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Impact of Polymer Modification on IDEAL-CT and I-FIT for Cracking Resistance Evaluation of Asphalt Mixtures

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16. Abstract (Limit: 250 words)

This study evaluated the impact of polymer modification, without changing the base binder, on the intermediate-temperature cracking resistance of asphalt mixtures characterized using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and the Illinois Flexibility Index Test (I-FIT). Twelve asphalt mixtures prepared with two mix designs and six virgin binders (including two unmodified and four polymer-modified asphalt binders per mix design) were evaluated. Each mixture was tested at three binder contents and two temperatures: 25°C and an equal stiffness temperature ($T_{=G*}$). In almost all cases, the polymer-modified asphalt (PMA) and unmodified mixtures with the same base binder had statistically equivalent IDEAL-CT and I-FIT results, indicating a lack of sensitivity to polymer modification. Increasing the binder content or adjusting the test temperature to $T_{=G*}$ did not discriminate the PMA and unmodified mixtures in the two tests. Interaction diagram analysis of the IDEAL-CT and I-FIT results showed that polymer modification generally affected the toughness and post-peak behavior of the mixture, but these effects tended to offset each other on the final cracking index parameters. Unlike the IDEAL-CT and I-FIT, the two cyclic loading tests evaluated in the study demonstrated the benefits of polymer modification. This discrepancy highlighted the potential limitation of the monotonic loading tests in assessing the fatigue cracking resistance of PMA binders and mixtures. Finally, asphalt binders extracted from the PMA versus unmodified mixtures with the same base binder showed distinctly different rheological properties, but these differences were not captured in the IDEAL-CT or I-FIT when the test variability was considered.

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IMPACT OF POLYMER MODIFICATION ON IDEAL-CT AND I-FIT FOR CRACKING RESISTANCE EVALUATION OF ASPHALT MIXTURES

FINAL REPORT

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%R	Percent Recovery
$\|G^*\|$	Complex Shear Modulus
$\|m\|$	Post-peak Slope at Inflection Point
$\|m_{75}\|$	Post-peak Slope at 75% of Peak Load
AI	Asphalt Institute
AMAP	Association of Modified Asphalt Producers
BBR	Bending Beam Rheometer
BMD	Balanced Mix Design
CG	Cracking Group
CT_{Index}	Cracking Tolerance Index
DSR	Dynamic Shear Rheometer
ESAL	Equivalent Single Axle Load
FI	Foamability Index
G_f	Fracture Energy
G-R Parameter	Glover-Rowe Parameter
GTR	Ground Tire Rubber
HiMA	Highly Polymer Modified Asphalt
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
I-FIT	Illinois Flexibility Index Test
J_{nr}	Non-recoverable Creep Compliance
l_{75}	Post-peak Displacement at 75% of Peak Load
LAS	Linear Amplitude Sweep
LVE	Linear Viscoelastic
M-E	Mechanistic-Empirical
MnDOT	Minnesota Department of Transportation
MnROAD	Minnesota Road Research Facility
MSCR	Multiple Stress Creep Recovery
MTE	Mathy Technology and Engineering
NCAT	National Center for Asphalt Technology

N_f	LAS Fatigue Parameter
NMAS	Nominal Maximum Aggregate Size
NRRA	National Road Research Alliance
OBC	Optimum Binder Content
PAV	Pressure Aging Vessel
PG	Performance Grade
PMA	Polymer-modified Asphalt
r	Pearson's Correlation Coefficients
RAP	Reclaimed Asphalt Pavement
RET	Reactive Ethylene Terpolymer
RTFO	Rolling Thin Film Oven
R-Value	Rheological Index
SBR	Styrene-Butadiene Rubber
SBS	Styrene-Butadiene-Styrene
SGC	Superpave Gyratory Compactor
SHA	State Highway Agency
S-VECD	Simplified Viscoelastic Continuum Damage
$T_{=G*}$	Equal Stiffness Temperature
TAP	Technical Advisory Panel
TB	Torsion Bar
$T_{C,m}$	Critical Low-temperatures based on m-value
$T_{C,S}$	Critical Low-temperatures based on Stiffness
t_f	Failure Time
γ_{max}	Maximum Expected Binder Strain for a Given Pavement Structure
δ	Phase Angle
ΔT_c	Delta T_c
ω_c	Crossover Frequency

EXECUTIVE SUMMARY

Polymer-modified asphalt (PMA) is a well-established technology to improve the performance and life span of asphalt pavements. Numerous laboratory studies and field projects have demonstrated that polymer modification improves both the rutting and cracking resistance of asphalt mixtures. Because of these performance improvements, some state and local highway agencies now require using PMA for high-traffic-volume roadways. However, recent studies have shown that the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and the Illinois Flexibility Index Test (I-FIT) are not sensitive to polymer modification. In many cases, the PMA mixture had equivalent or lower cracking tolerance index (CT_{Index}) or flexibility index (FI) results than the unmodified mixture, which indicates similar or reduced intermediate-temperature cracking resistance. These results disagree with the existing literature and warrant investigation to identify the causes of the discrepancy and resolve the issue.

This study aimed to determine the impact of polymer modification with styrene-butadiene-styrene (SBS) and reactive ethylene terpolymer (RET), without changing the base binder, on the IDEAL-CT and I-FIT results for evaluating the intermediate-temperature cracking resistance of asphalt mixtures. Specifically, the study assessed two hypotheses for the lack of sensitivity of the IDEAL-CT and I-FIT to polymer modification.

- Hypothesis 1: "*Testing the IDEAL-CT and I-FIT at the volumetric optimum binder content (OBC) of the mixture is insufficient for evaluating the effect of polymer modification*." Due to the limitations of the volumetric mix design system, many Superpave mixtures do not have enough asphalt binder to provide adequate durability and cracking resistance. Despite the improvement in the quality of asphalt binder due to polymer modification, using PMA binders in a volumetrically lean mixture may not be sufficient to improve its cracking resistance. In this case, increasing the asphalt binder content is needed to capture the benefits of polymer modification in improving the IDEAL-CT and I-FIT results.
- Hypothesis 2: "*The IDEAL-CT and I-FIT must be conducted at an equal stiffness condition to properly demonstrate the benefits of polymer modification*." Both tests are conducted at a single temperature and loading rate and require the calculation of a cracking index parameter (i.e., CT_{Index} for IDEAL-CT and FI for I-FIT) based on the fracture energy (G_f) and post-peak behavior of the load-displacement curve. To yield higher CT_{Index} and FI values, higher G_f and more ductile post-peak behavior are required for mixture toughness and brittleness considerations, respectively. However, polymer modification typically provides increased binder stiffness and elasticity, which have opposing impacts on the CT_{Index} and FI results. Thus, the resultant PMA mixtures may have lower CT_{Index} or FI values than the unmodified mixtures, which could be interpreted as being more susceptible to intermediate-temperature cracking. One potential approach to overcome this issue is to conduct the tests at an equal stiffness temperature ($T_{=G*}$) to avoid the potential confounding impact of asphalt stiffness on the cracking resistance evaluation of PMA versus unmodified mixtures.

The experimental plan of the study focused on the IDEAL-CT and I-FIT testing of asphalt mixtures prepared with two mix designs, six virgin binders (per mix design), and three binder contents. The six virgin binders evaluated with each mix design included two sets of three binders each, including a neat binder, a reactive ethylene terpolymer (RET)-modified binder, and a styrene-butadiene-styrene (SBS)-modified binder. Within each set, the RET- and SBS-modified binders were formulated using the same neat binder to isolate the confounding impact of having different base binders from the evaluation of polymer modification. The IDEAL-CT and I-FIT were conducted at two temperatures: 25°C and $T_{=G*}$ determined from the Torsion Bar (TB) Modulus test. Test results showed that increasing the binder content consistently improved the IDEAL-CT and I-FIT results at 25°C, but it did not provide better discrimination of the PMA versus unmodified mixtures in the two tests. In almost all cases, PMA and unmodified mixtures with the same mix design and base binder had statistically equivalent IDEAL-CT and I-FIT results at 25°C when tested at the same binder content, which caused rejection of Hypothesis 1 of the study. Adjusting the test temperature from 25°C to $T_{=G*}$ also failed to capture the impact of polymer modification on the IDEAL-CT and I-FIT results. In all cases, PMA and unmodified mixtures with the same mix design, base binder, and binder content had statistically equivalent IDEAL-CT and I-FIT results at $T_{=G*}$. As a result, Hypothesis 2 of the study was also rejected.

Interaction diagram analysis was conducted on the IDEAL-CT and I-FIT results to understand the impact of polymer modification on the toughness and post-peak behavior of asphalt mixtures and their combined impacts on the final cracking index parameters. The analysis results showed that polymer modification generally affected the G_f and post-peak slope (and displacement) of the mixture, but these effects tended to offset each other when used to calculate the CT_{Index} and FI parameters. In this case, the direction of change in the IDEAL-CT or I-FIT results due to polymer modification on the interaction diagram was almost perpendicular to the direction of increasing CT_{Index} or FI. As a result, PMA and unmodified mixtures with the same mix design and base binder fell on contour curves with similar CT_{Index} or FI values despite having different toughness and post-peak behaviors in the IDEAL-CT and I-FIT.

In addition to the IDEAL-CT and I-FIT, the TB Fatigue and Linear Amplitude Sweep (LAS) tests were conducted to assess the impact of polymer modification on the fatigue resistance of asphalt mixtures and the extracted binders under a cyclic loading condition. The results from both tests indicated that asphalt modification with RET and SBS significantly improved the fatigue resistance of unmodified mixtures and their corresponding extracted binders, which disagreed with the IDEAL-CT and I-FIT results. This discrepancy was believed to be attributed to the different loading conditions of the tests, as the TB Fatigue and LAS tests were conducted with cyclic loading while the IDEAL-CT and I-FIT were conducted with monotonic loading, which did not capture the benefits of polymer modification.

Finally, the Superpave Performance Grade (PG), Multiple Stress Creep Recovery (MSCR), and Dynamic Shear Rheometer (DSR) Frequency Sweep test were conducted on asphalt binders extracted from the mixtures containing different virgin binders. Test results showed that the extracted binders containing PMA versus unmodified binders with the same base binder had distinctly different rheological properties. Overall, asphalt modification with RET and SBS yielded extracted asphalt binders with increased high-temperature stiffness, elasticity, and rutting resistance. The correlation analysis for the extracted binder results versus the IDEAL-CT and I-FIT results showed that the R-value determined from the DSR Frequency Sweep test had a strong positive correlation to the IDEAL-CT results at 25°C. However, this correlation should be interpreted with caution because it is based on a limited range of IDEAL-CT and R-value results, and it is contradictory to the impact of aging on the IDEAL-CT and R-value results. Several binder rheological parameters exhibited a strong or very strong correlation to the limited I-FIT results at 25°C and warrant further verification with additional data.

Based on the findings of this study, it is recommended that state highway agencies that have implemented or are in the process of implementing the IDEAL-CT or I-FIT use the same test criteria for mix design approval of asphalt mixtures of the same mix type and nominal maximum aggregate size (NMAS) but containing PMA and unmodified binders with the same base binder grade. It is also recommended for future research to further investigate the discrepancy between the performance tests that use monotonic loading versus cyclic loading in evaluating the fatigue cracking resistance of PMA binders and mixtures.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The asphalt pavement industry has a long history of using polymer-modified asphalt (PMA) to improve the performance and extend the service lives of asphalt pavements. In a recent survey conducted by the Association of Modified Asphalt Producers (AMAP), all participating state highway agencies (SHAs) reported the use of PMA in asphalt mixtures in 2018 and 2019, but the tonnage varied greatly from state to state (AMAP, 2019). The three most reported types of asphalt modifiers were styrene-butadiene-styrene (SBS), ground tire rubber (GTR), and styrene-butadiene rubber (SBR). Reactive ethylene terpolymer (RET) has also been widely used in PMA formulations. At the early stage of Superpave implementation, the primary distress in asphalt pavements was rutting. To address this issue, SHAs evaluated and implemented different mix design strategies including the use of PMA. Since the 1990s, a vast number of laboratory and field studies on polymer modification have reached a consistent conclusion that PMA mixtures have significantly better rutting resistance than those with unmodified binders.

Over the past decade, many SHAs have recognized that rutting is no longer a major concern; instead, durability-related distresses such as cracking and raveling have become the primary factor controlling the service lives of asphalt pavements. In response to this, SHAs have further adjusted their mix design requirements to improve the durability of asphalt mixtures. These adjustments are generally focused on increasing binder quantity or improving the quality of asphalt binder. The latter includes polymer modification as it improves the high- and intermediate-temperature rheological properties of asphalt binders.

One of the most comprehensive studies on quantifying the benefits of PMA was initiated by the Asphalt Institute (AI) in 2005, which compared the field performance of pavement sections using PMA versus unmodified mixtures by monitoring the performance of existing projects and conducting mechanistic-empirical (M-E) performance prediction analyses (AI, 2005). The study concluded that asphalt pavements with PMA mixtures had significantly better cracking performance than those with unmodified mixtures and that the difference varied depending on the underlying layer condition. Similar findings have also been reported by many field studies, including the Cracking Group (CG) experiments on the National Center for Asphalt Technology (NCAT) Test Track and the Minnesota Road Research Facility (MnROAD), as well as a full-scale accelerated pavement testing experiment of modified asphalt binders at the Federal Highway Administration's Pavement Testing Facility (Qi et al., 2006; Qi et al., 2008). The NCAT Cracking Group (CG) experiment included two companion sections of 20% reclaimed asphalt pavement (RAP) surface mixes with a Performance Grade (PG) 67-22 unmodified binder (section N1) and a PG 94-28 highly polymer modified (HiMA) binder (section S6). After 20 million equivalent single axle loads (ESALs), section N1 had 44.5% lane area cracking while section S6 had only 0.9% lane area cracking (West et al., 2021). The MnROAD CG experiment also included two companion sections of 20% RAP mixes with a PG 64S-22 unmodified binder (cell 18) and a PG 58H-34 PMA binder (cell 21).

After approximately 6 years of trafficking with 4.5 million ESALs, cell 18 had 72% total cracking while cell 21 had 63% total cracking (Vrtis, 2022). All these field performance data indicated that PMA binders provided asphalt mixtures with better cracking resistance than unmodified binders. The same AMAP survey also found that most SHAs recognize the importance of PMA in preventing the fatigue cracking of asphalt pavements (Figure 1) (AMAP, 2019). For this reason, it has become a common practice for some SHAs to require the use of PMA as a premium mix treatment for high-traffic-volume roadways, with an expectation that the increased cost for PMA compared to unmodified asphalt can be justified by improved pavement performance.

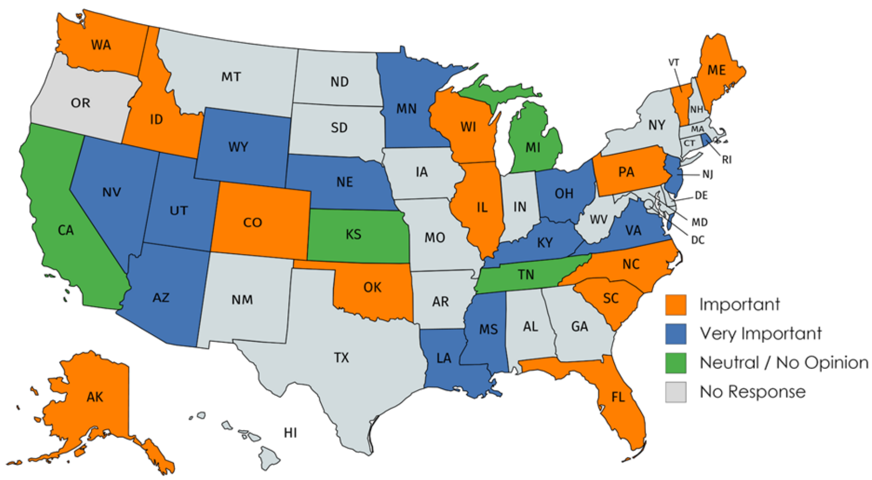


Figure 1. SHA Responses on the Degree of Importance for Using PMA to Prevent Fatigue Cracking of Asphalt Pavements (AMAP, 2019)

Currently, the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) per ASTM D8225 and Illinois Flexibility Index Test (I-FIT) per AASHTO T 393 (formerly TP 101) are two popular mixture cracking tests for use in balanced mix design (BMD) among SHAs. These two tests have reasonable correlations with field cracking data and are sensitive to many mix design variables (West et al., 2018; Al-Qadi et al., 2019; Zhou, 2019). However, several recent studies found that PMA mixtures do not always show better cracking resistance than the unmodified mixtures in the IDEAL-CT or I-FIT (Hanz, 2017; Fort, 2018). As shown in Figure 2, a 20% RAP mixture containing a PG 64-22 unmodified binder has a higher average cracking tolerance index (CT_{Index}) in the IDEAL-CT than those with PG 64-28 and PG 76-22 SBS-modified binders, although the difference between the unmodified and SBS-modified mixtures is not statistically significant (Yin, 2020). Nevertheless, these results indicate that the two PMA mixtures could be slightly more susceptible to intermediate-temperature cracking than the unmodified mixture, which contradicts the existing literature. Therefore, research is needed to identify the causes of discrepancy between the IDEAL-CT/I-FIT results and field performance data regarding the intermediate-temperature cracking resistance of asphalt mixtures containing PMA versus unmodified binders.

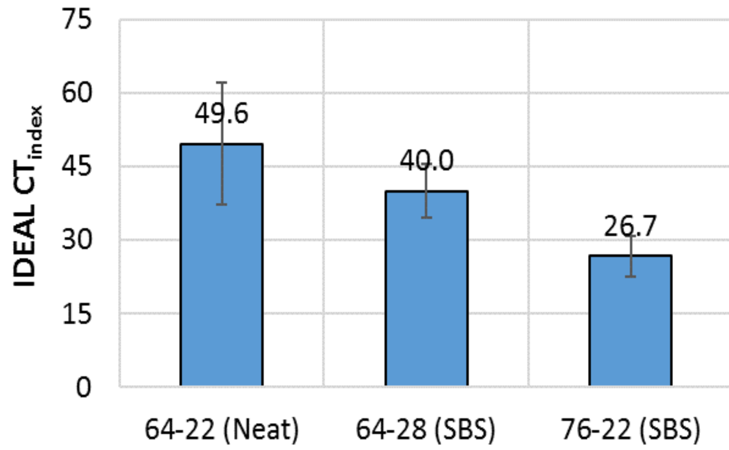


Figure 2. IDEAL-CT Results of 20% RAP Mixtures containing PG 64-22 Unmodified, PG 64-28 SBS-modified, and PG 76-22 SBS-modified Binders (Yin, 2020)

1.2 RESEARCH OBJECTIVES

The overall objective of this study was to determine the impact of polymer modification with SBS and RET, without changing the base binder source and grade, on the IDEAL-CT and I-FIT results for evaluating the intermediate-temperature cracking resistance of asphalt mixtures. Specifically, the study assessed two hypotheses for the lack of sensitivity of the IDEAL-CT and I-FIT to polymer modification.

Hypothesis 1 of the study is, "*Testing the IDEAL-CT and I-FIT at the volumetric OBC of the mixture is insufficient to capture the benefits of polymer modification*." Due to the limitations of volumetric mix design system, many Superpave mixtures do not have enough asphalt binder required to provide adequate durability and cracking resistance. Despite the improvement in the quality of asphalt binder due to polymer modification, using PMA in a volumetrically lean mixture may not be sufficient to improve its cracking resistance. In other words, polymer modification alone cannot fix a "dry mix" issue. In this case, increasing the asphalt binder content is needed to capture the benefits of polymer modification on improving the IDEAL-CT and I-FIT results, highlighting the importance of both binder quality and binder quantity on the intermediate-temperature cracking resistance of asphalt mixtures. This hypothesis is graphically illustrated in Figure 3.

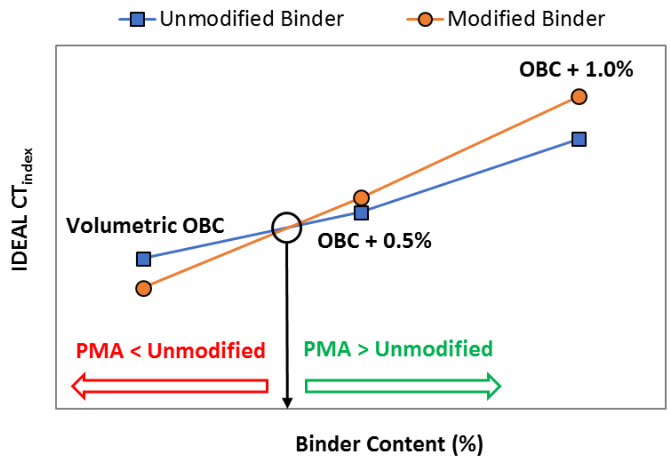


Figure 3. Graphical Illustration of Hypothesis 1 for IDEAL-CT Results

Hypothesis 2 of the study is, "*The IDEAL-CT and I-FIT must be conducted at an equal stiffness condition to properly demonstrate the benefits of polymer modification*." Both tests are conducted at a single temperature and loading rate and require the calculation of a cracking index parameter [i.e., CT_{Index} for IDEAL-CT and flexibility index (FI) for I-FIT] based on the fracture energy (G_f) and post-peak behavior of the load-displacement curve. Asphalt mixtures with better cracking resistance require higher G_f and more ductile post-peak behavior. However, polymer modification typically provides increased binder stiffness and elasticity, which will have opposing impacts on the CT_{Index} and FI results. If the final cracking test parameters are more sensitive to changes in the post-peak behavior of the load-displacement curve than G_f, then PMA mixtures will have lower CT_{Index} or FI values, indicating reduced intermediate-temperature cracking resistance, than the unmodified mixtures. However, in this case, the CT_{Index} and FI are predominately governed by the overall mixture stiffness; as a result, the tests would always favor the use of softer binders without appropriately considering their toughness and relaxation properties.

