FINAL REPORT ~ FHWA-OK-16-05

RECOMMENDED FATIGUE TEST FOR OKLAHOMA DEPARTMENT OF TRANSPORTATION

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October 2016

Oklahoma Department of Transportation

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16. ABSTRACT

The primary objective of this study was to evaluate different fatigue test methods and to recommend the most suitable one to Oklahoma Department of Transportation (ODOT). In order to achieve this objective, six commonly used asphalt mixes were tested using five different fatigue test methods. These fatigue test methods were evaluated with respect to the following criteria: (i) repeatability of test results; (ii) time spent for sample preparation and testing; (iii) training level needed for sample preparation and testing; and (iv) personnel expertise level and complexities involved in the data analysis. It was found that the SCB test method as per ASTM D 8044 is the most suitable fatigue test method, and thereby, this particular fatigue test method is recommended to ODOT for screening asphalt mixes based on their fatigue resistance.

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Asphalt mixture screening, Mixture design, Fatigue properties, Semi-circular bend, HMA, WMA

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APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
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*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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PART A

RECOMMENDED FATIGUE TEST FOR OKLAHOMA DEPARTMENT OF TRANSPORTATION

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1. INTRODUCTION

1.1 General

Fatigue cracking is a critical distress in asphalt pavements. This distress occurs due to repeated traffic load application, insufficient pavement structure, and most importantly due to use of fatigue prone asphalt mixes in the construction. A survey conducted under the scope of this study indicated that a large number of asphalt pavements fail due to fatigue cracking. However, the current Superpave® volumetric-based mix design method does not account for the fatigue behavior of asphalt mixes. The fatigue resistance of asphalt mix can be determined by conducting the following tests: (i) Semi-Circular Bend (SCB), (ii) Four-Point Beam Fatigue (BF), (iii) Indirect Tension (IDT), (iv) Cyclic Direct Tension (CDT), (v) Disc-shaped Compact Tension (DCT) and (vi) Overlay Tester (OT), etc. In most cases, one specialized equipment and trained personnel are required for performing fatigue tests on asphalt mixes. Unfortunately, even though several fatigue test methods are available, many state Departments of Transportation (DOTs) do not have guidelines and specifications for performing fatigue tests for their prevailing conditions. This is mainly due to the following reasons: (i) significant variability among different fatigue test methods, (ii) use of different test protocols by agencies, (iii) considerable amount of time needed for conducting fatigue tests, (iv) complexities involved in conducting the tests and high level of expertise needed for analyzing and interpreting the test results, (v) shortage of trained personnel, and (vi) more importantly lack of consensus over the most suitable fatigue test method.

Focusing on the afore-mentioned implementation-oriented issue, this study was conducted to identify a suitable and simple fatigue test method for screening asphalt mixes during the mix design stage. The primary objective of this study was to evaluate different fatigue test methods and to recommend the most suitable method to Oklahoma Department of Transportation (ODOT). Five different fatigue test methods were considered in this study, namely, SCB, BF, IDT, CDT, and OT. The DCT test which is mainly used for characterizing the thermal cracking resistance was not considered in this study. It may be mentioned that most of the tests considered in NCHRP 9-5, 2016 study have also been considered in this study. Six different asphalt mixes were considered in this study to evaluate the abovementioned five fatigue test methods. Fatigue test methods were evaluated with respect to the following: (i) repeatability of test results; (ii) time spent for sample preparation and testing; (iii) training level needed for sample preparation and testing; and (iv) personnel expertise level and complexities involved in the data analysis and computational procedure.

The project started in October 2012 and was scheduled to be completed by September 2015. As the tasks of the original project dealt with only testing of laboratory produced mixes, some additional tasks were planned later on and added to the original project as part of a one-year extension. The one-year extension mainly dealt with comparing the fatigue properties of asphalt mixes between field cores and laboratory-and- plant produced mixes. The field cores and mixes were collected from a Long Term Pavement Performance (LTPP) project constructed on a 4.08-mile-long section on SH-66 near Yukon, Oklahoma in Canadian county. In this report, this point onwards the extension project is referred as the “LTPP project” and the original project is referred as the “fatigue project”. PART A of this report deals with the fatigue project and PART B presents the LTPP project.

In the Year one of this study (October 2012 to September 2013), efforts were made in the following areas: (i) literature review to collect pertinent information about the latest developments in the fatigue evaluation methods; (ii) arranging/procuring the necessary fixtures and equipment to conduct fatigue tests; (iii) developing the test procedures for conducting fatigue tests in accordance with various test methods using the existing laboratory equipment; (iv) collecting materials (aggregate and asphalt binders) required during the course of the study; (v) conducting a number of fatigue tests on two selected asphalt mixes; and (vi) conducting a comprehensive survey among the various participating DOTs to collect information related to the fatigue test methods used by different DOTs. This survey indicated that many DOTs do not screen asphalt mixes for fatigue resistance before the construction of the pavement mainly due to the lack of consensus about the most suitable fatigue test method and lack of trained personnel. A statistical analysis was performed on the collected responses and submitted as a stand-alone report to ODOT.

In the Years two - four (October 2013 to September 2016), fatigue tests were conducted on the remaining asphalt mixes in addition to performing tasks of the LTPP project. Results of different fatigue tests were analyzed to verify the repeatability and effectiveness of those tests. The time spent on sample preparation and testing, personnel training, data analysis and computational work were evaluated. It was found that that the SCB test method is the most appropriate method for screening of asphalt mixes in terms of their fatigue resistance for the state of Oklahoma. The testing and data analysis procedure followed by the state of Louisiana appeared to be simple and feasible for regular screening of asphalt mixes.

An Asphalt Mixture Performance Tester (AMPT), manufactured by IPC Global Co.®, Australia, was purchased from InstroTek Co.®, North Carolina, during September 2014. Not only the SCB test, but also the CDT and OT test can be conducted in this equipment. Test protocol for the SCB was developed. The Oklahoma DOT personnel were trained through multiple demonstrations and hands-on training sessions.

1.2 OBJECTIVES

The main goal of this study was to recommend the most suitable fatigue test method for the Oklahoma DOT so that they can screen the asphalt mixes based on the fatigue resistance. This goal was achieved through the following specific objectives:

(i) Examine the fatigue resistance of different types of asphalt mixes commonly used in Oklahoma;
(ii) Compare and rank these mixes based on their fatigue resistance;
(iii) Evaluate repeatability and complexity of selected five fatigue test methods;
(iv) Select the most suitable fatigue test method;
(v) Purchase an equipment for ODOT that can be used to conduct the selected fatigue test;

(vi) Develop a test protocol and provide the training necessary for using the equipment and performing data analysis.

1.3 TASKS PLAN

In order to accomplish the objectives noted above, six different asphalt mixes were selected. The mixes considered in this study are commonly used in Oklahoma. ODOT representatives were consulted in selecting these mixes. These mixes include representation of different asphalt binder types (modified vs. unmodified), different aggregate gradations (coarse (S3) vs. fine (S5)), and different mix types (hot mix vs warm mix). These selected mixes represent high, medium and low fatigue resistance mixes. One rich intermediate layer (RIL) mix was included to represent a high fatigue resistance mix. A warm mix asphalt (WMA) with RAP was included to possibly represent as a low fatigue resistance mix. Description of these mixes is presented in Table 1. Selection of the five different fatigue test methods was based on the literature review as presented in the next section. These methods have gained popularity in recent years and some of them have been used in different states already.

Table 1: Selected six mixes for the project.

Mix no.	Mix type	Mix designation	Mix description
Mix-1	Unmodified mix	Mix-1 (S3-PG 64-22 OK)	S3 mix with PG 64-22 OK asphalt binder
Mix-2	Modified mix	Mix-2 (S3-PG 76-28 OK)	S3 mix with PG 76-28 OK asphalt binder
Mix-3	Rich layer mix	Mix-3 (S5-PG 76-28 E)	S5 mix (RIL) with PG 76-28 E asphalt binder
Mix-4	Fine mix	Mix-4 (S5-PG 76-28 OK)	S5 mix with PG 76-28 OK asphalt binder
Mix-5	WMA mix	Mix-5 (S3-F-PG 64-22 OK)	S3 foamed mix with PG 64-22 OK asphalt binder
Mix-6	WMA mix	Mix-6 (S3-C-PG 64-22 OK)	S3 chemical additive mix with PG 64-22 OK asphalt binder

The following specific tasks were pursued in this project to achieve the objectives of the project: (i) literature review, (ii) survey of DOTs' specification on fatigue test method, (iii) evaluation of climate data, (iv) selection of materials, (v) laboratory testing of asphalt mixes, (vi) sample preparation, (vii) fabrication of test setups, (viii) laboratory testing and analysis of test results, (ix) comparison of results between the asphalt mixes, (x) analysis of repeatability and variability of test Methods, (xi) selection of test method and equipment, (xii) purchase of equipment for ODOT, (xiii) development of test protocol and method, (xiv) training and workshop for ODOT personnel.

