			**1**	0.057	-0.114	0.067	0.280
Agg. Blend 2				**1**	-0.302	-0.237	-0.294
Agg. Blend 3					**1**	-0.196	0.137
Agg. Blend 4						**1**	0.445
Log CT_{index}							**1**

Table 16. Analysis of Variance for the CT_{index} Model.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	5	2.407	0.481	62.618	<0.0001
Error	24	0.185	0.008		
Corrected Total	29	2.591			

R^2 = 91.4%, adjusted for degrees of freedom.

Table 17. Model Parameters for the CT_{index} **Model.**

Source	Value	Standard error	t	Pr > |t|
Intercept	2.675	0.084	31.721	<0.0001
Log G*	-0.346	0.025	-13.778	<0.0001
Excess Elastic Recovery	0.00749	0.002	3.141	0.004
Aggregate Blend 2	-0.125	0.042	-2.988	0.006
Aggregate Blend 3	0.087	0.048	1.805	0.084
Aggregate Blend 4	0.342	0.052	6.539	<0.0001

The analysis suggests that aggregate blend 1 and blend 3 exhibit similar CT_{index} values, all else being equal. Figure 7 shows predicted and observed values for Log CT_{index}, coded for test temperature. It can be concluded from this analysis that for the purposes of developing an IMD model from these data, CT_{index} reflects binder modulus and polymer modification (as indicated by excess elastic recovery) along with the effect of different aggregate blends. Aggregate blend 4 showed unusually high values for CTindex at a given binder modulus and EER value. As mentioned below, CTindex was also a significant predictor of fatigue performance, and this blend also showed increased fatigue life compared to the other aggregates. The explanation here does not seem related to volumetrics—aggregate 4 had the lowest asphalt content and VMA of the four aggregate blends tested. The small difference in air void content also doesn't seem to explain the difference (around 2.0% for aggregates 1 through 3 and around 1.0% for aggregate 4). One possible explanation for the high performance of aggregate blend 4 is the high mineral dust (passing #200) content—9.0% compared to 6.2% to 7.0% for the other blends. It is possible that the small aggregate particles act to arrest cracks in the mixture, increasing toughness and improving fatigue life. Further research is needed to fully address the effects of aggregate gradation and properties on fatigue performance.

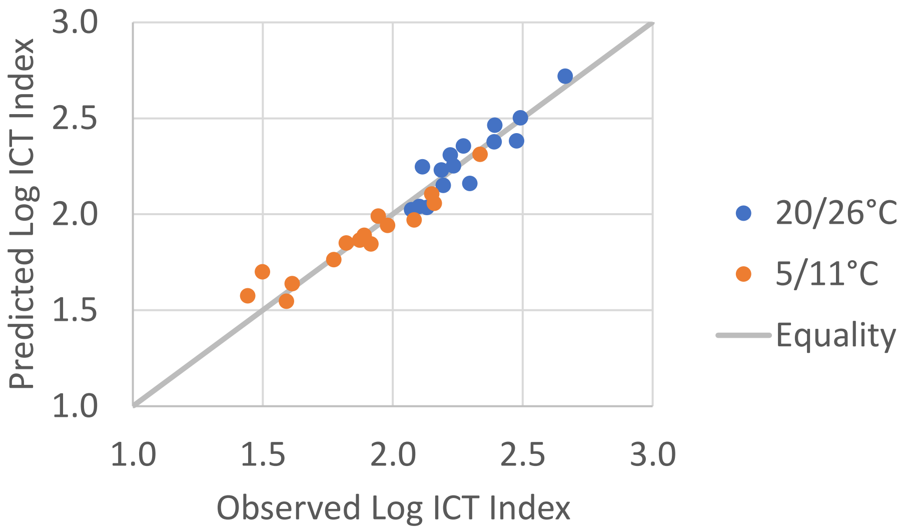

Figure 7. Predicted and Observed Values for Log CT_{index}**.**

The NCHRP 9-59 fatigue model includes a fatigue exponent that varies inversely with the binder phase angle. In the IMD data set, the binder phase angles fall into a relatively narrow range, which is a function of having binders with similar modulus values and similar rheologic type (ΔTc values). Also, the effect of phase angle on fatigue life tends to be muted because it is offset by the effect of modulus. Therefore, for the purpose of predicted IMD fatigue life, the effect of phase angle can be ignored. The first step in developing an IMD prediction method is to examine the linear correlations (r^2 values) between log fatigue life (Nf) and the various potential predictors; This is shown in Table 18. Unsurprisingly, the single best predictor of fatigue life for IMDs is binder modulus, with an r^2 value of 88%. The next best is DENT normalized extension at 82%. Because binder modulus is an existing specification test and shows the highest correlation to fatigue life, it should be used as one of the predictors in the IMD fatigue model. Plots of log fatigue life as a function of the various predictors included in Table 18 are shown in Figures 8 through 14.

Table 18. R-squared Values Between Possible Predictors and Log N_f.

Parameter	r^2
Log G*	88
ΔTc	59
Binder yield energy	3
Excess elastic recovery	37
DENT normalized extension	82
LAS FFPR	37
Log CT_{index} at 20/26°C	30
Log CT_{index} at 5/11°C	61

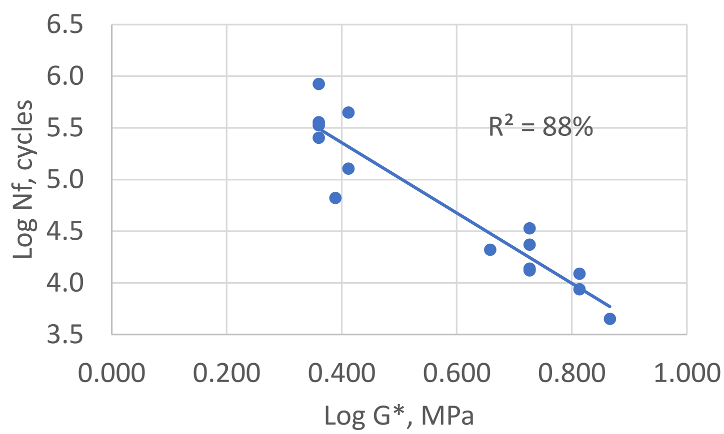

Figure 8. Log Fatigue Life as a Function of Log Binder G*.

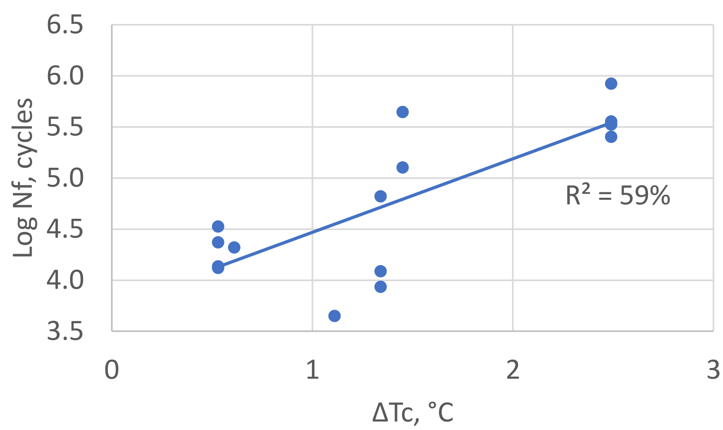

Figure 9. Log Fatigue Life as a Function of ΔTc.

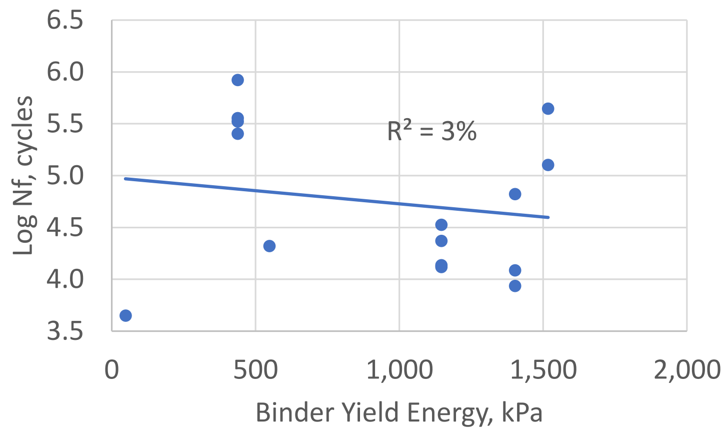

Figure 10. Log Fatigue Life as a Function of Binder Yield Energy.

