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Evaluation of Overlay Tester Test Procedure to Identify Fatigue Cracking Prone Asphalt Mixtures

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16. Abstract

Fatigue cracking is a major problem on asphalt pavements and airfields. Design and production procedures continually result in lean asphalt mixtures, while the use of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) increases the relative stiffness and aged condition of the asphalt mixture, significantly decreasing the material's flexibility and natural ability to withstand crack initiation and propagation. The literature has shown that the Overlay Tester is a test method that can identify cracking prone asphalt mixtures and is highly sensitive to recycled asphalt, asphalt content, polymer modification, and asphalt mixture volumetrics. The purpose of the study is to evaluate the Overlay Tester using field cores from the recently completed FHWA ALF Sustainability study. The study comprised of 10 different test lanes, each produced to the same target volumetrics, while varying recycled asphalt contents, base asphalt binder grades, and the addition of warm mix asphalt technologies. Each lane was trafficked until fatigue cracking failure, and therefore, provided an excellent means to compare field and laboratory performance.

The results of the study showed that the Overlay Tester, as well as the SCB Flexibility test, are test methods capable of discriminating between "Good" and "Poor" fatigue cracking performing asphalt mixtures. The general ranking of performance from both test methods were shown to compare well with the field performance. Additionally, asphalt binder testing, performed on recovered asphalt binder from the top ½ - ¾" of the asphalt surface, correlated very well with the measured cracking performance of the FHWA ALF. The Loss Tangent2, Glover-Rowe Parameter, and DTc parameter showed excellent to good agreement to the Number of Cycles to 1st Crack at the ALF. Ultimately, the research study provided asphalt mixture and binder test methods capable of capturing the fatigue cracking performance in asphalt mixture produced with varying amounts of recycled asphalt binders, PG grades, and warm mix asphalt technologies.

17. Key Words

Overlay Tester, SCB Flexibility Index, Glover-Rowe Parameter, Loss Tangent, Fatigue Cracking, Recycled Asphalt, Warm Mix Asphalt

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DESCRIPTION OF THE PROBLEM

Fatigue cracking is a major problem on asphalt pavements and airfields. Design and production procedures continually result in lean asphalt mixtures, while the use of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) increases the relative stiffness of the asphalt mixture, significantly decreasing the material's flexibility and natural ability to withstand crack initiation and propagation.

Premature fatigue cracking in asphalt pavements can lead to a significantly reduced pavement service life. If not quickly treated, water intrusion and additional aging can accelerate pavement deterioration. When occurring on airfields, severe cracking may result in loosen particles that can cause potential engine damage. The costs of crack treatments can range for the physical application and treatment, but it is often the user delays via lane and runway closures during treatment that is sometimes more costly. Therefore, the ability to determine material properties and performance thresholds is extremely important to help provide durable and fatigue resistant asphalt materials for highway and airfield applications.

APPROACH

The literature has shown that the Overlay Tester is a test method that can identify cracking prone asphalt mixtures and is highly sensitive to recycled asphalt, asphalt content, polymer modification, and asphalt mixture volumetrics. The propose of the study is to evaluate the Overlay Tester using field cores from the recently completed FHWA ALF Fatigue Cracking study. The study comprised of 10 different lanes, each produced to the same target volumetrics, while varying recycled asphalt contents, base asphalt binder grades, and the addition of warm mix asphalt technologies. Each lane was trafficked until fatigue cracking failure, and therefore, provides an excellent means to compare field and laboratory performance.

In addition to the Overlay Tester, the SCB Flexibility Index was also included in the mixture testing study to compare to the FHWA ALF performance, as well as the results generated by the Overlay Tester. Asphalt binder characterization of the ALF asphalt materials was also conducted to help better understand the asphalt binder performance of the recycled asphalt and warm mix asphalt (WMA) modified materials. Conventional asphalt binder performance grading (PG), fracture testing, and rheologically-based test methods were utilized to evaluate the recovered asphalt binder.

METHODOLOGY

The research study utilized the accelerated loading results from the FHWA's Accelerated Loading Facility (ALF) at the Turner-Fairbanks facility as a means to evaluate different asphalt mixture and binder fatigue cracking test methods and parameters. The ALF contained ten (10) different test lanes consisting of the identical pavement structure to evaluate the impact of recycled asphalt and warm mix asphalt (WMA) on the fatigue cracking performance of asphalt pavements. The study entitled, *Advance Use of Recycled Asphalt in Flexible Pavement Infrastructure: Develop and Deploy Framework for Proper Use and Evaluation of Recycled Asphalt in Asphalt Mixtures*, produced the asphalt layers of the testing lanes with varying amounts of recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), WMA technologies and different asphalt binder grades. Table 1 shows how the asphalt mixture was varied for each testing lane.

Table 1 – Experimental Design for FHWA ALF Sustainability Study

ALF Lane #	% ABR		Virgin PG Grade	Drum Discharge Temperature	WMA Process	Passes to First ALF Crack
	RAP	RAS				
1	0	--	64-22	300-320	--	368,254
2	40	--	58-28	240-285	Water Foaming	123,035
3	--	20	64-22	300-320	--	42,399
4	20	--	64-22	240-270	Evotherm	88,740
5	40	--	64-22	300-320	--	36,946
6	20	--	64-22	300-320	--	122,363
7	--	20	58-28	300-320	--	23,005
8	40	--	58-28	300-320	--	47,679
9	20	--	64-22	240-285	Water Foaming	270,058
11	40	--	58-28	240-270	Evotherm	81,044

The main ALF parameter used to compare the performance of the different asphalt mixtures was the Number of Passes to 1st Crack. Additionally, the Cracking Rate, which is defined as the measured crack length in inches per ALF pass, was also included in the comparison.

The pavement structure at the FHWA ALF consisted of silty sand subgrade (resilient modulus ≈ 9,000 psi) overlaid by 22 inches of crushed aggregate base (resilient modulus ≈ 12,000 psi). The surface consisted of 4 inches of asphalt. The asphalt layer was placed in two lifts of 2 inches thick. The asphalt mixture type was dependent on the experimental lane, as noted in Table 1. The production asphalt mixture properties, as well as the average in-place air voids, are shown in Table 2.

The test lanes were loaded using a 425/65R22.5 wide base tire at an inflation pressure of 100 psi. A wheel load of 14,200 lbs was applied during the trafficking. The travel speed of the applied tire load was 11 mph (4.9 m/s). The temperature of the test lanes was controlled to maintain at 20oC temperature at the mid-depth (2 inches below the surface) of the asphalt layer.

Table 2 – Quality Control Results for Asphalt Materials During Production

Asphalt Mixture Parameter for Quality Control Testing		**Lane 1**	**Lane 2**	**Lane 3**	**Lane 4**	**Lane 5**	**Lane 6**	**Lane 7**	**Lane 8**	**Lane 9**	**Lane 11**
Mix Type		Virgin, PG64-22	40% RAP, 58-28 Foam	20% RAS, PG64-22	20% RAP, 64-22, Evo	40% RAP, PG64-22	20% RAP, PG64-22	20% RAS, PG58-28	40% RAP, PG58-28	20% RAP, 64-22 Foam	40% RAP, 58-28 Evo
Ave In-place AV%	Top Lift	7.2	8.0	7.9	8.7	7.6	7.2	8.3	8.5	7.2	7.8
	Bottom Lift	5.8	4.6	7.7	6.0	6.9	5.4	7.6	6.0	5.3	7.4
Gmm	Top Lift	2.753	2.727	2.744	2.743	2.742	2.737	2.744	2.743	2.744	2.723
	Bottom Lift	2.747	2.718	2.743	2.736	2.744	2.744	2.736	2.715	2.728	2.720
AC%	Top Lift	5.02	5.00	4.93	4.93	4.57	4.90	4.96	4.87	4.79	4.88
	Bottom Lift	5.14	5.13	5.02	3.97	4.62	4.92	4.85	5.02	5.16	4.89
VMA%	Top Lift	16.2	15.6	14.6	15.7	15.4	14.7	15.3	16.6	15.1	16.6
	Bottom Lift	15.9	16.7	14.7	15.5	16.4	15.0	15.4	16.1	15.1	16.5
VFA%	Top Lift	71.5	75.0	77.1	70.4	69.6	77.3	73.3	65.4	72.4	69.9
	Bottom Lift	75.4	72.2	77.6	73.5	65.0	74.0	74.0	75.1	78.6	71.0
Effective AC% by Volume	Top Lift	11.6	11.7	11.3	11.1	10.7	11.4	11.2	10.9	11.0	11.6
	Bottom Lift	12.0	12.0	11.4	11.4	10.7	11.1	11.4	12.1	11.9	11.7
D/B Ratio	Top Lift	1.05	1.15	1.27	1.13	1.37	1.17	1.23	1.14	1.14	1.17
	Bottom Lift	1.02	1.14	1.30	1.12	1.39	1.17	1.27	1.13	1.16	1.19
% Passing 19mm	Top Lift	100	100	100	100	100	100	100	100	100	100
	Bottom Lift	100	100	100	100	100	100	100	100	100	100
% Passing 12.5mm	Top Lift	98.5	97.4	97.2	97.6	96.5	97.6	97.4	96.5	97.4	96.3
	Bottom Lift	98.0	97.9	98.0	97.6	97.8	98.3	97.4	97.0	98.4	96.5
% Passing #4	Top Lift	48.1	39.8	40.3	45.3	37.4	43.5	39.6	34.7	41.9	36.4
	Bottom Lift	47.1	41.1	41.9	45.6	39.3	45.7	39.2	38.1	48.1	37.2
% Passing #8	Top Lift	28.8	24.6	26.0	27.5	24.1	28.0	25.2	22.1	26.7	23.3
	Bottom Lift	28.7	23.8	27.0	27.6	23.8	28.1	25.6	23.5	29.5	23.3
% Passing #200	Top Lift	5.3	5.8	6.3	5.6	6.3	5.7	6.1	5.6	5.5	5.7
	Bottom Lift	5.3	5.9	6.5	5.5	6.4	5.8	6.2	5.7	6.0	5.8

Cracking was assessed and traced with a planimeter to capture the number of passes associated with the total cracking length. This provided a means for the FHWA to determine Crack Rate. The fatigue cracking results for the FHWA ALF Sustainability Study is shown in Figure 1.

To evaluate the Overlay Tester and its correlation to the field cracking measured at the FHWA ALF, field cores were recovered from the test lanes (Figure 2). A total of 11 field cores were recovered for each of the test lanes and used in the research study. Due to the thickness of the lifts, the asphalt mixture performance testing was conducted on the Bottom lift. This was based on reducing the potential for an aged asphalt gradient at the surface of the asphalt layer that may have created repeatability issues during testing. By conducting the asphalt mixture performance testing on the Bottom lift, an “aged” specimen condition resembling immediately after field placement would be achieved, and therefore simulate a Quality Control testing condition. Meanwhile, asphalt binder testing was conducted on asphalt binder recovered from the top ½ to ¾” of the Surface lift. This was an attempt to capture the asphalt binder properties at the same aged condition as the time of cracking in the field.