2. LITERATURE REVIEW

2.1 General

Fatigue cracks occur due to repeated vehicle loading on the pavement, which induces excessive tensile strains in the asphalt layer (ARA, 2004). This distress is one of the most common distresses in flexible pavements. Therefore, characterization of fatigue resistance of asphalt mixes at the design stage is very important to limit the occurrence of premature failure of pavements due to fatigue. The current mix design methods do not address fatigue performance of associated asphalt mixes (AASHTO 2013, Wen and Kim, 2002 and Witczak et al., 2002). Also, many Departments of Transportation (DOTs) do not screen asphalt mixes to estimate their fatigue resistance (Hobson, 2012; Witczak et al., 2002).

In order to become acquainted with the different fatigue test methods and their advantages and disadvantages, a literature review was performed continuously throughout the project duration. The literature review was focused on understanding the principles of each of the five fatigue testing methods and their applications as published in the open literature. The commonly used tests include SCB, BF, IDT, CDT, and OT. The DCT test method is primarily used for characterization of thermal crack resistance of asphalt mixtures; Minnesota DOT (MnDOT) screen their asphalt mixes using this test method (Johanneck et al., 2015). Table 2 presents a list of the test standards, sample shapes, sample dimensions, loading patterns, tentative pass/fail criteria, and test outputs for the above-mentioned methods. Table 3 presents a summary of the literature reviewed in this study, the agencies/ research organizations/institutes involved in each of the literatures are also provided in Table 3.

Table 2: Description of fatigue test methods.

Method	SCB	BF	IDT	CDT	OT
Test Standard	Mohammad et al., 2006	AASHTO T-321, 2007	ASTM D 7369, 2011	AASHTO TP-107, 2014	Tex-248-F, 2012
Sample shape	Semi-circular beam	Beam	Cylinder	Cylinder	Beam
Sample dimensions	6-in D x 3-in H x 2-in T	15-in L x 2.5-in W x 2-in H	6-in D x 2-in T	4-in D x 6-in H	6-in L x 3-in W x 1.5-in H
Sample preparation equipment	SGC, saw	LNC, saw	SGC, saw	SGC, Coring machine, saw	LNC, saw
Loading pattern	Monotonic or cyclic	Cyclic	Monotonic or cyclic	Monotonic or cyclic	Monotonic or cyclic
Tentative pass or fail criteria	Not yet established	Number of cycles to 50% stiffness	85<tensile strength <200 psi	Number of cycles to fail at 300 micro strain (approx.)	OT Cycles> 300 at 93% stress reduction
Test output	Tensile strength and strain	Number of cycles, dissipated energy	Tensile strength and strain	Tensile strength, strain, damage curve	Number of cycles to failure

Note: D: Diameter; T: Thickness; H: Height; W: Width; L: Length; SGC: Superpave Gyratory Compactor; LNC: Linear Kneading Compactor

Table 3: Summary of literature review for different types of tests used to evaluate fatigue resistance of asphalt mixes.

Test method	Institute/ Agency/ DOT/ Country	List of references
SCB	Iran	Pirmohammad and Ayatollahi
SCB	Iowa State University	Tang, S., 2014
SCB	Brazil	Aragao and Kim, 2012
SCB	Sweden	Biligiri et al., 2012a; Biligiri et al., 2012b
SCB	LTRC	Kim et al., 2012
SCB	University of Tennessee	Huang et al., 2011
SCB	Louisiana State University	Cooper et al., 2015; Mohammad et al., 2011; Wu et al. ,2005
SCB	China Three Gorges University	Liu, 2011
SCB	University of Liverpool, UK	Hassan et al., 2010
SCB	Technical University, Spain	Perez-Jimenez et al., 2010

Test method	Institute/ Agency/ DOT/ Country	List of references
SCB	Turner-Fairbank Highway Research Center (TFHRC)	Li et al., 2010a; Li et al., 2010b; Lie et al., 2004
SCB	Hunan University, China	Huang et al., 2009
SCB	University of New Mexico	Tarefder et al., 2009
BF	University of New Mexico	Amina et al., 2015
BF	Virginia Tech	Boriack et al., 2015
BF	University of New Mexico	Mannan et al.,2015
BF	Iran	Modarres et al., 2015
BF	California State University	Saadeh et al., 2011
BF	Morehead State University	Adhikari et al., 2010
BF	University of Tennessee	Huang et al., 2011; Shu et al., 2008
BF	UIUC	Chiangmai,2010
BF	Clemson University	Xiao et al., 2010
BF	Hunan University, China	Huang et al., 2009
BF	Texas A & M University	Zhou et al., 2007a
BF	University of Liverpool, UK	Khalid, 2000
IDT	Iran	Modarres et al., 2015
IDT	Bogotá	Rondon et al., 2015
IDT	Worcester Polytechnic Institute, Massachusetts	Gong et al., 2012
IDT	Washington State University	Wen, H., 2013; Wen, H., 2003
IDT	Louisiana Transportation	Kim et al., 2012;
IDT	Research Center (LTRC)	Mohammad et al., 2011
IDT	Texas A & M University	Walubita et al., 2011
IDT	University of Tennessee	Huang et al., 2011; Shu et al., 2008
IDT	California State University	Saadeh et al., 2011
IDT	University of Florida and Florida DOTs	Kim et al., 2009b; Roque et al., 2004
IDT	Hunan University, China	Huang et al., 2009
IDT	Auburn University	Timm et al., 2009
IDT	University of Illinois at Urbana Champagne (UIUC)	Kim et al., 2009a
IDT	University of Liverpool, UK	Khalid,2000
IDT	Institute/ Agency/ DOT/ Country	List of references
CDT	Turner-Fairbank Highway Research Center	Gibson and Li, 2015

Test method	Institute/ Agency/ DOT/ Country	List of references
CDT	North Carolina State University (NCSU)	Safaei et al., 2014
CDT	North Carolina State University (NCSU)	Lee et al., 2000
CDT	North Carolina State University (NCSU)	Underwood et al., 2009
CDT	University of Massachusetts	Haggag et al., 2011
CDT	North Carolina State University (NCSU)	Underwood et al., 2010
CDT	TexasA&M	Walubita et al., 2011; Walubita et al., 2010
CDT	Washington State University	Wen, H., 2003
CDT	North Carolina State University	Underwood et al., 2012; Underwood and Kim, 2011
CDT	Seoul National University	Mun and Lee, 2011
CDT	TFHRC	Gibson et al., 2003
OT	Texas A& M University	Walubita et al., 2012; Walubita et al., 2011; Hu et al.,
OT	Texas A& M University	OT TexasA&M 2011; Walubita et al., 2010; Zhou et al., 2007a; Zhou et al., 2007b; Chen, 2007

2.2 Semi-Circular Bend (SCB) Test

Several researchers (Al-Qadi et al.2015; Pirmohammad and Ayatollahi, 2015; Tang, S., 2014; Aragao and Kim, 2012; Biligiri et al., 2012a; Biligiri et al., 2012b; Kim et al., 2012; Huang et al., 2011; Mohammad et al., 2011; Liu, 2011; Hassan et al., 2010; Perez-Jimenez et al., 2010; Li et al., 2010a; Li et al., 2010b; Huang et al., 2009; Tarefder et al., 2009; Wu et al. ,2005; Lie et al., 2004) have reported that the SCB test method can be used for fatigue evaluation of asphalt mixes. This test can be conducted on laboratory-compacted samples as well as on field cores. SCB test is conducted by applying a monotonically increasing load on a semi-circular sample until failure (AASHTO TP 105-13) (Figure 1). Biligiri et al. (2012) recommended SCB test to estimate the residual life of flexible pavements during their design periods. The SCB test method for asphalt is relatively new and currently being investigated by several DOTs to verify the feasibility of using it for screening asphalt mixes. AASHTO TP 105, 2015 is available for the SCB test method. However, this standard is not uniformly followed across the country. Illinois (Ozer, 2016) and Louisiana (Kim et al., 2012) have come up with their own SCB test and data analysis procedures.

The fracture resistance is analyzed based on an elasto-plastic fracture mechanics concept of critical strain energy release rate (Mohammad et al., 2011; Wu et al., 2005). In order to study the asphalt fatigue resistance, critical strain energy release rate or the J-integral (J_c) is computed from the SCB test data. The method for computing the J_c is illustrated in Figure 2. To determine J_c, the strain energy at failure (U) is calculated from the load - vertical deformation curve. The area under the load - vertical deformation curve until the peak load (shaded portion in the Figure 2) is equivalent to U. J_c is computed using the specimen thickness and rate of change of U over the notch depth (dU/da, slope of the curve in Figure 2), as given in the following Equation. The higher the J_c value, the higher the fatigue resistance (Kim et al., 2012).

$$J_c = \frac{-1}{b}\left(\frac{dU}{da}\right) \quad (1)$$

where, J_c = critical strain energy release rate (kJ/m^2);
b = specimen thickness (mm);
a = notch depth (mm);
U = strain energy at failure (kN-mm).