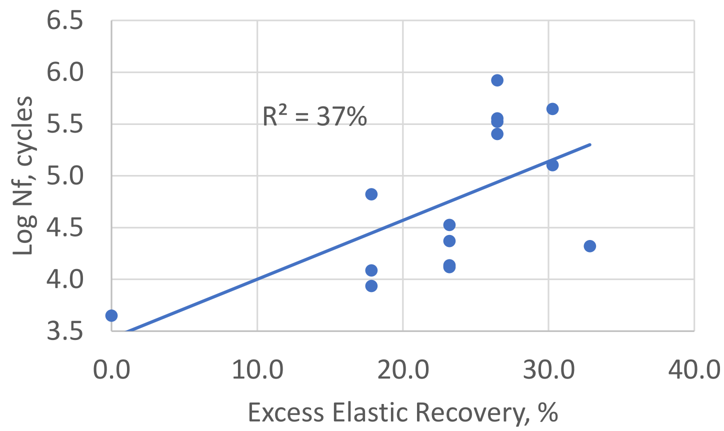

Figure 11. Log Fatigue Life as a Function of Excess Elastic Recovery.

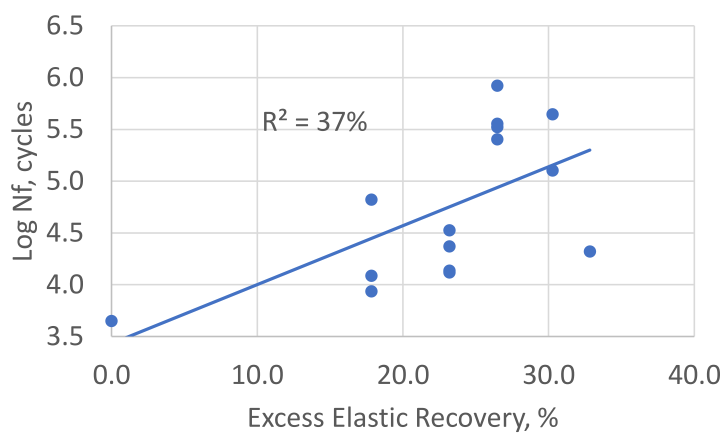

Figure 12. Log Fatigue Life as a Function of DENT Normalized Extension (NEXT75).

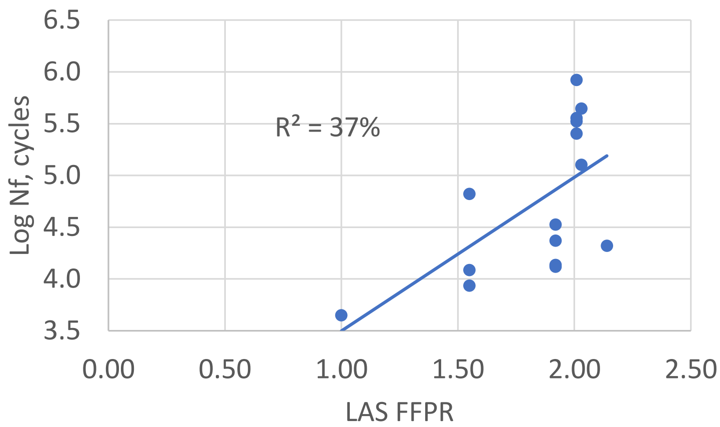

Figure 13. Log Fatigue Life as a Function of LAS Fracture/Fatigue Performance Ration (FFPR).

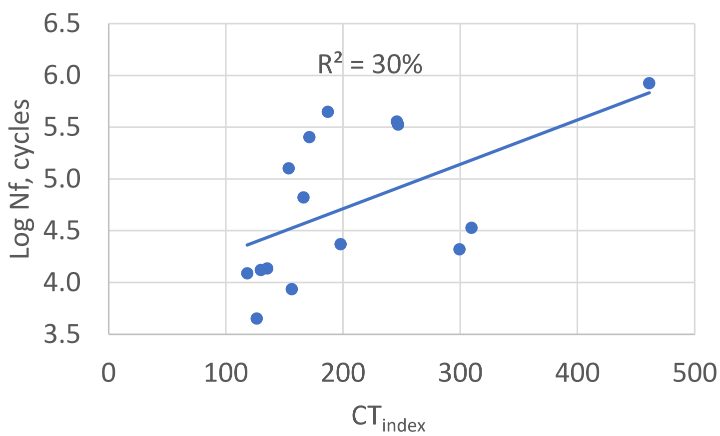

Figure 14. Log Fatigue Life as a Function of CT_{index}.

The next question is what other predictor can be added to G* to improve the accuracy of the IMD fatigue prediction model? Table 19 shows the R^2 values, adjusted for degrees of freedom, for regression models including the various other predictors. This table also include values for mean square error (MSE), an indicator of the error in the predictions of log Nf for the various models. The models using IDEAL-CT indices showed the best correlation and lowest MSE values. Log transforms were included for these IDEAL-CT indices to determine if this would provide better results (they did not). Although the R^2 value for CT_{index} at 5/11ºC was slightly higher than for the CT_{index} at 20/26ºC, the difference is small and the 20ºC test is the standard approach and would be easier to implement. As discussed above, it is desirable to include CT_{index} in the IMD fatigue prediction method, because it is the only candidate test able to evaluate the effects of different aggregate blends and potential asphalt-aggregate interactions.

As discussed in several other places in this report, 14 of the 15 data points used in the analyses summarized in Table 19 were done using fatigue, G* and CT_{index} tests at 20°C, while one point involved testing at 26°C. In many analyses, the 26°C data point appears to be an outlier. As an example, Figure 15 shows observed and predicted values for log Nf, using only log G* as a predictor. The 26°C data point is circled in red. This point has a large standardized residual (-2.2) and given that it was collected at a different temperature from the other data—and a non-standard temperature for IMDs—it seems reasonable to omit this data point in the final data analysis. Table 20 shows the same information given in Table 19, but in this case the 26°C data point has been removed. Table 20 also includes the level of significance for the secondary predictor (the level of significance for log G* was < 0.001 for all models). This table makes the superiority of CT_{index} as a predictor of fatigue life (along with log G*) much clearer. The two models using CT*index* as predictors are the only ones that have a level of significance below 0.050. The two models using the log transforms of CT_{index}, although not below 0.050, are significantly lower than for the other candidate predictors, which have levels of significance ranging from 0.602 to 0.991. Although the model using CT_{index} at 5°C appears to be slightly better than the one using CT_{index} at 20°C, the difference is quite small, and the standard IDEAL-CT is done at 20°C. Therefore, the improved IMD specification should be based on binder G* and CT_{index} at 20°C.

Table 19. R^2 and MSE Values for Regression Models for Fatigue Life Using G* and One Other Predictor.

Parameter	r^2	MSE
Log G* alone	87.5	0.066
ΔTc	87.6	0.066
Binder yield energy	86.6	0.071
Excess elastic recovery	87.5	0.067
DENT normalized extension	90.5	0.051
LAS FFPR	88.8	0.064
CT_{index} at 20/26°C	91.1	0.047
CT_{index} at 5/11°C	91.5	0.045
Log CT_{index} at 20/26°C	90.7	0.050
Log CT_{index} at 5/11°C	89.5	0.056

Table 20. R^2 and MSE Values for Regression Models for Fatigue Life Using G* and One Other Predictor, with 26°C Data Point Omitted.