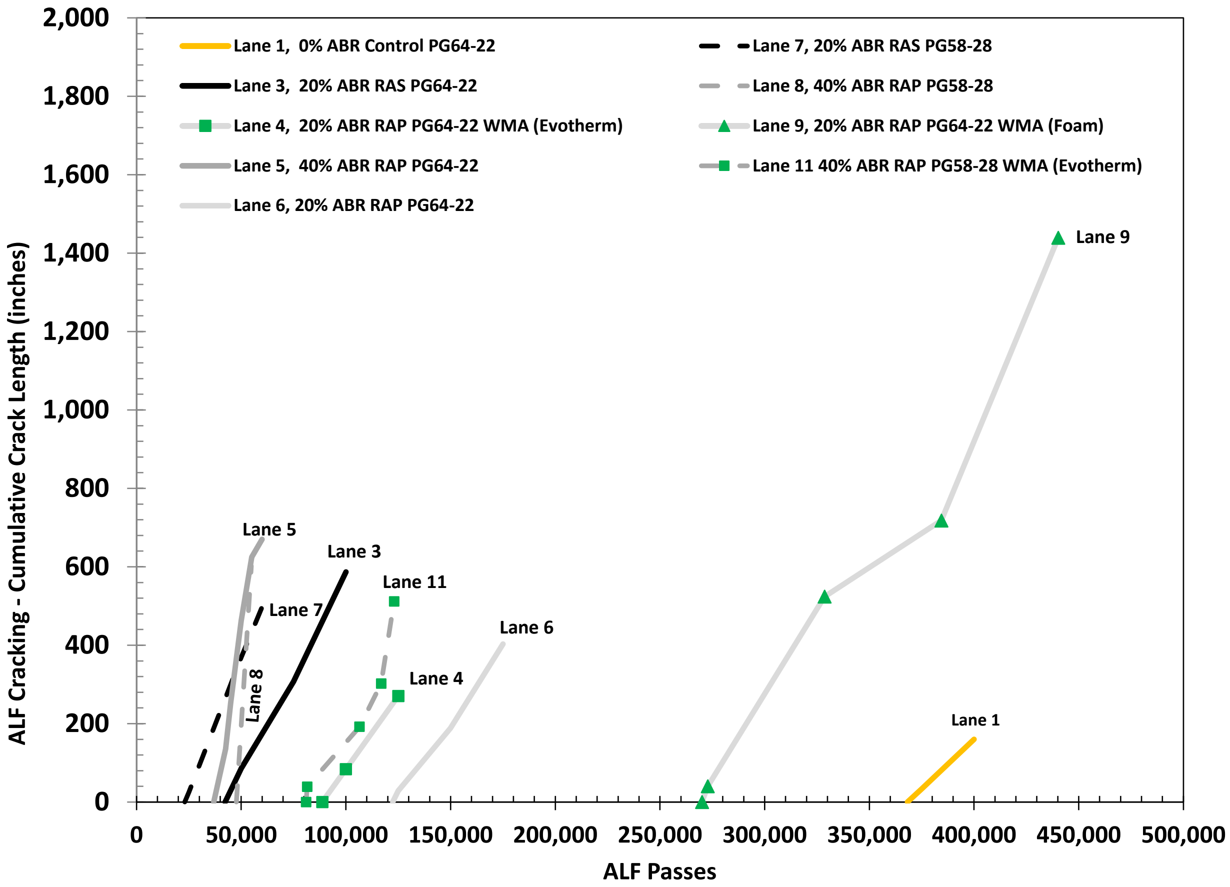

Figure 1 – FHWA ALF Fatigue Cracking from Sustainability Study

Figure 2 – Field Cores Recovered from FHWA ALF for Asphalt Mixture and Binder Testing

Test Methods – Asphalt Mixtures

Two different asphalt mixture test procedures were utilized to characterize the fatigue cracking performance of the FHWA ALF asphalt mixtures; 1) Overlay Tester and 2) Semi-circular Bend (SCB) Flexibility Index.

Overlay Tester Test

The Overlay Tester, described by Zhou and Scullion (2005), has shown to provide an excellent correlation to field cracking for both composite pavements (Zhou and Scullion, 2005; Bennert et al., 2009) as well as flexible pavements (Zhou et al., 2007; Bennert and Maher, 2013; Bennert et al., 2016; Bennert et al., 2017). The test procedure utilizes a test specimen glued to two platens – one platen is fixed while the other platen moves horizontally to create a tensional strain. The test procedure is conducted cyclically using a triangular, displacement-controlled waveform. Figure 3 shows a picture of the Overlay Tester used in this study. Sample preparation and test parameters used in this study followed that of NJDOT B-10 testing specifications. These include:

- 25^{o}C (77^{o}F) test temperature;
- Opening width of 0.025 inches;
- Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and
- Specimen failure defined as 93 percent reduction in Initial Load.

Figure 3 – Picture of the Overlay Tester (Chamber Door Open)

One of the major benefits of the Overlay Tester when conducting forensic studies is that the test specimen thickness is only 37.5 mm (1.5 inches). This allows the testing for most asphalt materials placed at a lift thickness of 1.5 inches or greater.

Semi-Circular Bend (SCB) Flexibility Index

Researchers at the University of Illinois developed a test procedure utilizing the semi-circular bend (SCB) test to evaluate the fatigue cracking resistance of asphalt mixtures at intermediate temperatures (Al-Qadi et al., 2016). The SCB Flexibility Index (FI) is determined by calculating the fracture energy from the SCB test and dividing the fracture energy by the slope of the post peak load vs vertical displacement curve (Figure 4). Al-Qadi et al. (2016) found that the post peak slope was related to the brittleness of the asphalt mixture – steeper the slope, greater the brittleness. The test procedure is conducted at a test temperature of 25°C and a cross-head deformation rate of 50 mm/min.

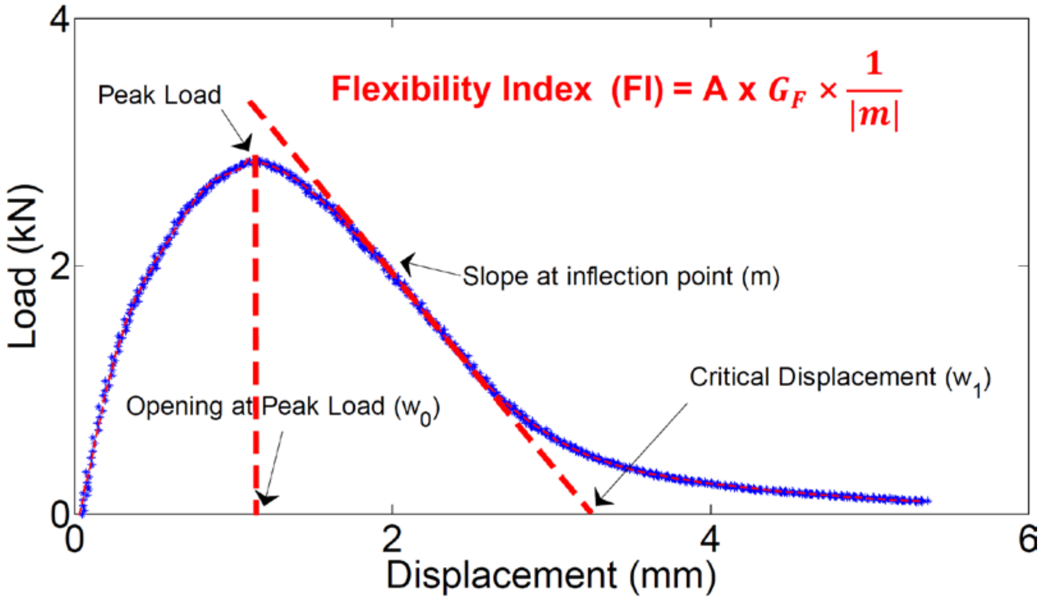

Figure 4 – Schematic of Determining SCB Flexibility Index (FI)

Test specimen thickness of the SCB FI test is recommended to be 50 mm (2 inches). However, Al-Qadi et al. (2016) has included a “thickness correction” within the calculations to allow test specimens slightly smaller or larger in specimen thickness.

Test Methods – Asphalt Binders

A variety of asphalt binder tests were conducted on the asphalt binder recovered from the top ½ - ¾ inches of the surface layer. The asphalt binder was not conditioned beyond the aged condition at the time of recovery.

Recovering of Asphalt Binder and Binder Testing

The asphalt binder from the field cores were extracted and recovered in accordance with AASHTO T164, *Procedure for Asphalt Extraction and Recovery Process* using tri-chlorethylene (TCE) as the solvent medium. The asphalt binder was recovered from the TCE solvent in accordance with ASTM D5404, *Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator* (Figure 5). After recovery, the asphalt binder was tested for its respective PG grade, in accordance with AASHTO M320, *Standard Specification for Performance-Graded Asphalt Binder*, and Multiple Stress Creep Recovery (MSCR) in accordance with ASTM D7405, *Standard Test Method for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*. In addition to the performance grading, the asphalt binders were also tested to their respective rheological, durability, and fracture properties.

Figure 5 – Asphalt Binder Recovery Equipment at Rutgers University

Along with the PG grading and high temperature characterization using the MSCR test, the recovered asphalt binders were evaluated using newer testing protocols for the fatigue performance of asphalt binders. Currently, high temperature and low temperature characterization of the asphalt binder is well understood and standardized. Unfortunately, the asphalt industry is still struggling to understand the fatigue properties of asphalt binders. Recently, Rutgers University has been working with a number of promising testing protocols that appear to be related to the fatigue cracking of the asphalt mixtures. Since field distresses are being measured, the asphalt binder fatigue cracking tests were included to evaluate their ability to rank, and possibly predict, the field cracking. The other advantage of measuring these properties is that once reliable criteria is established, the asphalt binder testing protocols can be used to screen asphalt binders prior to use to ensure durable, asphalt pavements are being produced and placed. Descriptions of the different test procedures are described below.

Difference in Low Temperature Critical Cracking (ΔT_C)

Low temperature PG grading using the Bending Beam Rheometer (BBR) was conducted to ultimately determine the low temperature PG grade. However, a more detailed review of the low temperature grades predicted by the m-slope and Stiffness (S) provides insight as to the general level of oxidative-related aging that has occurred in the asphalt binder. Anderson et al. (2011) identified this difference as a means of indexing the non-load associated cracking potential of asphalt binders and defined it as follows:

$$\Delta T_{cr} = T_{cr\,(Stiffness)} - T_{cr\,(m-slope)} \qquad (1)$$

where,

ΔT_{cr} = Difference in critical low temperature PG grade
T_{cr} = Critical low temperature grade predicted using the BBR m-slope
T_{cr} = Critical low temperature grade predicted using the BBR Stiffness (S)

In Equation (1), as the ΔT_{cr} decreases and becomes negative, the asphalt binder is considered to be more prone to non-load associated cracking. Initially, Anderson et al., (2011) set a limit of $\Delta T_{cr} \leq -2.5^{o}C$ for when there is an identifiable risk of cracking and preventative action should be considered. Rowe (2011) further advanced this methodology, eventually developing a new asphalt binder fatigue property termed Glover-Rowe parameter, which will be discussed later, but recommended that at a $\Delta T_{cr} \leq -5^{o}C$ immediate remediation should be considered.