One potential approach to overcome this issue is to refine the test temperature for IDEAL-CT and I-FIT. Instead of using a constant temperature of 25°C, testing at an equal stiffness temperature ($T_{=G*}$) allows the cracking resistance evaluation of asphalt mixtures with different PG binders at an equal stiffness condition. For this approach, asphalt mixtures with a stiffer binder would need to be tested at a higher temperature than those with a softer binder to account for the difference in binder stiffness. Existing literature has demonstrated the effectiveness of the equal stiffness condition in properly characterizing the fatigue resistance of PMA binders (Anderson et al., 2001; Safaei and Castorena, 2016). Using a single temperature for IDEAL-CT and I-FIT irrespective of binder stiffness could yield misleading conclusions because PMA binders may experience more brittle failure (due to increased stiffness) despite the improved elasticity over softer unmodified binders. Besides adjusting the test temperature, the equal stiffness condition can also be achieved by adjusting the loading rate of the IDEAL-CT and I-FIT. However, this approach is not considered practical for implementation because of the difficulty and complexity in accurately determining the loading rate of non-servo hydraulic test devices.

CHAPTER 2: EXPERIMENTAL PLAN

This chapter presents the experimental plan and discusses the mix design, materials selection, and laboratory tests used in the study. The experimental plan included four laboratory experiments on IDEAL-CT and I-FIT testing at 25°C; selection of $T_{=G^*}$ followed by IDEAL-CT and I-FIT testing at $T_{=G^*}$; supplementary cyclic fatigue testing; and extracted binder rheological testing. Prior to the execution of the experiments, two asphalt mix designs were selected from Alabama and Wisconsin. Each mix design was evaluated with six virgin binders, including two neat binders, two RET-modified binders, and two SBS-modified binders. For the IDEAL-CT and I-FIT, each mixture was tested at three binder contents: volumetric OBC, OBC +0.3%, and OBC +0.6%. The scope and details of the four experiments are discussed below:

- The first experiment focused on the IDEAL-CT and I-FIT testing of asphalt mixtures prepared with different mix designs, virgin binders, and binder contents at 25°C. Data analysis was conducted to test the first proposed hypothesis of the study by comparing the IDEAL-CT and I-FIT results of asphalt mixtures containing PMA versus unmodified binders with the same base binder at different binder contents.
- The second experiment started with conducting the Torsion Bar (TB) Modulus test to determine the $T_{=G^*}$ of asphalt mixtures prepared with different mix designs and virgin binders, followed by the IDEAL-CT and I-FIT testing at $T_{=G^*}$. Data analysis was conducted to test the second proposed hypothesis of the study by comparing the IDEAL-CT and I-FIT results of asphalt mixtures containing PMA versus unmodified binders with the same base binder at $T_{=G^*}$.
- The third experiment focused on conducting the TB Fatigue test and the Linear Amplitude Sweep (LAS) test to supplement the IDEAL-CT and I-FIT in assessing the impact of polymer modification on the fatigue cracking resistance of asphalt binders and mixtures under a cyclic loading condition. The TB Fatigue test was conducted on all the mixtures from the first two experiments at only the volumetric OBC, while the LAS test was conducted on asphalt binders extracted from the same mixtures in the TB Fatigue test.
- The last experiment focused on characterizing the rheological properties of the extracted binders from the third experiment. The Superpave PG, Multiple Stress Creep Recovery (MSCR), and Dynamic Shear Rheology (DSR) Frequency Sweep tests were conducted. Data analysis was conducted to compare the extracted binders containing PMA versus unmodified virgin binders with the same base binder. Furthermore, the extracted binder results were compared against the IDEAL-CT and I-FIT results from the first experiment for correlation analysis.

2.1 MIX DESIGN AND MATERIAL SELECTION

Two asphalt mix designs from Alabama and Wisconsin were selected to execute the experimental plan of the study. The Alabama mix design was a 9.5 mm nominal maximum aggregate size (NMAS) Superpave mixture with 20% RAP, and the Wisconsin mix design was a 12.5 mm NMAS Superpave mixture with 23% RAP. The volumetric OBC of the Alabama and Wisconsin mix designs was 5.5% and 5.1%, respectively. Additional details of the two mix designs are summarized in Table 1.

Table 1. Mix Design Summary

Properties	Alabama Mix Design	Wisconsin Mix Design
NMAS (mm)	9.5	12.5
RAP Content (%)	20	23
RAP Binder Content (%)	5.03	4.70
Volumetric OBC (%)	5.5	5.1
Sieve (mm)	Percent Passing (%)	
19	100	100
12.5	100	94.6
9.5	97.7	85.4
4.75	67.9	67.9
2.36	49.1	53.6
1.18	39.5	41.7
0.6	26.2	32.7
0.3	13.8	19.8
0.15	7.9	7.0
0.075	5.5	3.7

Each mix design was evaluated with six virgin binders corresponding to two sets of three binders each, which included a neat binder, a RET-modified binder, and an SBS-modified binder. The two PMA binders within each set were formulated using the neat binder for polymer modification to have the same base binder for both. The two sets of virgin binders used with the Alabama mix design included 1) a PG 64-22 neat binder, a PG 76-22 RET-modified binder, and a PG 76-22 SBS-modified binder; and 2) a PG 58-28 neat binder, a PG 64-28 RET-modified binder, and a PG 64-28 SBS-modified binder. The two SBS-modified binders were sampled from an asphalt supplier as terminal blended binders while the two RET-modified binders were formulated in the laboratory by reasonably matching the rheological properties of the SBS-modified binders. Table 2 summarizes the viscosity, Superpave PG, delta T_c (ΔT_c), and MSCR results of the Alabama virgin binders.

The two sets of virgin binders used with the Wisconsin mix design included 1) a PG 58S-28 neat binder, a PG 58V-28 RET-modified binder, and a PG 58V-28 SBS-modified binder; and 2) a PG 52S-34 neat binder, a PG 58V-34 RET-modified binder, and a PG 58V-34 SBS-modified binder. Different from the Alabama binders, the two RET-modified binders used with the Wisconsin mix design were sampled from an asphalt supplier as terminal blended binders while the two SBS-modified binders were formulated in the laboratory by reasonably matching the rheological properties of the RET-modified binders. Table 3 summarizes the viscosity, Superpave PG, ΔT_c, and MSCR results of the Wisconsin virgin binders.

Table 2. Superpave PG and MSCR Results of Virgin Binders used with the Alabama Mix Design

Binder Properties	Set 1			Set 2		
	PG 64-22 Neat	PG 76-22 RET	PG 76-22 SBS	PG 58-28 Neat	PG 64-28 RET	PG 64-28 SBS
Viscosity (Pa.s)	0.512	1.718	1.746	0.252	0.930	0.996
Continuous PG	68.1-23.4	79.7-25.0	77.2-26.1	59.6-28.5	71.5-28.3	69.7-29.7
ΔT_c	1.1	0.8	-0.6	0.5	1.0	-0.8
J_{nr} @ 3.2 kPa (kPa^{-1})	2.661*	0.234*	0.191*	3.299#	0.251#	0.320#
J_{nr} Difference (%)	9.2*	17.6*	45.8*	8.7#	17.3#	41.0#
%R @3.2 kPa	1.3*	65.6*	77.1*	0.8#	68.0#	66.7#

Notes: *MSCR tested at 64°C; #MSCR tested at 58°C

Table 3. Superpave PG and MSCR Results of Virgin Binders used with the Wisconsin Mix Design

Binder Properties	Set 1			Set 2		
	PG 58S-28 Neat	PG 58V-28 RET	PG 58V-28 SBS	PG 52S-34 Neat	PG 58V-34 RET	PG 58V-34 SBS
Viscosity (Pa.s)	0.272	1.086	0.96	0.189	0.79	0.682
Continuous PG	59.2-30.1	72.5-30.6	71-30.0	53.2-35.1	66.0-36.9	65.1-35.1
ΔT_c	-0.15	0.69	-0.735	0.965	1.06	-0.135
J_{nr} @ 3.2 kPa (kPa^{-1})	3.015*	0.208*	0.284*	3.141#	0.539*	0.495*
J_{nr} Difference (%)	11.3*	20.9*	49.5*	11.1#	28.3*	56.6*
%R @3.2 kPa	1.2*	69.7*	65.5*	1.2#	59.5*	67.6*

Notes: *MSCR tested at 58°C; #MSCR tested at 52°C

2.2 LABORATORY MIXTURE TESTS

This section presents the test procedure and data analysis of the mixture performance tests used in the study, which included the IDEAL-CT, I-FIT, TB Modulus test, and TB Fatigue test.

2.2.1 IDEAL-CT

The IDEAL-CT test was performed per ASTM D 8255 to evaluate the intermediate-temperature cracking resistance of asphalt mixtures. The specimens were compacted to a target height of 62 mm and 7.0 ± 0.5% using an Superpave gyratory compactor (SGC). A minimum of four replicates were tested for each mixture. Prior to testing, the specimens were conditioned in an environmental chamber for 2 hours. The IDEAL-CT was performed using a common indirect tensile (IDT) test fixture loaded at a rate of 50 mm/min, as presented in Figure 4. During the test, the load and displacement data were recorded at a rate of 50 Hz. For data analysis, the load vs. displacement curve was plotted and used to determine the G_f, post-peak slope at 75% of the peak load ($|m_{75}|$), and post-peak displacement at 75% of the peak load (l_{75}), as shown in Figure 5. The final cracking index parameter, CT_{Index}, was then calculated using Equation 1. A higher CT_{Index} value is desired for asphalt mixtures with better intermediate-temperature cracking resistance.

$$CT_{Index} = \frac{t}{62} \times \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{D} \qquad \text{Equation 1}$$

Where, *t* = specimen thickness; and *D* = specimen diameter.

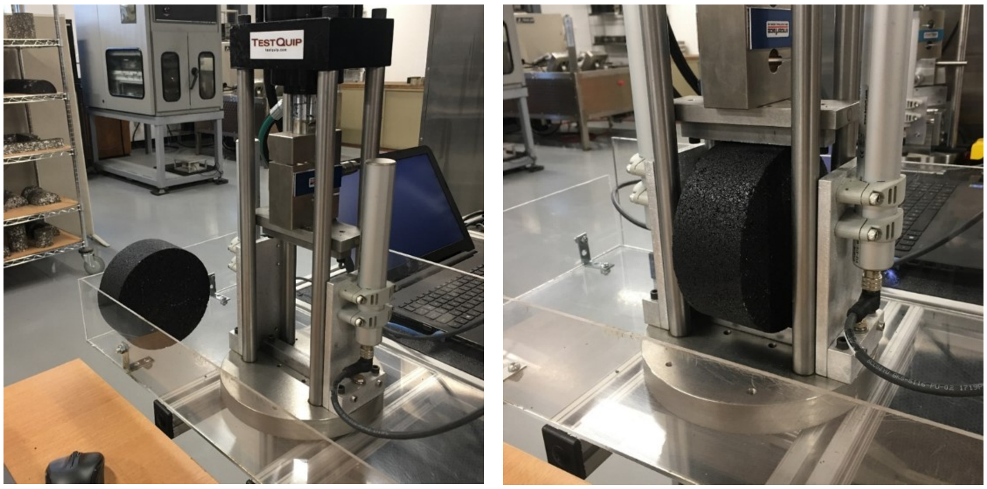


Figure 4. IDEAL-CT Test Device and Specimen Setup

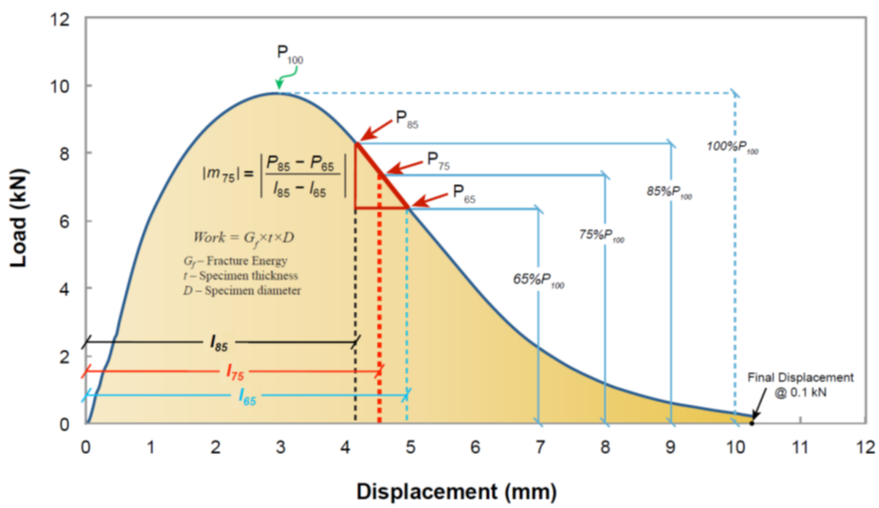


Figure 5. IDEAL-CT Data Analysis (Zhou et al., 2017)

2.2.2 I-FIT

The I-FIT was performed in accordance with AASHTO T 393 to evaluate the intermediate-temperature cracking resistance of asphalt mixtures. The test used a notched semi-circular specimen, which was trimmed from a larger 160 mm tall by 150 mm diameter SGC specimen. Four semi-circular specimens were obtained per gyratory specimen, and the thickness was controlled at 50 ± 1 mm. A notch was then cut into each semi-circular specimen at a target depth of 15 ± 1 mm and width less than 2.25 mm along the center axis of the specimen, as shown in Figure 6. A minimum of four notched semi-circular specimens were tested for each mixture, and the specimen air voids were controlled at 7.0 ± 0.5% after trimming. Prior to testing, the specimens were conditioned in an environmental chamber for 2 hours.

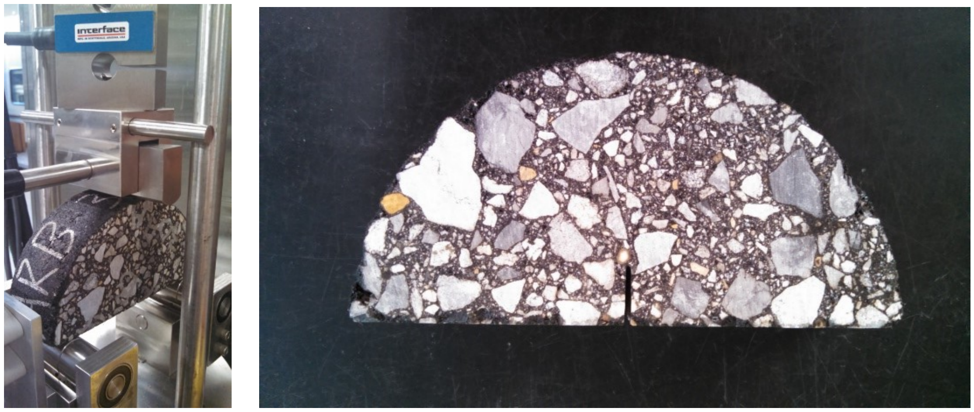


Figure 6. I-FIT Test Setup and Specimen

During the test, the specimen was loaded over two rollers at a rate of 50 ± 2.0 mm/min, and the load and corresponding displacement were recorded at a rate of 50 Hz. The load versus displacement curve was then plotted and used to determine the G_f and the post-peak slope at the inflection point ($|m|$), as shown in Figure 7. The final cracking index parameter, FI, was calculated using Equation 2. A higher FI value is desired for asphalt mixtures with better intermediate-temperature cracking resistance.

$$FI = A \times \frac{G_f}{|m|} \qquad \text{Equation 2}$$

Where, A = constant, 0.01.

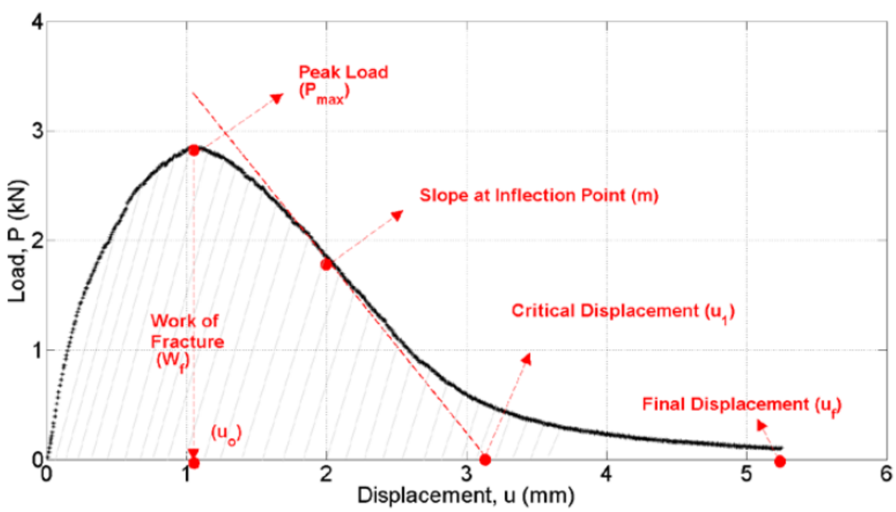


Figure 7. I-FIT Data Analysis (Al-Qadi et al., 2015)

2.2.3 TB Modulus Test

The TB Modulus test was conducted in accordance with ASTM D 7552 using a DSR device to measure the complex shear modulus (|G*|) and phase angel (δ) of asphalt mixtures. The TB specimen was trimmed from a cylindrical gyratory sample and had a dimension of approximately 50 mm in length, 14 mm in width, and 7 mm in thickness after trimming. Prior to testing, the TB specimen was loaded in the DSR with a clamping fixture, as shown in Figure 8. During the test, the |G*| and δ of the mixture were measured at three isothermal temperatures (i.e., 20, 25, and 30°C) and discrete frequencies ranging from approximately 10^{-5} to 10^{12} rad/s. The measured |G*| was then used to develop a temperature-sweep |G*| curve at 10 rad/s using the RHEA™ software, as shown in Figure 9.

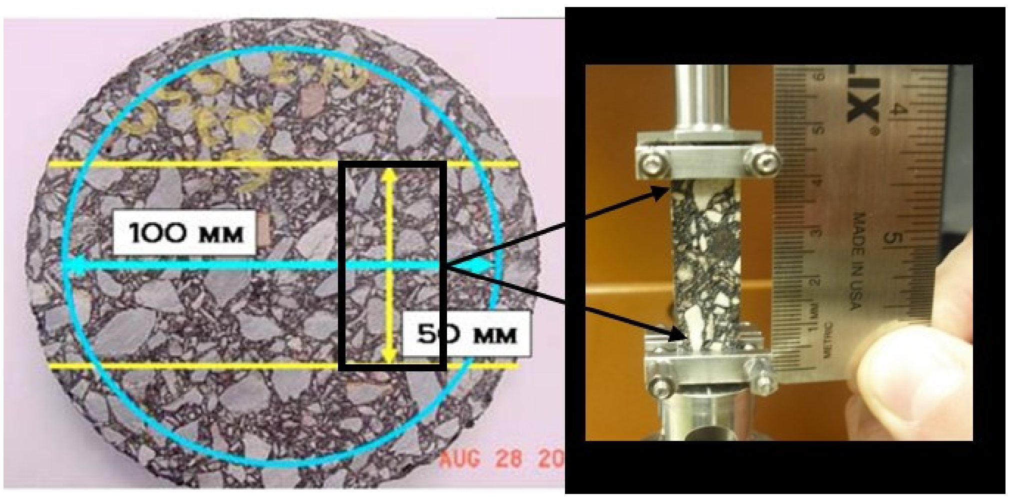


Figure 8. TB Specimen Preparation and Setup

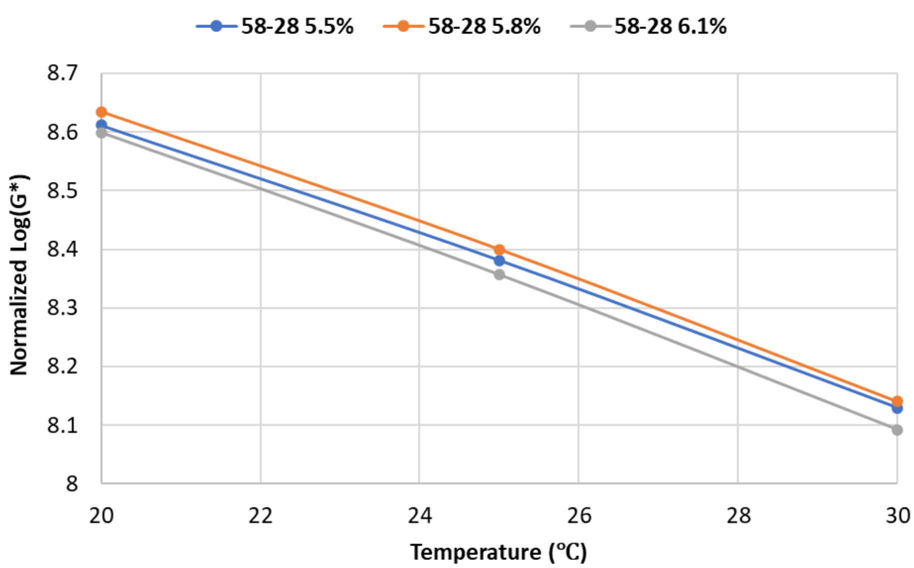


Figure 9. Development of Temperature-sweep |G*| Curve from the TB Modulus Test Results

2.2.4 TB Fatigue Test

The TB Fatigue test was conducted with a standard operation procedure developed at MTE, which is a time-sweep test at a prescribed displacement and temperature (Hanz and Reinke, 2017). The test used the same TB specimen preparation and setup procedures as the TB Modulus test (Figure 8). In this study, the TB Fatigue test was conducted at 25°C and 10Hz with a controlled displacement of 0.01 radians. This displacement level was selected to avoid having early failures with inadequate results for data analysis and having excessively long testing times. A maximum test duration of 10 hours was selected for the study. During the test, the |G*| of the TB specimen was recorded and plotted against the test time. As shown in Figure 10, the |G*| decreased over time as fatigue damage accumulated within the specimen. For data analysis, the product of |G*| and time (|G*| × t) was calculated and plotted against time. The time corresponding to the maximum |G*| × t value was defined as the time to failure (t_f), which is consistent with the data analysis of the Bending Beam Fatigue test results per AASHTO T 321. In general, a higher t_f value is desired for asphalt mixtures with better cyclic fatigue resistance.