Parameter	r^2	MSE	p-value
Log G* alone	92.9	0.040	< 0.0001
ΔTc	93.5	0.044	0.740
Binder yield energy	92.5	0.043	0.602
Excess elastic recovery	92.3	0.044	0.951
DENT normalized extension	92.4	0.044	0.710
LAS FFPR	92.3	0.044	0.991
CT_{index} at 20/26°C	94.8	0.030	0.041
CT_{index} at 5/11°C	94.9	0.029	0.035
Log CT_{index} at 20/26°C	94.5	0.031	0.059
Log CT_{index} at 5/11°C	93.7	0.036	0.149

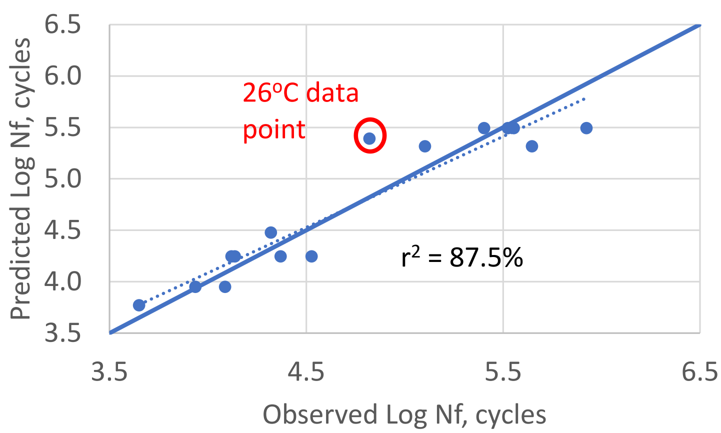

Figure 15. Observed and Predicted Fatigue Life Using Log G* Alone as a Predictor, with 26°C Data Point Included in Calculation of r^2.

Although Tables 19 and 20 might seem to suggest that polymer modification isn't a significant factor in determining fatigue performance of IMD mixtures, this would probably be a misleading conclusion. The aggregate blends used in the project exhibited a wide range of fracture and fatigue properties as seen in both the flexural fatigue tests and the IDEAL-CTs. It seems likely that for the models using binder tests alone, the variability due to differences in the aggregate masked the effect of the different polymer modifiers. The CTindex did better than the binder parameters because it is sensitive to aggregate type and gradation. As discussed above, CTindex is also sensitive to polymer modification, so the results summarized in Table 20 do in fact support the conclusion that polymer modification has a significant effect on fatigue performance of IMD mixtures.

Figures 16 through 23 show plots of observed and predicted fatigue life for the model using log G* alone, and for the models summarized in Table 20. The r^2 and R^2 values in these figures have been calculated after omitting the 26ºC data point, although the outlying data point has been included in these plots and is shown in red. When the outlier is included in these plots, they represent the models listed in Table 19, although the r^2 and R^2 values correspond to the values in Table 20, since they have been calculated without the outlier. There are not large differences among these plots, as should be expected given the narrow range in R^2 values for the various models. This again demonstrates the great importance of binder modulus in determining mixture fatigue performance.

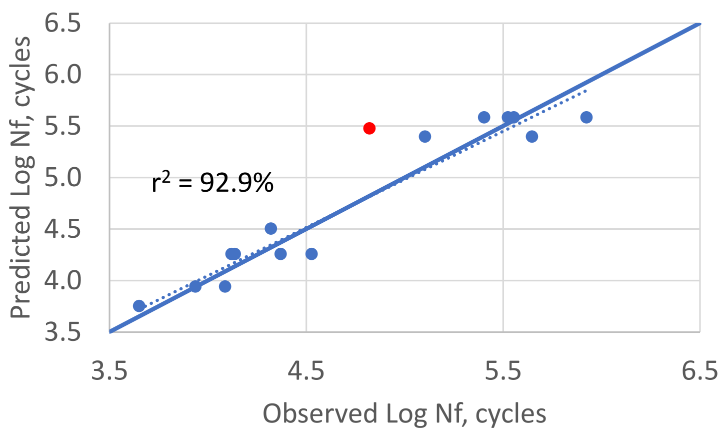

Figure 16. Observed and Predicted Fatigue Life Using Log G* Alone as a Predictor, with 26°C Data Point Omitted from Calculation of r^2.

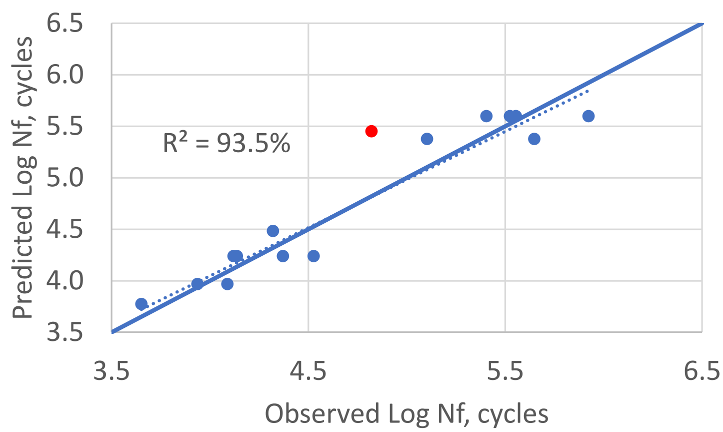

Figure 17. Observed and Predicted Fatigue Life Using Log G* and ΔTc as Predictors, with 26°C Data Point Omitted from Calculation of R^2.

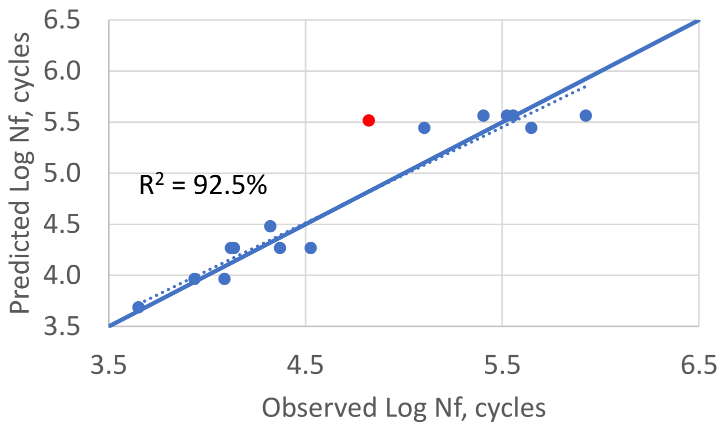

Figure 18. Observed and Predicted Fatigue Life Using Log G* and Binder Yield Energy as Predictors, with 26°C Data Point Omitted from Calculation of R^2.

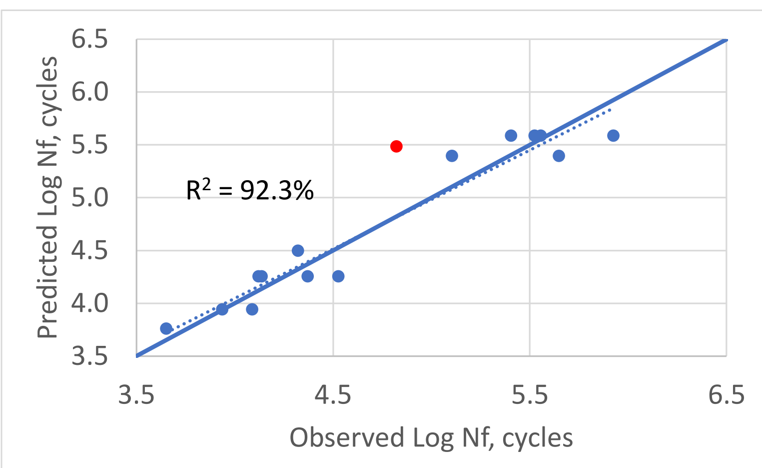

Figure 19. Observed and Predicted Fatigue Life Using Log G* and Excess Elastic Recovery as Predictors, with 26°C Data Point Omitted from Calculation of R^2.

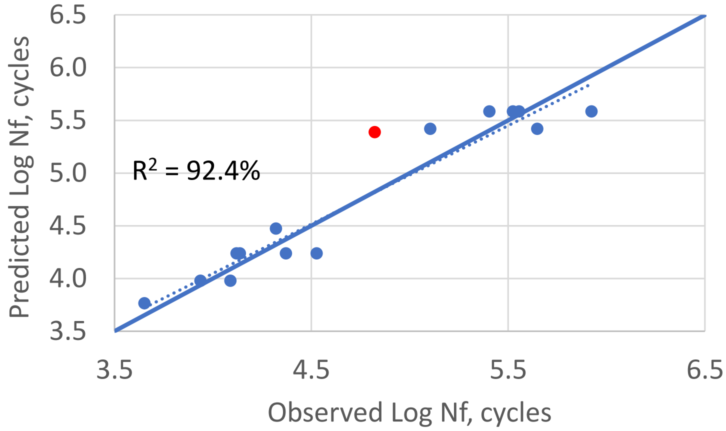

Figure 20. Observed and Predicted Fatigue Life Using Log G* and DENT Normalized Extension as Predictors, with 26°C Data Point Omitted from Calculation of R^2.