Double Edge Notched Tension (DENT) Test

The Double Edge Notched Tension (DENT) test has also been proposed for characterizing binder fatigue fracture resistance. The DENT test is a monotonic fracture test, similar to the direct tension test (DTT) used in the Superpave PG system with the exception that notches are imposed on the specimen. The test can be conducted in a standard force-ductility instrument, such as that used for the DTT test. The DENT test was developed by Queen's University in Canada (Andriescu et al. 2004) and modified and adapted for intermediate temperature testing by the FHWA (Gibson et al. 2011). The DENT test is formalized in specifications in Ontario, Canada (Ontario Ministry of Transportation Test Method LS-299).

The Double-Edged Notch Tension (DENT) was conducted in accordance with AASHTO TP113, *Determination of Asphalt Binder Resistance to Ductile Failure Using Double-Edge-Notched Tension (DENT) Test*. The DENT test utilizes the concept of fracture mechanics to evaluate the ductility of asphalt binders. The test procedure is based on measuring the energy needed for fracturing ductile materials consists of two parts; an essential portion of work performed in a local region of the advancing crack creating two surfaces and a non-essential work away from the local region of cracking/tearing associated with ductility, plasticity and yielding. To determine the essential work of fracture and critical tip opening displacement (CTOD), the DENT test is performed using similar specimens with different ligament lengths (5, 10, and 15mm). Figure 6 shows a schematic of a typical test specimen showing the notch in the middle of the test specimen, resulting in a “ligament” length (Figure 7a). The test specimens are then pulled using a force-ductility instrument (Figure 7b) and the Force and Displacement is measured (Figure 8). The area under the curve is measured for each ligament length allowing for the determination of the Essential and Non-essential Work. The CTOD is also determined, which has been found to be a good indicator of fatigue resistance. Larger CTOD values indicates better fatigue resistance.

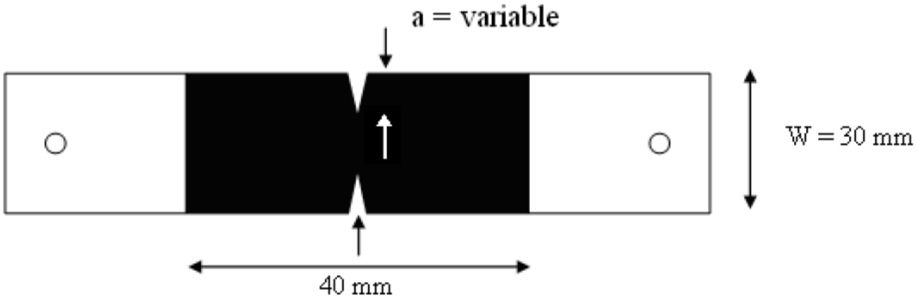

Figure 6 – Double Edged Notched Tension (DENT) Test Specimen

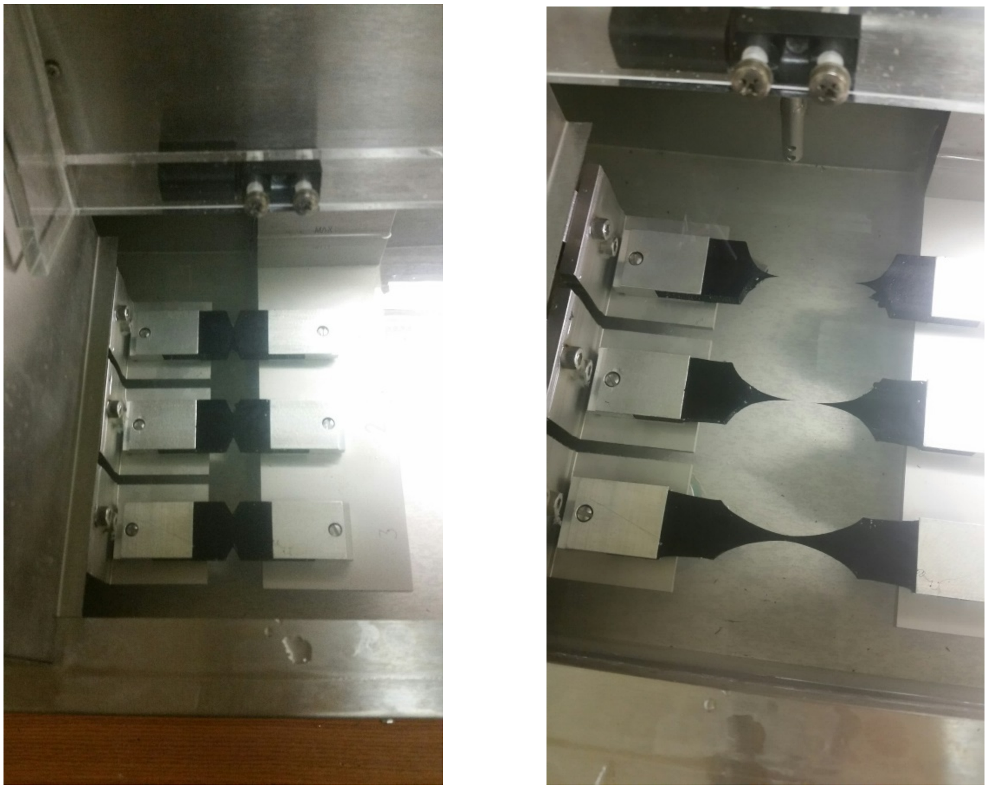
(a) (b)

Figure 7 – DENT Test Specimens; (a) Just Before Starting the Test, (b) Test Specimens of Different Ligament Lengths Failing

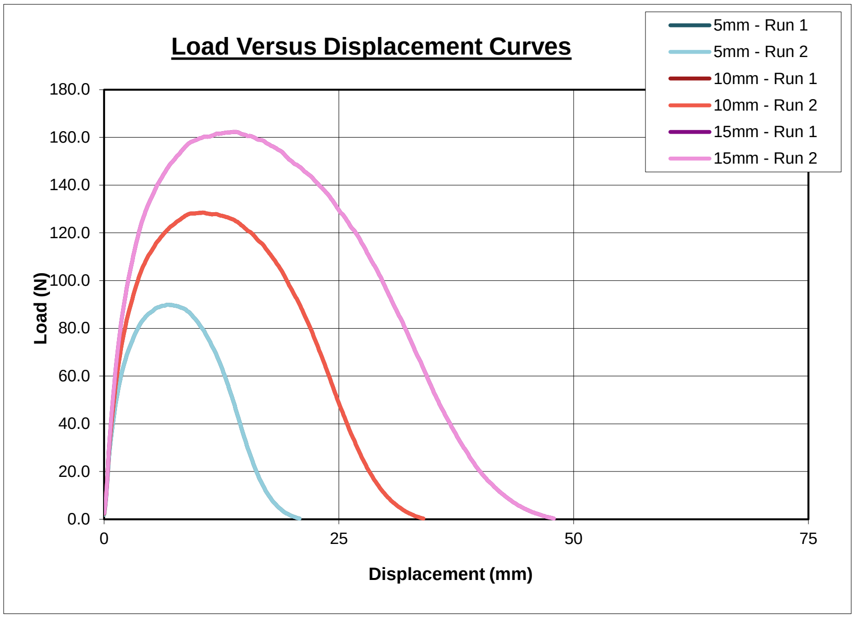

Figure 8 – Example of Load vs Displacement Curves for DENT Test with Different Ligament Lengths

Rheological Indices Related to Brittleness and Durability

Researchers have demonstrated that several rheological indices can be derived that provide indicators of brittleness and can be easily measured using the DSR. These parameters have been primarily proposed for thermally induced cracking and surface raveling but also have promise for identifying asphalt binders susceptible to fatigue cracking as a result of oxidation induced embrittlement. Glover et al. (2005) proposed the rheological parameter, $G'/(\eta'/G')$, as an indicator of ductility based on a derivation of a mechanical analog to represent the ductility test consisting of springs and dashpots. It has been well demonstrated that the Glover parameter is directly correlated to measured ductility. The Glover parameter can be calculated based on DSR frequency sweep testing results, making it much more practical than directly measuring ductility using traditional methods. Rowe (2011) re-defined the Glover parameter in terms of $|G^*|$ and δ based on analysis of a black space diagram as shown in Equation (2) and suggested use of the parameter $|G^*|\cdot(\cos\delta)^2/\sin\delta$, termed the Glover-Rowe (G-R) parameter in place of the original Glover parameter.

$$\frac{G'}{\eta'/G'} = \frac{|G^*|\cdot(\cos\delta)^2}{\sin\delta}\cdot\omega \tag{2}$$

Rowe proposed measuring the G-R parameter based on construction of a master curve from frequency sweep testing at 5°C, 15°C, and 25°C in the DSR and interpolating to find the value of G-R at 15°C and 0.005 rad/sec to assess binder brittleness (Rowe et al. 2014). A higher G-R value indicates increased brittleness. It has been proposed that a G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 600 kPa corresponds to significant cracking based on a study relating binder ductility to field block cracking and surface raveling by Anderson et al. (2011).

Additional rheological indices have been proposed as indicators of aging susceptibility. The asphalt binder phase angle has shown to be good indicator of the healing and strain tolerance of asphalt binders (Christensen et al., 2018). Unfortunately, at elevated temperatures, the influence of polymers may be distorted or exaggerated. Therefore, to help negate this issue, the phase angle of the recovered asphalt binders were compared at the same binder stiffness (G*) of 10 MPa. It has been proposed by Anderson and Rowe (2015) that the evaluating asphalt binders between a stiffness (G*) of 10 to 30 MPa helps to reduce stiffness dependency issues regarding loading rate and temperature while evaluating the asphalt binder at a more “brittle” condition. In addition to simply looking at the phase angle at a G* = 10 MPa, the phase angle will be used to calculate the loss tangent value. Work conducted by Button et al., (1997) showed that higher loss tangent values at low testing temperatures indicates good resistance to fatigue cracking. Further, Goodrich (1991) noted that the loss tangent “… is an excellent indicator of whether an asphalt behaves as a brittle elastic solid or whether it maintains a viscous component.” However, instead of using low testing temperatures for evaluation, the phase angle will be determined at a high stiffness (G* = 10 MPa) to alleviate the issue of temperature and loading rate. The loss tangent is defined as the ratio between the viscous to elastic modulus and shown in the following equation;

$$loss\ tangent = \frac{G^{"}}{G'} = \tan\delta \quad (3)$$

where,

G” = shear loss modulus; viscous component of G* of the asphalt binder
G’ = shear storage modulus; elastic component of G* of the asphalt binder
δ = phase angle of the asphalt binder

For this study, the loss tangent will be squared based on the recommendations of Christensen (2018) as work conducted under NCHRP 9-59 showed a strong relationship of the δ^2 to the fatigue/fracture performance ratio.

FINDINGS - ASPHALT MIXTURE RESULTS

The overall performance of the FHWA ALF is shown in Figure 9. A quick review of the overall performance shows;

1. The asphalt mixture with 0% recycled asphalt performed the best;
2. The second best performing asphalt mixture was the 20% RAP asphalt mixture utilizing a foaming WMA technology;
3. The asphalt mixtures with high recycled asphalt content, 40% RAP and 20% RAS, performed the worst when not utilizing a warm mix additive. In fact, the worst performing asphalt mixture in the study was the 20% RAS asphalt mixture with the PG58-28 asphalt binder;
4. The addition of the WMA technology appears to improve the asphalt mixture fatigue cracking performance when directly compare to the same asphalt mixture with no WMA technology. However, it is not understood whether it was due to modification of the asphalt mixture or simply the reduced production temperature; and
5. Simply using a softer asphalt binder grade did not always result in better fatigue cracking performance. In one case, the use of the PG58-28 asphalt binder improved the fatigue cracking performance of the 40% RAP mix, but it was found to be ineffective with the 20% RAS asphalt mixture.