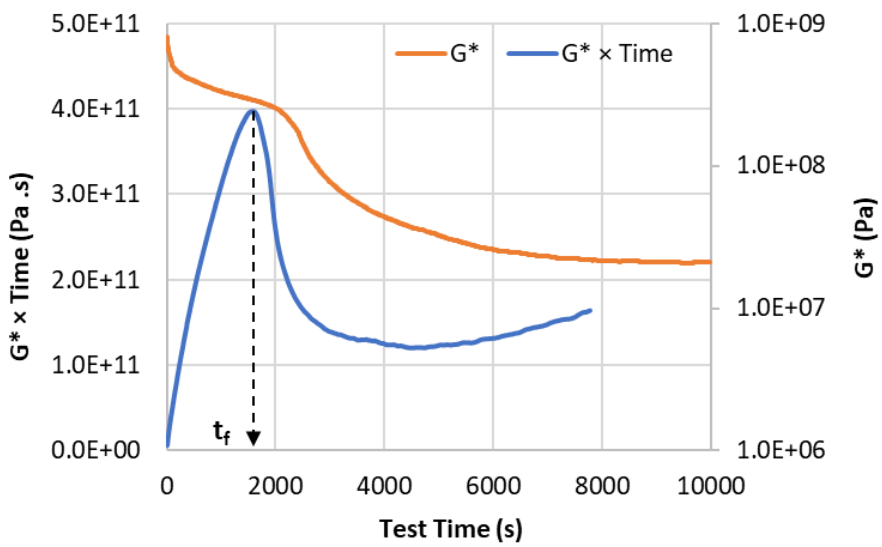


Figure 10. TB Fatigue Test Results and Data Analysis

2.3 LABORATORY BINDER TESTS

This section presents the test procedure and data analysis of the performance tests conducted on the extracted binders in the study, which included the Superpave PG, ΔT_c, MSCR, DSR Frequency Sweep, and LAS tests. Asphalt binders were extracted using the centrifuge method in ASTM D2172 and recovered with the rotary evaporator per ASTM D7906.

2.3.1 Superpave PG and ΔT_c

The high-temperature PG of the extracted binders was determined following AASHTO T 315 and AASHTO M 320. The low-temperature PG of the extracted binders was determined using the 4-mm parallel plate geometry DSR testing. In this method, the relaxation modulus |G|(t) and relaxation rate m_r (i.e., relaxation modulus slope at 60 s) of the binder were determined at the low PG + 10°C and low PG + 20°C. The results were then correlated with the Bending Beam Rheometer (BBR) stiffness and m-value results to calculate the critical low-temperatures based on stiffness ($T_{C,S}$) and m-value ($T_{C,m}$). For conversion to the critical BBR stiffness of 300 MPa and m-value of -0.300 (AASHTO T313), |G|(t) of 143 MPa and m_r of -0.275 were used, respectively (Sui et al., 2011; Farrar et al., 2015). The ΔT_c was determined based on the converted BBR results, where ΔT_c is defined as the numerical difference between $T_{C,S}$ and $T_{C,m}$ (Anderson et al., 2011). The ΔT_c parameter has recently been used to assess the loss of stress relaxation properties of asphalt binders. Generally, a more positive (or less negative) ΔT_c value is desirable for asphalt binders with better ductility and block cracking resistance.

2.3.2 MSCR Test

The MSCR test was conducted in accordance with AASHTO T 350. The extracted binders were tested as recovered without additional Rolling Thin Film Oven (RTFO) or PAV aging. The test was conducted at 64°C on asphalt binders extracted from the Alabama mixtures and 58°C on those extracted from the Wisconsin mixtures. The two MSCR parameters used in the study were percent recovery (%R) and non-recoverable creep compliance (J_{nr}) at the 3.2 kPa stress level. A higher %R value and a lower J_{nr} value are desired for asphalt binders with better elasticity and rutting resistance, respectively.

2.3.3 DSR Frequency Sweep Test

The DSR Frequency Sweep test was conducted at multiple test temperatures (ranging from -40°C to 40°C) over an angular frequency range of 0.2 to 100 rad/s. During the test, the peak-to-peak strain of the binder sample was adjusted for different isotherms to ensure its behavior remained in the linear viscoelastic range. For data analysis, the RHEA™ software was used to construct a DSR master curve by fitting the shear complex modulus (|G*|) and phase angle (δ) data to the Christensen-Anderson-Marasteanu (CAM) model (Marasteanu and Anderson, 1999). The Glover-Rowe (*G-R*) parameter was then calculated using Equation 3 based on the binder |G*| and δ values at 15°C and 0.005 rad/s. In general, a high *G-R* parameter indicates low ductility and high susceptibility to block cracking.

$$G - R\ Parameter = \frac{|G^*|\,cos(\delta)^2}{sin(\delta)} \qquad \text{Equation 3}$$

In addition to the *G-R* parameter, the crossover frequency (ω_c) and rheological index (R-value) were also determined from the DSR master curve. The ω_c is defined as the reduced frequency at which the δ is 45°, which is a measure of the overall hardness of an asphalt binder. As ω_c decreases, the binder's hardness increases. The R-value is the log of the glassy modulus of the binder minus the log of the |G*| where the δ is 45°. As R-value increases, the master curve becomes flatter, indicating a more gradual transition from elastic behavior to steady-state flow. In this study, the R-value was calculated following the method by Christen and Tran (2022) as shown in Equation 4, where the |G*| and δ at a frequency of 1 rad/s from the last isotherm that exceeded a modulus of 10 MPa was used.

$$R = \log(2)\frac{log(|G^*|/1 \times 10^9)}{log(1-\delta/90)} \qquad \text{Equation 4}$$

2.3.4 LAS Test

The LAS test was conducted per a modified AASHTO T 391 procedure by Safaei and Castorena (2016) to assess the fatigue resistance of the extracted binders. During the test, the asphalt binder sample was subjected to a frequency sweep and then multiple amplitude sweeps at various testing durations. The frequency sweep test (using the 8mm DSR plate) was to determine the linear viscoelastic stiffness of the binder, while the amplitude sweep test was to characterize the fatigue damage resistance of the binder. In the amplitude sweep test, a series of oscillatory load cycles at systematically increasing amplitudes (up to 30% applied strain) was applied to the binder to induce accelerated fatigue damage. Data analysis of the LAS results was based on the simplified viscoelastic continuum damage (S-VECD) model. The primary outcome of the test was a relationship between the fatigue parameter (N_f, normalized to 1 million ESALs) versus the applied shear strain as a pavement structure indicator (Equation 5). In addition to the N_f, the strain-at-peak-stress was also examined to assess the binder's ability to relax stresses induced by traffic loading. A higher N_f and a higher strain-at-peak-stress are desired for asphalt binders with better fatigue resistance.

$$N_f = A(\gamma_{max})^{-B} \qquad \text{Equation 5}$$

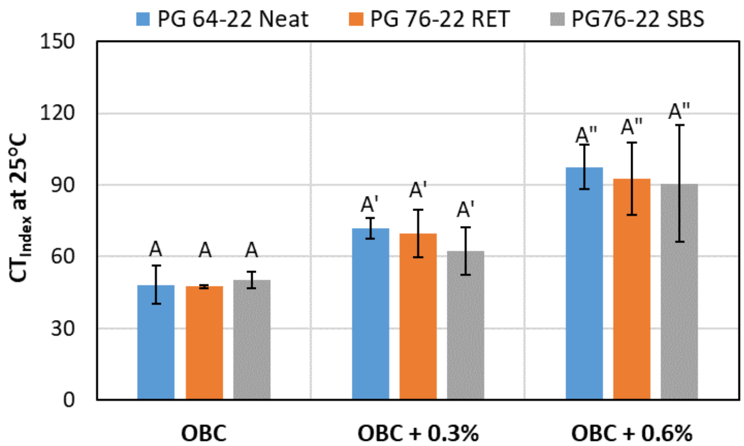
Where, γ_{max} = the maximum expected binder strain for a given pavement structure; and A, B = fatigue performance model parameters.

CHAPTER 3: IDEAL-CT AND I-FIT RESULTS AT 25°C

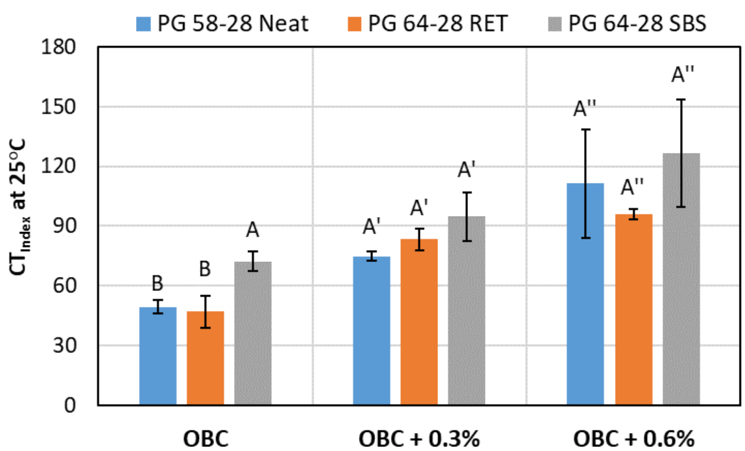
This chapter presents the IDEAL-CT and I-FIT results at 25°C. A total of 12 mixtures were tested, which corresponded to a combination of two mix designs and six virgin binders per mix design (including two unmodified binders, two SBS-modified binders, and two RET-modified binders). Each mixture was tested at three binder contents: volumetric OBC, OBC + 0.3%, and OBC + 0.6%. The intermediate-temperature cracking resistance of the Alabama mixtures was evaluated using the IDEAL-CT while the Wisconsin mixtures was evaluated using both the IDEAL-CT and I-FIT. Data analysis of the IDEAL-CT and I-FIT results was conducted to test Hypothesis 1 of the study: "*Testing the IDEAL-CT and I-FIT at the volumetric OBC of the mixture is insufficient to capture the benefits of polymer modification*."

All the test results in this chapter are presented using column charts, where the columns represent the average CT_{Index} and FI values and the error bars represent one plus and minus standard deviation among the replicates. For data analysis, both the mean value analysis and the Games-Howell post-hoc group analysis at a significance level of 0.05 were conducted to compare the test results of mixtures prepared with the same mix design, virgin binders formulated with the same base binder, and the same binder content, to isolate the impact of polymer modification from other confounding factors. The capital letters shown above the columns represent the group analysis results, where mixtures sharing the same letter had no statistically significant difference among their test results. The letters A, A', and A'' represent the group analysis results of mixtures at the volumetric OBC, OBC+0.3%, and OBC +0.6%, respectively.

Figure 11 presents the IDEAL-CT results of the Alabama mixtures at 25°C. As shown in Figure 11(a), the PG 64-22 unmodified mixture had a slightly higher or similar average CT_{Index} compared to the PG 76-22 RET- and SBS-modified mixtures at each of the three binder contents. For all three mixtures, the average CT_{Index} increased as the binder content increased from 5.5% (volumetric OBC) to 5.8%, and then to 6.1%. The statistical group analysis showed that these three mixtures shared the same letter at each of the three binder contents, which indicated that *polymer modification did not have a significant impact on the CT_{Index} results regardless of the binder content*. The results in Figure 11(b) showed that at all three binder contents, the PG 64-28 SBS-modified mixture had a consistently higher average CT_{Index} than the PG 58-28 unmodified mixture and the PG 64-28 RET-modified mixture. Furthermore, the average CT_{Index} of these mixtures also increased with higher binder content, which is consistent with the results in Figure 11(a). The group analysis results showed that the two PMA mixtures had statistically equivalent CT_{Index} results as the unmodified mixture, except that the PG 64-28 SBS mixture had a statistically higher CT_{Index} than the unmodified mixture at the volumetric OBC of 5.5%.



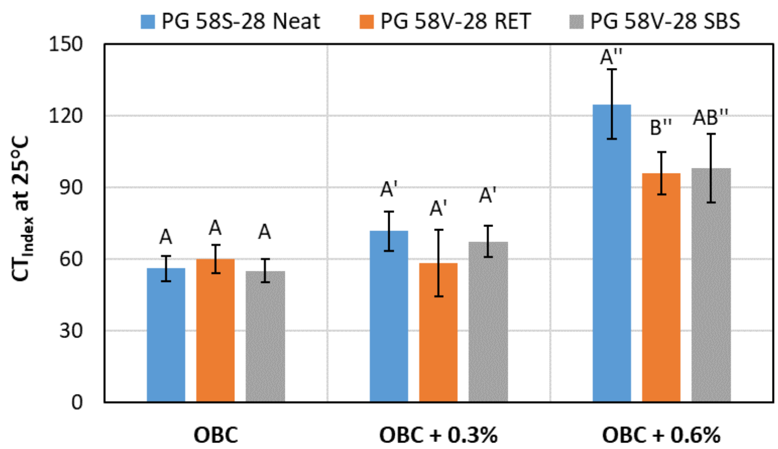
(a)



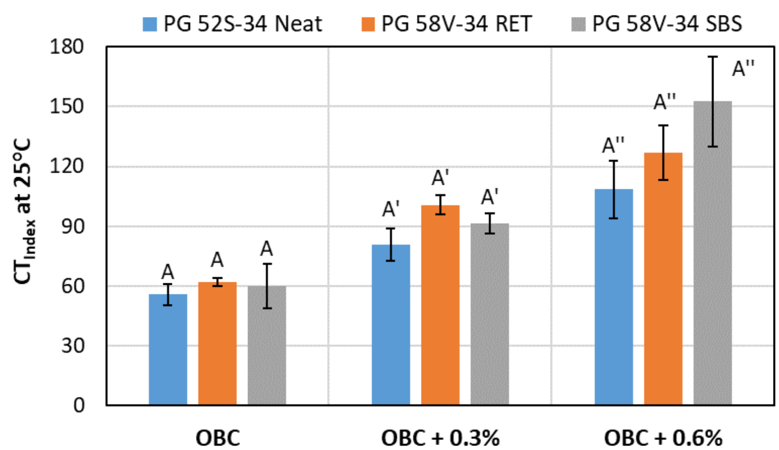
(b)

Figure 11. IDEAL-CT CT_{Index} Results of Alabama Mixtures at 25°C; (a) Mixtures with PG 64-22 Unmodified, PG 76-22 RET-modified, and PG 76-22 SBS-modified Binders, (b) Mixtures with PG 58-28 Unmodified, PG 64-28 RET-modified, and PG 64-28 SBS-modified Binders

Figure 12 presents the IDEAL-CT results of the Wisconsin mixtures at 25°C. As shown in Figure 12(a), the PG 58S-28 unmodified mixture had higher or similar average CT_{Index} results compared to the PG 58V-28 RET- and SBS-modified mixtures at each of the three binder contents. The average CT_{Index} of these mixtures also increased with the increasing binder content, which agreed with the results in Figure 11. The group analysis results showed that the two PMA mixtures had statistically similar or lower CT_{Index} results compared to the unmodified mixture at all three binder contents. This indicated that *polymer modification of the two base binders with RET and SBS did not improve the IDEAL-CT results at 25°C*. The results in Figure 12(b) showed that the PG 58V-34 RET- and SBS-modified mixtures had similar or higher average CT_{Index} than the unmodified mixture at the three binder contents, but the differences were not statistically significant based on the group analysis results.



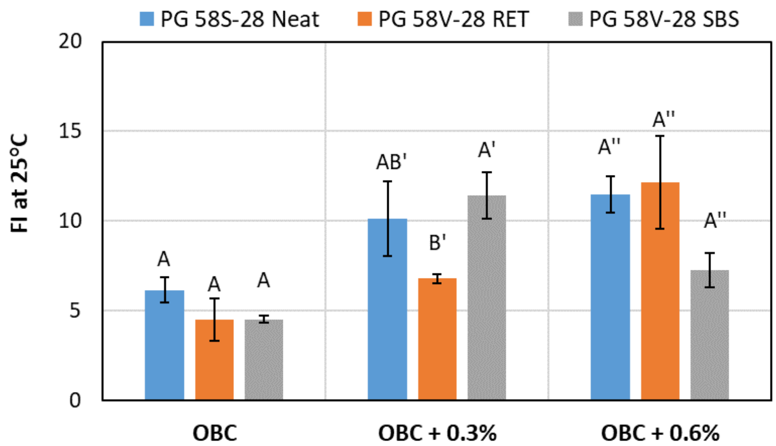
(a)



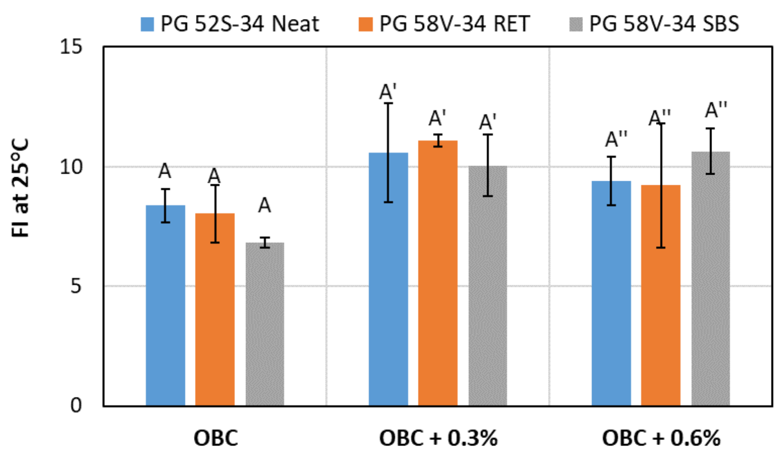
(b)

Figure 12. IDEAL-CT CT_{Index} Results of Wisconsin Mixtures at 25°C; (a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

Figure 13 presents the I-FIT results of the Wisconsin mixtures at 25°C. For both sets of mixtures, the unmodified mixture had statistically equivalent FI results as the two PMA mixtures regardless of the binder content, which indicated that *asphalt modification with RET and SBS did not improve the I-FIT results of the Wisconsin mixtures at 25°C*. In most cases, the FI of these mixtures increased as the binder content increased, indicating improved intermediate-temperature cracking resistance.



(a)



(b)

Figure 13. I-FIT FI Results of Wisconsin Mixtures at 25°C; (a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

In summary, the results in Figure 11 through Figure 13 consistently showed that the PMA mixtures did not outperform the unmodified mixtures in IDEAL-CT and I-FIT when the tests were conducted at 25°C, regardless of the binder content. In other words, increasing the binder content did not help discriminate the unmodified versus PMA mixtures in the two tests conducted at 25°C. Therefore, Hypothesis 1 of the study, "*testing the IDEAL-CT and I-FIT at the volumetric OBC of the mixture is insufficient to capture the benefits of polymer modification,*" was rejected.

CHAPTER 4: IDEAL-CT AND I-FIT RESULTS AT $T_{=G*}$

This chapter presents the selection of $T_{=G*}$ based on the TB Modulus test results and the IDEAL-CT and I-FIT results at $T_{=G*}$. As with the IDEAL-CT and I-FIT testing at 25°C (discussed in Chapter 3), a total of 12 mixtures were tested, corresponding to a combination of two mix designs and six virgin binders per mix design (including two unmodified binders, two SBS-modified binders, and two RET-modified binders). Each mixture was tested at three binder contents: volumetric OBC, OBC + 0.3%, and OBC + 0.6%. The intermediate-temperature cracking resistance of the Alabama mixtures was evaluated using the IDEAL-CT at $T_{=G*}$ while the Wisconsin mixtures was evaluated using both the IDEAL-CT and I-FIT. Data analysis of the IDEAL-CT and I-FIT results was conducted toward testing Hypothesis 2 of the study: "*The IDEAL-CT and I-FIT must be conducted at an equal stiffness condition to properly demonstrate the benefits of polymer modification*."

4.1 SELECTION OF $T_{=G*}$ BASED ON TORSION BAR MODULUS TEST RESULTS

For the selection of $T_{=G*}$, the TB Modulus test results were analyzed based on the following steps:

1) Develop a temperature-sweep |*G**| curve at 10 rad/s. This frequency was selected because it simulates a traffic speed of 55 mph. For illustration purposes, Figure 14 presents the temperature-sweep |*G**| curves of three Alabama mixtures containing different virgin binders at the volumetric OBC (i.e., 5.5%). As shown, the PG 76-22 SBS-modified mixture had the highest |*G**|, followed by the PG 64-22 unmodified mixture and then the PG 58-28 unmodified mixture. This trend was expected based on the PG of the virgin binders used.