Figure 1: Semi-circular bend (SCB) test.

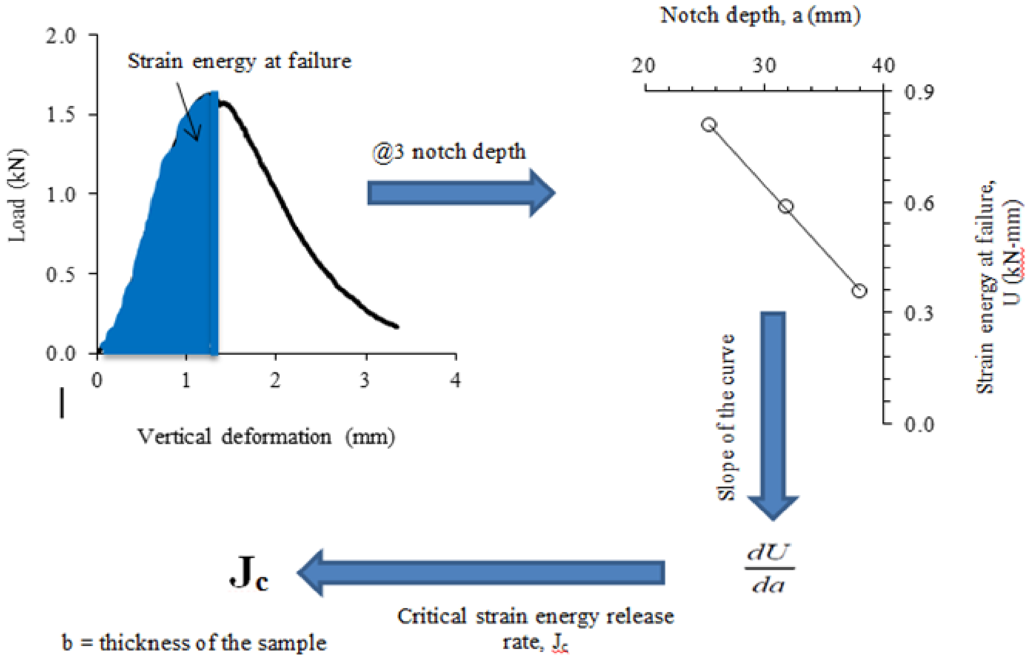


Figure 2: Computation of J_c using SCB test results.

The test results of the SCB test can also be also analysed in terms of flexibility index (FI) (Al-Qadi, 2015). The concept of flexibility index facilitates characterization of the asphalt mixes based on their post-crack performance. “The FI describes the fundamental fracture processes consistent with the size of the crack tip process zone (Al-Qadi, 2015).” Different parameters involved in the calculation of FI is provided in Figure 3. Theoretically FI is can be expressed by the following equation.

$$FI = A \times (\text{Fracture Energy}/\text{slope at inflection}) \qquad (2)$$

where A is the calibration coefficient for unit conversions and age shifting for lab versus plant versus field materials.

The main advantage of the SCB test is its simplicity in performing the test. Also, different notch depths can be introduced quite easily and the crack propagation can be directly evaluated (Wu et al., 2005). The potential weakness of the current SCB test protocol is that only monotonic load is applied on the sample. However, the fatigue failure in pavement occurs due to cyclic loading. Therefore, application of cyclic loading to conduct the SCB test would be a better representation of the fatigue failure mechanisms in the field.

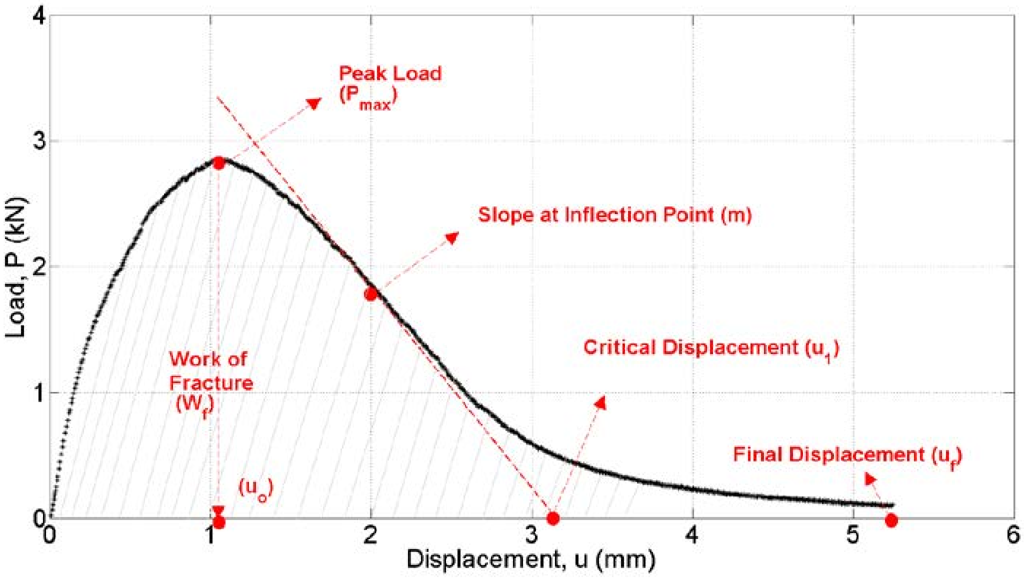


Figure 3: A typical outcome of the Illinois-SCB test illustrating the parameters derived from the load-displacement curve, including peak load (could be related to tensile strength), critical displacement, slope at inflection point, displacement at peak load, and fracture energy (After Al-Qadi, 2015).

2.3 Four-Point Beam Fatigue (BF) Test

Several researchers (Boriack et al., 2015; Amina et al., 2015; Huang et al., 2011; Saadeh et al., 2011; Adhikari et al., 2010; Chiangmai, 2010; Xiao et al., 2010; Huang et al., 2009; Shu et al., 2008; Zhou et al., 2007a; Khalid, 2000) reported that the BF test (Figure 4) method closely simulates the field conditions of pavements and, therefore, can be used to evaluate the fatigue life of a given asphalt mix. Depending upon the thickness of the pavement, BF test is conducted under two different conditions, namely strain-controlled and stress-controlled. In this method, a constant haversine load is applied on an asphalt beam, using a special fixture supporting the beam at four points, until failure. Application of this fixture introduces pure bending in the mid-span of the beam and causes the sample to fail due to cyclic bending. The failure is defined as the 50% of the beam's initial stiffness measured at the first 50 loading cycles (Adhikari and You, 2010).

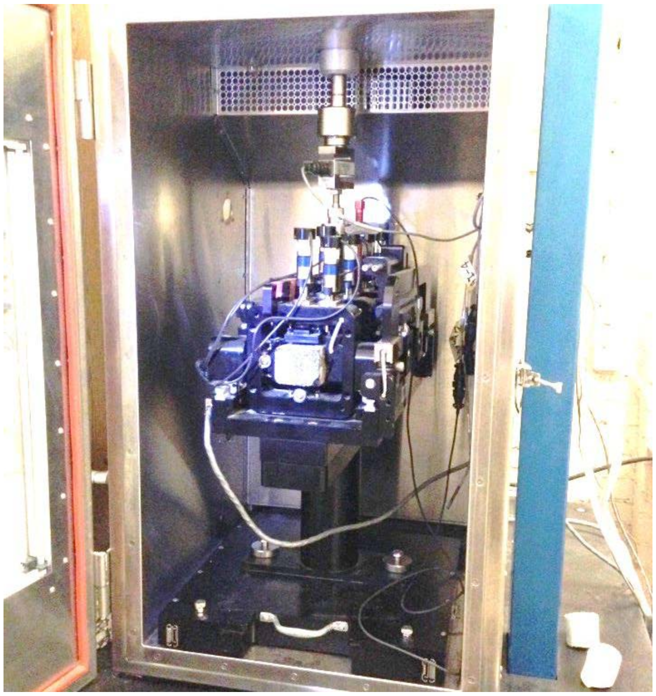


Figure 4: Four-point beam fatigue (BF) test setup.

A constant cyclic flexural strain (e.g., 400 micro-strain in the present study) is maintained at the bottom mid-span of the sample. It may be mentioned that in this study, a constant strain level was maintained for all the mixes so that the fatigue behaviors of the mixes could be compared at an identical strain level. The applied load, phase angle, and deformation at the mid-span are recorded for each cycle to compute the stiffness. A schematic of the principle of the test is shown in Figure 5. The maximum tensile stress, maximum tensile strain and flexural stiffness are calculated using the following equations.

$$\sigma_t = \frac{3aP}{bh^2} \quad (3)$$

$$\varepsilon_t = \frac{12h\delta}{3L^2 - 4a^2} \quad (4)$$

$$FS = \frac{\sigma_t}{\varepsilon_t} \tag{5}$$

where σ_t = maximum tensile stress; ε_t = maximum tensile strain; *FS* = flexural stiffness; a = distance between clamps; b = width of the beam; P = Applied load; h = thickness of the beam; δ= measured deflection; L = distance between the outside supports.