The results of the FHWA ALF study do not show favorably for recycled asphalt mixtures. Using the number of loading passes to the 1st crack as a means of establishing pavement life, the percent of pavement life was calculated using the 0% recycled asphalt mixture as the comparison. In doing so, it was found that on average;

- The addition of 20% RAP resulted in the ALF lanes having only 43.6% of the pavement life as the 0% recycled asphalt mixture;
- The addition of 40% RAP resulted in the ALF lanes having only 19.6% of the pavement life as the 0% recycled asphalt mixture; and
- The addition of 20% RAP resulted in the ALF lanes having only 8.9% of the pavement life as the 0% recycled asphalt mixture.

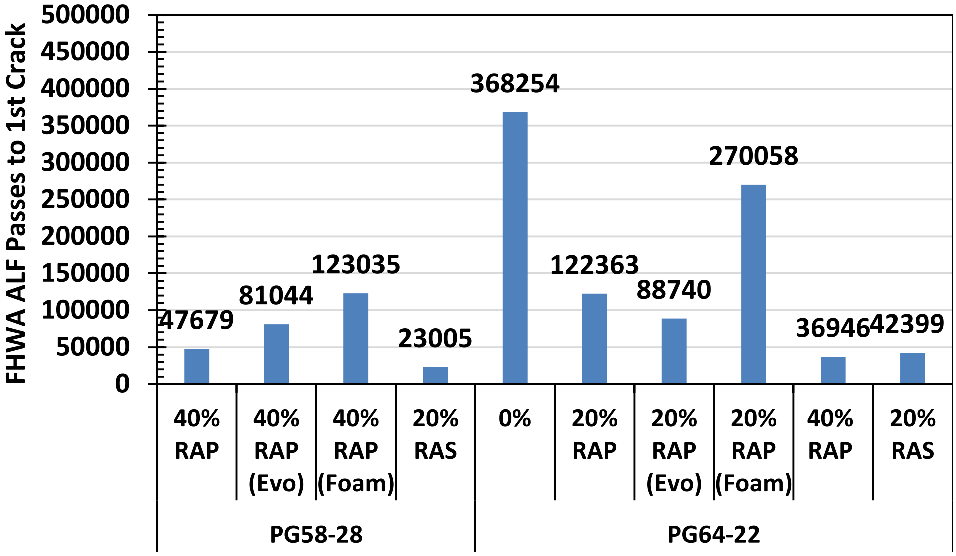

Figure 9 – FHWA ALF Passes to 1st Crack Results for Different Asphalt Mixtures

Overlay Tester Results

The results of the Overlay Tester are shown in Figure 10. The overall trend of the Overlay Tester fatigue life trended with the ALF passes to 1st crack, whereas the recycled asphalt content increased, the fatigue life decreased. Figure 11 shows that there exists a moderate to good relationship between the Overlay Tester and the FHWA ALF passes to 1st crack.

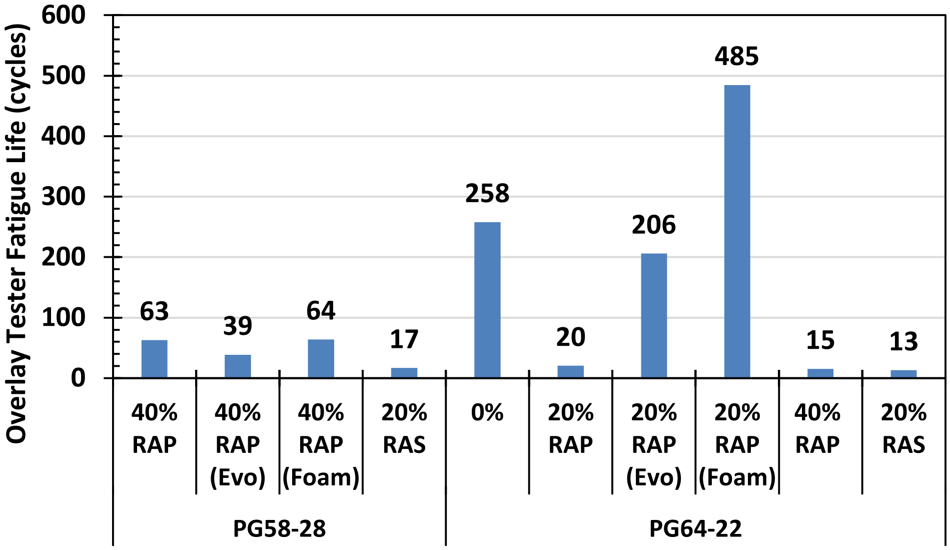

Figure 10 – Overlay Tester Results for FHWA ALF Asphalt Mixtures

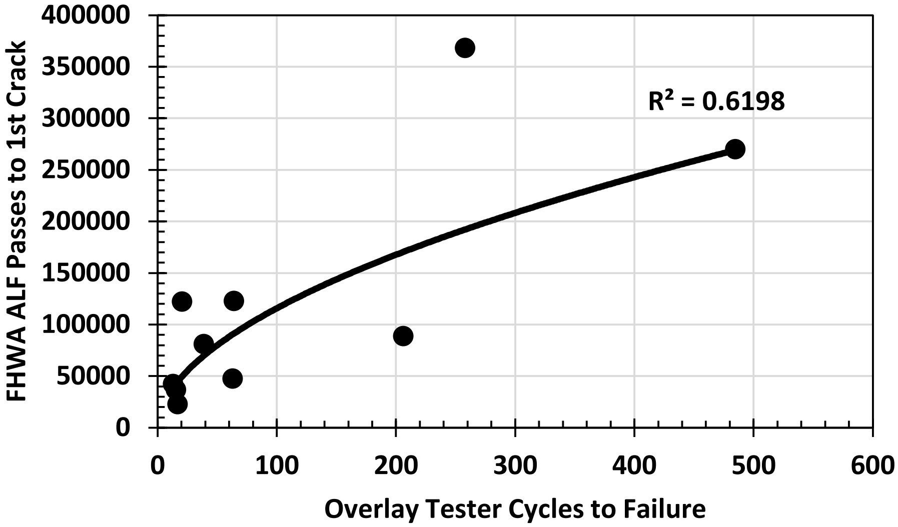

Figure 11 – Overlay Tester Results Compared to FHWA ALF Fatigue Performance

SCB Flexibility Index Results

The SCB Flexibility Index test was also conducted on the recovered cores from the FHWA ALF sections. The results of the testing are shown in Figure 12. The SCB FI results indicate that the 0% recycled asphalt resulted in the highest SCB FI value with the two 20% RAS and 40% RAP PG64-22 asphalt mixtures achieving the lowest SCB FI values. There was a moderate to good correlation between the SCB Flexibility Index and FHWA ALF number of passes to 1st crack and overall slightly better than what was observed with the Overlay Tester.

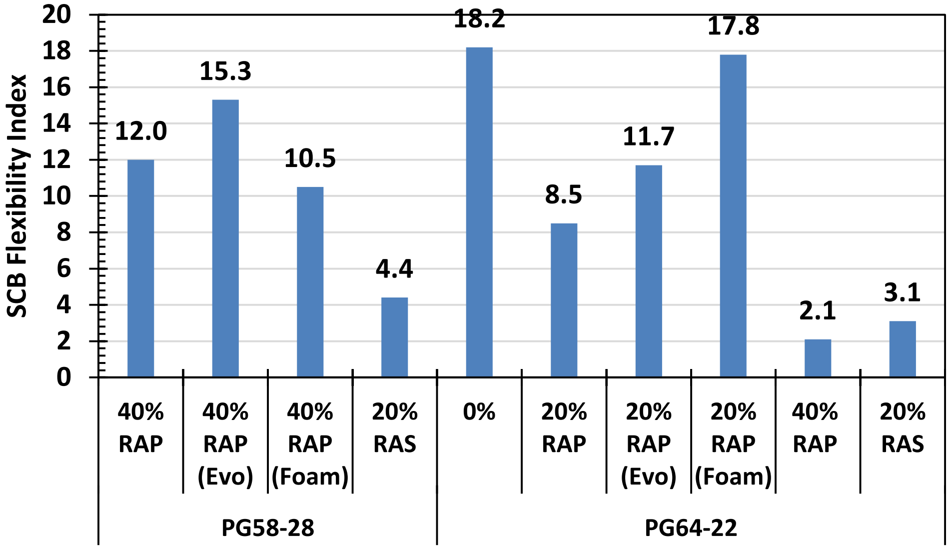

Figure 12 – SCB Flexibility Index Results for FHWA ALF Asphalt Mixtures

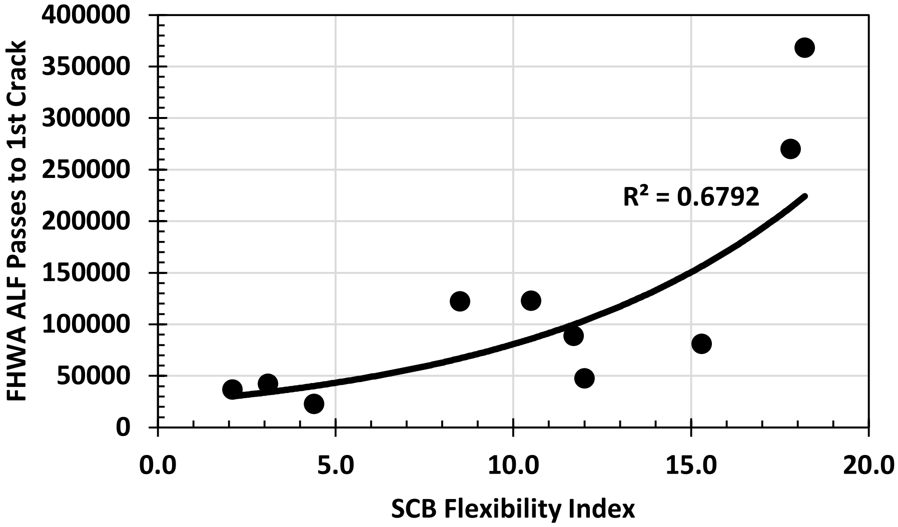

Figure 13 – SCB Flexibility Index Compared to FHWA ALF Number of Passes to 1st Crack

A comparison of the performance rankings using the average values of the Overlay Tester and the SCB Flexibility Index are shown in Table 3. Table 3 shows a relatively good comparative ranking between the FHWA ALF and the two asphalt mixture fatigue cracking tests. There are a few discrepancies within the comparison but the most any of the fatigue cracking tests were off was a ranking of "3" units. This occurred once for the Overlay Tester and three times for the SCB Flexibility Index.