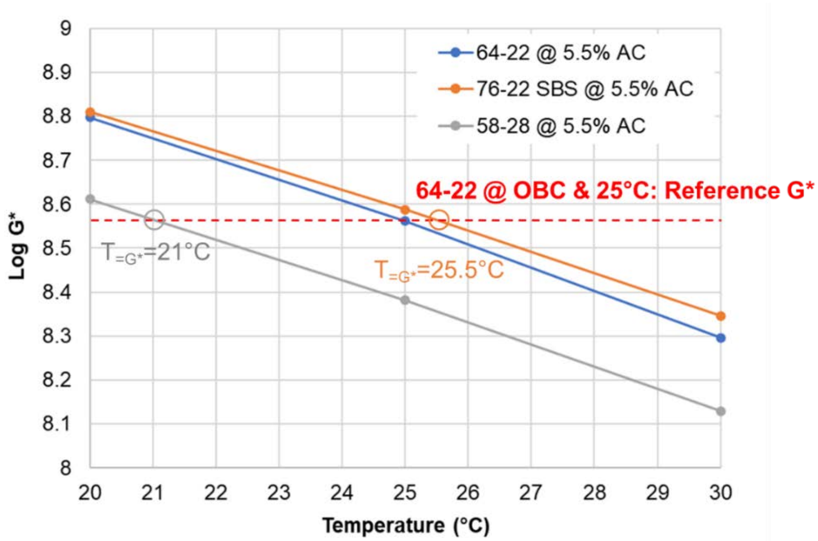


Figure 14. Illustration of $T_{=G*}$ Determination by Interpolating Temperature-sweep |*G| Curves with Reference |*G**|**

2) Select a reference |*G**| for each mix design. For the Alabama mix design, the reference |*G**| was selected using the 25°C |*G**| of the PG 64-22 unmodified mixture at the volumetric OBC

(i.e., 5.5%) because PG 64-22 is the standard virgin binder grade in Alabama. For the Wisconsin mix design, the reference |*G**| was selected using the 25°C |*G**| of the PG 58S-28 unmodified mixture at the volumetric OBC (i.e., 5.1%) because PG 58S-28 is considered the standard virgin binder grade in Wisconsin.

3) For each mix design, determine the $T_{=G*}$ of mixtures with different virgin binders and different binder contents based on log-linear interpolation of the temperature-sweep |G|* curves with the reference |*G**|. This step is graphically illustrated in Figure 14. In this example, because the PG 76-22 SBS-modified mixture was slightly stiffer than the reference PG 64-22 unmodified mixture, it had a $T_{=G*}$ of 25.5°C. The PG 58S-28 unmodified mixture, on the other hand, was softer than the reference mixture and had a $T_{=G*}$ of 21.0°C.

4) Average the $T_{=G*}$ for the mixtures with the same mix design and virgin binder, but at different binder contents (e.g., the Alabama PG 76-22 SBS-modified mixture at 5.5%, 5.8%, and 6.1% binder contents).

5) For mixtures with the same mix design and virgin binder, adjust the average $T_{=G*}$ by rounding it to the nearly intermediate-temperature PG grade in AASHTO M 320, which varies from 4°C to 40°C at 3°C increments. The adjusted $T_{=G*}$ after 3°C-increment rounding aligns with the Superpave PG specification and the suggested temperature tolerance for IDEAL-CT (i.e., ± 1.0°C) and I-FIT (i.e., ± 0.5°C) in NCHRP project 09-57A (Zhou, 2019a; Zhou, 2019b). For example, the Alabama PG 58-28 unmodified mixture at different binder contents had an average $T_{=G*}$ of 21.2°C, which would be rounded up to 22°C as the final $T_{=G*}$.

Table 4 summarizes the final $T_{=G*}$ results of the Alabama and Wisconsin mixtures. As shown, the Alabama mixtures had two $T_{=G*}$: 22°C for those containing a PG xx-28 virgin binder and 25°C for those containing a PG xx-22 virgin binder (including the reference PG 64-22 unmodified mixture). In both cases, asphalt modification with SBS and RET did not change the final $T_{=G*}$ of the mixtures after the 3°C-increment rounding. Before rounding, the $T_{=G*}$ increased by 0.1 to 1.4°C among the different PMA mixtures. For the two unmodified mixtures, using the softer PG 58-28 binder reduced the $T_{=G*}$ by 3°C compared to the reference PG 64-22 binder. The Wisconsin mixtures had three $T_{=G*}$: 19°C for those containing a PG xx-34 virgin binder, 25°C for the reference PG 58S-28 unmodified mixture, and 28°C for mixtures containing a PG 58V-28 RET- or SBS-modified binder. Asphalt modification with RET and SBS increased the final $T_{=G*}$ of the PG 58S-28 unmodified mixture by 3°C but did not affect the final $T_{=G*}$ of the softer PG 52S-34 unmodified mixture. Without the 3°C-increment rounding, the $T_{=G*}$ of the PG 52S-34 unmodified mixtures increased by 0.9 to 2.7°C due to polymer modification. Compared to the reference PG 58S-28 binder, the softer PG 52S-34 binder reduced the $T_{=G*}$ of the unmodified mixture by 6°C.

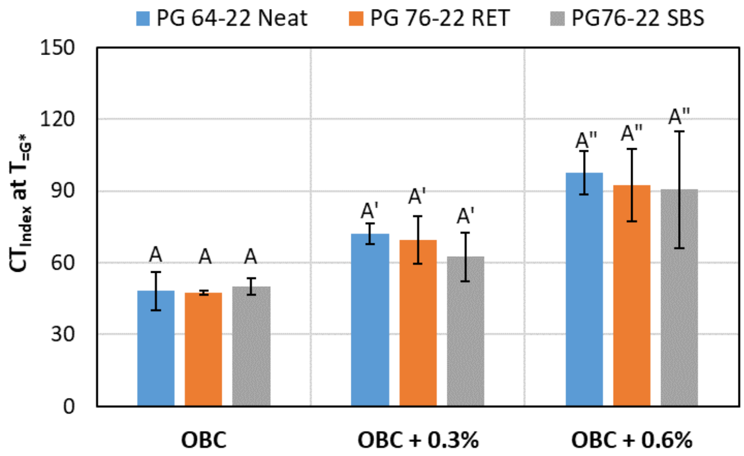
Table 4. $T_{=G^*}$ Results of Alabama and Wisconsin Mixtures with Different Virgin Binders

Mix Design	Virgin Binder Type (Base Binder for Polymer Modification)	$T_{=G^*}$
Alabama	PG 64-22 Neat	25°C (rounded from 25.3°C)
	PG 76-22 RET-modified (64-22)	25°C (rounded from 25.4°C)
	PG 76-22 SBS-modified (64-22)	25°C (rounded from 25.7°C)
	PG 58-28 Neat	22°C (rounded from 21.2°C)
	PG 64-28 RET-modified (58-28)	22°C (rounded from 22.6°C)
	PG 64-28 SBS-modified (58-28)	22°C (rounded from 22.5°C)
Wisconsin	PG 58S-28 Neat	25°C (rounded from 24.8°C)
	PG 58V-28 RET-modified (58S-28)	28°C (rounded from 26.6°C)
	PG 58V-28 SBS-modified (58S-28)	28°C (rounded from 26.7°C)
	PG 58S-34 Neat	19°C (rounded from 17.6°C)
	PG 58V-34 RET-modified (58S-34)	19°C (rounded from 20.3°C)
	PG 58V-34 SBS-modified (58S-34)	19°C (rounded from 18.5°C)

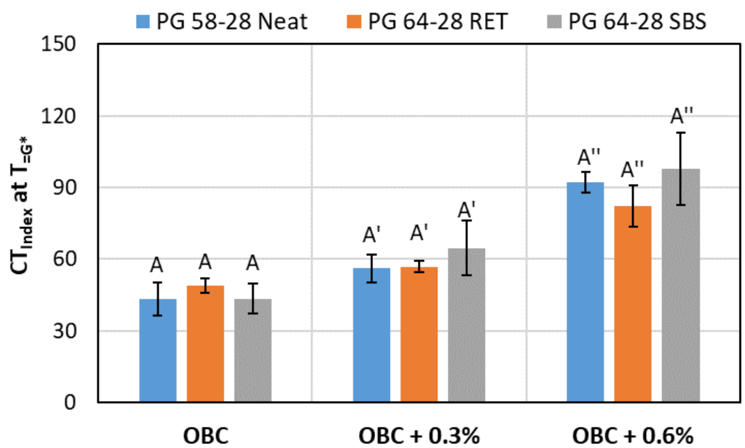
4.2 IDEAL-CT AND I-FIT RESULTS FOR PMA VERSUS UNMODIFIED MIXTURES AT $T_{=G^*}$

This section presents the IDEAL-CT and I-FIT results of the Alabama and Wisconsin mixtures at $T_{=G^*}$. All the results are presented using column charts, where the columns represent the average CT_{Index} and FI values and the error bars represent one plus and minus standard deviation among the replicates. For data analysis, both the mean value analysis and the Games-Howell post-hoc group analysis at a significance level of 0.05 were conducted to compare the results of mixtures prepared with the same mix design, virgin binders formulated with the same base binder, and the same binder content, to isolate the impact of polymer modification from other confounding factors. The capital letters shown above the columns represent the group analysis results, where mixtures sharing the same letter had no statistically significant difference among their test results. The letters A, A', and A'' represent the group analysis results of mixtures at the volumetric OBC, OBC+0.3%, and OBC +0.6%, respectively.

Figure 15 presents the IDEAL-CT results of the Alabama mixtures at $T_{=G^*}$. As shown in Figure 15(a), the PG 64-22 unmodified mixture had similar or slightly higher average CT_{Index} than the two PG 76-22 PMA modified mixtures at all three binder contents. These differences, however, were not statistically significant based on the statistical group analysis. A similar trend was observed in the results in Figure 15(b), where the PG 58-28 unmodified mixture and the two PG 64-28 PMA modified mixtures had statistically equivalent CT_{Index} results at $T_{=G^*}$. Overall, these results indicated that *testing at $T_{=G^*}$ did not discriminate the IDEAL-CT results of the Alabama mixtures containing unmodified, RET-modified, and SBS-modified binders*.



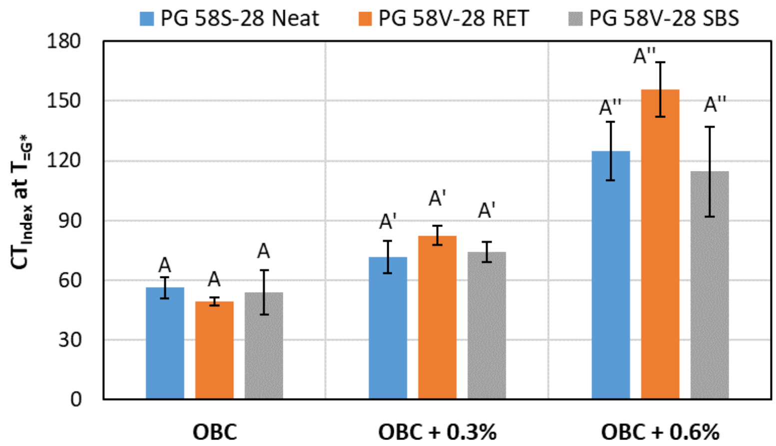
(a)



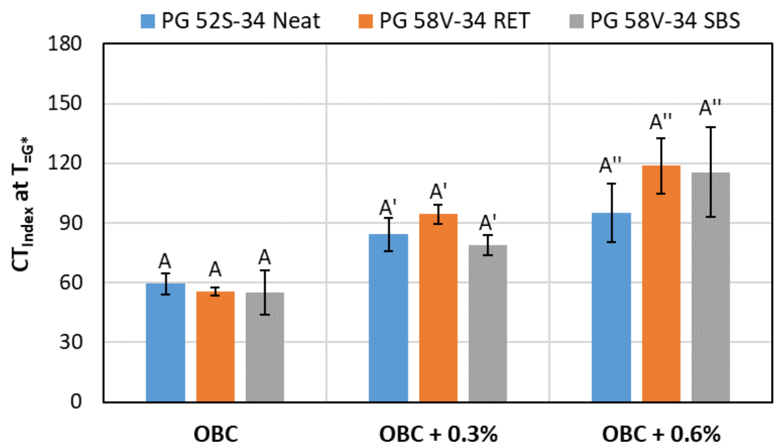
(b)

Figure 15. IDEAL-CT CT_{Index} Results of Alabama Mixtures at $T_{=G*}$; (a) Mixtures with PG 64-22 Unmodified, PG 76-22 RET-modified, and PG 76-22 SBS-modified Binders, (b) Mixtures with PG 58-28 Unmodified, PG 64-28 RET-modified, and PG 64-28 SBS-modified Binders

Figure 16 presents the IDEAL-CT results of the Wisconsin mixtures at $T_{=G*}$. For both sets of virgin binders [PG xx-28 for Figure 16(a) and PG xx-34 for Figure 16(b)], the unmodified mixture and the two PMA mixtures had statistically equivalent CT_{Index} results if the test variability was considered, which indicated that *testing at $T_{=G*}$ did not discriminate the IDEAL-CT results of the Wisconsin mixtures containing unmodified, RET-modified, and SBS-modified binders*. This finding was consistent with the Alabama results in Figure 15.



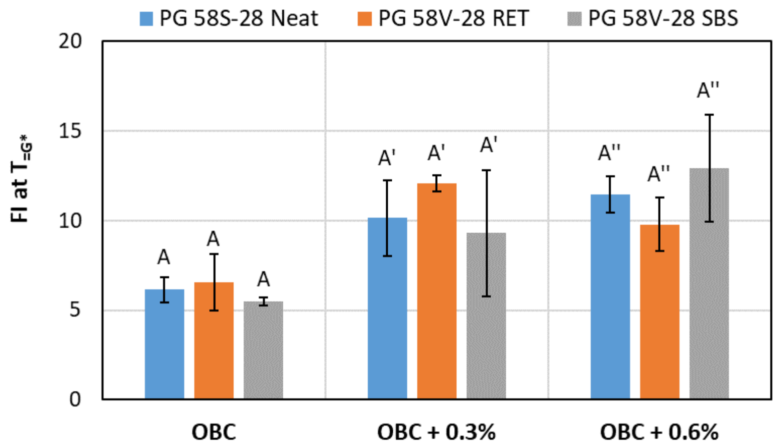
(a)



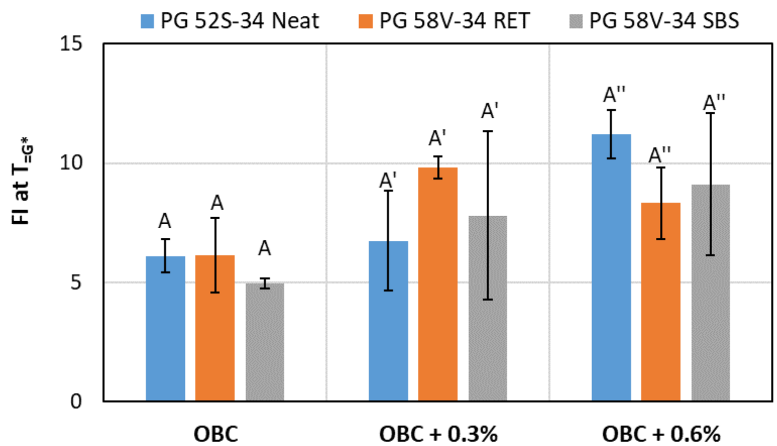
(b)

Figure 16. IDEAL-CT CT_{Index} Results of Wisconsin Mixtures at $T_{=G*}$; (a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

Figure 17 presents the I-FIT results of the Wisconsin mixtures at $T_{=G*}$. For all the mixtures, the average FI generally increased as the binder content increased, which indicated improved intermediate-temperature cracking resistance at higher binder contents. However, for both sets of virgin binders [PG xx-28 for Figure 17(a) and PG xx-34 for Figure 17(b)], the unmodified, RET-modified, and SBS-modified mixtures had statistically equivalent FI results if the test variable was considered. Overall, these results showed that *testing at $T_{=G*}$ did not discriminate the I-FIT results of the Wisconsin mixtures containing unmodified versus PMA binders*.



(a)



(b)

Figure 17. I-FIT FI Results of Wisconsin Mixtures at $T_{=G^*}$; (a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

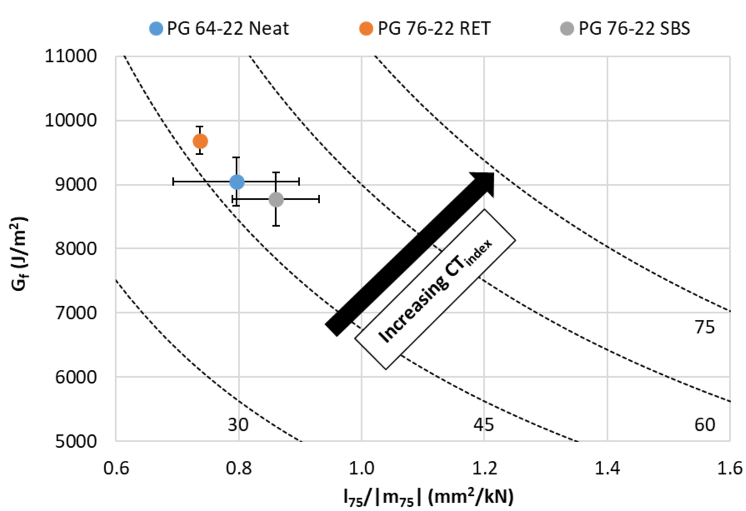
In summary, the results in Figure 15 through Figure 17 indicated that testing IDEAL-CT and I-FIT at $T_{=G^*}$ over 25°C did not help demonstrate the impact of polymer modification on improving the intermediate-temperature cracking resistance of asphalt mixtures evaluated in the study. Therefore, Hypothesis 2 of the study, "*the IDEAL-CT and I-FIT must be conducted at an equal stiffness condition to properly demonstrate the benefits of polymer modification*," was rejected.

CHAPTER 5: IDEAL-CT AND I-FIT INTERACTION DIAGRAM ANALYSIS RESULTS

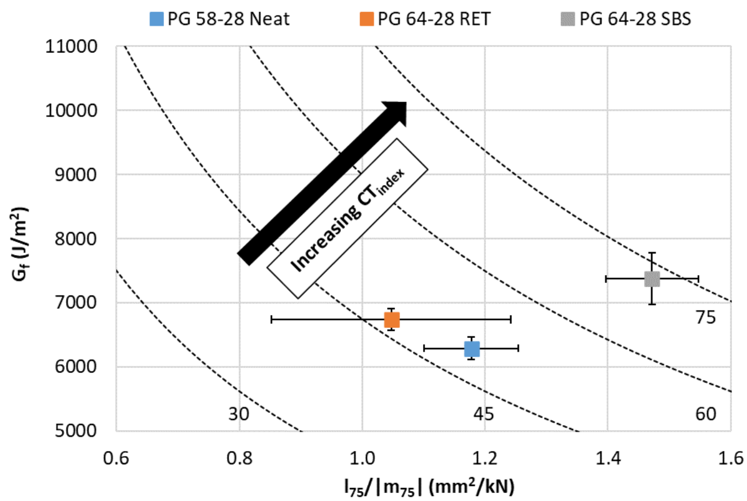
This chapter presents the interaction diagram analysis of the IDEAL-CT and I-FIT results for the Alabama and Wisconsin mixtures at the volumetric OBC. The interaction diagram analysis provides a more comprehensive interpretation of the IDEAL-CT and I-FIT results by considering mixture toughness, brittleness, and their interactions on the intermediate-temperature cracking resistance than solely relying on the CT_{Index} and FI parameters. More details about the development of the interaction diagram analysis for the IDEAL-CT results can be found in Chen et al. (2022) and Yin et al. (2022). Similar with the previous analyses discussed in Chapter 3 and Chapter 4, the interaction diagram analysis focused on comparing mixtures containing PMA versus unmodified binders with the same base binder to isolate the impact of polymer modification from potential confounding factors such as mix design and base binder.

5.1 IDEAL-CT RESULTS OF ALABAMA MIXTURES

Figure 18 presents the IDEAL-CT interaction diagram analysis results of the Alabama mixtures at 25°C. The diagram is developed by plotting the G_f results of the mixtures on the y-axis against the l_{75}-over-$|m_{75}|$ ratio ($l_{75}/|m_{75}|$) results on the x-axis. The error bars represent one standard deviation of the G_f and $l_{75}/|m_{75}|$ results among the replicates. G_f indicates mixture toughness and $l_{75}/|m_{75}|$ reflects the relative ductile-brittle behavior of the mixture. According to Equation 1, increasing G_f and $l_{75}/|m_{75}|$ will result in a higher CT_{Index}. Therefore, asphalt mixtures with higher CT_{Index} will be located closer to the upper right corner of the interaction diagram with higher G_f and $l_{75}/|m_{75}|$ values than those with lower CT_{Index}. The arrow in the figure indicates the direction of increasing CT_{Index}. The diagram also includes a series of CT_{Index} contour curves that connect the two interim IDEAL-CT paraments (i.e., G_f and $l_{75}/|m_{75}|$) to the final cracking index parameter, CT_{Index}. Data points on each contour curve have the same CT_{Index} value but different G_f and $l_{75}/|m_{75}|$ results.