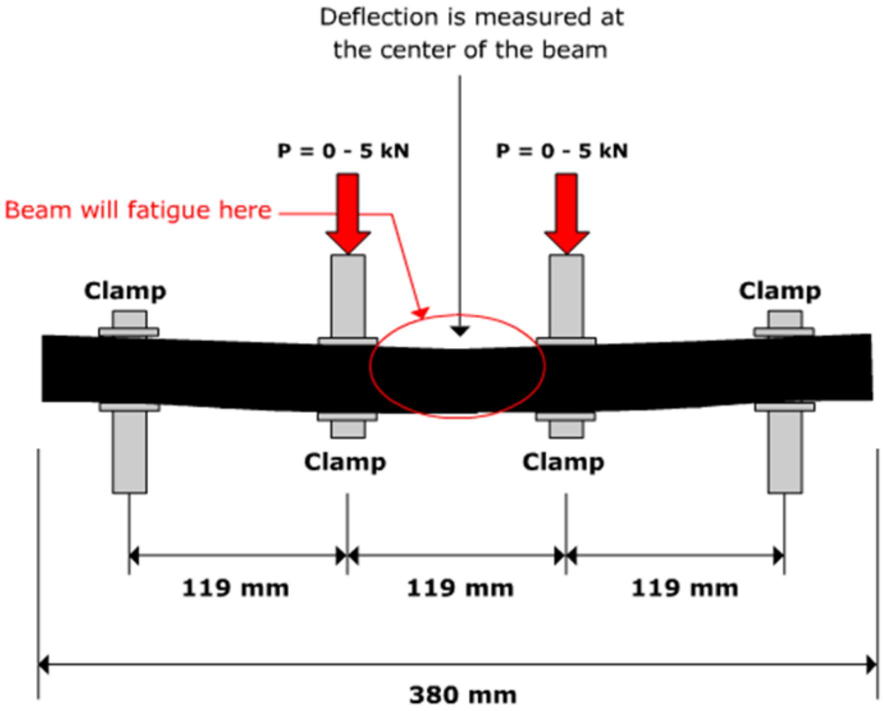


Figure 5: Schematic of the principle of BF test method (pavementinteractive, http://www.pavementinteractive.org/article/flexural-fatigue/)

The dissipated energy at a given load cycle and the cumulative dissipated energy at the failure can be calculated using the following equations.

$$w_i = \pi \sigma_i \varepsilon_i Sin\varphi_i \tag{6}$$

$$w_N = \sum_{i}^{N_f} w_i \quad {}_{i} \tag{7}$$

where, w_i = dissipated energy at cycle; σ_i = stress level at cycle i; ε_i= strain level at cycle i; φ_i = phase angle at cycle i; and w_N= cumulative dissipated energy at the failure.

The main advantage of this test method is that the fatigue life of asphalt mixes can be evaluated in terms of flexural stiffness and dissipated energy as a function of number of load cycles. The reduction of flexural stiffness can be related to the micro-crack propagation, while the number of load cycles and loading frequencies can be related to the anticipated traffic load characteristics in the field. One of the difficulties associated with conducting the BF test is that it can take a considerable amount of time to conduct a test. Also, a high variability in the test results could be obtained from testing two identical beam samples prepared with the same asphalt mix.

2.4 Indirect Tensile (IDT) Test

Indirect Tensile Test has been used by several researchers (Modarres et al., 2015; Rondon et al., 2015; Wen, H., 2013; Gong et al., 2012; Kim et al., 2012; Mohammad et al., 2011; Huang et al., 2011; Walubita et al., 2011; Saadeh et al., 2011; Huang et al., 2009; Kim et al., 2009a; Kim et al., 2009b; Timm et al., 2009; Shu et al., 2008; Roque et al., 2004; Wen, H., 2003; Khalid,2000) to evaluate the fatigue resistance of asphalt mixes. The IDT test is conducted by applying a monotonically increasing load along the diameter of a cylindrical sample until failure due to indirect tension (Figure 6). This test can be conducted on laboratory-compacted samples as well as on field cores (Kim et al., 2012).

Figure 6: Indirect tensile (IDT) test setup.

The IDT test results can be used to determine the toughness index (TI) and fracture energy ratio (ER) (Wen, 2013; Yin et al., 2008; Roque et al., 2004) in order to characterize the fatigue resistance of asphalt mixes. This test, in association with the resilient modulus (M_r) (ASTM D7369) and creep compliance (CC) (AASHTO T 322) tests, provides fracture properties of asphalt mixes. Fracture toughness index is determined directly from the load vs. vertical deformation curve obtained in the IDT test.

The TI is determined by using the normalized ITS - strain curve. The normalized ITS value is obtained by normalizing the stress values with respect to the peak stress. Figure 7 shows a typical normalized ITS - strain curve; this figure also illustrates the computational procedure for TI, which can be computed using the following equation.

$$\mathrm{TI} = \frac{\mathrm{A}_{\varepsilon} - \mathrm{A}_{\mathrm{P}}}{\varepsilon - \varepsilon_{\mathrm{P}}} \tag{8}$$

where TI = toughness index; A_ε = area under normalized ITS - strain (%) curve up to terminal strain ε; ε = terminal strain; A_P = area under normalized ITS - strain (%) curve up to strain ε_P; and ε_P = strain corresponding to peak stress. These parameters are defined in Figure 7.

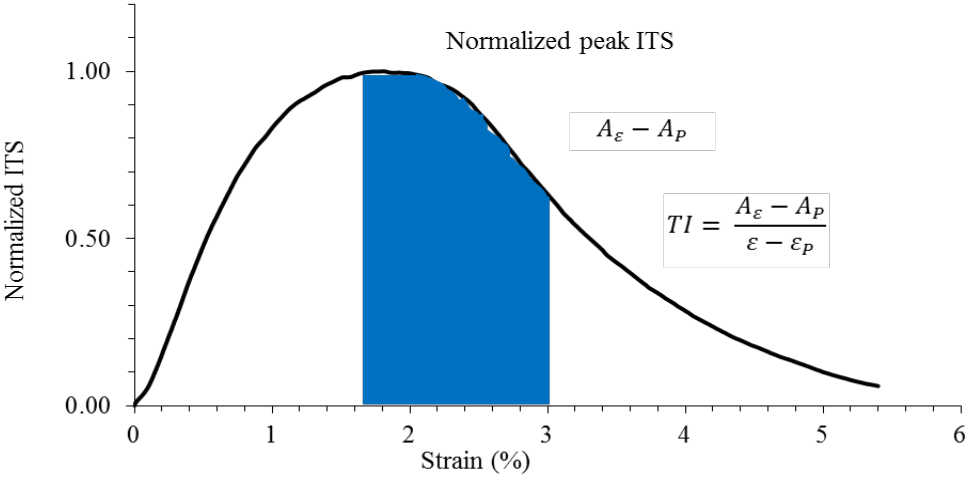


Figure 7: Normalized ITS - strain curve in IDT test and computation of TI.

The IDT test has several advantages, such as being one of the simplest test methods reported to correlate well with the fatigue performance of actual pavements (Wen, H., 2012; Kim et al., 2009a; Roque et al., 2004; Wen, H., 2003) and having potential for possible adoption as a screening tool for fatigue resistance. The main disadvantage of this test method is the lack of consensus on using this test as a quality control and quality assurance tool to evaluate fatigue resistance of an asphalt mix. Also, this test is conducted using a monotonic load. However, the fatigue failure in pavement occurs due to cyclic loading.

2.5 Cyclic Direct Tension (CDT) test

Asphalt mix is a visco-elastic composite material. When it is subjected to repeated traffic loads, structural damage occurs primarily in the form of micro-cracks due to the high stress concentrations along the aggregate-binder interfaces. Researchers (Kim et al., 2009) at North Carolina State University (NCSU) developed material models that can capture various critical phenomena such as micro-crack-induced damage, strain-rate temperature interdependence, and viscous flow in asphalt mixes. The resulting model is known as the Visco-elastic Continuum Damage (VECD) model. The CDT test (Figure 8), in association with the dynamic modulus (DM) test (AASHTO T 342), provides the mechanistic parameters for the visco-elastic continuum damage (VECD) analysis. In this test, a controlled cyclic direct tension load is applied on the cylindrical sample. The applied stress and on-specimen axial strain responses are measured to calculate the pseudo strain, pseudo secant modulus and damage. The damage characteristic curve (damage vs. pseudo secant modulus) is then developed (AASHTO PP 107-14). Figure 9 shows an example of damage characteristics curves.

Figure 8: Cyclic direct tensile (CDT) test setup.