Table 3 – FHWA ALF Performance Rankings for Overlay Tester and SCB Flexibility Index

Lane #	Performance Ranking		
	FHWA ALF	OT	SCB FI
Lane #1	1	2	1
Lane #2	3	4	6
Lane #3	8	10	9
Lane #4	5	3	5
Lane #5	9	9	10
Lane #6	4	7	7
Lane #7	10	8	8
Lane #8	7	5	4
Lane #9	2	1	2
Lane #11	6	6	3

FINDINGS - ASPHALT BINDER RESULTS

As described earlier, the asphalt binder from the top ½ to ¾" of the asphalt surface was recovered via solvent extraction and recovery procedures. After recovery, the asphalt binders underwent a series of asphalt binder PG grading and durability/fatigue cracking-based test procedures to evaluate and compare to the fatigue cracking performance on the FHWA ALF test sections. It should be noted that recovered asphalt binder was not available for Lane 2.

Performance Grading (PG) Methods

Conventional Performance Grading (PG) methods were used to compare to the fatigue cracking performance of FHWA ALF Sustainability study asphalt mixtures. In particular, the PG grading parameters that would be relate to the expected fatigue cracking performance. For this study, the Intermediate PG Grade and the Low Temperature PG Grade based on the m-value was used for comparisons. The Low Temperature PG Grade based on the m-value was included as the m-value is directly related to the relaxation properties of the asphalt binder under cold conditions. Asphalt binders that are capable of better relaxation characteristics under lower temperatures will be capable of resisting cracking.

The PG Grading results are shown in Figures 14 and 15. The Intermediate Temperature PG grading does not show a significantly large difference between asphalt materials when compared to the asphalt mixture differences in the m-value Low Temperature PG grade results. Both of the PG Grading parameters were compared with the FHWA ALF Number of Passes to 1st Crack to determine if either value correlated with the final cracking performance (Figures 16 and 17). The figures show that a poor to moderate correlation was found between the PG grade parameters and fatigue cracking performance from the ALF test lanes. The fact that a poor to moderate relationship exists between the PG grading parameters and the measured fatigue cracking is most likely why recent research has emphasized the need to develop and evaluate new procedures that target durability/fatigue cracking performance of asphalt binders.

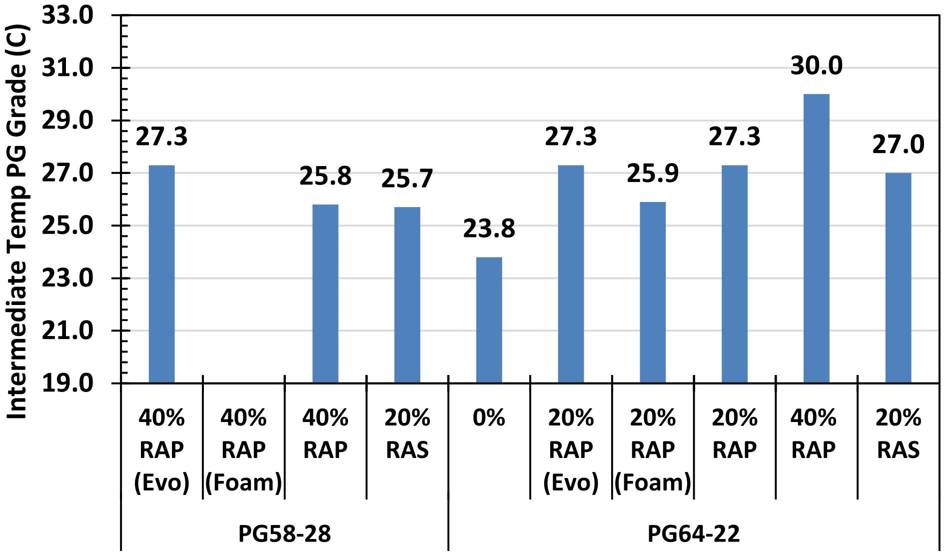

Figure 14 – Intermediate PG Grading Results for Different FHWA ALF Asphalt Mixtures

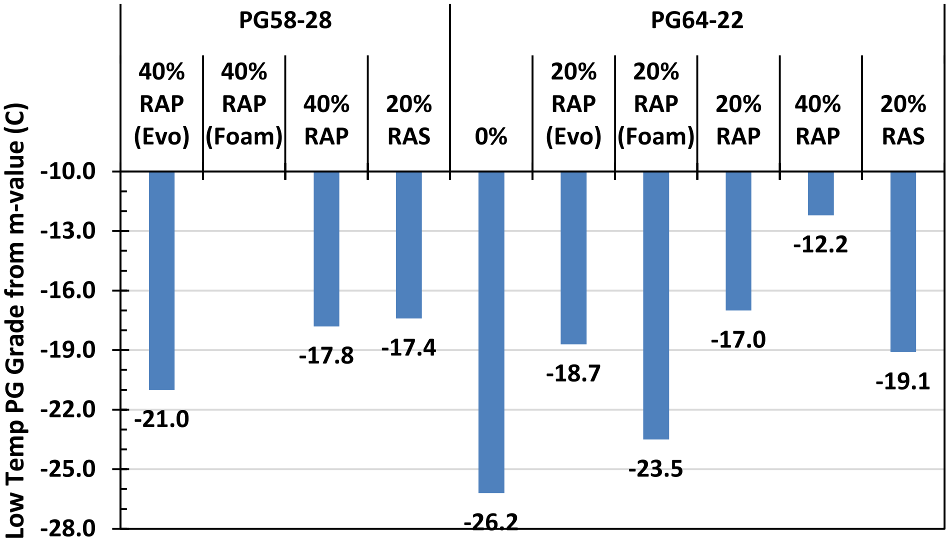

Figure 15 – Low Temperature PG Grading Results for FHWA ALF Asphalt Mixtures

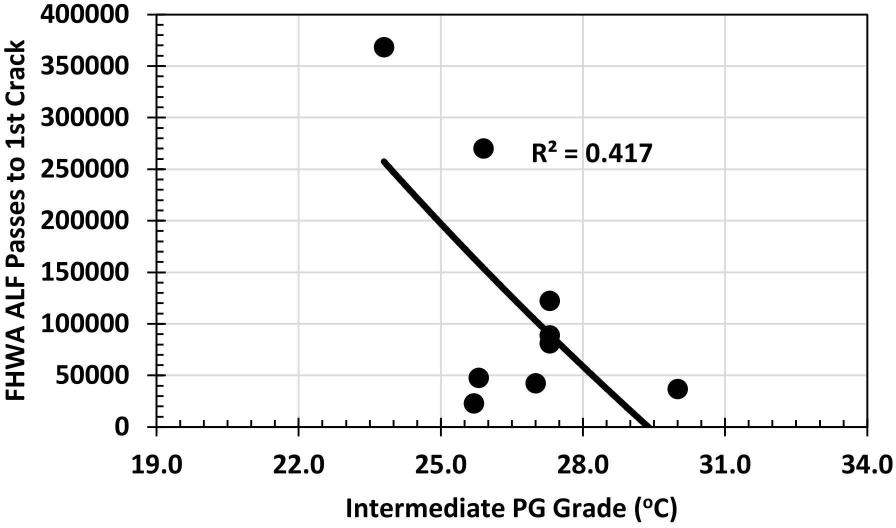

Figure 16 – Intermediate Temperature PG Grade vs FHWA ALF Passes to 1st Crack

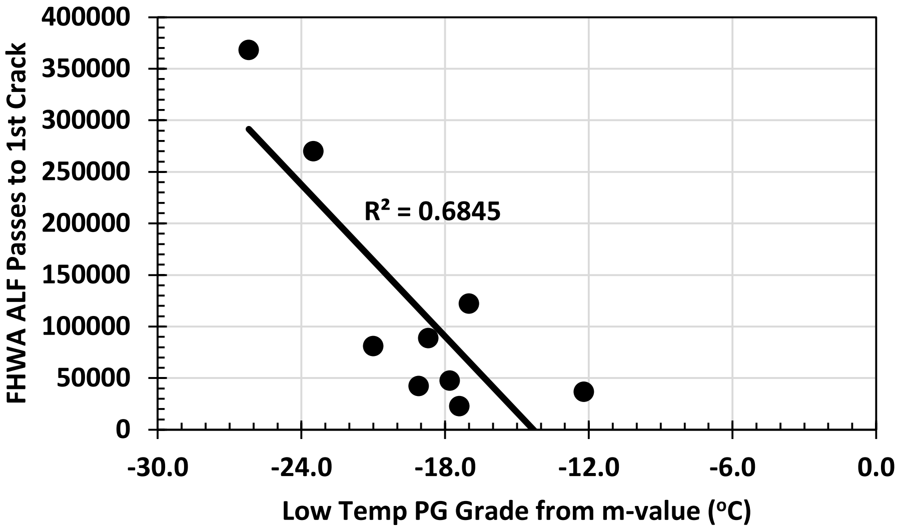

Figure 17 – m-value Low Temperature PG Grade vs FHWA ALF Passes to 1st Crack

The Difference in the Low Temperature PG Grade (ΔTc) was evaluated and compared to asphalt mixture performance on the FHWA ALF test sections. The ΔTc utilizes the Stiffness (S) and relaxation (m-value) parameters from the low temperature PG grading to address the reduction in relaxation properties due to asphalt materials and production practices. The results of the ΔTc for the ALF asphalt mixtures are shown in Figure 18. The results show a wide range of performance with the 0% recycled asphalt mixture resulting in the warmest ΔTc value. It should be noted that the more negative (colder) the ΔTc value, the poorer the durability/fatigue cracking performance of the asphalt binder.

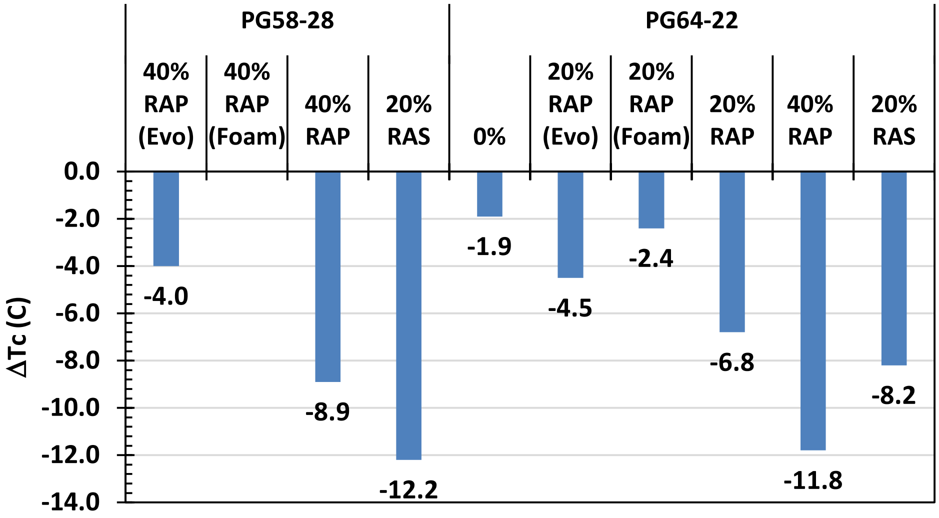

Figure 18 – ΔTc Parameter vs FHWA ALF Passes to 1st Crack

The comparison between the ΔTc to the FHWA ALF Number of Passes to 1st Crack is shown as Figure 19. The results show a good comparison between the ΔTc and the FHWA ALF performance, where the number of passes to the 1st crack increases as the ΔTc value becomes warmer (less negative).