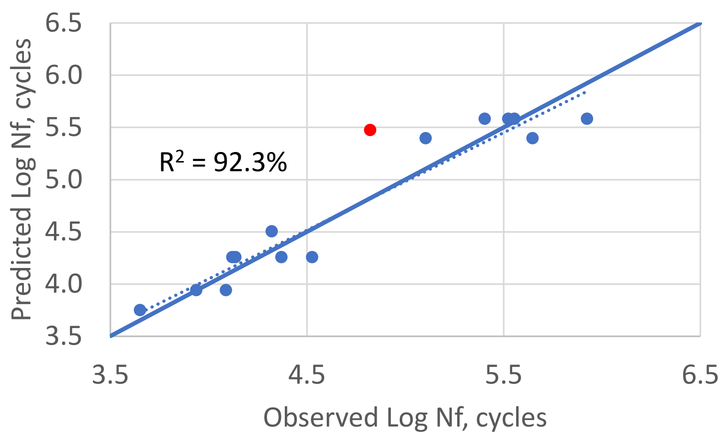

Figure 21. Observed and Predicted Fatigue Life Using Log G* and LAS FFPR as Predictors, with 26°C Data Point Omitted from Calculation of R^2

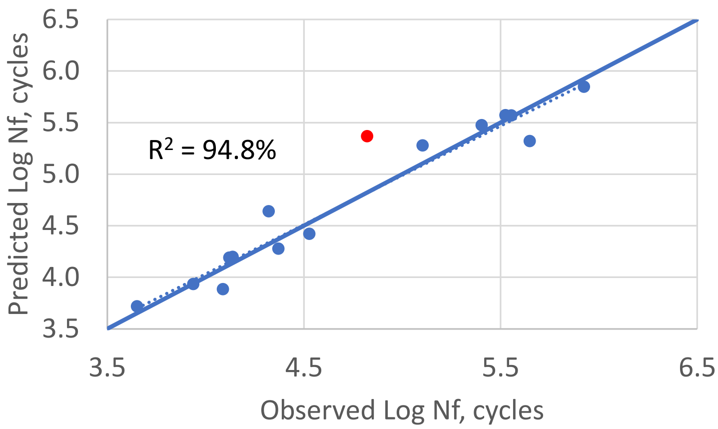

Figure 22. Observed and Predicted Fatigue Life Using Log G* and CTindex at 20/26°C as Predictors, with 26°C Data Point Omitted from Calculation of R^2.

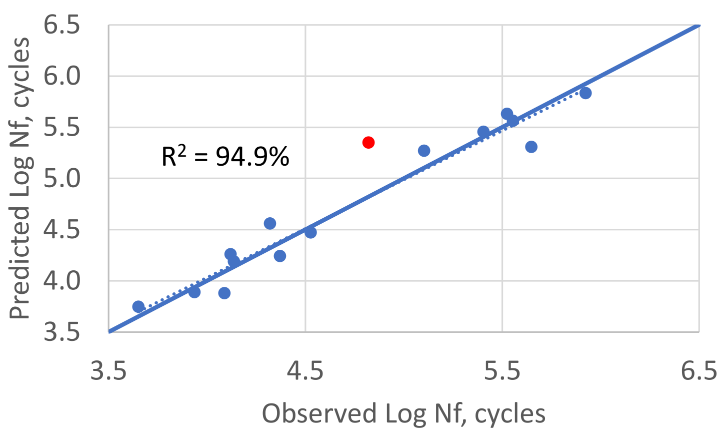

Figure 23. Observed and Predicted Fatigue Life Using Log G* and CTindex at 5/11°C as Predictors, with 26°C Data Point Omitted from Calculation of R^2.

The final method for predicting IMD fatigue performance uses binder modulus and CT_{index} at 20ºC as predictors. The corresponding statistical model is summarized in Tables 21 (analysis of variance) and 22 (model parameters). This analysis included one data point at 26ºC—all other data was at 20ºC, the normal temperature for IMD fatigue tests. As discussed below, the 26ºC data point appeared to be an outlier when attempting to construct specification limits to control IMD fatigue. A second analysis was therefore done in which the 26ºC data point was removed. The results of this analysis are shown in Tables 23 and 24. The model parameters listed in Table 22 lead to the following equation for predicting cycles to failure for IMD mixtures tested at 20ºC and 2,000 micro-strain:

$$Nf = 1.71 \times 10^6 G^{*-3.10} CT_{index}^{0.00168} \quad (2)$$

Where:

Nf = cycles to failure at 20ºC and a strain of 2,000 × 10^{-6}
G^* = binder complex modulus at 20ºC and 10 Hz, MPa
CT_{index} = mixture CT_{index} at temperature at 20ºC

Figure 24 is a plot of the predicted and observed values for fatigue life, for the model without the 26ºC data. Included in this plot is a one-sided 80% confidence interval for the regression function, which accounts for uncertainty in this relationship when constructing a rule for predicting IMD fatigue performance, which will be discussed in the next section of this report.

Table 21. Analysis of Variance for IMD Fatigue Model.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	2	6.877	3.438	72.457	**<0.0001**
Error	12	0.569	0.047		
Corrected Total	14	7.446			

R^2 = 91.1%, adjusted for degrees of freedom.

Table 22. Model Parameters for IMD Fatigue Model.

Source	Value	Standard error	t	Pr > |t|
Intercept	6.192	0.275	22.493	<0.0001
Log G*	-3.097	0.313	-9.896	<0.0001
CT_{index} **at 20ºC**	0.00168	0.00068	2.480	0.029

Table 23. Analysis of Variance for IMD Fatigue Model--26ºC Data Point Removed.

Source	DF	Sum of squares	Mean squares	F	Pr > F
Model	2	7.114	3.557	120.041	<0.0001
Error	11	0.326	0.030		
Corrected Total	13	7.439			

R^2 = 94.8%, adjusted for degrees of freedom.

Table 24. Model Parameters for IMD Fatigue Model—26ºC Data Point Removed.

Source	Value	Standard error	t	Pr > |t|
Intercept	6.459	0.237	27.297	<0.0001
Log G*	-3.352	0.263	-12.755	<0.0001
CT_{index} at 20ºC	0.00129	0.00055	2.320	0.041

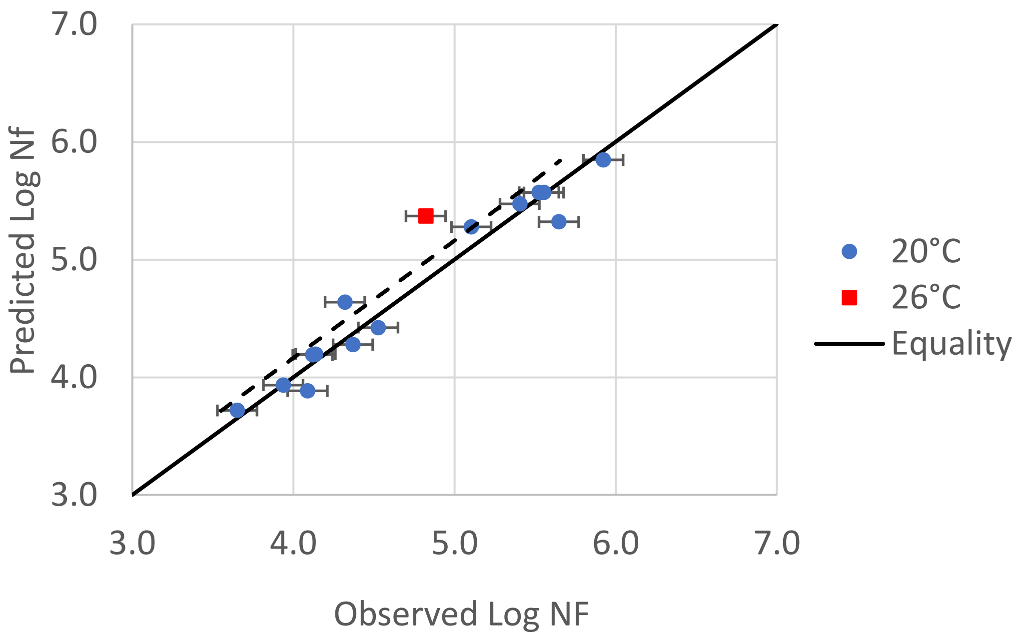

Figure 24. Plot of Predicted vs Observed Fatigue Life—26ºC Data not included in model. *Dashed line represents 80% one-sided confidence interval for the regression. The red square represents the outlier removed from the analysis.*

5.2. Discussion

The analysis presented above has led to a model using binder modulus and CT_{index} at 20ºC as predictors of IMD fatigue life. The was based on two important findings:

1. This model was one of the best in terms of accuracy; and
2. CT_{index} is the only candidate parameter than can account for differences in aggregate type and gradation.