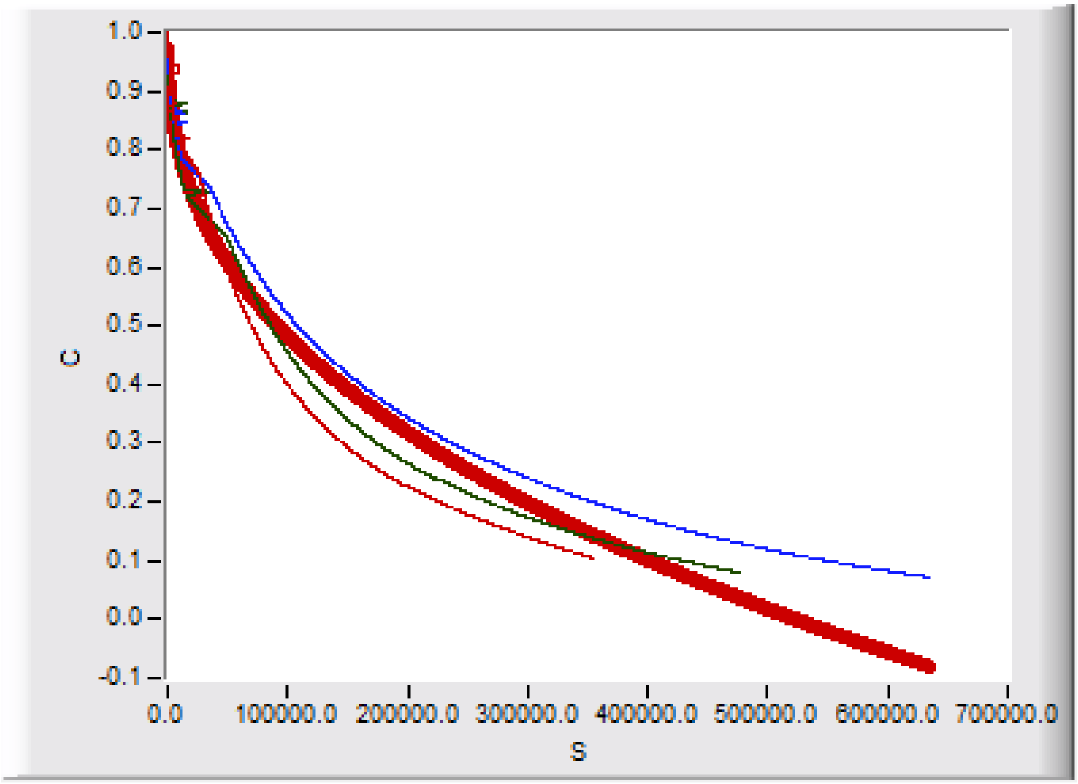


Figure 9: Damage Characteristics Curve in CDT test.

The main advantage of this method is that the damage characteristic curve combined with the linear visco-elastic properties of asphalt mixes can be used to determine the fatigue characteristics of the asphalt mixes. The damage characteristic curve represents the fundamental relationship between damage and material integrity. Also, this curve is independent of temperature, frequency, and mode of loading. Although the CDT test can provide promising results, conducting this test in the laboratory and analyzing data are cumbersome, and need special training and expertise for conducting the test and analyzing and interpreting the test results. The repeatability of the test results is a big concern.

2.6 Overlay Tester (OT) Test

The OT test (Figure 10) has recently been used by several researchers (Walubita et al., 2012; Walubita et al., 2011; Walubita et al., 2010; Zhou et al., 2007a; Chen, 2007; Zhou et al., 2007b;) to evaluate the reflective cracking potential of asphalt mixes. This test was developed by the Texas Transportation Institute (TTI) and is conducted in accordance with the Tex-248-F test method (TxDOT, 2012; Walubita et al., 2012; Walubita et al., 2011; Walubita et al., 2010; Zhou et al., 2007a; Zhou et al., 2007b). This test is conducted on a beam sample as listed in Table 2. A cyclic load is applied to the beam in the horizontal direction to simulate the opening and closing of crack under an overlay. The number of cycles to failure is then recorded. It has been reported that an overlay tester can be used to screen asphalt mixes for fatigue life within a relatively short period of time (Walubita et al., 2012; Walubita et al., 2011).

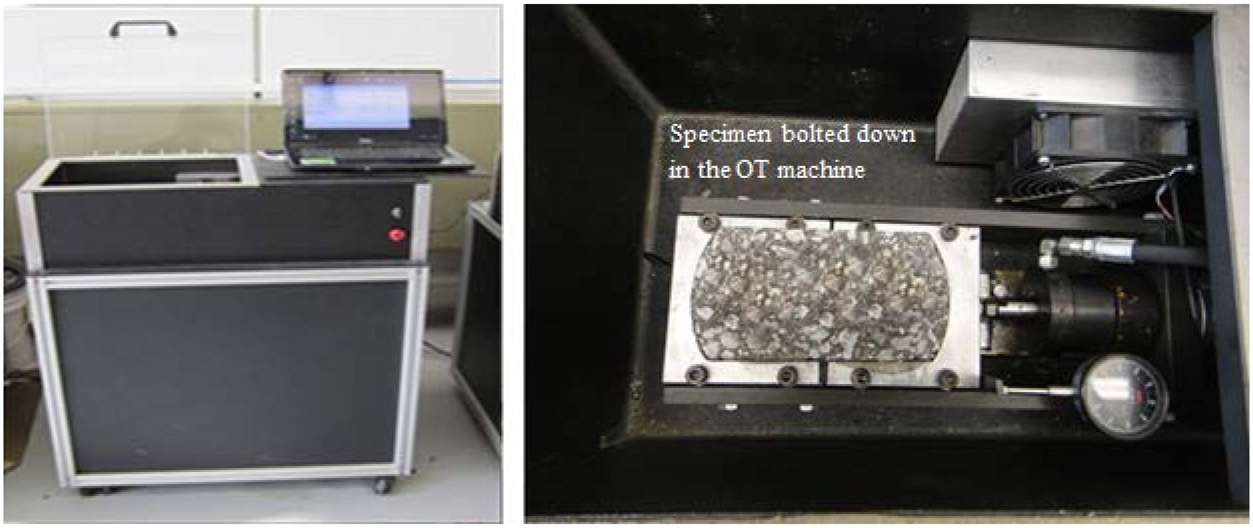


Figure 10: Overlay tester (OT) setup.

3. SURVEY OF DOTS' SPECIFICATION

3.1 General

One of the important components of the present study was collecting information about the DOT's practices on fatigue performance evaluation of asphalt mixes at the design stage. Since the DOT practices are generally not available in the open literature, a survey was conducted in 2013 for collecting information about the fatigue test related experiences gained by different DOTs. Their preferences for a fatigue test method were documented through this survey. This following subsection presents a discussion on the survey results. It may be noted that the survey was conducted in mid-2013 and the results were analyzed in December 2013; the 2016 trends may be slightly different.