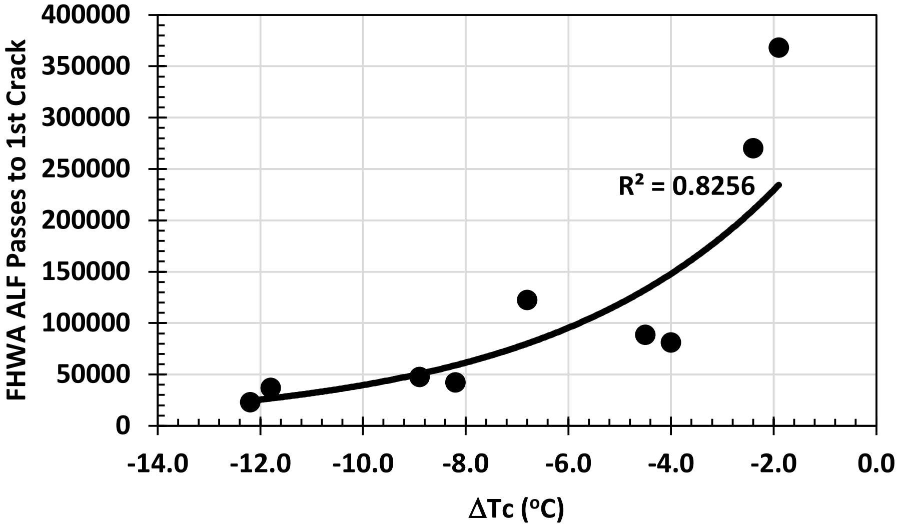

Figure 19 – ΔTc Parameter vs the FHWA ALF Number of Passes to 1st Crack

Double-Edged Notched Tension (DENT) Test

The Double-Edged Notched Tension (DENT) was incorporated in the study as a “true” fracture type test. The DENT test procedure, similar to the low temperature Direct Tension Test and the intermediate temperature Ductility test, “pulls” the asphalt binder until it “breaks”. The DENT utilizes notches at different depths to determine where the failure occurs and utilizes the trend with elongation vs notch depth to calculate Work and Fracture parameters. For this study, the DENT Critical Tip Opening Displacement (CTOD) was used for comparisons as previous research conducted at the FHWA ALF showed a strong relationship to performance.

The DENT CTOD results for the different ALF asphalt mixtures are shown in Figure 20 and the comparison to the FHWA ALF Number of Passes to 1st Crack are shown in Figure 21. The DENT CTOD had a moderate relationship to the ALF cracking with an R^2 value of 0.58. There clearly exists a trend of increasing FHWA ALF Number of Passes to 1st Crack with increasing DENT CTOD. However, there is clear scatter in the data resulting there is an average relationship between the DENT CTOD and the recovered asphalt binder properties of FHWA ALF asphalt mixtures.

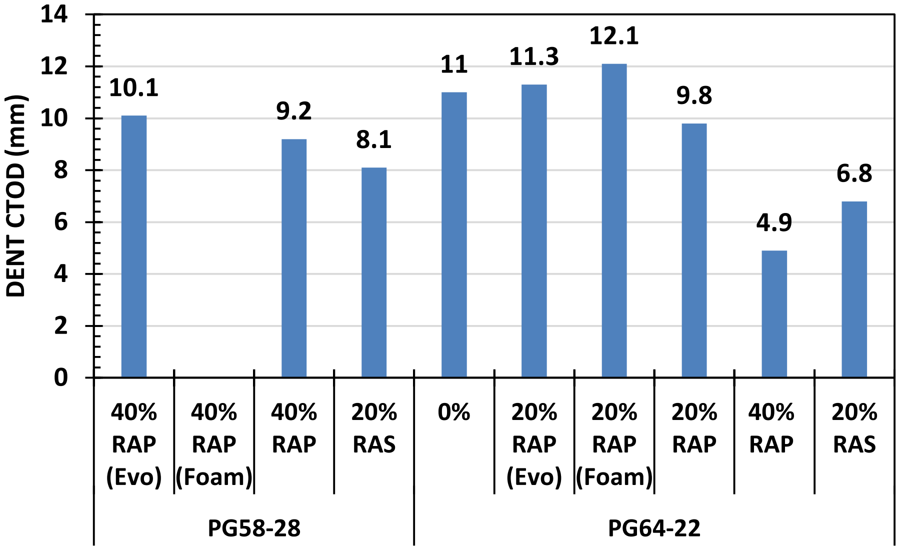

Figure 20 – DENT CTOD Results for FHWA ALF Asphalt Mixtures

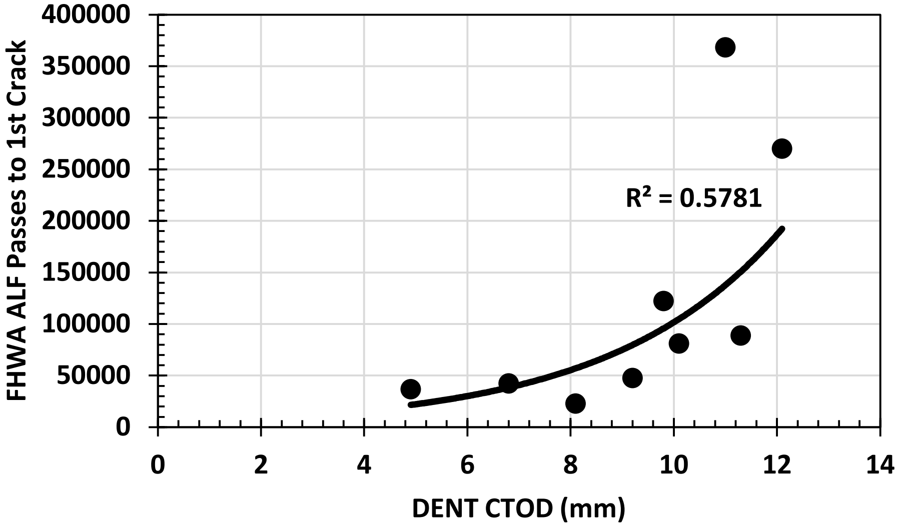

Figure 21 – DENT CTOD vs FHWA ALF Number of Passes to 1st Crack

Rheological Indices Related to Brittleness and Durability – Test Results

A Dynamic Shear Rheometer (DSR) frequency sweep test was conducted on each recovered asphalt binder to construct a master curve. The general procedure used follows that recommended by Rowe (2015) and extracted below;

Run the DSR in the oscillatory mode, within the strain range 0.005 to 0.02 (± 5%) ensuring that the test specimen will be tested over the linear region over the temperature range chosen. The typical range of stiffness being captured in a frequency sweep measurement will be 10 Pa to 10 MPa.

> *NOTE: Linearity check - This is most conveniently carried out by a torque sweep at both the highest and lowest test temperature to be used for the rheological characterization. For the majority of binders, it has been found that testing within the strain range 0.005 to 0.02 lies within the linear range. However, for PMBs, the linear range may be much less. The linear range available depends upon the stiffness of a binder at the condition being evaluated.*
>
> *It is recommended to use a strain value of 1% when G* is below 1e5 Pa and 2% when G* is above 1e5 Pa. This stiffness has been found to be a convenient for switching plate size with the DSR.*
>
> *The value of 1e5 Pa should lie in two isotherms since the value of G* is frequency dependent. Ideally, the 1e5 value should be measured with both plate diameters. The majority of the data with a G* below 1e5 should be collected with a 25mm plate size whereas the majority of the data generated with a G* greater than 1e5 Pa should be collected with an 8mm plate.*

Select the test temperatures appropriate to the binder being tested, to define the stiffness in the desired range but including test temperatures of 95, 80, 70, 60, 45, 35, 25, 15 and 5°C. Equilibrate the test specimen before testing.

> *NOTE: Caution should be taken when testing at the lower test temperatures that the measured shear modulus values are not being affected by possible machine/geometry compliance, or by the test specimen de-bonding from the plates. Also, it may not always be possible to test at the high end of the range since materials will be too fluid.*

The recommended range of frequencies (radians per second) for use in the frequency sweep testing is shown in Table 4. The idea of utilizing the selected frequencies shown in Table 4 is that the range covers two decades of loading times, providing five data points per log decade of frequency tested.

Table 4 – Recommended Range of Frequencies for DSR Frequency Sweep Testing

Log Basis (radians/second)	Linear Basis (radians/second)
-1.0	0.100
-0.8	0.159
-0.6	0.251
-0.4	0.398
-0.2	0.631
0.0	1.00
0.2	1.59
0.4	2.51
0.6	3.98
0.8	6.31
1.0	10.0

The data initial should be inspected for quality by plotting the results of G* and phase angle. The objective of this plot is to enable gross errors in the data to be spotted. Some typical examples are shown in Figures 22 and 23. It should be noted that smooth curves may not always exist due to transitions that may occur in materials. However, most asphalt binders when tested in the linear range, without modifiers, generally have a smooth relationship in this plot. Curves as shown in the second figure are generally associated with lower quality testing or utilizing too fast of a loading frequency during testing.