(a)



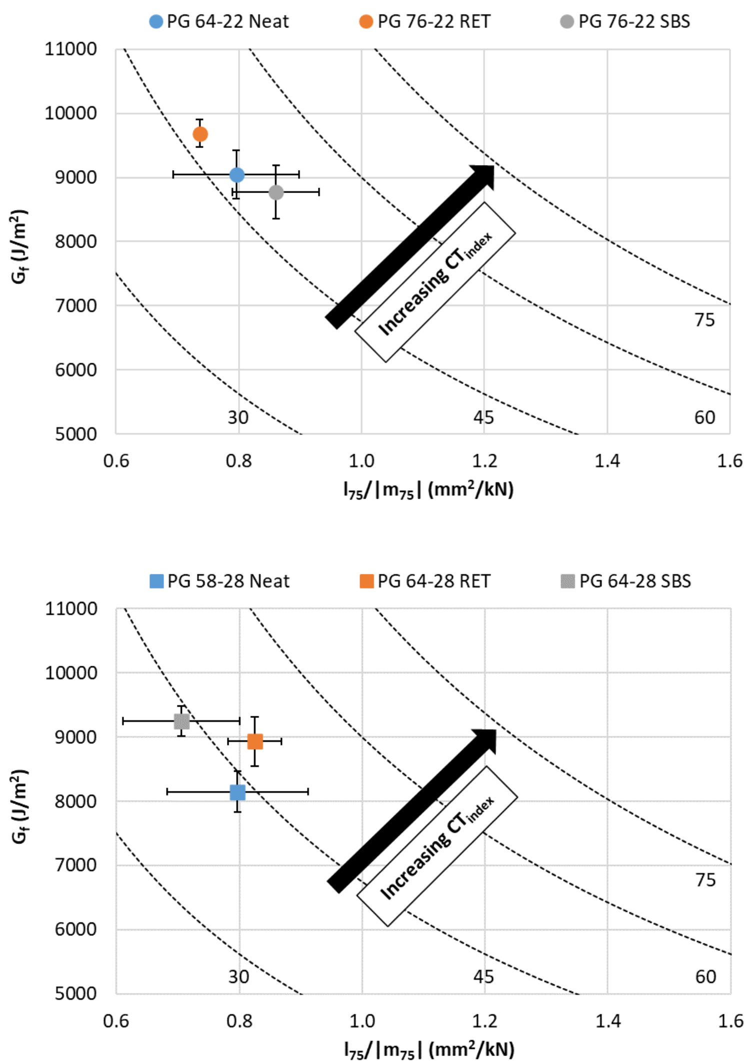
(b)

Figure 18. IDEAL-CT Interaction Diagram of Alabama Mixtures at 25°C; a) Mixtures with PG 64-22 Unmodified, PG 76-22 RET-modified, and PG 76-22 SBS-modified Binders, (b) Mixtures with PG 58-28 Unmodified, PG 64-28 RET-modified, and PG 64-28 SBS-modified Binders

The results in Figure 18(a) show that the direction of asphalt modification with RET and SBS on the IDEAL-CT results of the PG 64-22 unmodified mixture on the interaction diagram was almost perpendicular to the direction of increasing CT_{Index}. Specifically, the PG 76-22 RET-modified mixture had a higher average G_f but a lower average $l_{75}/|m_{75}|$ than the PG 64-22 unmodified mixture while the PG 76-22 SBS-modified mixture showed the opposite trend. Nevertheless, in both cases, the changes in the IDEAL-CT results for the PMA mixtures from the unmodified mixture moved along a generally parallel direction with the CT_{Index} contour curves, which indicated that the changes in the G_f and $l_{75}/|m_{75}|$ results due to polymer modification tended to offset each other in terms of their impacts on the CT_{Index}. These observations explain the results in Figure 11(a) that the PG 64-22 unmodified, PG 76-22 RET-modified, and PG 76-22 SBS-modified mixtures had almost identical average CT_{Index} values at the volumetric OBC. Statistical group analysis indicated that the differences in the G_f and $l_{75}/|m_{75}|$ results of the PMA versus unmodified mixtures were not significant if the test variability was considered.

The results in Figure 18(b) show that the direction of change in the IDEAL-CT results due to RET modification of the PG 58-28 virgin binder on the interaction diagram was almost perpendicular to the direction of increasing CT_{Index}. Therefore, the PG 64-28 RET-modified mixture had a higher average G_f (statistically significant) and a lower average $l_{75}/|m_{75}|$ (not statistically significant) than the PG 58-28 unmodified mixture, but the two mixtures had similar average CT_{Index} values. The impact of SBS modification, on the other hand, showed a different trend as it moved the IDEAL-CT results of the PG 58-28 unmodified mixture along the direction of increasing CT_{Index} on the interaction diagram. Specifically, the PG 64-28 SBS-modified mixture had a higher average G_f and $l_{75}/|m_{75}|$ (both are statistically significant) than the PG 58-28 unmodified mixture and thus, was located on a significantly higher CT_{Index} contour curve on the interaction diagram.

Figure 19 presents the IDEAL-CT interaction diagram results of the Alabama mixtures at $T_{=G^*}$. For both sets of virgin binders with the same base binder (PG 64-22 for Set 1 and PG 58-28 for Set 2), the direction of change in the average IDEAL-CT results due to RET and SBS modifications on the interaction diagram was almost perpendicular to the direction of increasing CT_{Index}. As a result, the PMA and unmodified mixtures with the same base binder fell on contour curves with similar CT_{Index} values.



(a)

(b)

Figure 19. IDEAL-CT Interaction Diagram of Alabama Mixtures at $T_{=G^*}$; a) Mixtures with PG 64-22 Unmodified, PG 76-22 RET-modified, and PG 76-22 SBS-modified Binders, (b) Mixtures with PG 58-28 Unmodified, PG 64-28 RET-modified, and PG 64-28 SBS-modified Binders

5.2 IDEAL-CT RESULTS OF WISCONSIN MIXTURES

Figure 20 presents the IDEAL-CT interaction diagram analysis results of the Wisconsin mixtures at 25°C. As shown in Figure 20(a), asphalt modification with RET and SBS did not significantly affect the G_f and

$I_{75}/|m_{75}|$ results of the PG 58S-28 unmodified mixture if the test variability was considered. As a result, the three mixtures were located close to each other on the interaction diagram with the average CT_{Index} varying between 55 and 61. The results in Figure 20(b) show that polymer modification of the softer PG 52S-34 virgin binder yielded PMA mixtures with notably higher average G_f (statistically significant) and lower average $I_{75}/|m_{75}|$ (statistically significant for SBS modification but not significant for RET modification). Nevertheless, the direction of these changes in the IDEAL-CT results on the interaction diagram was almost perpendicular to the direction of increasing CT_{Index}, which indicated that the impact of polymer modification on the IDEAL-CT G_f and $I_{75}/|m_{75}|$ results tended to offset each other in terms of their impacts on the CT_{Index}. As a result, the unmodified and PMA mixtures had similar average CT_{Index} values, as previously discussed in Figure 12(b).

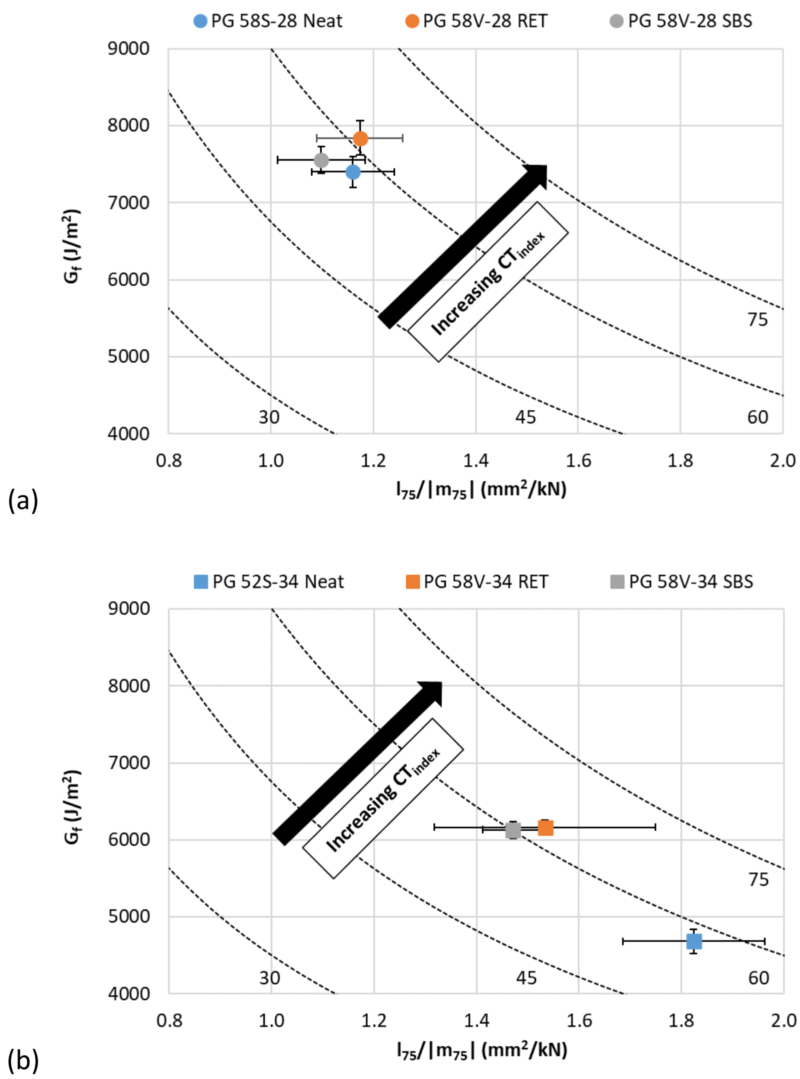
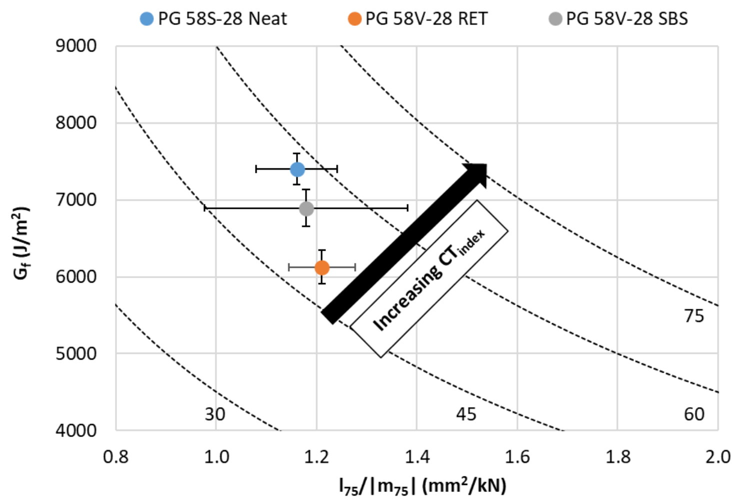
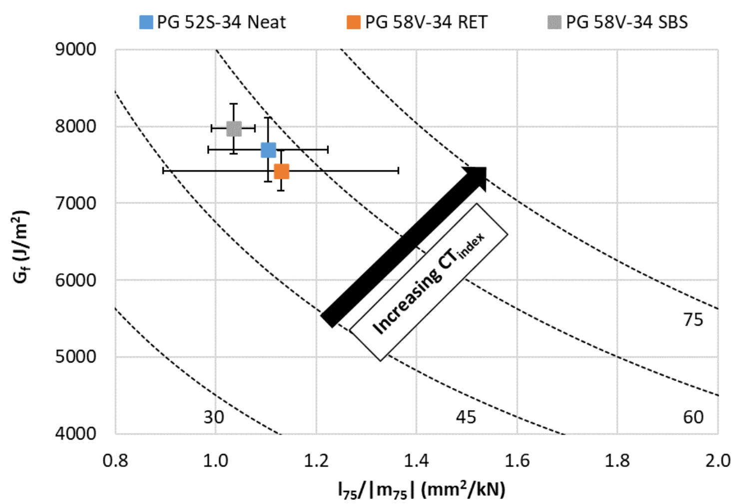


Figure 20. IDEAL-CT Interaction Diagram of Wisconsin Mixtures at 25°C; a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

Figure 21 presents the IDEAL-CT interaction diagram analysis results of the Wisconsin mixtures at $T_{=G*}$. The results in Figure 21(a) show that asphalt modification with RET and SBS significantly decreased the G_f but did not change the $l_{75}/|m_{75}|$ of the PG 58S-28 unmodified mixture. As a result, the two PMA mixtures were located under the unmodified mixture on the diagram and fell on contour curves of lower CT_{Index}. However, the differences in the CT_{Index} results of these mixtures were not statistically significant [as previously discussed in Figure 16(a)] if the test variability was considered. The results in Figure 21(b) show that polymer modification did not significantly affect the G_f or $l_{75}/|m_{75}|$ results of the PG 52S-34 unmodified mixture when the test was conducted at $T_{=G*}$. Therefore, the resultant PMA mixtures and the unmodified mixture fell on similar CT_{Index} contour curves on the interaction diagram.



(a)



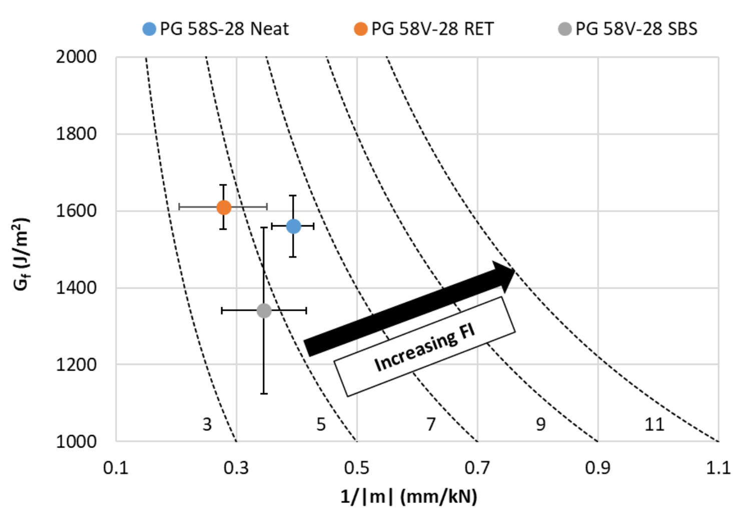
(b)

Figure 21. IDEAL-CT Interaction Diagram of Wisconsin Mixtures at $T_{=G*}$; a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

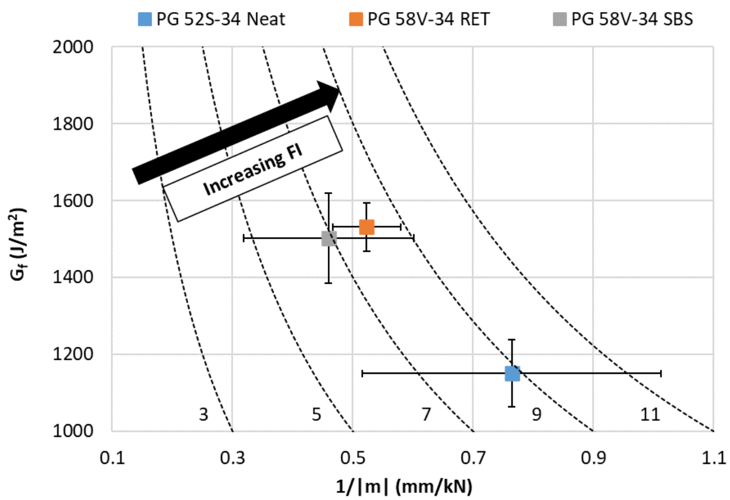
5.3 I-FIT RESULTS OF WISCONSIN MIXTURES

Figure 22 presents the I-FIT interaction diagram analysis results of the Wisconsin mixtures at 25°C. Similar with the IDEAL-CT diagram, the I-FIT diagram is developed by plotting the G_f results on the y-axis against the multiplicative inverse of the $|m|$ ($1/|m|$) results on the x-axis. The error bars represent one standard deviation of the G_f and $1/|m|$ results among the replicates. G_f indicates mixture toughness and $1/|m|$ reflects the relative ductile-brittle behavior of the mixture. According to Equation 2, increasing G_f and $1/|m|$ will increase the FI. Therefore, asphalt mixtures with higher FI will be located closer to the upper right corner of the interaction diagram with higher G_f and $1/|m|$ values than those with lower FI. The arrow in the figure indicates the direction of increasing FI on the interaction diagram. The diagram also includes a series of FI contour curves that connect the two interim I-FIT paraments (i.e., G_f and $1/|m|$) to the final cracking index parameter, FI. Data points on each contour curve have the same FI value but different G_f and $1/|m|$ results.

As shown in Figure 22(a), the PG 58V-28 RET-modified mixture had a slightly higher average G_f and a considerably lower average $1/|m|$ than the PG 58S-28 unmodified mixture, while the PG 58V-28 SBS-modified mixture had noticeably lower average G_f and $1/|m|$ than the PG 58S-28 unmodified mixture. As a result, the two PMA mixtures fell on lower FI contour curves than the unmodified mixture. Nevertheless, the differences in the G_f, $1/|m|$, and FI results between the two PMA mixtures and the unmodified mixture were not statistically significant if the test variability was considered. The results in Figure 22(b) show that polymer modification increased the average G_f (statistically significant) and decreased the average $1/|m|$ (not statistically significant) of the PG 52S-34 unmodified mixture, indicating increased toughness and brittleness. These changes, however, tended to offset each other in terms of their impacts on the FI. As a result, the PMA and unmodified mixtures fell between the two contour curves corresponding to an average FI of 7 and 9. As previously discussed in Figure 13(b), these differences were not statistically significant if the test variability was considered.



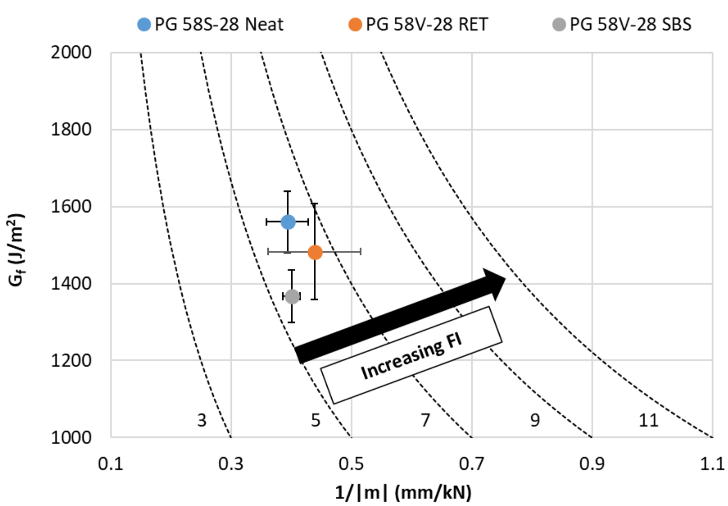
(a)



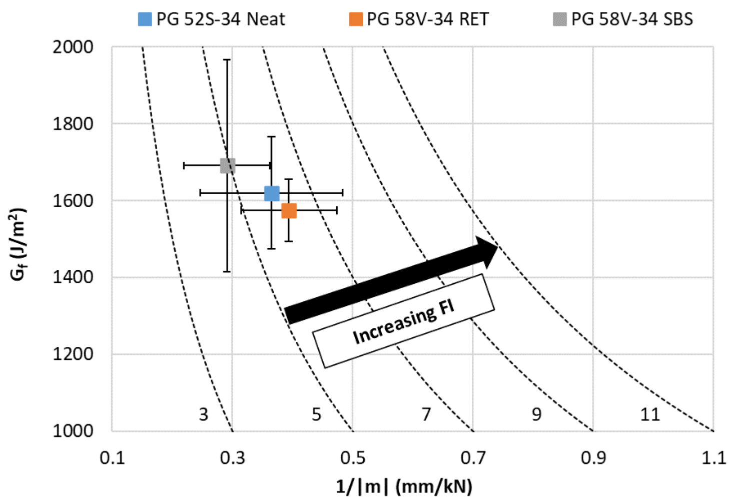
(b)

Figure 22. I-FIT Interaction Diagram of Wisconsin Mixtures at 25°C; a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

Figure 23 presents the I-FIT interaction diagram analysis results of the Wisconsin mixtures at $T_{=G*}$. For both sets of virgin binders with the same base binder (PG 58S-28 for Set 1 and PG 52S-34 for Set 2), polymer modification did not significantly affect the G_f and $1/|m|$ results of the mixtures when the test was conducted at $T_{=G*}$. As a result, all the mixtures fell between two contour curves corresponding to an average FI of 5 and 7. Because of the test variability, the FI results of these mixtures were not statistically significant.



(a)



(b)

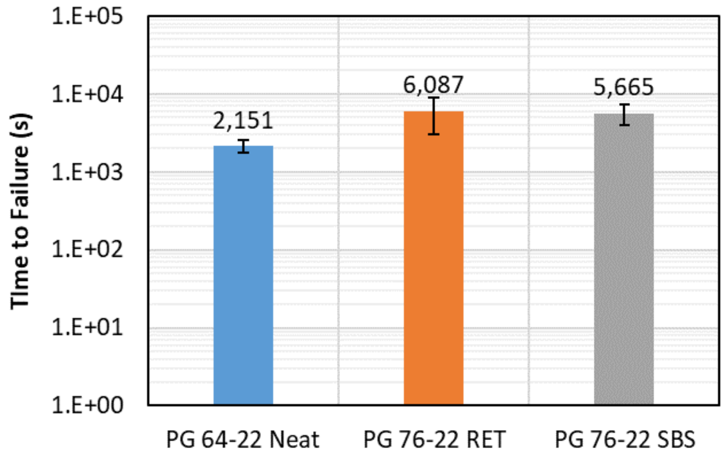
Figure 23. I-FIT Interaction Diagram of Wisconsin Mixtures at $T_{=G*}$; a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

CHAPTER 6: SUPPLEMENTARY CYCLIC FATIGUE TEST RESULTS

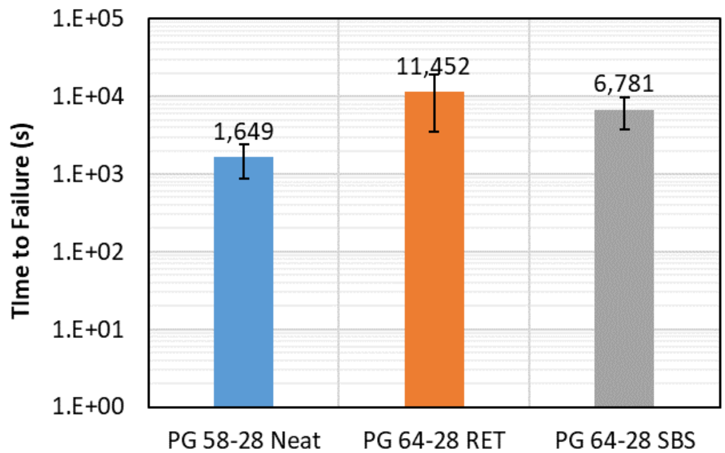
This chapter presents the results of the TB Fatigue test and the LAS test. These two tests were conducted to supplement the IDEAL-CT and I-FIT in evaluating the impact of polymer modification on the fatigue resistance of asphalt binders and mixtures under a cyclic loading condition. The TB Fatigue test was conducted on 12 mixtures, which corresponded to a combination of two mix designs and six virgin binders per mix design (including two unmodified, two RET-modified, and two SBS-modified binders). Each mixture was tested at the volumetric OBC only. The LAS test was conducted on the asphalt binders extracted from the same 12 mixtures. The extracted binders were tested as recovered to mimic the same aging condition of the mixtures. As with the IDEAL-CT and I-FIT results discussed previously, data analysis of the TB Fatigue and LAS test results was conducted to compare the mixtures (and the corresponding extracted binders) prepared with the same mix design and virgin binders formulated with the same base binder to isolate the impact of polymer modification from other confounding factors.