3.2 Objective of the Survey

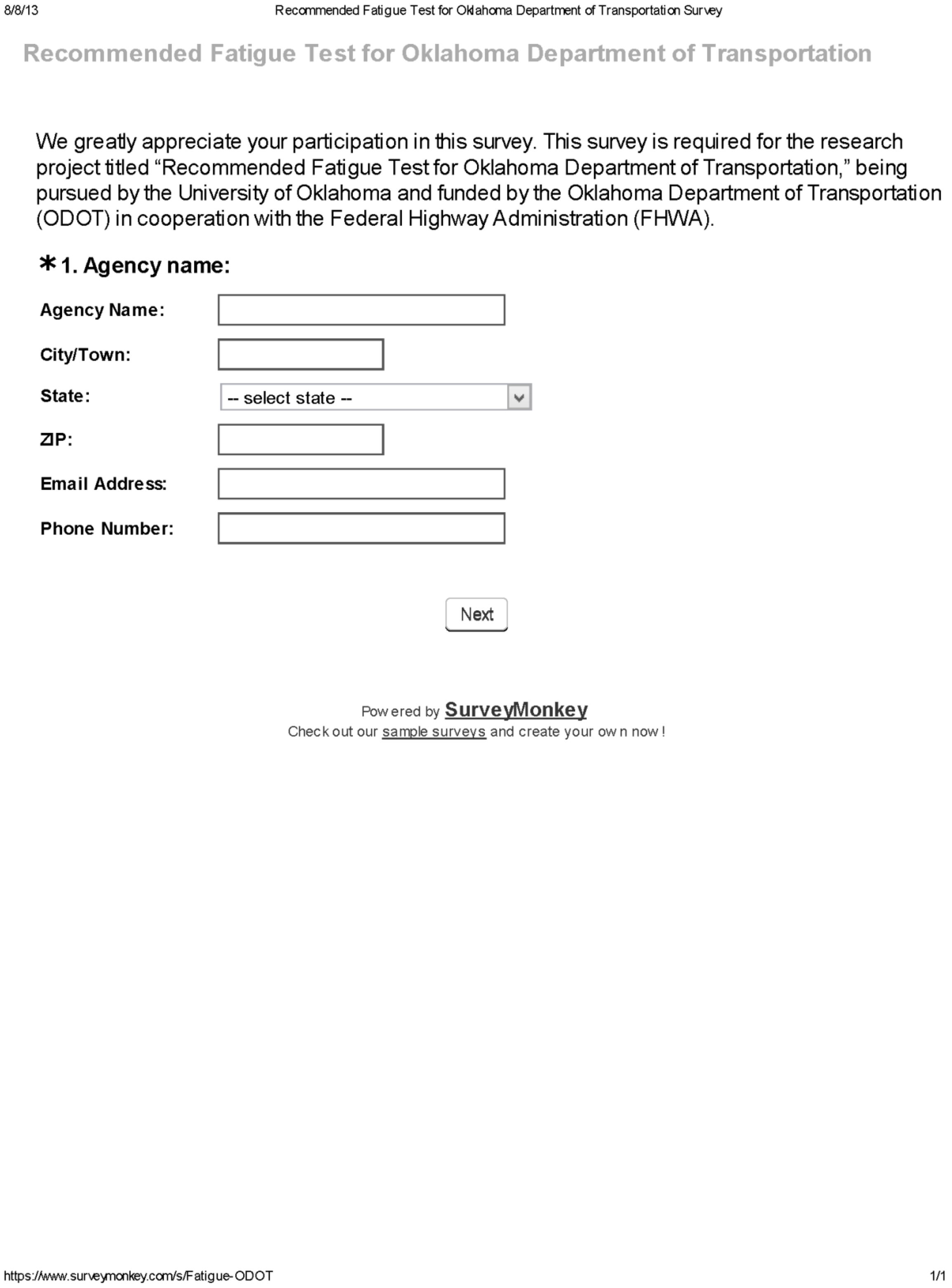
The main objective of the survey was to gather information about the fatigue test methods that are currently used by different DOTs for screening of asphalt mixes. In addition to understanding DOT practices, the survey gathered information on test facilities available at DOTs across the country and DOT preferences for the selection of a particular fatigue test method.

3.3 Execution of the Survey

The questionnaires for this survey were prepared by the research team and were revised in a meeting held at the University of Oklahoma (OU) on April 11, 2013. The meeting was attended by Mr. Kenneth Hobson from the ODOT Materials Division and the OU research team. The survey was conducted online using www.surveymonkey.com. The link for the survey website was sent to Mr. Hobson of ODOT in July 2013, and it was distributed to different DOTs by Mr. Reynolds Toney, Materials & Research Division Engineer.

3.4 Survey Questionnaire

A copy of the questionnaire used in this survey is included below. The format of the survey questionnaire is same as that was distributed through the website, www.surveymonkey.com. Agency name and contact information were requested in the first question. The other questions were related to fatigue-related distresses, strategies adopted for the prevention of fatigue distresses, and DOT preferences for fatigue performance evaluation, which include test methods and materials.



8/8/13 Recommended Fatigue Test for Oklahoma Department of Transportation Survey

Recommended Fatigue Test for Oklahoma Department of Transportation

We greatly appreciate your participation in this survey. This survey is required for the research project titled “Recommended Fatigue Test for Oklahoma Department of Transportation,” being pursued by the University of Oklahoma and funded by the Oklahoma Department of Transportation (ODOT) in cooperation with the Federal Highway Administration (FHWA).

* 1. Agency name:

Agency Name:

City/Town:

State: -- select state --

ZIP:

Email Address:

Phone Number:

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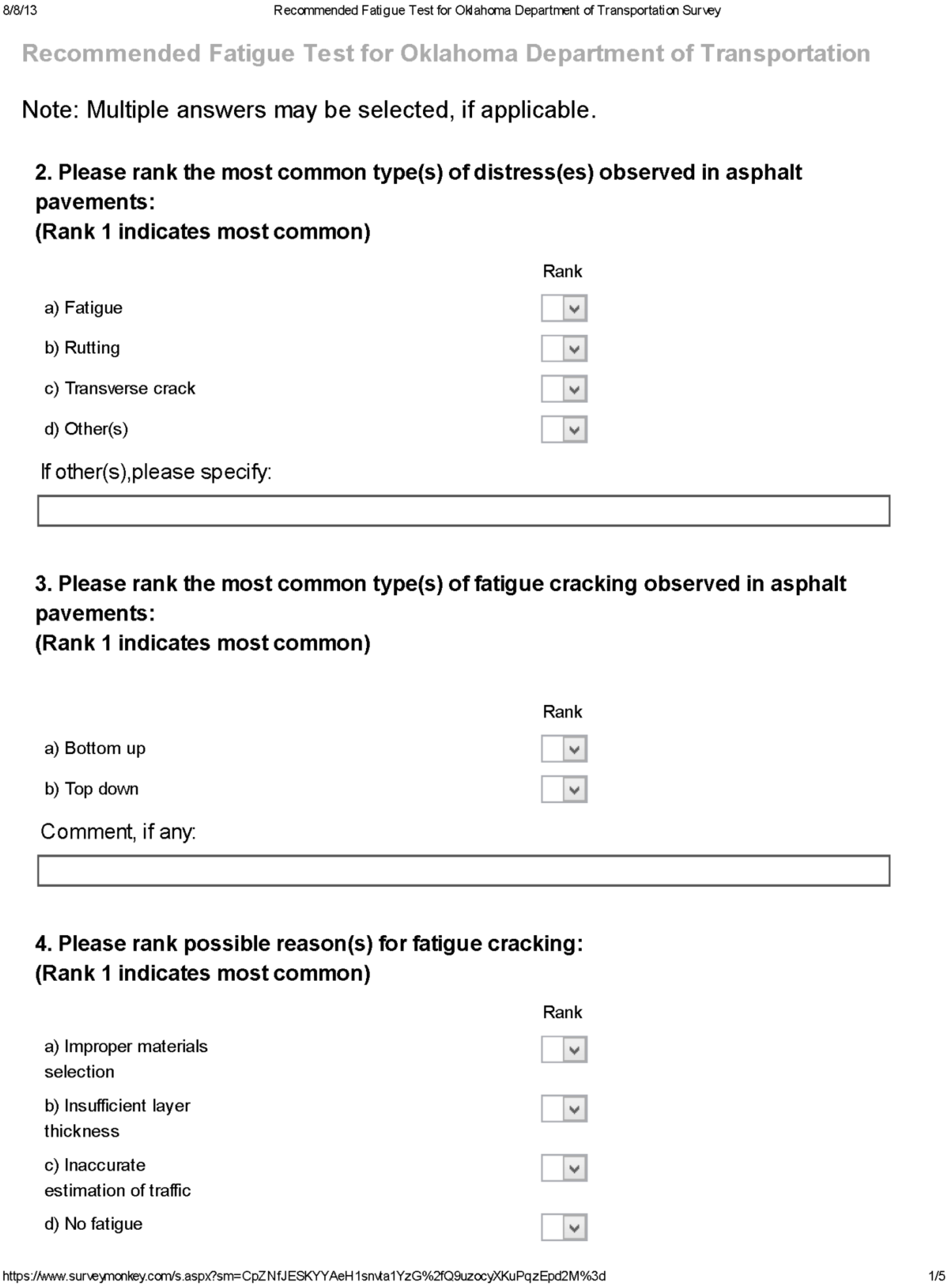

8/8/13 Recommended Fatigue Test for Oklahoma Department of Transportation Survey

Recommended Fatigue Test for Oklahoma Department of Transportation

Note: Multiple answers may be selected, if applicable.