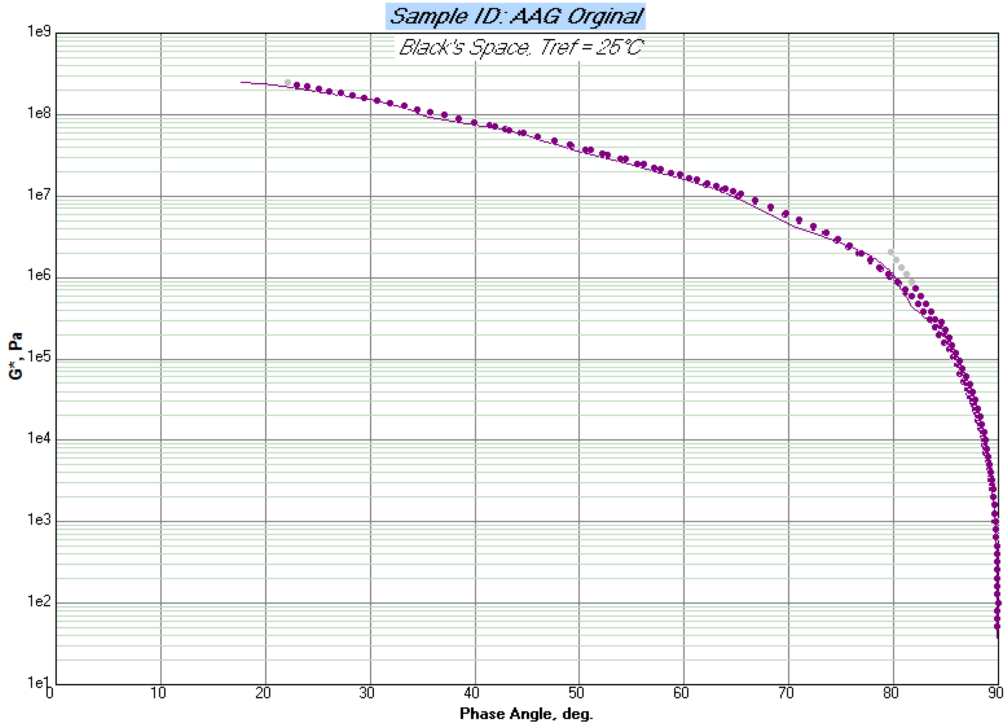

Figure 22 - Example of Acceptable Quality

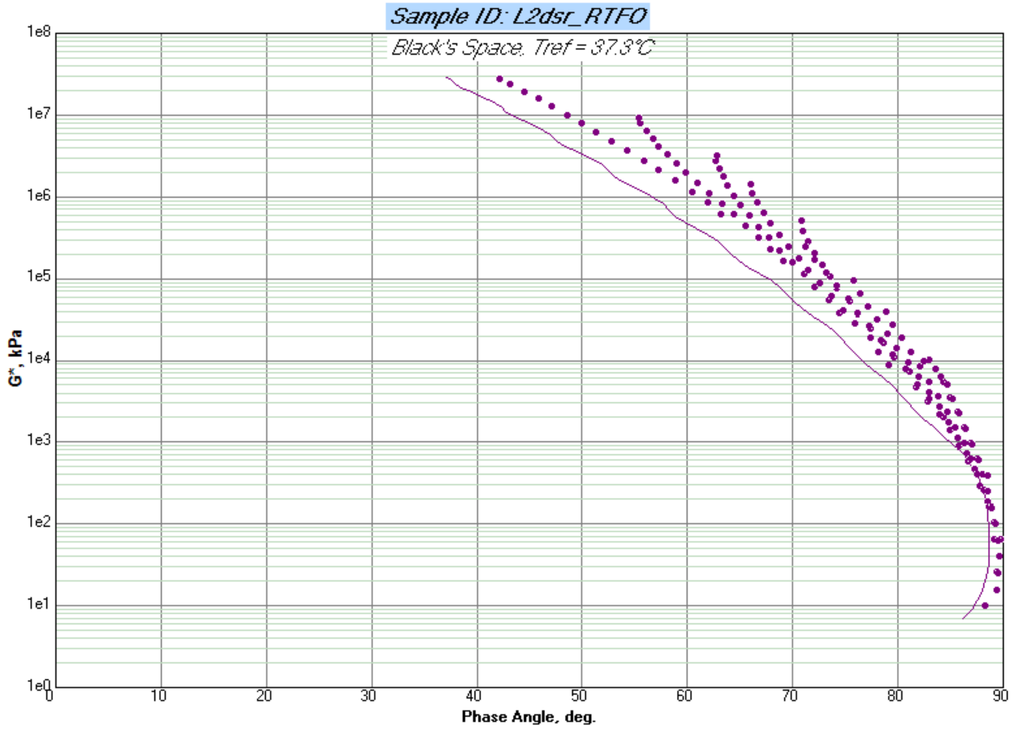

Figure 23 - Lower Quality Data with Isotherms Trending Upwards as Frequency Increases Suggesting Some Compliance Issues

Glover-Rowe Parameter (GRP)

As previously discussed, the GRP parameter is based on the construction of a master curve from frequency sweep testing at 5°C, 15°C, and 25°C in the DSR and interpolating to find the value of GPR at 15°C and 0.005 rad/sec to assess binder brittleness. Using this methodology, the GRP was determined for each of the recovered asphalt binders and compared to the fatigue cracking performance of the FHWA ALF test lanes. The result of the comparison is shown in Figure 24. The figure shows a good correlation between the GRP and the FHWA ALF Passes to 1st Crack, resulting in a very similar R^2 value to that of the previous ΔTc analysis. A further look at the relationship between ΔTc and GRP (Figure 25) indicates the test parameters, along tested on different test equipment and different test temperatures, do strongly correlate. Figure 25 also contains the FHWA ALF Number of Passes to 1st Crack, which shows both asphalt binder test procedures rank the performance of the ALF asphalt materials in an extremely similar manner.

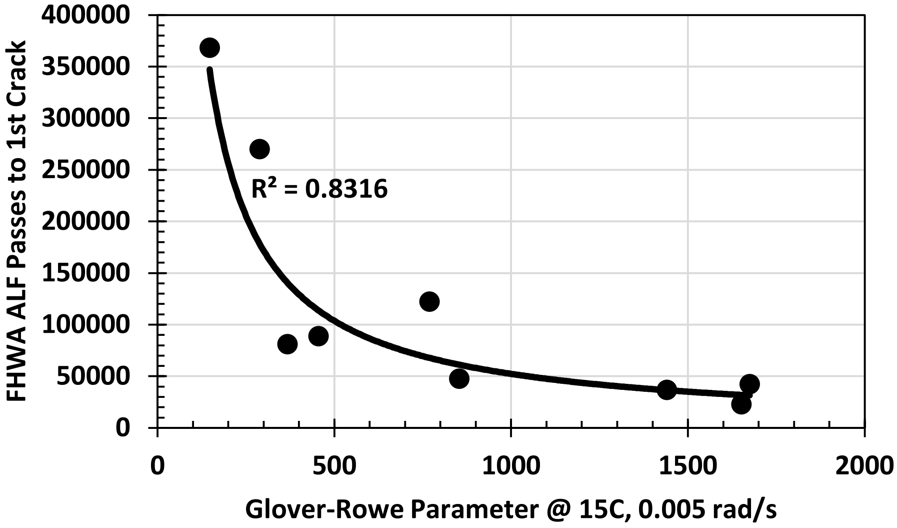

Figure 24 – Glover-Rowe Parameter vs FHWA ALF Passes to 1st Crack

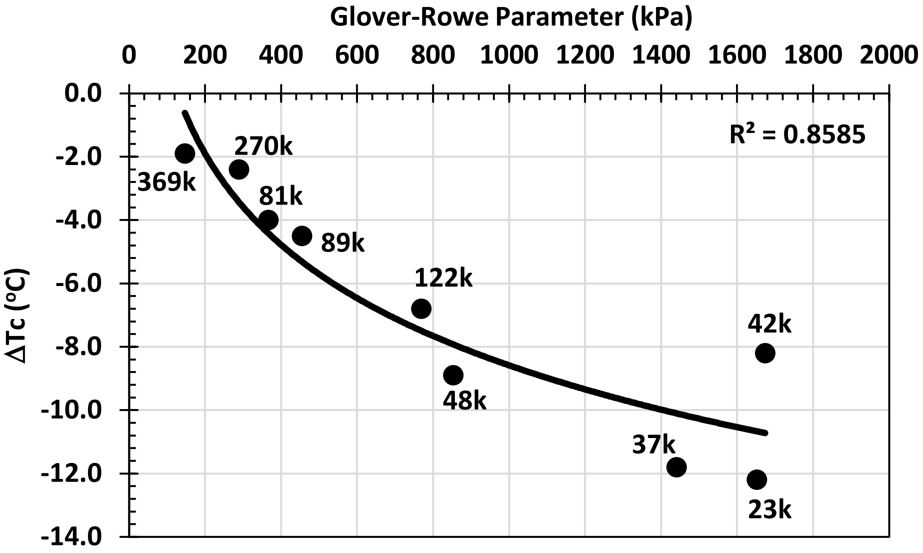

Figure 25 – Relationship Between ΔTc and Glover-Rowe Parameter

Phase Angle (δ) and Loss Tangent^2 at 10 MPa

As discussed previously, literature suggests that to help alleviate the influence of temperature and loading rate when comparing asphalt binder performance, it is important to test the asphalt binder at the same stiffness. Therefore, the phase angle (δ) and the Loss Tangent^2 at a G* = 10 MPa were determined using the master curve analysis from the frequency sweep testing and compared to the performance of the FHWA ALF test lanes.

Figure 26 shows the results of the comparison between the Phase Angle at G* = 10 MPa and FHWA ALF Passes to 1st Crack. The test results show an excellent relationship. It is rational to think that an excellent correlation exists as a decrease in phase angle would signify the asphalt binder becoming more elastic and stiff, while an increase in the phase angle would signify the asphalt binder is becoming more viscous and has a higher affinity for relaxation. This can be further be shown in Figure 27 where an excellent relationship between ΔTc and the Phase Angle at G* = 10 MPa was determined. ΔTc, cited in the literature to be directly related to an asphalt binder's ability to relax, clearly increases (becomes warmer) as the Phase Angle at G* = 10 MPa increases. Also shown in Figure 27 are the associated FHWA ALF Passes to 1st Crack, which clearly increases as the Phase Angle increases.

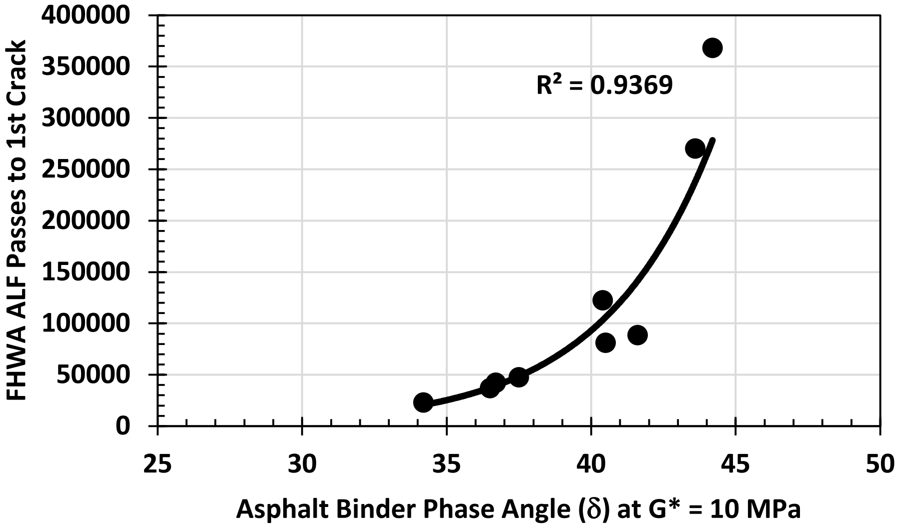

Figure 26 – Asphalt Binder Phase Angle at G* = 10 MPa vs FHWA ALF Passes to 1st Crack

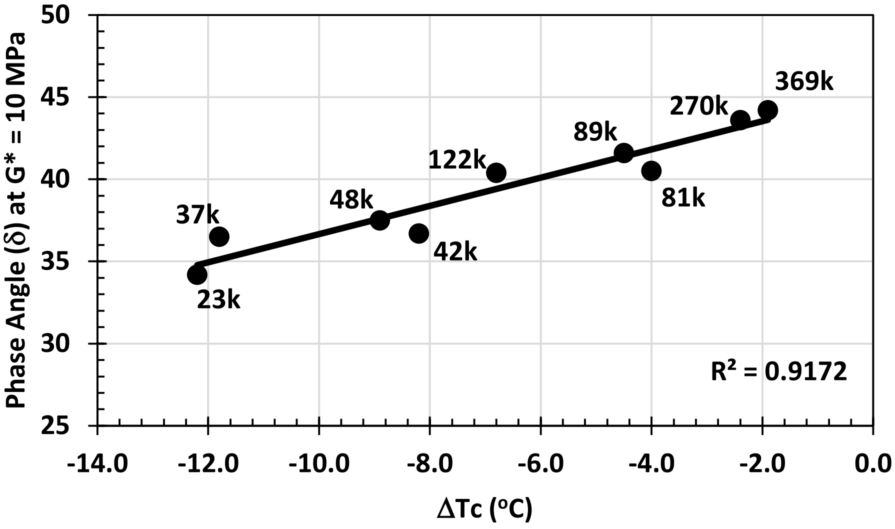

Figure 27 – Phase Angle at G* = 10 MPa vs ΔTc for FHWA ALF Test Lanes

The Loss Tangent^2 at G* = 10 MPa is compared to the FHWA ALF Passes to 1st Crack in Figure 28. The results show an excellent comparison to the fatigue performance of the FHWA ALF test lanes, and a slightly better correlation than simply the Phase Angle at G* = 10 MPa.