Although the regression model presented in the previous section could be used by contractors and the WisDOT to directly predict IMD fatigue life, a simpler approach that would be easier to implement would involve simply having a maximum value for binder modulus at 20ºC and 10 Hz, and a minimum value for CT_{index} at 20ºC. Based on the data and analysis presented above, the following limits are suggested:

1. Maximum binder G* at 20ºC and 10 Hz: 2.8 MPa
2. Minimum mixture CT_{index} at 20ºC: 140

Figure 25 shows these limits graphically, on a plot of CT_{index} against binder modulus. This plot includes all fatigue data, coded for whether the life exceeded 100,000 cycles. It also shows the boundary line based upon the regression analysis presented in the previous section. Note that this boundary is based upon the 80 %, one-sided confidence interval shown in Figure 24. For the 20ºC data, all mixtures meeting the proposed criteria had a fatigue life exceeding 100,000 cycles. For those failing these limits, all showed a fatigue life less than 100,000 cycles. The single data point at 26ºC met the proposed criteria, but showed a fatigue life of 66,300 cycles, slightly less than the 100,000 minimum. However, it is not clear that applying the proposed criteria at a higher temperature in this manner is a completely accurate test of the proposed method. It appears that the proposed specification is an effective method for ensuring adequate IMD fatigue performance without the need for flexural fatigue testing.

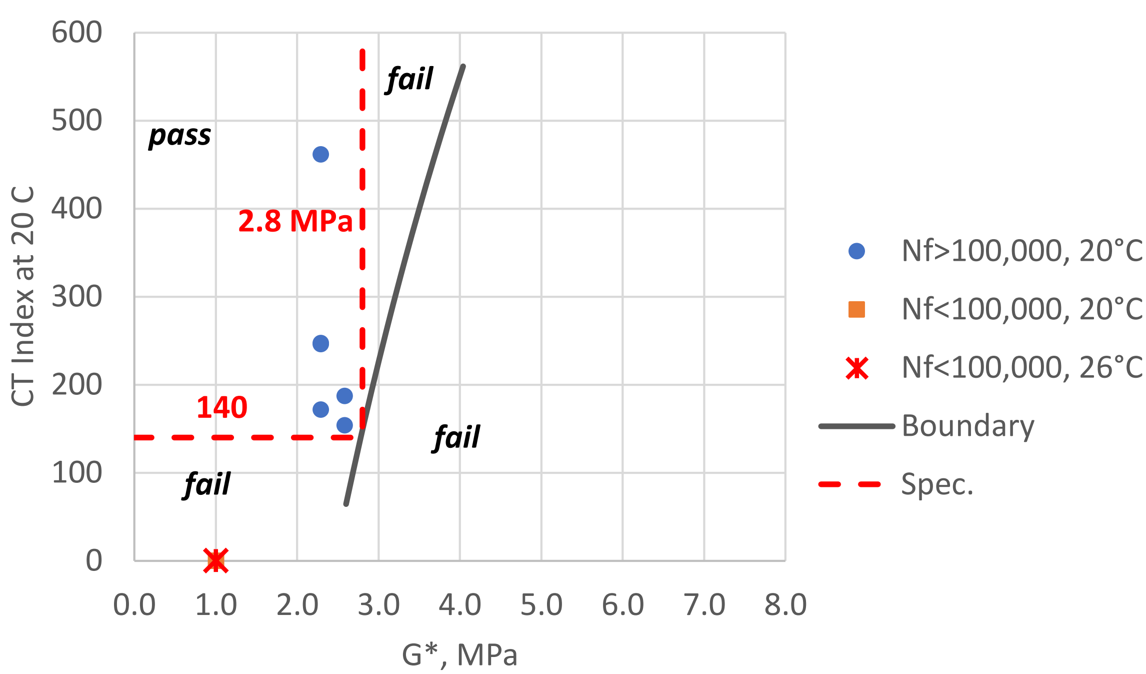

Figure 25. CT_{index} **at 20ºC as a Function of Binder G* at 20ºC and 10 Hz, Coded for Fatigue Life.** *Plot includes proposed specification limits for IMDs and Boundary Determined from 80% Confidence Interval from Regression Model.*

One question that arises from the proposed model and specification is why is it necessary to include binder modulus along with CT_{index} to control IMD fatigue life? Isn't CT_{index} affected by binder modulus just like fatigue life? CT_{index} is in fact affected by binder modulus, but not in the same way and to the same extent as fatigue life. The exponent for G* for the CT_{index} model is −0.35 (Table 17), whereas the G* exponent for the fatigue model is nearly ten times as large, at −3.34 (Table 24). Compared to fatigue life, CT_{index} is insensitive to binder modulus, so to predict fatigue life we need to look at both CT_{index} and a separate measure of binder modulus.

An important question is whether it is possible to adequately control IMD binder stiffness simply through specifying the binder low temperature grade—that is, limiting IMD binders to those with a low temperature grade of -34°C or lower. Examining Table 6, all the IMDs with fatigue life exceeding 100,000 cycles had a low temperature grade of -34°C, and all such binders passed the 100,000 cycle IMD requirement. However, additional data is needed to verify that there is in fact a solid relationship between BBR low temperature grade and binder modulus at 20°C. Figure 26 shows a plot of binder modulus at 20°C and 10 Hz (RTFOT) as a function of BBR continuous low temperature grade (RTFOT/PAV) for the IMD project binder sand for a variety of binders previously tested at AAT's laboratory for several different project (FWHA ALF, MNRoad and Westrack). The correlation here is very good for the entire data set, and the relationship appears to only be slightly different for the too data sets—perhaps because of differences in aging and/or testing protocols when the other tests were performed. This lends confidence to the idea of using BBR low temperature grade to control binder stiffness for IMD binders. This would make implementation much simpler and effective, since it would eliminate the need for evaluating binder modulus at 20°C.

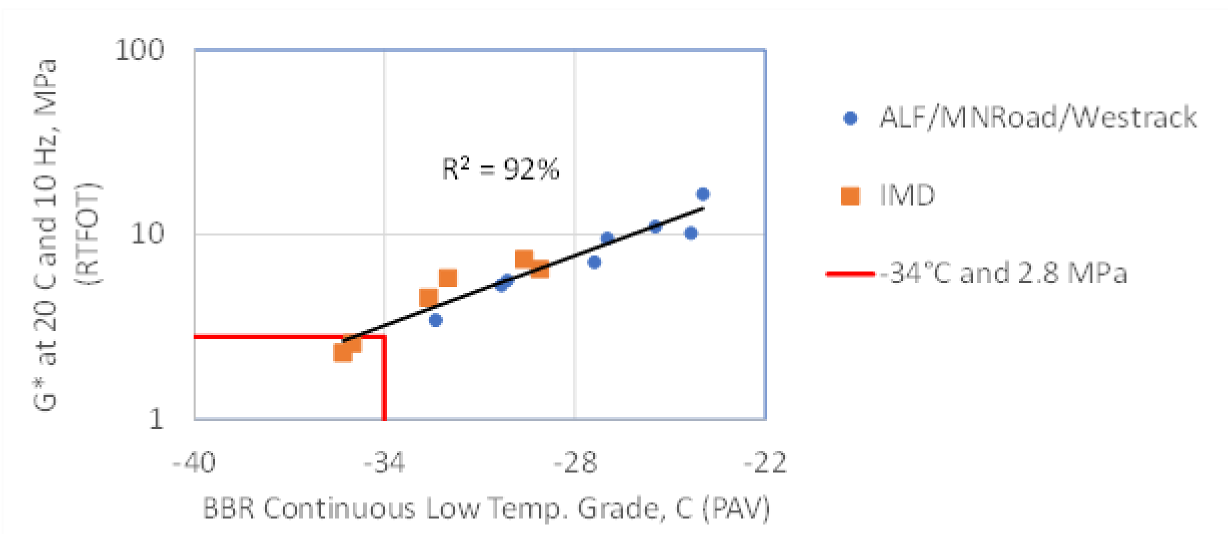

Figure 26. Relationship between Binder G* at 20°C and 10 Hz (RT FOTR) and BBR Continuous Low Temperature Grade (RTFOT/PAV) for IMD Binders and Various Binders Tested at AAT's Laboratory.