2. Please rank the most common type(s) of distress(es) observed in asphalt pavements:
(Rank 1 indicates most common)

	Rank
a) Fatigue	▾
b) Rutting	▾
c) Transverse crack	▾
d) Other(s)	▾

If other(s),please specify:

3. Please rank the most common type(s) of fatigue cracking observed in asphalt pavements:
(Rank 1 indicates most common)

	Rank
a) Bottom up	▾
b) Top down	▾

Comment, if any:

4. Please rank possible reason(s) for fatigue cracking:
(Rank 1 indicates most common)

	Rank
a) Improper materials selection	▾
b) Insufficient layer thickness	▾
c) Inaccurate estimation of traffic	▾
d) No fatigue	▾

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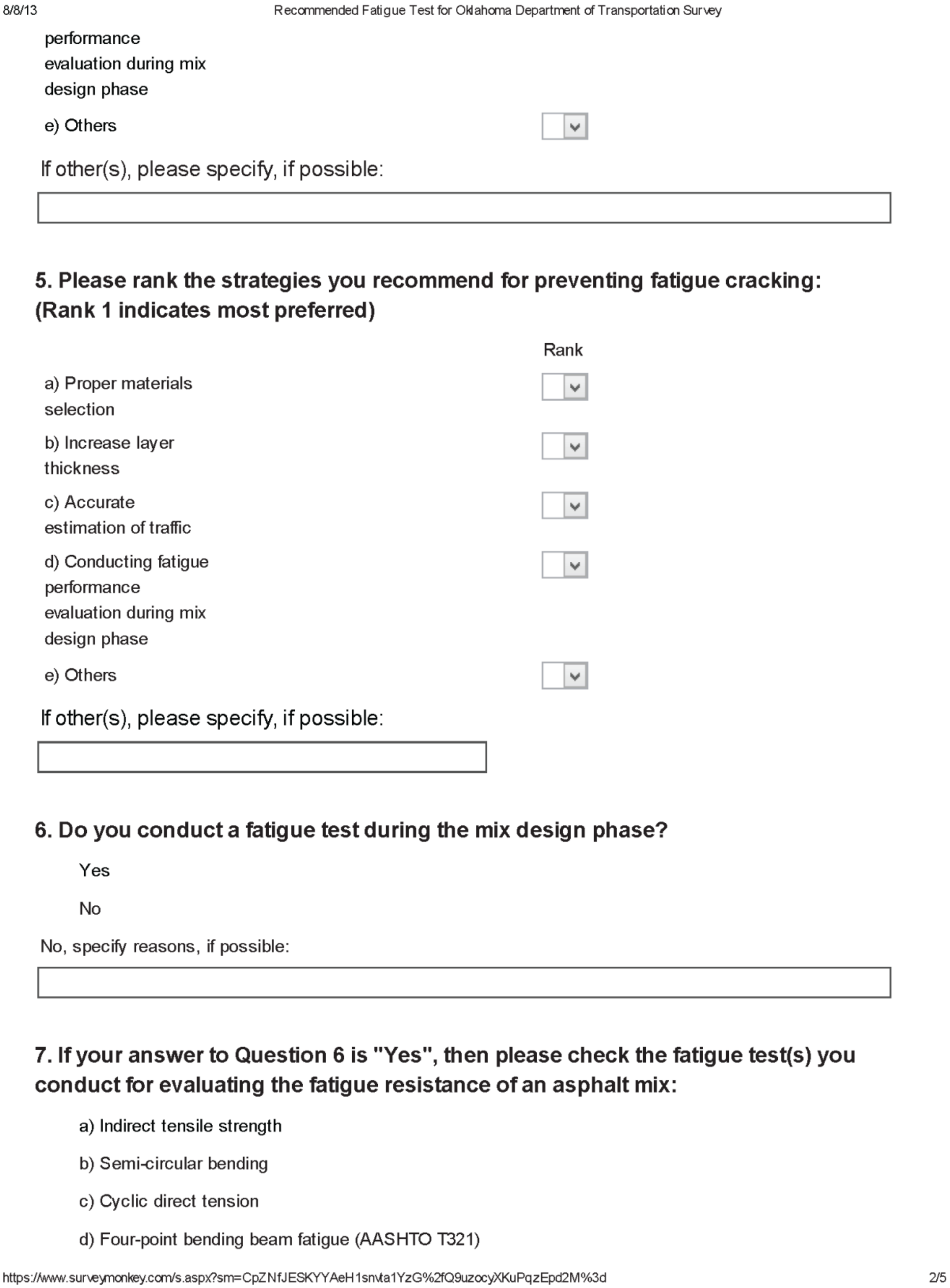


performance evaluation during mix design phase	
e) Others	

If other(s), please specify, if possible:

5. Please rank the strategies you recommend for preventing fatigue cracking: (Rank 1 indicates most preferred)

	Rank
a) Proper materials selection	
b) Increase layer thickness	
c) Accurate estimation of traffic	
d) Conducting fatigue performance evaluation during mix design phase	
e) Others	

If other(s), please specify, if possible:

6. Do you conduct a fatigue test during the mix design phase?

Yes

No

No, specify reasons, if possible:

7. If your answer to Question 6 is "Yes", then please check the fatigue test(s) you conduct for evaluating the fatigue resistance of an asphalt mix:

a) Indirect tensile strength

b) Semi-circular bending

c) Cyclic direct tension

d) Four-point bending beam fatigue (AASHTO T321)

e) Overlay tester (Texas)

f) Other

If other, please specify, if possible:

8. Do you recommend a fatigue test during the mix design phase?

Yes

No

If no, please specify reasons, if possible:

9. Please rank the fatigue test method(s) you prefer for evaluating the fatigue resistance of an asphalt mix: (Rank 1 indicates most preferred)

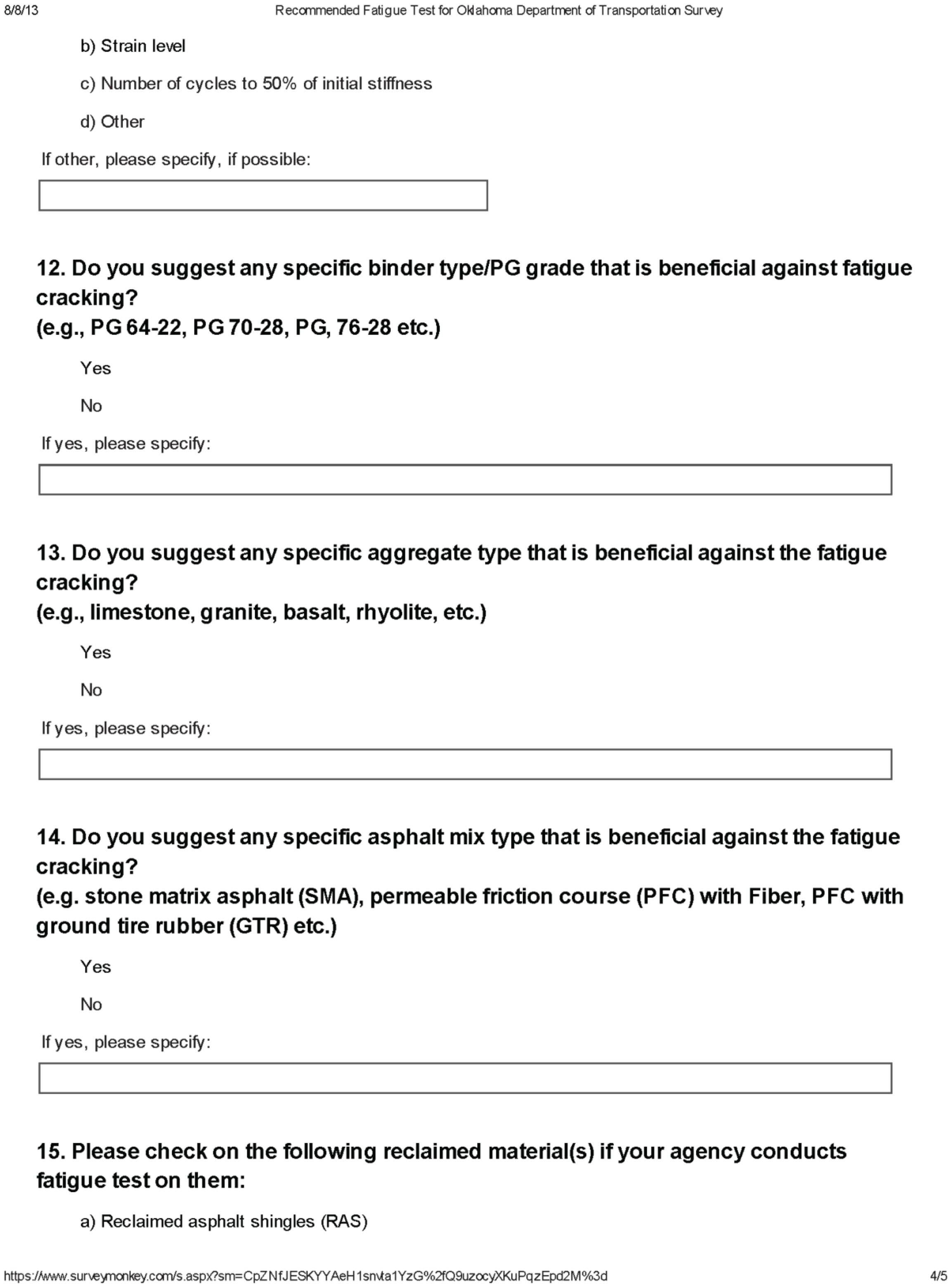
	Rank
a) Indirect tensile strength	
b) Semi-circular bending	
c) Cyclic direct tension	
d) Four-point bending beam fatigue (AASHTO T321)	
e) Overlay tester (Texas)	
f) Other	

If other, please specify, if possible:

10. Please specify the temperature(s) at which you conduct the fatigue test.

11. Please check the pass or fail criterion/criteria used in a fatigue test in the laboratory:

a) Tensile strength



b) Strain level

c) Number of cycles to 50% of initial stiffness

d) Other

If other, please specify, if possible:

12. Do you suggest any specific binder type/PG grade that is beneficial against fatigue cracking?
(e.g., PG 64-22, PG 70-28, PG, 76-28 etc.)