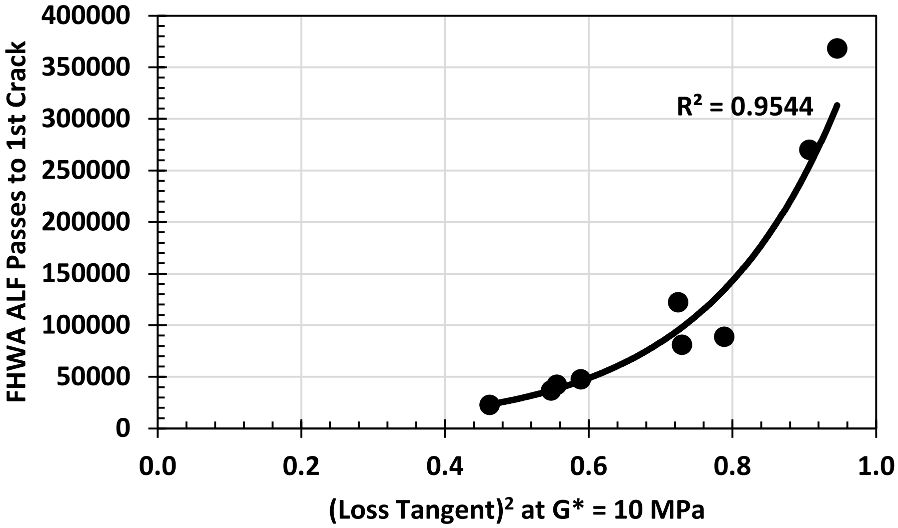

Figure 28 – Loss Tangent^2 at G* = 10 MPa vs FHWA ALF Passes to 1st Crack

CONCLUSIONS

The FHWA ALF Sustainability study was used to help evaluate the Overlay Tester test procedure's ability to identify fatigue cracking prone asphalt mixtures. In addition to the Overlay Tester, the SCB Flexibility Index test procedure was also used to characterize the asphalt mixtures' fatigue cracking performance. Asphalt binder tests were conducted on the top ½ - ¾" of the asphalt pavement surface to determine if the recovered asphalt binder properties could be correlated to the FHWA ALF fatigue cracking performance. Based on the testing conducted in the study, the following conclusions can be drawn:

- Both the Overlay Tester and the SCB Flexibility Index test procedures appear to be capable of identifying poor and good fatigue resistant asphalt mixtures. Both test procedures were able to rank the asphalt mixtures with the performance of the ALF results and appear to be sensitive to the varying asphalt mixture properties included in the FHWA ALF Sustainability study. Overall, the SCB Flexibility Index provided a slightly better correlation to the ALF's Number of Cycles to 1st Crack and takes less time for sample preparation. However, the Overlay Tester can be utilized on asphalt layers as thin as 1.5 inches, unlike the SCB Flexibility Index that requires a 2.0 inch thick test specimen.
- Current PG grading parameters, Intermediate PG Grade and Low Temperature PG Grade, did not provide a good correlation to the FHWA ALF Sustainability study's fatigue cracking. This confirms previous literature that cited the need for improved and better asphalt binder tests that related to the durability and fatigue cracking performance of asphalt binders.
- Three asphalt binder tests were found to provide good to excellent correlations to the fatigue cracking performance of the FHWA ALF test sections. They are (in order); 1) Loss Tangent^2 at G* = 10 MPa (and Phase angle at G* = 10 MPa); 2) Glover-Rowe Parameter (GRP), and 3) ΔTc. Both the Loss Tangent^2 and the Glover-Rowe Parameters are determined using the dynamic shear rheometer (DSR) frequency sweep test and the ΔTc parameter is determined during low temperature PG grading using the Bending Beam Rheometer (BBR).
- Although the general thought is that "more asphalt binder equals better fatigue performance", the quality of the asphalt binder is a much, and sometimes more important, than the actual quantity. Figures 29 to 31 show the three best asphalt binder parameters vs total asphalt binder content (as reported by the FHWA) and compared to the FHWA ALF Number of Cycles to 1st Crack. As the figures show, there is a narrow range of asphalt binder content (generally 4.8 to 5.0%), yet there is a wide range of fatigue cracking performance. The ALF fatigue cracking performance generally follows the combined effect of asphalt binder performance and total asphalt content. However, it should also be noted, that asphalt mixtures will have difficulty with durability/fatigue cracking when the asphalt binder content is too low, even when using the best asphalt binders.

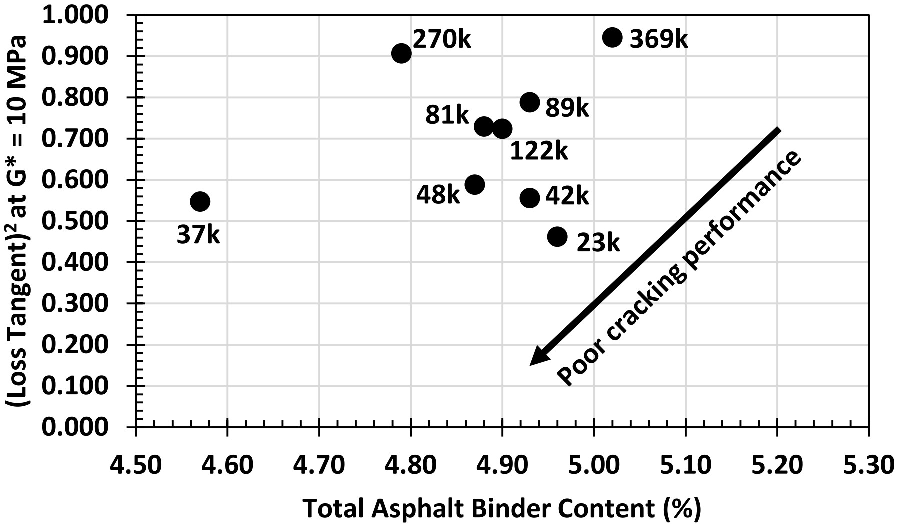

Figure 29 – Loss Tangent^2 at G* = 10 MPa vs Total Asphalt Binder Content for FHWA ALF Number of Cycles to 1st Crack (shown as data labels)

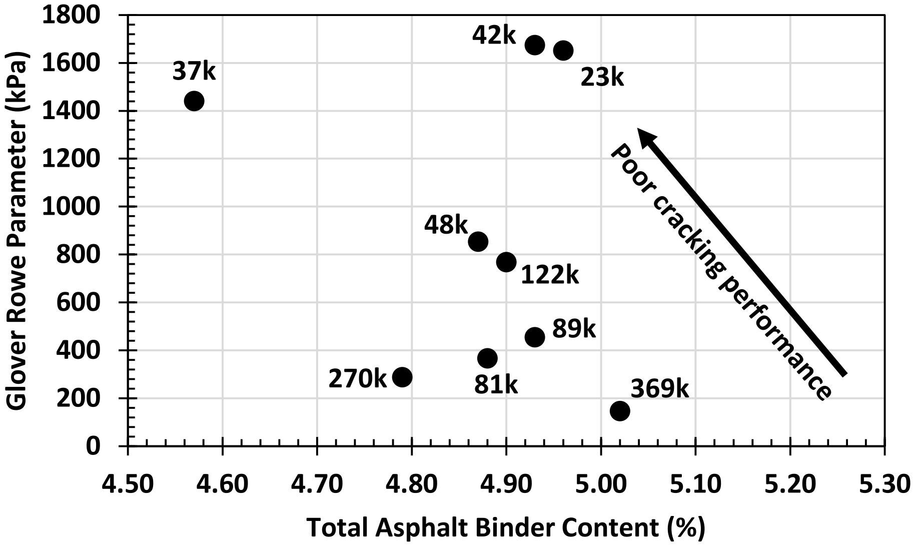

Figure 30 – Glover-Rowe Parameter vs Total Asphalt Binder Content for FHWA ALF Number of Cycles to 1st Crack (shown as data labels)

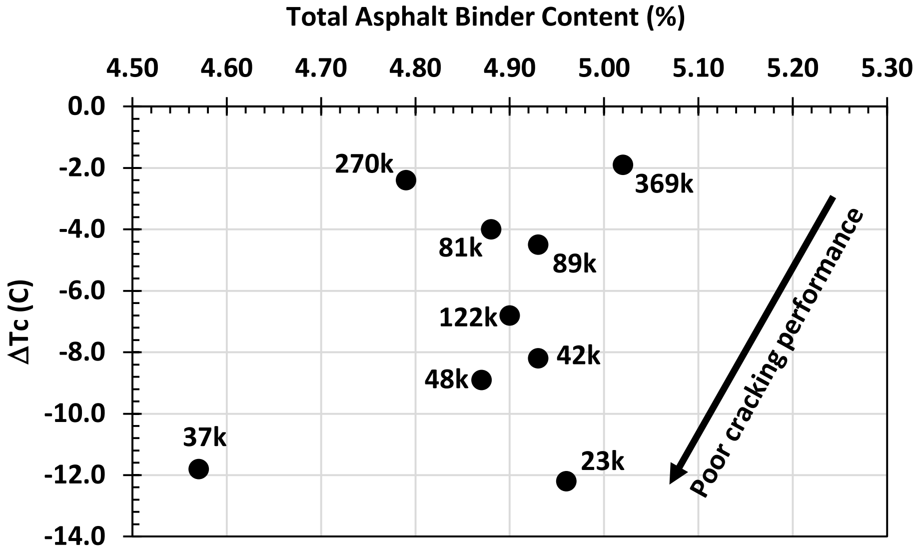

Figure 31 – ΔTc vs Total Asphalt Binder Content for FHWA ALF Number of Cycles to 1st Crack (shown as data labels)

RECOMMENDATIONS

Based on the results of the research study, a few recommendations are provided for future adoption and implementation;

- Both the Overlay Tester and SCB Flexibility Index should be considered as possible Quality Control test methods during asphalt mixture production, as well as their potential use within Performance-Based Specifications. However, state agencies need to evaluate their existing asphalt mixtures and their relative field performance to help establish state-specific performance criteria.
- Although the asphalt mixtures were produced with approximately the same amount of total asphalt binder content, the FHWA ALF performance and the asphalt binder testing clearly showed there existed quite a range of asphalt binder quality between the asphalt mixtures. This demonstrates that the asphalt binder from the recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) can have quite a detrimental impact on the asphalt mixture fatigue performance. Therefore, additional research is needed on how to best utilized recycled asphalt so as the fatigue cracking properties of the asphalt mixtures are not compromised.
- The Loss Tangent[2] at G* = 10 MPa shows great potential as an asphalt binder indicator of durability/fatigue resistance. Additional research with a larger data set of asphalt binders and performance is recommended to further quantify the correlation developed in this study.

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