To further evaluate the possibility of using BBR low temperature grade to control the stiffness of IMDs, Figures 27 and 28 were constructed. Figure 27 Shows fatigue life as a function of continuous low temperature grade, coded for CTindex. In this figure, it appears that low temperature grade alone might differentiate the fatigue performance of IMDs. However, when fatigue life is plotted against CTindex for PG 58-34X binders only (all of which exceeded a fatigue life of 100,000 cycles), as in Figure 28, there is a clear relationship between fatigue life and CTindex, supporting the use of both low temperature grade and CTindex in ensuring the fatigue performance of IMD mixtures. It does in fact appear that this would be a simple and effective way of implementing the improved IMD specification.

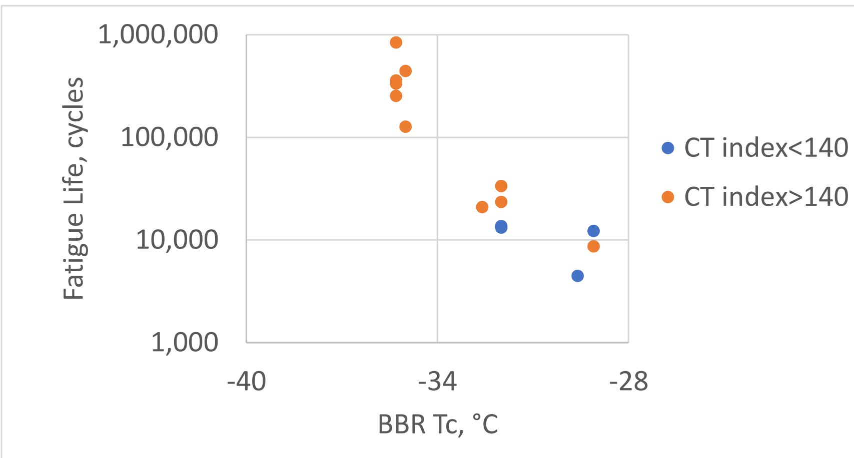

Figure 27. Fatigue as a Function of BBR Low Continuous Temperature Grade, °C, Coded for CT_{index} at 20°C. *Data point at 26°C omitted.*

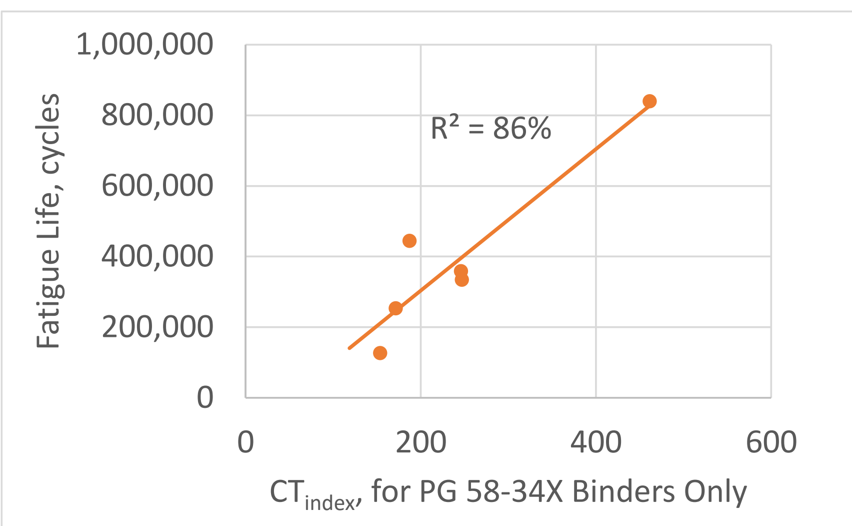

Figure 28. Fatigue Life as a Function of CT_{index} at 20°C, for PG 58-34X Binders Only. *Data point at 26°C omitted.*

What about binder rheologic type, as indicated by ΔTc and other related parameters? In this analysis, ΔTc did not appear to affect CT_{index} significantly. However, the ΔTc values included in this study fell over a narrow range of from +0.5 to +2.5. Also, as discussed previously, there does appear to be some confounding between excess elastic recovery and ΔTc. Therefore, it cannot be concluded that ΔTc in general does not affect CT_{index}. It is quite possible that if mixtures containing binders with a wider range of ΔTc values for both polymer modified and non-modified binders, an effect of ΔTc on CT_{index} would be observed. Final recommendations on allowable ΔTc values for binders used in IMDs should be made after the WHRP project on this topic is completed and the results reviewed for their implications for IMDs. It should also be pointed out here that this study involved only Wisconsin IMDs, which are a specific and unusual type of asphalt concrete mixture. In general, the results of this study should not be generalized to other mixture types or mixtures made with significantly different materials. This is especially true for the predictive models for fatigue life.

The use of CT_{index} values determined at both 20/26ºC and 5/11ºC warrants a few comments. Based on SCB data that AAT had gathered during the NCHRP 9-59 project, it was felt that IDEAL-CT indices at a significantly lower temperature than the corresponding fatigue test temperature might show better correlations to fatigue life. This hypothesis was also supported by the principle of time-temperature superposition: because IDEAL-CT is a much slower test than laboratory fatigue, running the IDEAL-CT at a lower temperature should provide closer rheological conditions than at the standard 20ºC. In fact, this was found to be true, but once G* was added to the prediction the advantage of determining CT_{index} at a lower temperature mostly disappeared. It is possible than running the IDEAL-CT at an even lower temperature, say -5 or even -10ºC—might provide even better correlations with fatigue life, but investigating this question was beyond the scope of this project. Furthermore, running the IDEAL-CT at such a low temperature would require special temperature-controlled testing cabinets which would make the test more difficult to perform and implement.

Another issue that should be addressed in the proposed IMD specification is the effect of polymer modified binders on fatigue performance. An important question is whether controlling binder low temperature grade and CTindex is enough to ensure adequate fatigue performance of IMDs. The statistical models described above suggest that this approach would be acceptable. It should however be kept in mind that there is uncertainty throughout this analysis—the measurement of fatigue life is quite variable, and statistical analyses by their nature deal in probabilities and not certainties. Additionally, the number of observations in this study, at 15, was not large. Figure 29 is a graphic illustration of the relationship among binder modulus, excess elastic recovery and fatigue life. It shows IMD fatigue as a function of binder modulus, coded for excess elastic recovery. This figure is completely consistent with implementing a maximum binder G* value of around 3.0 MPa, but strongly suggests that a minimum excess elastic recovery value of around 25% would help ensure adequate IMD fatigue performance. In fact, this approach correctly classifies the 26ºC fatigue test as being a failure, because of an excess elastic recovery below 25 %, whereas looking at modulus and CT_{index} passes this mix when tested at 26ºC. For extra certainty in ensuring IMD fatigue performance, it is recommended that IMD binders have a minimum excess elastic recovery of 25%.