6.1 TORSION BAR FATIGUE TEST RESULTS

Figure 24 presents the TB Fatigue test results, in terms of t_f, of the Alabama mixtures containing two sets of virgin binders: one with a PG xx-22 grade and the other with a PG xx-28 grade. In both cases, asphalt modification with SBS and RET yielded notably higher average t_f results, which indicated improved fatigue resistance. The improvement from polymer modification, especially for that with RET, was more pronounced for the PG 58-28 unmodified mixture than the PG 64-22 unmodified mixture. A similar trend was observed for the Wisconsin mixture results in Figure 25. For both sets of virgin binders, the RET- and SBS-modified binders had considerably higher average t_f results and thus, were expected to have better fatigue resistance than the unmodified mixture. *Overall, the TB Fatigue test results in Figure 24 and Figure 25 demonstrated the impact of polymer modification on improving the fatigue resistance of asphalt mixtures, which disagreed with the IDEAL-CT and I-FIT results discussed in Chapter 3 and Chapter 4*. This discrepancy is possibly because that the TB Fatigue test is a cyclic loading test while the IDEAL-CT or I-FIT is a monotonic loading test. In this case, the improved elasticity and stress relaxation properties of PMA over unmodified mixtures can be better discriminated under a cyclic loading condition than a monotonic one.

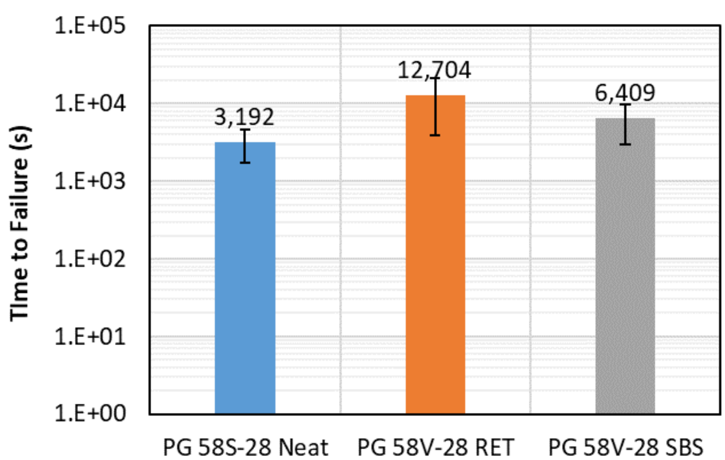


(a)

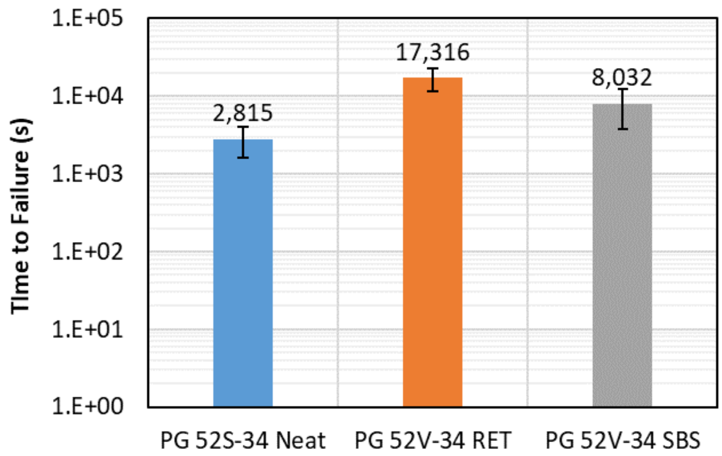


(b)

Figure 24. TB Fatigue Test Results of Alabama Mixtures; (a) Mixtures with PG 64-22 Unmodified, PG 76-22 RET-modified, and PG 76-22 SBS-modified Binders, (b) Mixtures with PG 58-28 Unmodified, PG 64-28 RET-modified, and PG 64-28 SBS-modified Binders



(a)



(b)

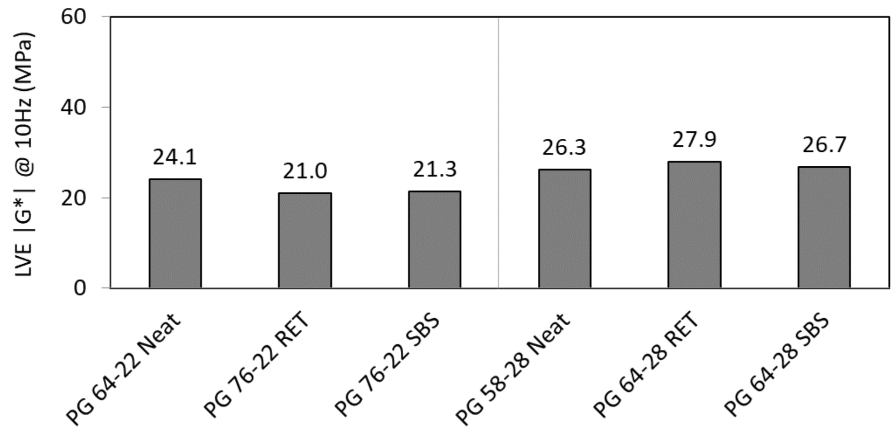
Figure 25. TB Fatigue Test Results of Wisconsin Mixtures; (a) Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders, (b) Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders

6.2 LINEAR AMPLITUDE SWEEP TEST RESULTS

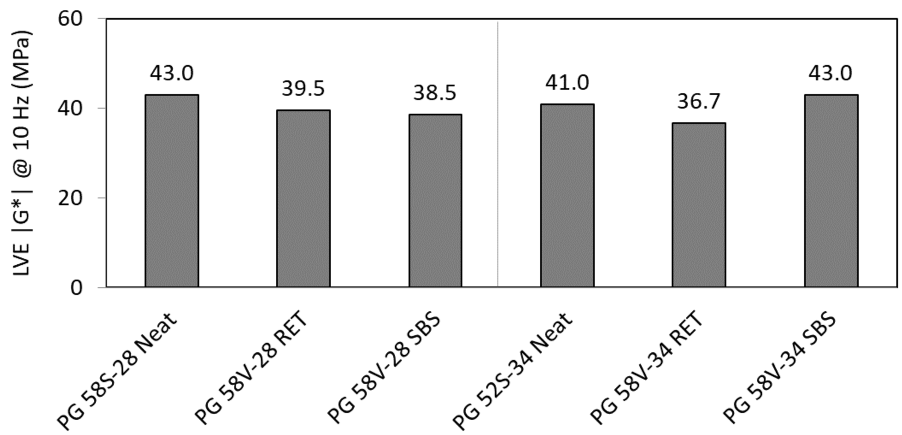
Table 5 summarizes the LAS test temperatures of asphalt binders extracted and recovered from the Alabama and Wisconsin mixtures at the volumetric OBC. According to Safaei and Castorena (2016), cohesive fatigue cracking occurs within the asphalt binder during the LAS test if the test temperature is selected when the linear viscoelastic (LVE) dynamic shear modulus ($|G^*|$) of the binder falls between 12 and 60 MPa at a loading frequency of 10 Hz. As shown in Figure 26, all the extracted binders from the Alabama and Wisconsin mixtures binders had similar LVE $|G^*|$ values within the 12- to 60-MPa range at their selected test temperatures (Table 5).

Table 5. LAS Test Temperatures of Extracted Asphalt Binders from Alabama and Wisconsin Mixtures

Mix Design	Virgin Binder Grade & Type	LAS Test Temperature (°C)
Alabama	PG 64-22 Neat	20
	PG 76-22 RET	
	PG 76-22 SBS	
	PG 58-28 Neat	15
	PG 64-28 RET	
	PG 64-28 SBS	
Wisconsin	PG 58S-28 Neat	10
	PG 58V-28 RET	
	PG 58V-28 SBS	
	PG 52S-34 Neat	5
	PG 58V-34 RET	
	PG 58V-34 SBS	



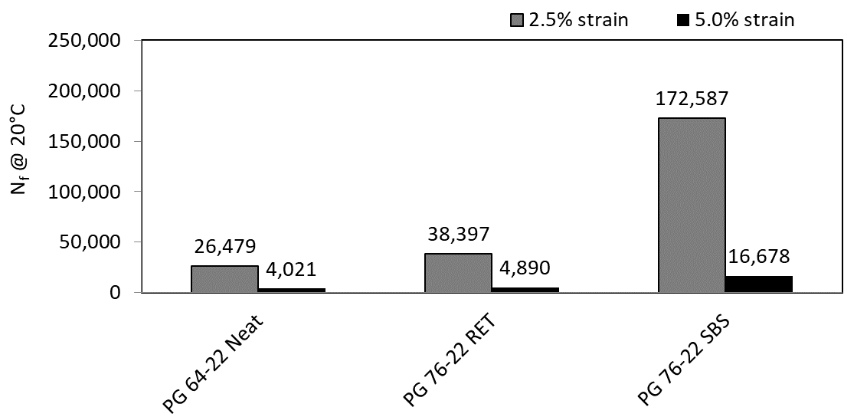
(a)



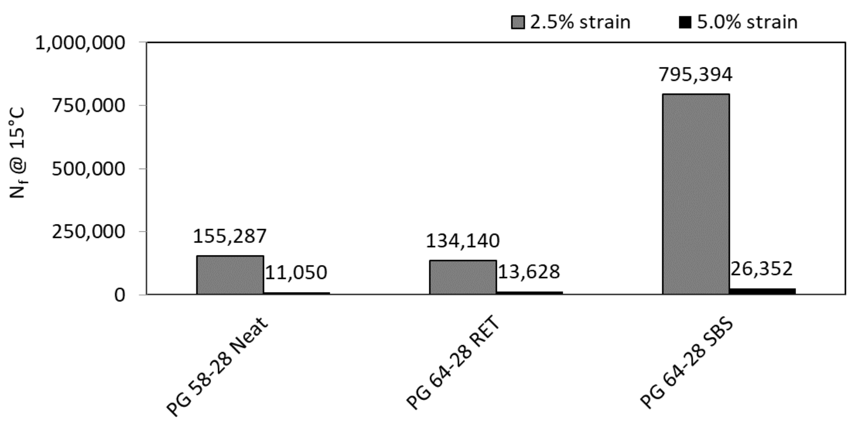
(b)

Figure 26. LVE |*G| @ 10Hz Results of Extracted Asphalt Binders from (a) Alabama Mixtures and (b) Wisconsin Mixtures at the Selected LAS Test Temperatures**

Figure 27 and Figure 28 present the LAS N_f results of asphalt binders extracted from the Alabama and Wisconsin mixtures, respectively. For both sets of the Alabama binders (Figure 27), SBS modification significantly improved the fatigue resistance of the extracted binders at the 2.5% and 5.0% strain levels, as indicated by higher N_f values. RET modification increased the N_f of the extracted binder from the PG 58-28 unmodified mixture only at the 5.0% strain level, while for the extracted binder from the PG 64-22 unmodified mixture, an increase in N_f was observed at both strain levels. For the Wisconsin extracted binders (Figure 28), both SBS and RET modifications significantly increased the N_f of the extracted binders at the 2.5% and 5.0% strain levels.

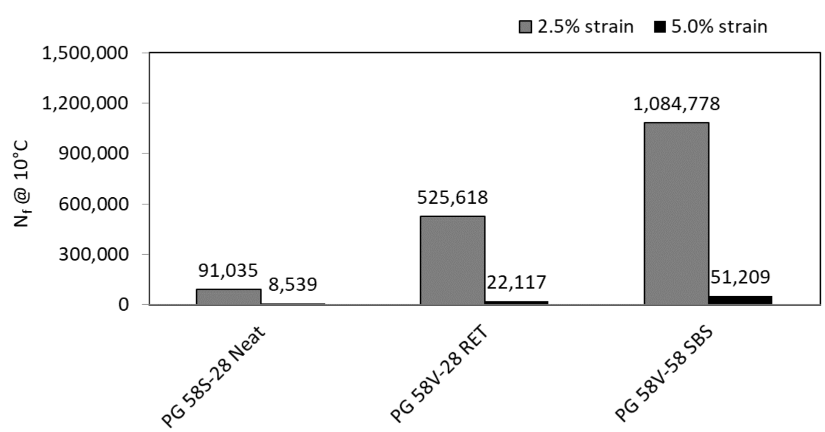


(a)

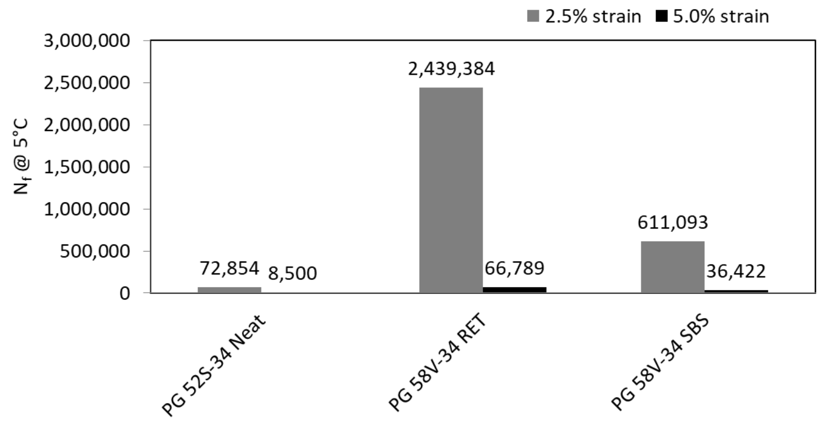


(b)

Figure 27. LAS N_f Results of Alabama Extracted Binders from (a) Mixtures with PG xx-22 Virgin Binders (using PG 64-22 Base Binder for Polymer Modification) and (b) Mixtures with PG xx-28 Virgin Binders (using PG 58-28 Base Binder for Polymer Modification)



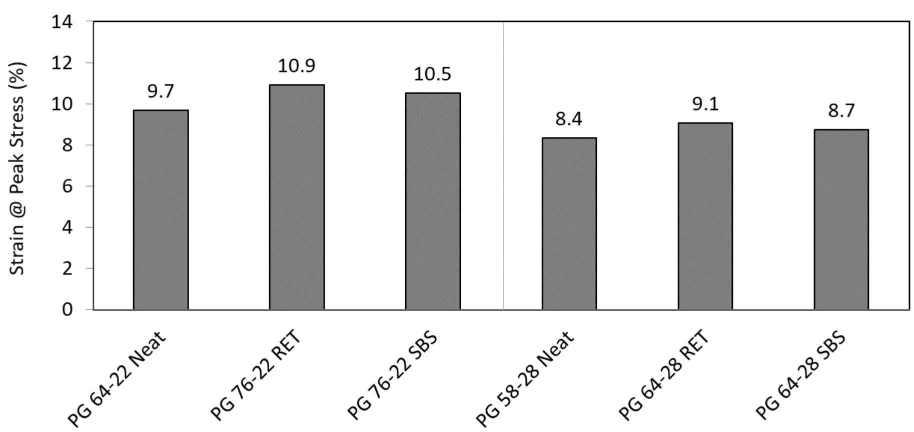
(a)



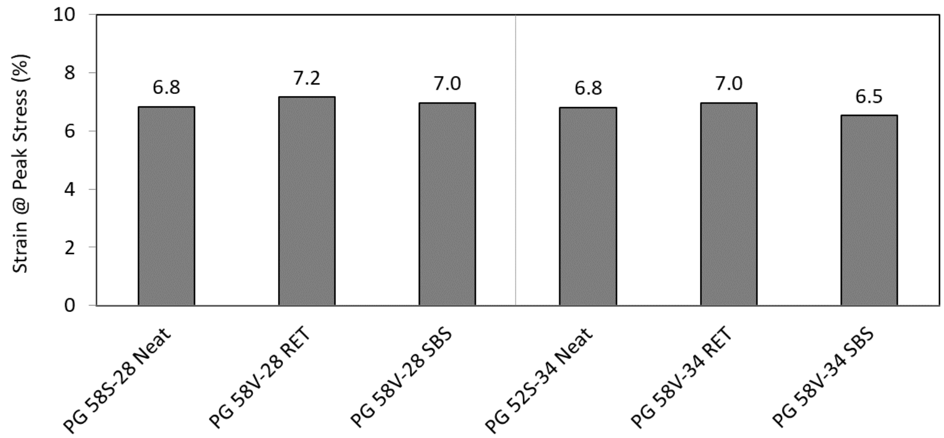
(b)

Figure 28. LAS N_f Results of Wisconsin Extracted Binders from (a) Mixtures with PG xx-28 Virgin Binders (using PG 58S-28 Base Binder for Polymer Modification) and (b) Mixtures with PG xx-34 Virgin Binders (using PG 52S-34 Base Binder for Polymer Modification)

In addition to a higher N_f, a higher strain at the maximum level of stress is believed to be beneficial as it indicates that the binder can better relax stresses induced by traffic loading. Figure 29 presents the strain-at-peak-stress results of the extracted binders from the Alabama and Wisconsin mixtures at the volumetric OBC. In all cases except one, polymer modification with RET and SBS increased the average strain-at-peak-stress results of the extracted binders, indicating potential improved stress relaxation properties.



(a)



(b)

Figure 29. LAS Strain-at-Peak-Stress Results of Extracted Asphalt Binders from (a) Alabama Mixtures and (b) Wisconsin Mixtures

Overall, the LAS test results in Figure 27 through Figure 29 demonstrated the benefits of asphalt modification with RET and SBS in improving the fatigue resistance of asphalt binders extracted and recovered from the Alabama and Wisconsin mixtures. This finding disagreed with the IDEAL-CT and I-FIT results presented in Chapter 3 and Chapter 4, which is possibly due to the different loading conditions of the IDEAL-CT and I-FIT (using monotonic loading) versus the LAS test (using cyclic loading).

CHAPTER 7: BINDER-MIXTURE CORRELATION ANALYSIS RESULTS

This chapter presents the rheological characterization results of asphalt binders extracted from the Alabama and Wisconsin mixtures at the volumetric OBC, which cover the Superpave PG, ΔT_c, %R, J_{nr}, *G-R* parameter, ω_c, and R-value. All the extracted binders were tested at two aging conditions: 1) as recovered without additional RTFO or PAV aging, and 2) after 20 hours of PAV aging at 100°C. The results were analyzed by comparing the unmodified and PMA mixtures prepared with the same mix design and virgin binders formulated with the same base binder to isolate the impact of polymer modification from other confounding factors. This chapter also presents the correlation analysis results for CT_{Index} and FI versus various binder rheological parameters based on the test results in the study.

7.1 EXTRACTED BINDER TEST RESULTS

7.1.1 Superpave PG and ΔT_c

Table 6 presents the Superpave PG and ΔT_c results of asphalt binders extracted from the two sets of Alabama mixtures containing different virgin binders; Set 1 includes the PG 64-22 neat, PG 76-22 RET-modified, and PG 76-22 SBS-modified binders, and Set 2 includes the PG 58-28 neat, PG 64-28 RET-modified, and PG 64-28 SBS-modified binders. All binders were tested as recovered without additional RTFO or PAV aging. For both sets of mixtures, RET and SBS modification of the virgin binder increased the high-temperature PG of the extracted binder by 6°C, indicating potentially improved rutting resistance. Furthermore, the extracted binders from the SBS and RET-modified mixtures had the same low-temperature PG (determined using the 4-mm DSR geometry approach) as the corresponding binder extracted from the unmodified mixture. Furthermore, the extracted binders containing PMA binders had similar ΔT_c values (less than 1.0°C difference) as those containing the unmodified binders, which indicated comparable stress relaxation properties at the as-recovered condition. It is worth noting that the extracted binders had different PG from the virgin binders because they included the binder in the RAP and were tested as recovered, while the virgin binders were graded after RTFO and PAV aging per AASHTO M 320.

Table 6. Superpave PG and ΔT_c Results of Asphalt Binders Extracted from Alabama Mixtures (Tested without Additional RTFO or PAV Aging)

Set ID	Virgin Binder Grade & Type	T_{cont}, High (°C)	T_{cont}, Low S (°C)	T_{cont}, Low m-value (°C)	ΔT_c (°C)	Superpave PG
Set 1	PG 64-22 Neat	79.8	-25.9	-26.5	0.6	76-22
	PG 76-22 RET	84.0	-26.1	-27.0	0.9	82-22
	PG 76-22 SBS	86.1	-27.0	-26.6	-0.4	82-22
Set 2	PG 58-28 Neat	73.6	-28.9	-29.4	0.5	70-28
	PG 64-28 RET	79.3	-29.9	-30.3	0.4	76-28
	PG 64-28 SBS	80.6	-30.6	-30.6	0.0	76-28

Table 7 presents the Superpave low-temperature PG and ΔT_c results of asphalt binders extracted from the Alabama mixtures after 20 hours of PAV aging at 100°C. For the Set 1 mixtures, the extracted binder from the RET-modified mixture had the same low-temperature PG as the binder extracted from the unmodified mixture, while the extracted binder from the SBS-modified mixture had a low-temperature PG that was 6°C lower, indicating potentially improved low-temperature cracking resistance after aging. For the Set 2 mixtures, all the extracted binders had the same low-temperature PG regardless of the virgin binder used. For both sets of the mixtures, the extracted binders from the unmodified and RET-modified mixtures had almost identical ΔT_c values after 20-hour PAV aging, which was approximately 1.0°C higher (less negative) than the extracted binder from the SBS-modified mixture. This could potentially indicate that SBS modification yielded the extracted binder with increased susceptibility to block cracking after oxidative aging due to reduced stress relaxation properties. However, these results should be interpreted with caution because several studies have recognized the limitations of the ΔT_c parameter in evaluating PMA binders (Kluttz, 2019; Elwardany, 2020).

Table 7. Superpave Low-temperature PG and ΔT_c Results of Asphalt Binders Extracted from Alabama Mixtures after 20-hour PAV Aging

Set ID	Virgin Binder Grade & Type	T_{cont}, Low S (°C)	T_{cont}, Low m-value (°C)	ΔT_c (°C)	Superpave Low-temperature PG
Set 1	PG 64-22 Neat	-22.5	-21.9	-0.6	-16
	PG 76-22 RET	-22.5	-21.8	-0.7	-16
	PG 76-22 SBS	-24.5	-22.7	-1.8	-22
Set 2	PG 58-28 Neat	-25.9	-24.5	-1.4	-22
	PG 64-28 RET	-26.2	-24.9	-1.3	-22
	PG 64-28 SBS	-26.9	-24.5	-2.4	-22

Table 8 presents the Superpave PG and ΔT_c results of asphalt binders extracted from the two sets of Wisconsin mixtures containing different virgin binders; Set 1 includes the PG 58S-28 neat, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified binders, and Set 2 includes the PG 52S-34 neat, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified binders. For the Set 1 mixtures, RET modification of the PG 58S-28 virgin binder did not change the high-temperature PG of the extracted binder, while SBS modification increased the high-temperature PG of the extracted binder by 6°C. For the Set 2 mixtures, both RET and SBS modification of the softer PG 52S-34 virgin binder increased the high-temperature PG of the extracted binder by 6°C, indicating potentially improved rutting resistance. Furthermore, the extracted binders from the RET- and SBS-modified mixtures had the same low-temperature PG as the corresponding binder extracted from the unmodified mixture. Similar with the Alabama results in Table 6, for both sets of the Wisconsin mixtures, the extracted binders containing PMA and neat binders had similar ΔT_c values (less than 1.0°C difference).

Table 8. Superpave PG and ΔT_c Results of Asphalt Binders Extracted from Wisconsin Mixtures (Tested without Additional RTFO or PAV Aging)

Set ID	Virgin Binder Grade & Type	T_{cont}, High (°C)	T_{cont}, Low S (°C)	T_{cont}, Low m-value (°C)	ΔT_c (°C)	Superpave PG
Set 1	PG 58S-28 Neat	75.2	-31.5	-31.9	0.4	70-28
	PG 58V-28 RET	81.4	-31.7	-32.1	0.4	76-28
	PG 58V-28 SBS	75.5	-32.7	-32.2	-0.5	70-28
Set 2	PG 52S-34 Neat	66.8	-35.8	-37.0	1.2	64-34
	PG 58V-34 RET	75.6	-36.5	-37.7	1.2	70-34
	PG 58V-34 SBS	73.0	-35.2	-35.6	0.4	70-34

Table 9 presents the Superpave low-temperature PG and ΔT_c results of asphalt binders extracted from the Wisconsin mixtures after 20 hours of PAV aging at 100°C. For both sets of the mixtures, the extracted binders from the PMA modified mixtures had the same low-temperature PG as the corresponding binder extracted from the unmodified mixture. Furthermore, all the extracted binders, regardless of the virgin binder used, had similar ΔT_c values (with no more than 0.4°C difference), indicating comparable stress relaxation properties after 20-hour PAV aging.

Table 9. Superpave Low-temperature PG and ΔT_c Results of Asphalt Binders Extracted from Wisconsin Mixtures after 20-hour PAV Aging

Set ID	Virgin Binder Grade & Type	T_{cont}, Low S (°C)	T_{cont}, Low m-value (°C)	ΔT_c (°C)	Superpave Low-temperature PG
Set 1	PG 58S-28 Neat	-28.0	-25.7	-2.3	-22
	PG 58V-28 RET	-27.8	-25.6	-2.2	-22
	PG 58V-28 SBS	-29.6	-27.3	-2.3	-22
Set 2	PG 52S-34 Neat	-32.0	-31.3	-0.7	-28
	PG 58V-34 RET	-33.4	-32.4	-1.0	-28
	PG 58V-34 SBS	-32.5	-30.7	-1.8	-28

7.1.2 MSCR J_{nr} and %R

Figure 30 presents the MSCR results of asphalt binders extracted from the Alabama mixtures at a test temperature of 64°C. As shown in Figure 30(a), the extracted binders from the PMA mixtures had lower $J_{nr,3.2}$ values than those from the unmodified mixtures, indicating improved rutting resistance due to asphalt modification with RET and SBS. The RET- and SBS-modified binders had similar $J_{nr,3.2}$ values, which agreed with the virgin binder PG results in Table 1. All the asphalt binders extracted from the Alabama mixtures were graded as PG 64E-xx (with the "Extremely Heavy Traffic" Designation) per AASHTO M 332 with exception of the binder extracted from the PG 58-28 mixture, which was graded as PG 64H-xx (with the "Heavy Traffic" designation). The results in Figure 30(b) show that the extracted binders from the PG 64-22 and PG 58-28 unmodified mixtures had small $\%R_{3.2}$ values (13.9% and 5.6%, respectively) at 64°C, indicating that almost all the shear strain accumulated in the MSCR test was non-recoverable. On the other hand, the RET- and SBS-modified binders presented significantly higher $\%R_{3.2}$ values, indicating enhanced binder elasticity due to the polymeric modification.

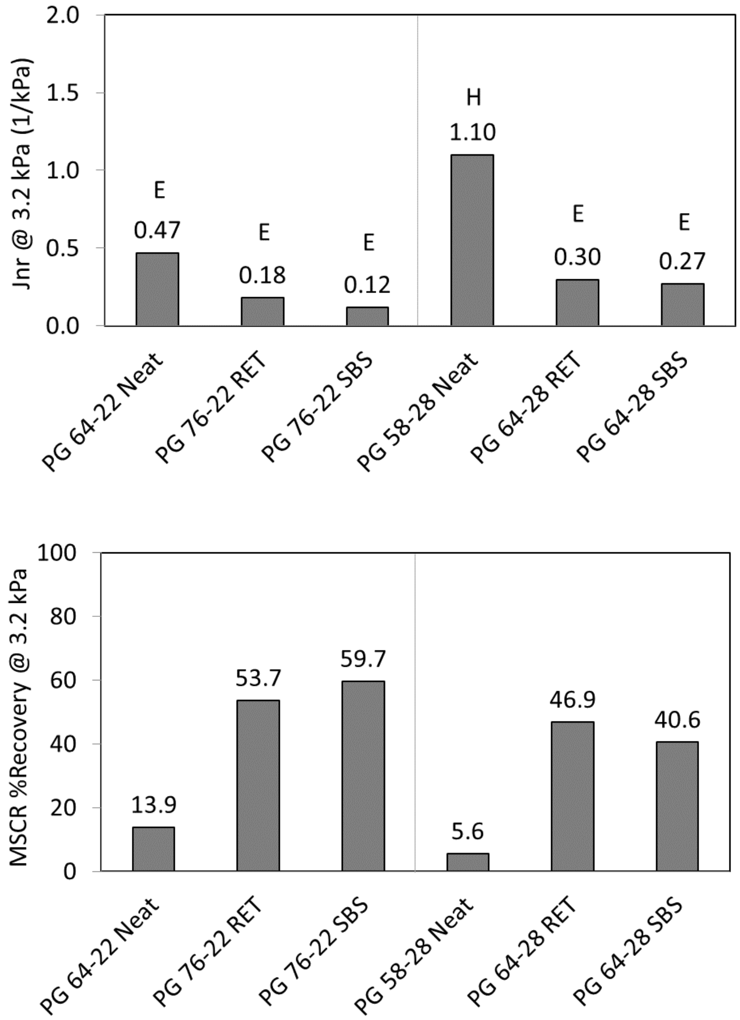


Figure 30. MSCR Results of Asphalt Binders Extracted from Alabama Mixtures at 64°C; (a) $J_{nr3.2}$, (b) $\%R_{3.2}$

Figure 31 presents the MSCR results of asphalt binders extracted from the Wisconsin mixtures at a test temperature of 58°C. For both set of mixtures, the extracted binders from the PMA mixtures showed lower $J_{nr,3.2}$ values than the control binders [Figure 31(a)], indicating improved resistance to rutting. All the asphalt binders extracted from the Wisconsin mixtures were graded as PG 58E-xx (with the "Extremely Heavy Traffic" Designation) per AASHTO M 332, except the binder extracted from the PG 52S-34 unmodified mixture, which was graded to be PG 58V-xx (with the "Heavy Traffic" Designation). The results in Figure 31(b) show that the RET- and SBS-modified binders had significantly higher $\%R_{3.2}$ values than the unmodified binders, indicating enhanced binder elasticity due to the polymeric modification.

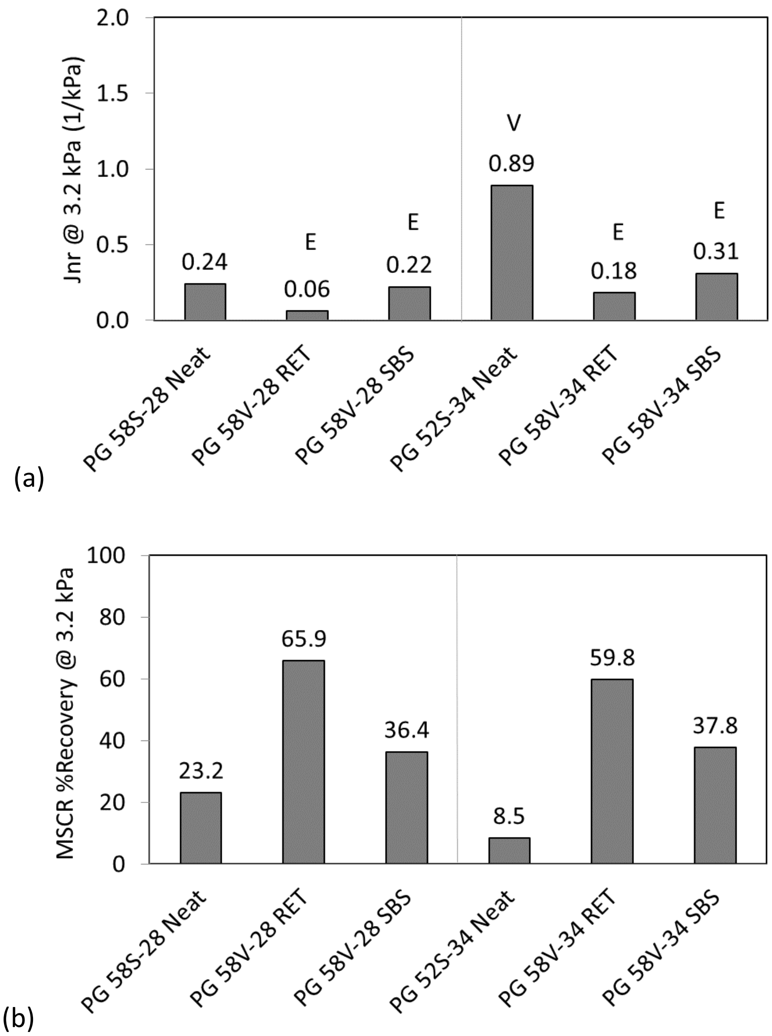


Figure 31. MSCR Results of Asphalt Binders Extracted from Wisconsin Mixtures at 58°C; (a) $J_{nr3.2}$, (b) $\%R_{3.2}$

7.1.3 Glover-Rowe Parameter

Table 10 summarizes the $|G^*|$ and δ at 15°C and 0.005 rad/s, and the *G-R* parameter results of asphalt binders extracted from the Alabama mixtures with and without 20 hours of PAV aging at 100°C. In all cases except one, polymer modification increased the *G-R* parameter of the resultant extracted binder, which was mainly due to the reduced δ after polymer modification with RET and SBS. This stiffening impact was more pronounced at the as-recovered condition than after 20-hour PAV aging. Figure 32 and Figure 33 present the *G-R* parameter results on a Black Space diagram, where the binder $|G^*|$ at 15°C and 0.005 rad/s is plotted on the y-axis *versus* δ at the same condition on the x-axis. The dashed and bold curves represent the two preliminary *G-R* parameter criteria of 180 kPa and 600 kPa for the onset of block cracking and visible surface cracking, respectively. However, it should be noted that these criteria were developed based on a limited number of unmodified binders and a PG 58-28 climate in

Pennsylvania; thus, their applicability to PMA binders and other climates remains unknown and needs further investigation. At the as-recovered condition, the extracted binders from the two PG 76-22 PMA mixtures had higher *G-R* parameter results (mainly due to lower *δ* values) and were located relatively closer to the cracking damage zone on the Black Space diagram [Figure 32(a)] than the extracted binder from the PG 64-22 unmodified mixture. After 20-hour PAV aging, the three extracted binders had similar *G-R* parameter results and fell between the two preliminary damage zone curves on the Black Space diagram, as shown in Figure 32(b). A similar trend was also observed in Figure 33 for the *G-R* parameter results of asphalt binders extracted from the PG 58-28 unmodified, PG 64-28 RET-modified, and PG 64-28 SBS-modified mixtures.

Table 10. |*G| and *δ* at 15°C and 0.005 rad/s and *G-R* Parameter Results of Asphalt Binders Extracted from Alabama Mixtures**

Set ID	Virgin Binder Grade & Type	As Recovered			As Recovered + 20-hour PAV Aging		
		|*G**| (kPa)	*δ* (°)	G-R (kPa)	|*G**| (kPa)	*δ* (°)	G-R (kPa)
Set 1	PG 64-22 Neat	316.4	64.8	63.6	1097.5	57.6	373.5
	PG 76-22 RET	327.6	61.8	83.1	1116.5	55.9	425.0
	PG 76-22 SBS	344.1	60.8	94.1	1000.0	55.5	389.0
Set 2	PG 58-28 Neat	183.4	65.2	35.5	758.5	56.7	274.7
	PG 64-28 RET	181.0	61.5	47.0	668.5	55.6	258.9
	PG 64-28 SBS	194.4	60.9	52.5	784.3	54.5	324.4

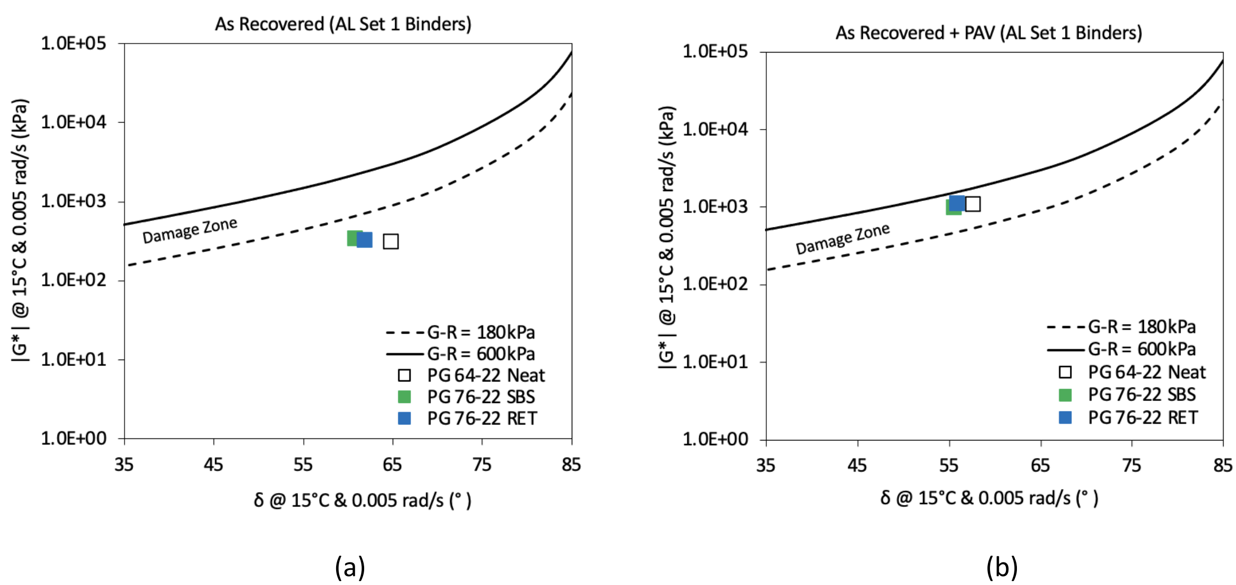


Figure 32. G-R Parameter Results of Asphalt Binders Extracted from Alabama Mixtures with PG 64-22 Unmodified, PG 76-22 RET-modified, and PG 76-22 SBS-modified Binders on a Black Space Diagram; (a) Tested as Recovered, (b) Tested after 20-hour PAV Aging

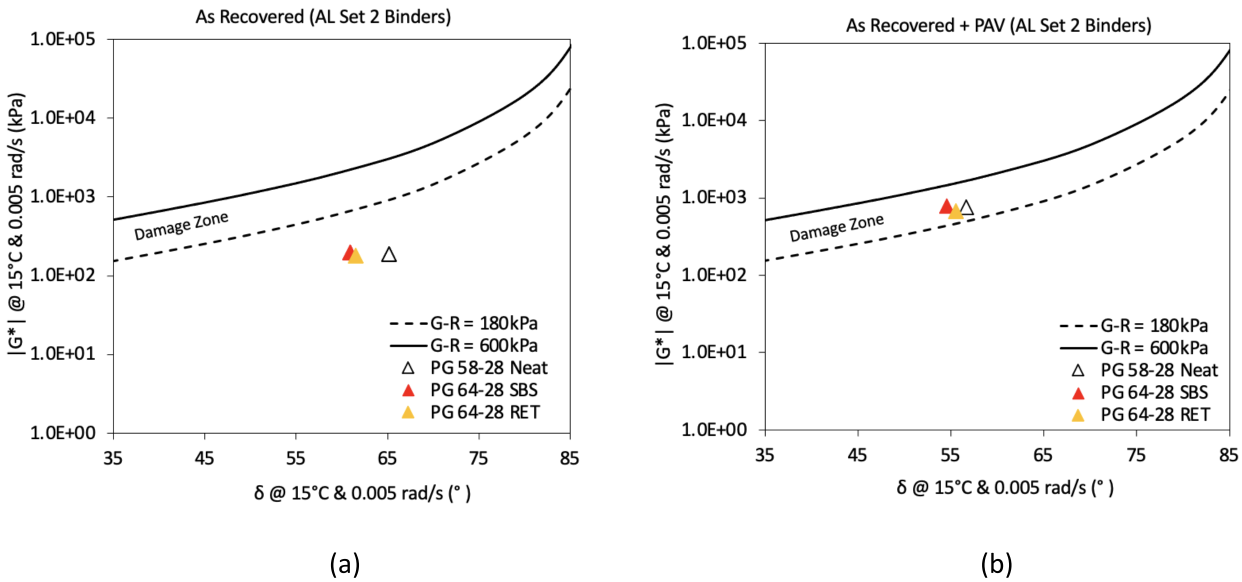


Figure 33. G-R Parameter Results of Asphalt Binders Extracted from Alabama Mixtures with PG 58-28 Unmodified, PG 64-28 RET-modified, and PG 64-28 SBS-modified Binders on a Black Space Diagram; (a) Tested as Recovered, (b) Tested after 20-hour PAV Aging

Table 11 summarizes the $|G^*|$ and δ at 15°C and 0.005 rad/s and the *G-R* parameter results of asphalt binders extracted from the Wisconsin mixtures with and without 20 hours of PAV aging at 100°C. In general, these results showed that asphalt modification with RET and SBS increased the *G-R* parameter of the extracted binders. Figure 34 and Figure 35 presents the *G-R* parameter results on a Black Space diagram. For the Set 1 mixtures (Figure 34), the extracted binder from the PG 58V-28 SBS-modified mixture had lower $|G^*|$ and higher δ values and consequently, lower *G-R* parameter results than the extracted binder from the PG 58S-28 unmodified mixture, at both aging conditions. The extracted binder from the PG 58V-28 RET-modified mixture, however, showed an opposite trend with higher *G-R* parameter results and thus, were located closer to the cracking damage zone on the Black Space diagram than the extracted binder from the PG 58S-28 unmodified mixture. For the Set 2 mixtures, both RET and SBS modification of the virgin binder increased the $|G^*|$ and decreased δ of the extracted binder, with and without 20-hour PAV aging. As a result, the extracted binders containing PMA binders had higher *G-R* parameter results than the unmodified binder and were located closer to the cracking damage zone on the Black Space diagram (Figure 35). These results were consistent with the Alabama results in Figure 32 and Figure 33.