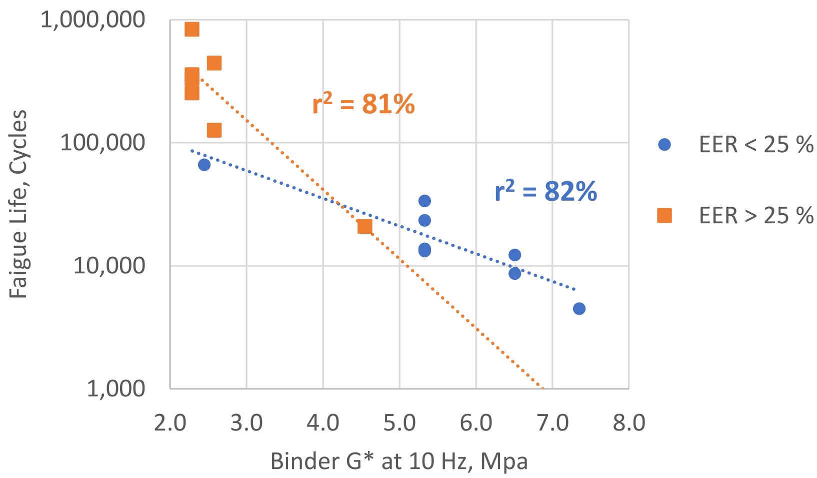

Figure 29. Fatigue Life as a Function of Binder G* at 10 Hz, Coded for Excess Elastic Recovery.

As discussed earlier in this report, it was decided to characterize the results of the binder elastic recovery test by calculating the excess elastic recovery, EER. This was an attempt to quantify how effect the modification of a particular binder was in a more precise way than simply determining if it met the requirements of Appendix X of AASHTO M 332. There is however at least one alternative approach, which would be to develop another equation for specifying the minimum elastic recovery as a function of J_{nr} for IMD binders. Figure 30 shows such an equation, plotted along with J_{nr} and elastic recovery data for the binders used in this study. Also included is the maximum elastic recovery limit given in Appendix X of AASHTO M 332 for elastomerically modified binders. The result equation is simply 25.0 added to the function in AASHTO M 332. By including this equation directly in the IMD specification, it will save producers and contractors the trouble of having to refer to this specification and minimize the potential for misunderstanding and errors.

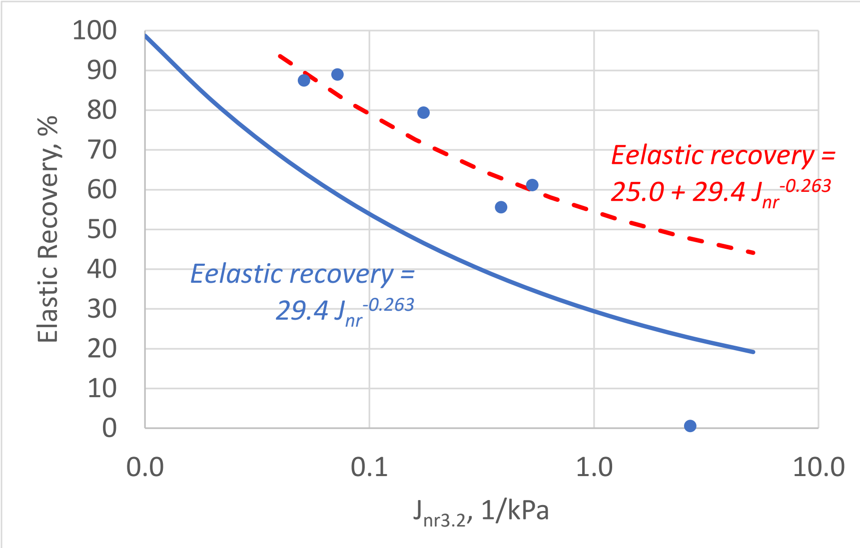

Figure 30. Elastic Recovery Limit as Given in Appendix A of AASHTO M 332 for Elastomerically Modified Binders and Limit Proposed for IMD Binders in Wisconsin.

An important practical question is the savings in time and money represented by the proposed changes in the Wisconsin IMD specification. A simple and direct way of comparing the original and revised specification is by looking at AAT's commercial rates for the testing involved. In this analysis, we are looking only at tests that have changed compared to the original IMD specification—that is, replacing flexural fatigue with the IDEAL-CT (the other requirements, for elastic recovery and low temperature grade, involve existing tests and specifications). AAT's commercial rate for flexural fatigue testing with four replicate beams is about $4,200, while our rate for IDEAL-CTs (3 replicate specimens) is $1,000. This represents a substantial savings of about $3,200 per mix, or 76 %. An additional benefit of the proposed specification is that it would make it possible to do quality control and acceptance testing on IMDs using the IDEAL-CT, something that is not practical with flexural fatigue testing.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Based on the testing and analysis done as part of this research project, the following conclusions are made:

1. This study involved only Wisconsin IMDs, which are a specific and unusual type of asphalt concrete mixture. In general, the results of this study should not be generalized to other mixture types or mixtures made with significantly different materials. This is especially true for the predictive models for fatigue life.
2. CT_{index} is sensitive to differences in aggregate gradation/type, binder modulus and the presence of polymer modification in the binder.
2. CT_{index} is a very useful parameter for characterizing the fatigue resistance of IMDs.
3. CT_{index} at 20ºC and 5ºC show similar relationships with IMD fatigue life. Because IDEAL-CT at 20ºC is the standard method and is simpler to run than the test at 5ºC, it is better for routine use in evaluating IMDs.
4. Of the various parameters included in this study, binder modulus was the single best predictor of IMD fatigue life—increasing binder modulus resulted in decreasing fatigue life.
5. The overall best statistical model for predicting IMD fatigue life used binder G* and CT_{index} at 20ºC as predictors. The accuracy of this model appears to be accurate enough to provide guidance in developing a specification for ensuring IMD fatigue performance.
6. Binder low temperature grade as determined using the BBR and the standard procedures is highly correlated to binder G* at 20°C and 10 Hz and can be used in place of modulus for controlling IMD stiffness and fatigue performance.
6. The range in ΔTc values for the binders included in this study was quite narrow and precluded a full evaluation of the effect of this parameter on IMD fatigue performance.

6.2. Recommendations

Based on the testing and analysis done as part of this research project, the following recommendations are made:

1. To ensure that IMDs have a fatigue life meeting or exceeding 100,000 cycles, binders for IMDs should meet the following requirements:
   - A low temperature grade no higher than -34°C (RTFOT/PAV aging), and

- a minimum elastic recovery (AASHTO M 332) given by the following equation:

$$Min. Elastic\ Recovery\ for\ IMDs = 25.0 + 29.4\, J_{nr3.2}^{-0.263} \quad (3)$$

  Where $J_{nr3.2}$ is the non-recoverable creep compliance at a stress of 3.2 kPa, in units of 1/kPa.

2. IMD mixtures should have a CTindex of at least 140 at 20ºC and a loading rate of 50 mm/min, following the procedure given in Appendix A of NCHRP Ideal Report 195 [12].

3. The current STSP for Interlayer Pavements should be modified as follows. Replace the third paragraph of Section 1 B with the following:

   Replace standard spec 460.2.3 with the following to specify asphalt binders to be used:

   (1) Furnish PG 58-34 asphalt binder with a designation of V (Very Heavy) or E (Extremely Heavy) as necessary to satisfy the CT_{index} requirement of Table 460-2 as modified herein. The elastic recovery for the binder (AASHTO T 350) shall have a minimum value of $25.0 + 29.4\, J_{nr3.2}^{-0.263}$, where $J_{nr3.2}$ is the non-recoverable creep compliance (in 1/kPa) at a stress of 3.2 kPa determined according to AASHTO M 332. Do not change the PG binder grade without the engineer's written approval. The department will designate the grade of modified asphaltic binder in the contract.

   In addition, replace the last row of Table 460-2 in the STSP with the following:

CT_{index} as determined in the IDEAL-CT Test, at 20ºC and a loading rate of 50 mm/min, following the procedure given in Appendix A of NCHRP Ideal Report 195 (Zhou, 2019).	> 140

4. Final recommendations on allowable ΔTc values for binders used in IMDs should be made after the WHRP project on this topic is completed and the results reviewed for their implications for IMDs.