Table 11. |G^*| and δ at 15°C and 0.005 rad/s and *G-R* Parameter Results of Asphalt Binders Extracted from Wisconsin Mixtures

Set ID	Virgin Binder Grade & Type	As Recovered			As Recovered + 20-hour PAV Aging		
		|G^*| (kPa)	δ (°)	G-R (kPa)	|G^*| (kPa)	δ (°)	G-R (kPa)
Set 1	PG 58S-28 Neat	142.1	63.3	32.2	650.5	55.7	250.6
	PG 58V-28 RET	158.3	59.0	48.9	707.0	52.6	327.7
	PG 58V-28 SBS	104.0	63.5	23.2	421.2	57.0	148.7
Set 2	PG 52S-34 Neat	39.5	68.0	6.0	203.7	60.5	56.6
	PG 58V-34 RET	59.1	59.1	18.2	209.5	55.0	84.2
	PG 58V-34 SBS	68.0	62.1	16.8	263.5	57.2	92.3

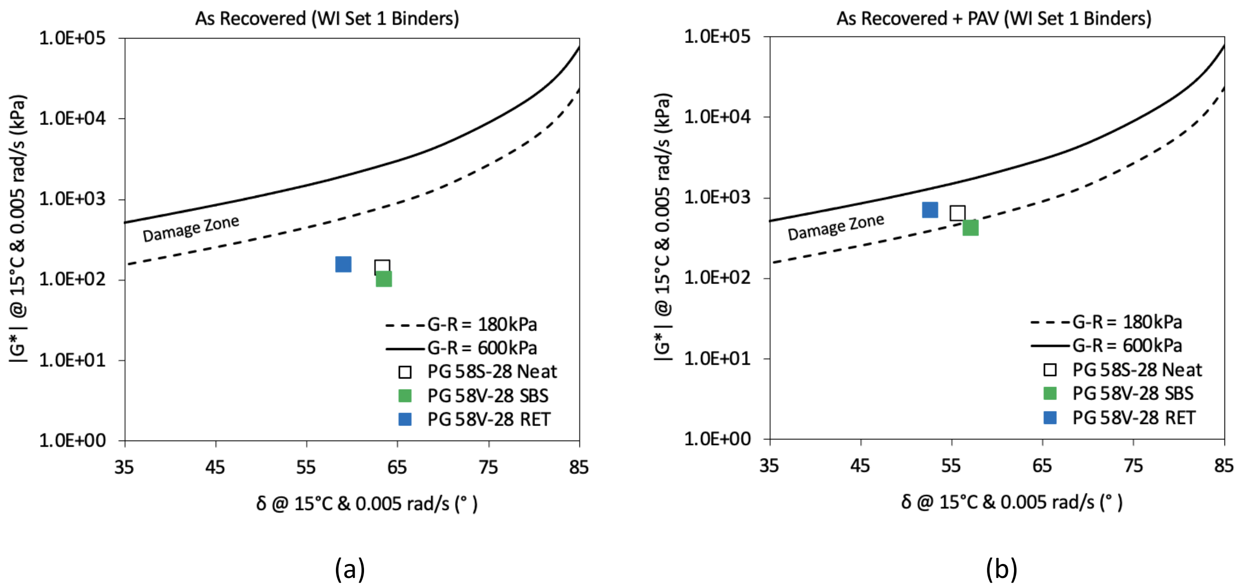


Figure 34. *G-R* Parameter Results of Asphalt Binders Extracted from Wisconsin Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders on a Black Space Diagram; (a) Tested as Recovered, (b) Tested after 20-hour PAV Aging

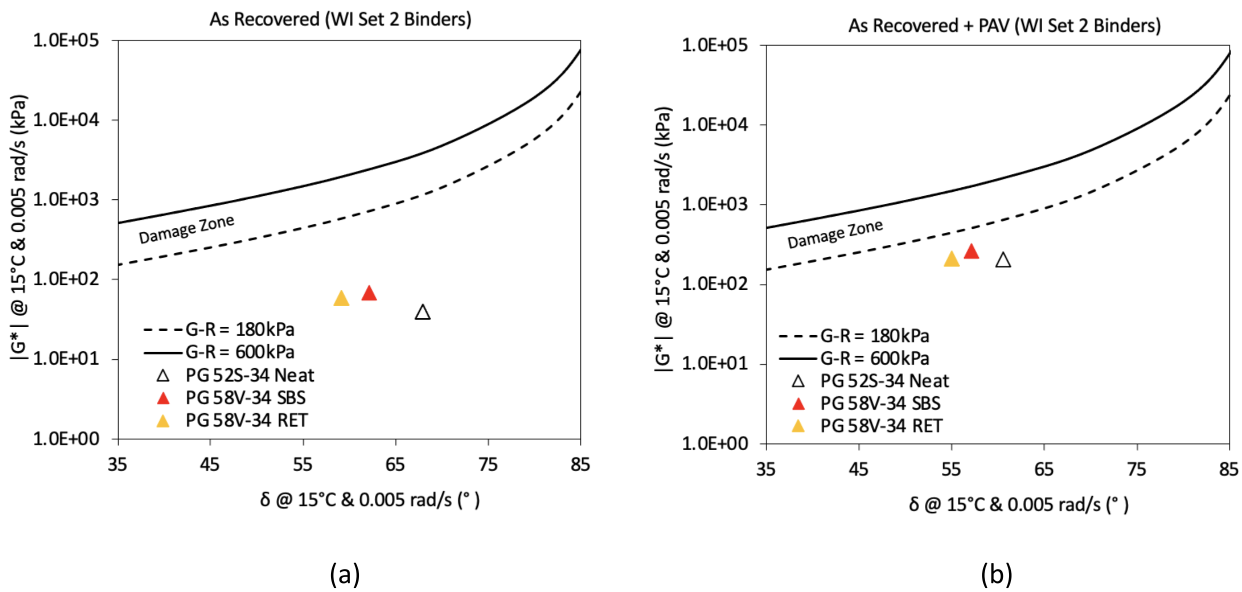


Figure 35. *G-R* Parameter Results of Asphalt Binders Extracted from Wisconsin Mixtures with PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders on a Black Space Diagram; (a) Tested as Recovered, (b) Tested after 20-hour PAV Aging

7.1.4 Crossover Frequency and R-value

Table 12 and Table 13 summarize the ω_c and R-value results of asphalt binders extracted from the Alabama and Wisconsin mixtures at the volumetric OBC. As shown, the extracted binders from the unmodified and PMA mixtures containing virgin binders with the same low-temperature grade exhibited different rheological properties. Specifically, asphalt modification with RET and SBS generally decreased the ω_c and increased the R-value of the extracted binders, which indicated increased binder stiffness and increased elastic-to-steady-state transition potential with a flatter |G*| master curve. Figure 36 and Figure 37 present the ω_c-versus-R-value plots on a Black Space diagram. For all the extracted binders regardless of the virgin binder used, ω_c decreased while R-value increased after PAV aging, which indicated that the binders became more brittle and prone to block cracking after oxidative aging in the PAV.

Table 12. Crossover Frequency (ω_c) and Rheological Index (R-value) Results of Asphalt Binders Extracted from Alabama Mixtures

Set ID	Virgin Binder Grade & Type	As Recovered		As Recovered + 20-hour PAV Aging	
		ω_c (rad/s)	R-value	ω_c (rad/s)	R-value
Set 1	PG 64-22 Neat	52.5	2.15	4.4	2.39
	PG 76-22 RET	76.0	2.15	6.6	2.29
	PG 76-22 SBS	40.9	2.24	3.3	2.55
Set 2	PG 58-28 Neat	92.1	2.28	4.3	2.63
	PG 64-28 RET	82.7	2.35	5.3	2.65
	PG 64-28 SBS	57.8	2.44	2.6	2.77

Table 13. Crossover Frequency (ω_c) and Rheological Index (R-value) Results of Asphalt Binders Extracted from Wisconsin Mixtures

Set ID	Virgin Binder Grade & Type	As Recovered		As Recovered + 20-hour PAV Aging	
		ω_c (rad/s)	R-value	ω_c (rad/s)	R-value
Set 1	PG 58S-28 Neat	89.4	2.42	3.5	2.79
	PG 58V-28 RET	74.9	2.52	2.4	2.89
	PG 58V-28 SBS	129.9	2.33	8.0	2.70
Set 2	PG 52S-34 Neat	612.2	2.33	29.0	2.68
	PG 58V-34 RET	308.8	2.58	19.6	2.87
	PG 58V-34 SBS	245.9	2.49	12.7	2.84

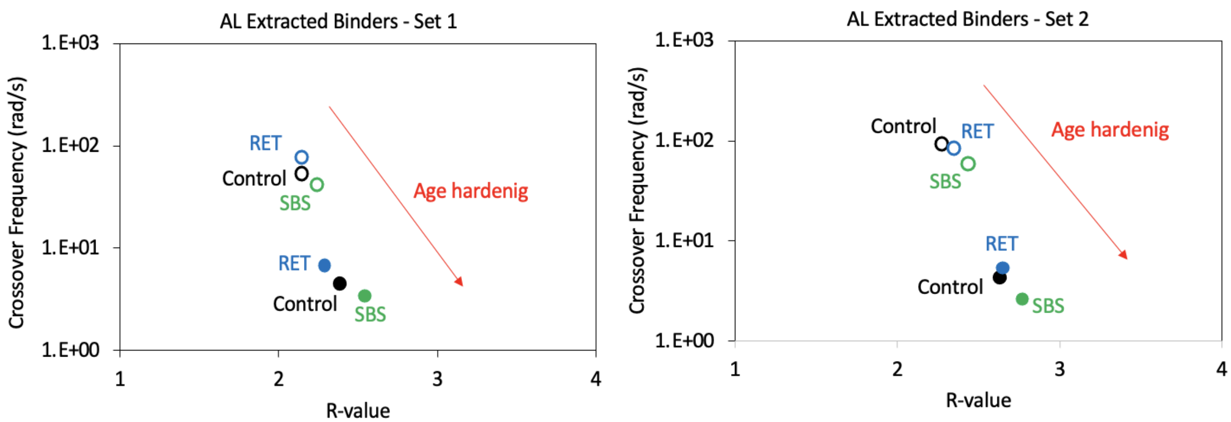


Figure 36. ω_c-versus-R-value Plots of Asphalt Binders Extracted from Alabama Mixtures with PG 64-22 Unmodified, PG 76-22 RET-modified, and PG 76-22 SBS-modified Binders (left), and PG 58-28 Unmodified, PG 64-28 RET-modified, and PG 64-28 SBS-modified Binders (right)

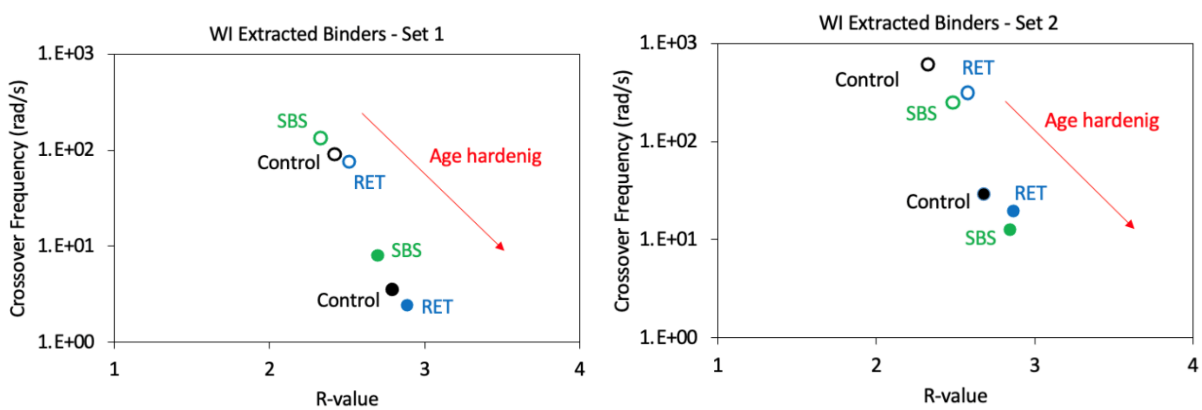


Figure 37. ω_c-versus-R-value Plots of Asphalt Binders Extracted from Wisconsin Mixtures with PG 58S-28 Unmodified, PG 58V-28 RET-modified, and PG 58V-28 SBS-modified Binders (left), and PG 52S-34 Unmodified, PG 58V-34 RET-modified, and PG 58V-34 SBS-modified Binders (right)

7.2 IDEAL-CT AND I-FIT CORRELATION ANALYSIS RESULTS

Figure 38 presents the Pearson's correlation coefficients for the 25°C CT_{Index} results of the Alabama and Wisconsin mixtures versus the extracted binder results for various rheological parameters. As a rule of thumb, a Pearson's correlation coefficient (*r*) above +0.80 (or below -0.80) indicates a very strong correlation, between +0.60 and +0.80 (or between -0.60 and -0.80) indicates a strong correlation, and between 0 and +0.6 (or between 0 and -0.6) indicates no to a moderate correlation (Evans, 1996). Among the various binder rheological parameters investigated in Figure 38, only the R-value had a strong positive correlation with the CT_{Index}, which had a *r* value of +0.74. However, this correlation should be interpreted with caution because it was based on a limited range of IDEAL-CT and R-value results. Furthermore, this positive correlation is contradictory to the impact of aging on the IDEAL-CT and R-value results, where the R-value increases aging with aging while the CT_{Index} decreases with aging.

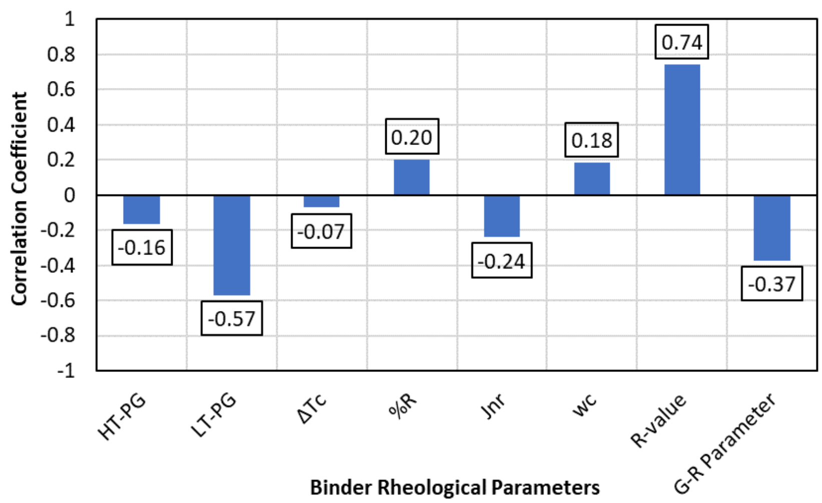


Figure 38. Pearson's Correlation Coefficients of CT_{Index} versus Different Binder Rheological Parameters (N=12)

Figure 39 presents the Pearson's correlation coefficients for the 25°C FI results of the Wisconsin mixtures versus the extracted binder results. As shown, the low-temperature PG had a very strong negative correlation (with a *r* value of -0.88) and the ΔT_c and ω_c showed a very strong positive correlation with the FI (with a *r* value of +0.89 and +0.83, respectively). Furthermore, the high-temperature PG and *G-R* parameter also showed a strong negative correlation with the FI with a *r* value of -0.74 and -0.78, respectively; and the J_{nr} had a strong positive correlation with a *r* value of +0.65. However, it should be noted that these correlations were based on only six sets of I-FIT results and thus, warrant further verification with additional data in future research.

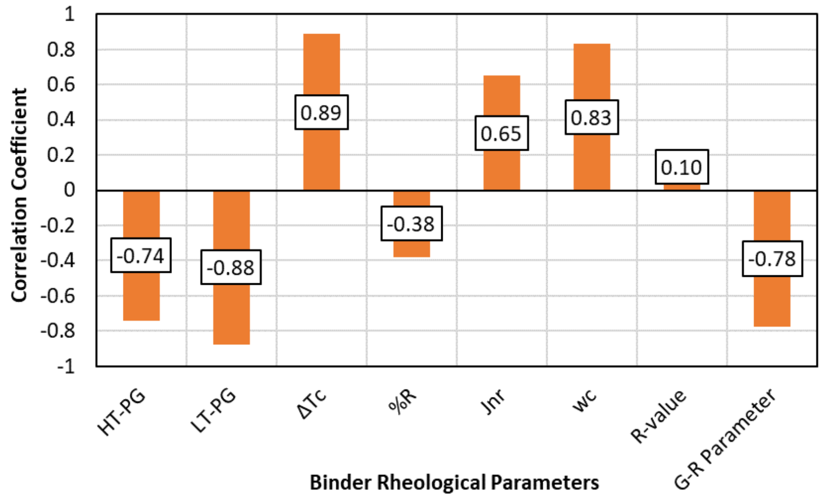


Figure 39. Pearson's Correlation Coefficients of FI versus Different Binder Rheological Parameters (N=6)

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

The overall objective of this study was to determine the impact of polymer modification with SBS and RET, without changing the base binder source and grade, on the IDEAL-CT and I-FIT results for evaluating the intermediate-temperature cracking resistance of asphalt mixtures. The experimental plan focused on the IDEAL-CT and I-FIT testing of asphalt mixtures prepared with two mix designs, six virgin binders per mix design (including two unmodified, two RET-modified, and two SBS-modified binders), and three binder contents. Both tests were conducted at two temperatures: 25°C and $T_{=G*}$ determined from the TB Modulus test. In addition to the IDEAL-CT and I-FIT, the TB Fatigue and LAS tests were conducted to supplement the two monotonic loading tests in evaluating the impact of polymer modification on the fatigue resistance of asphalt mixtures and the extracted binders under a cyclic loading condition. Finally, the Superpave PG, MSCR, and DSR Frequency Sweep tests were conducted to characterize the extracted binders' rheological properties and determine their correlations with the IDEAL-CT and I-FIT results at 25°C. The major findings and conclusions of the study are summarized below:

<u>IDEAL-CT and I-FIT Testing</u>

- The IDEAL-CT and I-FIT testing at 25°C did not discriminate the unmodified versus PMA mixtures at the volumetric OBC, which indicated a lack of sensitivity of the final test parameters (i.e., CT_{Index} and FI) to polymer modification.
- Increasing the binder content consistently improved the IDEAL-CT and I-FIT results at 25°C, but it did not help capture the benefits of polymer modification in the two tests. Regardless of the binder content, the PMA and unmodified mixtures with the same base binder had statistically equivalent IDEAL-CT and I-FIT results at 25°C. These results caused the rejection of Hypothesis 1 of the study: "*Testing the IDEAL-CT and I-FIT at the volumetric OBC of the mixture is insufficient to capture the benefits of polymer modification*."
- Adjusting the test temperature from 25°C to $T_{=G*}$ also failed to capture the impact of polymer modification on the IDEAL-CT and I-FIT results. In all cases, the PMA and unmodified mixtures prepared with the same base binder had statistically equivalent results at $T_{=G*}$ when tested at the same binder content. These results caused the rejection of Hypothesis 2 of the study: "*The IDEAL-CT and I-FIT must be conducted at an equal stiffness condition to properly demonstrate the benefits of polymer modification*."
- The interaction diagram analysis provided a comprehensive interpretation of the IDEAL-CT and I-FIT results for comparing PMA versus unmodified mixtures. The analysis results showed that polymer modification generally affected the toughness (as indicated by G_f) and the post-peak behavior (as indicated by $l_{75}/|m_{75}|$ for the IDEAL-CT or $1/|m|$ for the I-FIT) of the asphalt mixture, but these effects tended to offset each other on the final cracking index parameters. In this case, the direction of change in the IDEAL-CT or I-FIT results due to polymer modification on the interaction diagram was almost perpendicular to the direction of increasing CT_{Index} or FI. As a result, PMA and unmodified mixtures with the same base binder fell on contour curves with similar CT_{Index} or FI values despite having different G_f and $l_{75}/|m_{75}|$ or $1/|m|$ results.

- The interaction diagram analysis also showed that for both the IDEAL-CT and I-FIT, the interim test parameters describing the post-peak behavior of the mixture (i.e., $l_{75}/|m_{75}|$ and $1/|m|$) had considerably higher variability than the toughness parameter (i.e., G_f). For the IDEAL-CT, $l_{75}/|m_{75}|$ had an average coefficient of variation (COV) of 9.2%, while G_f had an average COV of 3.4%. For the I-FIT, $1/|m|$ and G_f had an average COV of 19.7% and 7.8%, respectively. Therefore, future research to reduce the variability of the IDEAL-CT and I-FIT should focus on investigating the post-peak behavior of the load-displacement curve.

TB Fatigue and LAS Testing

- The TB Fatigue and LAS test results showed that asphalt modification with RET and SBS significantly improved the fatigue resistance of asphalt mixtures and the corresponding extracted binders, which disagreed with the IDEAL-CT and I-FIT results. This discrepancy was possibly attributed to the different loading conditions of the tests, as the TB Fatigue and LAS tests were conducted with cyclic loading while the IDEAL-CT and I-FIT were conducted with monotonic loading.

Extracted Binder Rheological Testing

- Asphalt binders extracted from the mixtures containing PMA versus unmodified binders with the same base binder showed distinctly different rheological properties in the Superpave PG, MSCR, and DSR Frequency Sweep tests. Overall, asphalt modification with RET and SBS increased the high-temperature stiffness, elasticity, and rutting resistance of the extracted binders.
- Among the various binder rheological parameters evaluated in the study, only the R-value from the DSR Frequency Sweep test exhibited a strong positive correlation with the IDEAL-CT results at 25°C. However, this correlation should be interpreted with caution because it was based on a limited range of IDEAL-CT and R-value results. Furthermore, this positive correlation was contradictory to the impact of aging on the IDEAL-CT and R-value results, where the R-value increases aging with aging while the CT_{Index} decreases with aging.
- Several binder rheological parameters (including the high-temperature PG, low-temperature PG, ΔT_c, J_{nr}, ω_c, and *G-R* parameter) showed a strong or very strong correlation with the limited I-FIT results at 25°C. These correlations should be further verified with additional data before they can be used to select asphalt binders to improve the I-FIT results from the mix design perspective.

Based on the findings of this study, it is recommended that SHAs that have implemented or are in the process of implementing the IDEAL-CT or I-FIT use the same test criteria for mix design approval of asphalt mixtures of the same mix type and NMAS but containing PMA and unmodified binders with the same base binder grade. The test criteria should be established based on the correlation with field cracking performance while considering the traffic, climate, and underlying pavement conditions instead of based on mixture compositions. Furthermore, future research is recommended to investigate the discrepancy between the performance tests that use monotonic loading versus cyclic loading in evaluating the fatigue cracking resistance of PMA binders and mixtures.

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