6.3. Implementation

Implementation of the proposed method for ensuring IMD fatigue performance without flexural fatigue testing will involve three initial steps:

1. Notify contractors and suppliers in Wisconsin of the proposed change in IMD requirements.
2. Make one or more presentations to contractors, suppliers, DOT personnel and pavement consultants working in Wisconsin concerning this change and supporting technical information.
3. Compile comments from people with a stake in the IMD specification change, interpret these comments and modify the IMD specification accordingly.
4. When complete, evaluate the results of the WHRP project *Benchmarking Delta Tc (ΔTc) Values for Wisconsin Materials* and establish allowable ranges for ΔTc values for IMDs.
4. Require suppliers and contractors to report elastic recovery values for high performance binders to determine the typical range in this property.
5. Collect information on CT_{index} values for surface mixes placed in Wisconsin.
6. Construct several pilot IMD projects under the revised IMD specification and evaluate the fatigue performance of these projects using flexural fatigue testing.
7. Finalize the IMD specification, publish and distribute.

7. REFERENCES

1. I. Al-Qadi, I. H. Ozer, J. Lambros, A. El Khatib, P. Singhvi, T. Khan, J. River-Perez, and B. Doll, *Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Containing RAP and RAS*, Report FHWA-ICT-15-017, Springfield, VA: National Technical Information Service, December 2015.
2. Z. Wu, Mohammad, L. N., Wang, L. B., Mull, M. A., "Fracture Resistance Characterization of Superpave Mixtures Using the Semi-Circular Bending Beam Test," *Journal of ASTM International*, Vol. 2, No. 3, 2005.
3. L.N. Mohammad, Z. Wu, M.A. Aglan, "Characterization of Fracture and Fatigue Resistance of Recycled Polymer-Modified Asphalt Pavements," *5th RILEM Inter. Conf. Crack. Pave*., Limoges, France, 2004, pp. 375–382.
4. L.N. Mohammad, M. Kim, M. Elseifi, "Characterization of Asphalt Mixture's Fracture Resistance Using SCB Test," *7th RILEM Inter. Conf. Crack. Pave*., Delft, the Netherlands, 2012, pp. 1–10.
5. L. F. Walubita, R. N. A. N. Faruk, Y. Koohi, R. Luo, *The Overlay Tester (OT): Comparison with Other Crack Test Methods and Recommendations for Surrogate Crack Tests*. Alexandria, VA: National Technical Information Service, October 2013.
6. F. P. Germann, and R. L. Lytton. "Methodology for Predicting the Reflection Cracking Life of Asphalt Concrete Overlays." Report No. FHWA/TX-79/09+207-5, Texas Transportation Institute, College Station, Texas, 1979.
7. F. Zhou, and T. Scullion. "Upgraded overlay tester and its application to characterize reflection cracking resistance of asphalt mixtures" FHWA/ TX-04/0-4467-1, Texas Transportation Institute, College Station, Texas, 2003.
8. F. Zhou, and T. Scullion, (2006). Overlay Tester: A Simple and Rapid Screening Test for Characterizing Crack Resistance of HMA Mixes, Proceedings of 10th International Conference on Asphalt Pavement, Quebec, Canada, August 12-17, 2006.
9. F. Zhou, Hu, S., and T. Scullion. "Integrated asphalt (overlay) mixture design, balancing rutting and cracking requirements." FHWA/ TX-06/0-5123-1, Texas Transportation Institute, College Station, Texas, 2006.
10. F. Zhou, Hu, S., and T. Scullion, T. "Development and verification of the overlay tester based fatigue cracking prediction approach." FHWA/ TX-07/9-1502-01-8, Texas Transportation Institute, College Station, Texas, 2007.
11. F. Zhou, Hu S., and T. Scullion. "Overlay tester: a simple and rapid test for HMA fracture properties." Texas Transportation Institute, USA, 2009.

12. F. Zhou, S. *Development of an IDEAL Cracking Test for Asphalt Mix Design, Quality Control and Quality Assurance*. Final Report for NCHRP IDEA Project 195, Washington, DC: Transportation Research Board, January 2019.

13. F. Zhou, S. Im, L. Sun, and T. Scullion, "Development of an IDEAL Cracking Test for Asphalt Mix Design and QC/QA," *Road Materials and Pavement Design*, Vol. 18, Issue sup4, 2017, pp. 405-427.

14. C. J. Glover, R. R. Davison, C. H. Domke, Y. Ruan, P. Juristyarini, D. B. Knorr and S. H. Jung. *Development of a New Method for Assessing Asphalt Binder Durability with Field Validation*, Report 0-1872-2. Springfield, VA: National Technical Information Service, 2005.

15. G. Rowe, Written discussion to "Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking," R. M. Anderson et al., *Journal of the Association of Asphalt Paving Technologists*, Vol. 80, pp. 615-664, 2011.

16. D. W. Christensen, and D. A. Anderson, "Interpretation of Dynamic Mechanical Test Data for Paving Grade Asphalt Cements," *Journal of the Association of Asphalt Paving Technologists*, *61*, 67-98, 1992.

17. C. Hintz, R. Velasquez, C. Johnson, and H. U. Bahia. "Modification and Validation of the Linear Amplitude Sweep Test for Binder Fatigue Specification," *Transportation Research Record: Journal of the Transportation Research Board, No. 2207*, pp. 99–106, 2011.

18. C. Hintz, and H. Bahia, "Simplification of Linear Amplitude Sweep Test and Specification Parameter," *Transportation Research Record*, Vol. *2370, Issue 1*, pp. 10–16, 2013.

19. R. M. Anderson, G. N. King, D. I. Hanson, and P. B. Blankenship, "Evaluation of the Relationship between Asphalt Binder Properties and Non-Load Related Cracking," *Journal of the Association of Asphalt Paving Technologists*, Vol. 80, pp. 615-649, 2011.

20. M. D. Elwardany, J. P. Planche, and G. King, Proposed Changes to Asphalt Binder Specifications to Address Binder Quality-Related Thermally Induced Surface Damage, Transportation Research Record, Vol. 2676, Issue 5, May 2022, pp. 176-191.

21. D. W. Christensen, and N. Tran, "Relationships Between Asphalt Mixture Fatigue Performance and Asphalt Binder Properties," *Asphalt Pavement Technology*, the Journal of the Association of Asphalt Paving Technologists, Vol. 88, 2019.

22. D. W. Christensen, and N. Tran. *Relationships Between the Fatigue Properties of Asphalt Binders and the Fatigue Performance of Asphalt Mixtures, NCHRP Report 982*, Washington, D.C.: Transportation Research Board, 2022.

24. N. Gibson, X. Qi, A. Shenoy, G. Al-Khateeb, M. E. Kutay, A. Andriescu, K. Stuart, J. Youtcheff and T. Harman. *Performance Testing for Superpave and Structural Validation*, Final Report FHWA-HRT-11-045, Federal Highway Administration, November 2012.

24. T. Bennert, E. Haas, C. Ericson, and E. Wass, *Evaluation of Overlay Tester Test Procedure to Identify Fatigue Cracking Prone Asphalt Mixtures*, Report CAIT_UTC-NC57, Piscataway, NJ: Center for Advanced Infrastructure and Transportation, 2019.

25. C. Johnson, H. Wen, and H. Bahia, "Practical Application of Viscoelastic Continuum Damage Theory to Asphalt Binder Fatigue Characterization," *Asphalt Paving Technology*, Vol. 78, pp. 597-638, 2009.

26. A. Andriescu, N. H. Gibson, S. A. M. Hesp, X. Qi and J. S. Youtcheff, "Validation of the Essential Work of Fracture Approach to Fatigue Grading of Asphalt Binders," *Journal of the Association of Asphalt Paving Technologists*, Vol. 75E, 2006.

27. T. Bennert, C. Ericson, E. Haas, and E. Wass, *Investigation into the Identification and Potential Specification for the Fatigue Performance of Asphalt Binder*, Piscataway, NJ: Center for Advanced Infrastructure and Transportation, 2019.

28. R. West, F. Yin, C. Rodezno and A. Taylor, *Balanced Mix Design Implementation Support*, Report WHRP 0092-20-04, Springfield, VA: National Technical Information Service, 2021.