Yes

No

If yes, please specify:

13. Do you suggest any specific aggregate type that is beneficial against the fatigue cracking?
(e.g., limestone, granite, basalt, rhyolite, etc.)

Yes

No

If yes, please specify:

14. Do you suggest any specific asphalt mix type that is beneficial against the fatigue cracking?
(e.g. stone matrix asphalt (SMA), permeable friction course (PFC) with Fiber, PFC with ground tire rubber (GTR) etc.)

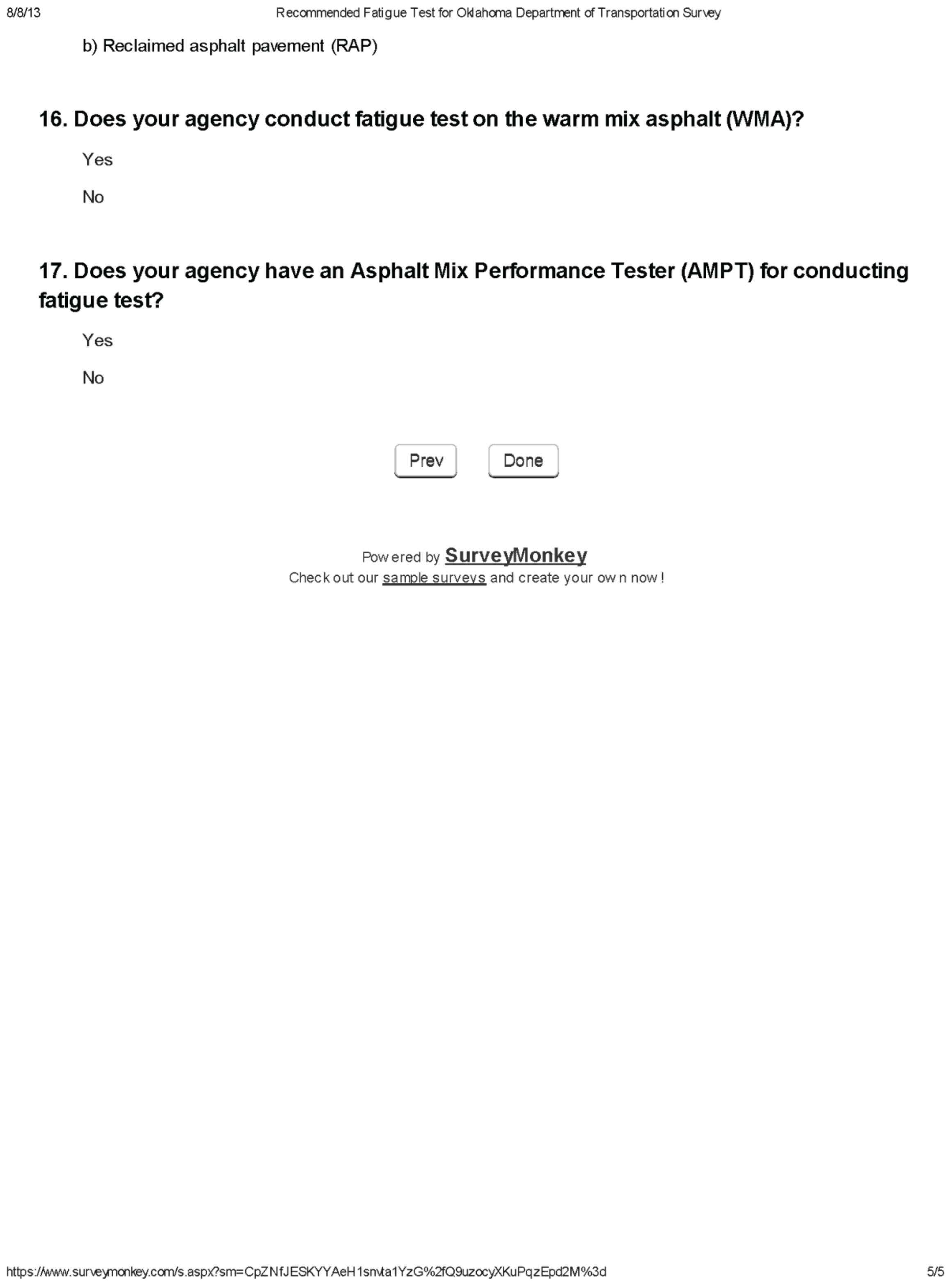
Yes

No

If yes, please specify:

15. Please check on the following reclaimed material(s) if your agency conducts fatigue test on them:

a) Reclaimed asphalt shingles (RAS)



8/8/13 Recommended Fatigue Test for Oklahoma Department of Transportation Survey

b) Reclaimed asphalt pavement (RAP)

16. Does your agency conduct fatigue test on the warm mix asphalt (WMA)?

Yes

No

17. Does your agency have an Asphalt Mix Performance Tester (AMPT) for conducting fatigue test?

Yes

No

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3.5 Analysis of the Survey Results

A total of 43 Engineers from 29 different DOTs responded to this survey. A list of the DOTs that participated in the survey is provided in Table 4. Graphical analyses are presented in Figure 11 through Figure 25. Each of these figures includes one question and the statistical analyses of the answers pertaining to that question. From Figure 11, it is evident that a large number of responders noted fatigue crack as one of the most severe distresses. Both the bottom-up and top-down fatigue cracks occur almost in equal proportions (Figure 12).

A majority of the responders indicated that insufficient thickness and improper material selection are primary causes of fatigue cracking (Figure 13 and Figure 14). However, only 8% (3 out of 25) responders indicated that fatigue test is conducted for screening the asphalt mixes during the mix design phase (Figure 15). These responders were from Texas Department of Transportation (TxDOT) and California Department of Transportation (Caltrans), and they indicated their preference for Indirect Tensile Test (IDT) and Overlay Tester (OT) fatigue test methods, respectively (Figure 16).

Many responders mentioned that lack of appropriate equipment, trained personnel, suitable test methods and specifications, and more importantly lack of consciousness are the reasons for the avoidance of a fatigue test during the mix design phase. However, many DOTs (~36%) recommended the necessity for a fatigue test (Figure 17). But, a clear preference for a particular type of fatigue test was not recognized (Figure 18). Oklahoma DOT indicted their preference for semicircular bend and Overlay tester fatigue test methods.

Regarding the pass/fail criterion in a fatigue test, many responders prefer 50% of the initial stiffness as the failure criteria; however, failure criteria such as 93% of the initial stiffness and peak load were also preferred by several responders (Figure 19). Responders from many DOTs (including Oklahoma DOT) recommend use of polymer-modified binder to reduce the fatigue cracking (Figure 20); however, they did not suggest any specific type of aggregate (Figure 21). Stone matrix asphalt (SMA) mix was chosen by a majority of the responders (Figure 22); according to these responders, this mix performs better against fatigue. Also, Texas Department of Transportation (TxDOT) and California Department of Transportation (Caltrans) mentioned conducting fatigue test on reclaimed asphalt mix (Figure 23); however, it was found that only TxDOT has experimented with the WMA (Figure 24). Lastly, it can be seen in Figure 25 that a good number of DOTs have asphalt mix performance tester (AMPT).

Overall, it was found that although many fatigue test methods are currently available, the repeatability of the test results of each method and the level of the personnel training and complexity associated with these tests shall be investigated, before using them as a standard screening method for mix design.

Table 4: List of DOTs participated in the Survey, until December 15, 2013.

Sl. No.	**State**	**DOT**
1	AL	Alabama Department of Transportation
2	AR	Arkansas State Highway and Transportation Department
3	AZ	Arizona Department of Transportation
4	CA	California Department of Transportation
5	CO	Colorado Department of Transportation
6	DC	District of Columbia government's Department of Transportation's
7	DE	Delaware Department of Transportation
8	FL	Florida Department of Transportation
9	IL	Illinois Department of Transportation
10	KY	Kentucky Transportation Cabinet
11	MI	Michigan Department of Transportation
12	MS	Mississippi Department of Transportation
13	MA	Massachusetts Department of Transportation
14	ME	Maine Department of Transportation
15	MD	Maryland State Highway Administration
16	NV	Nevada Department of Transportation
17	NY	New York State Department of Transportation
18	NH	New Hampshire Department of Transportation
19	NJ	New Jersey Department of Transportation
20	NC	North Carolina Department od Transportation
21	OK	Oklahoma Department of Transportation
22	OH	Ohio Department of Transportation

Sl. No.	State	DOT
23	PA	Pennsylvania Department of Transportation
24	RI	Rhode Island Department of Transportation
25	SC	South Carolina Department of Transportation
26	TX	Texas Department of Transportation
27	UT	Utah Department of Transportation
28	VA	Virginia Department of Transportation
29	WV	West Virginia Department of Transportation

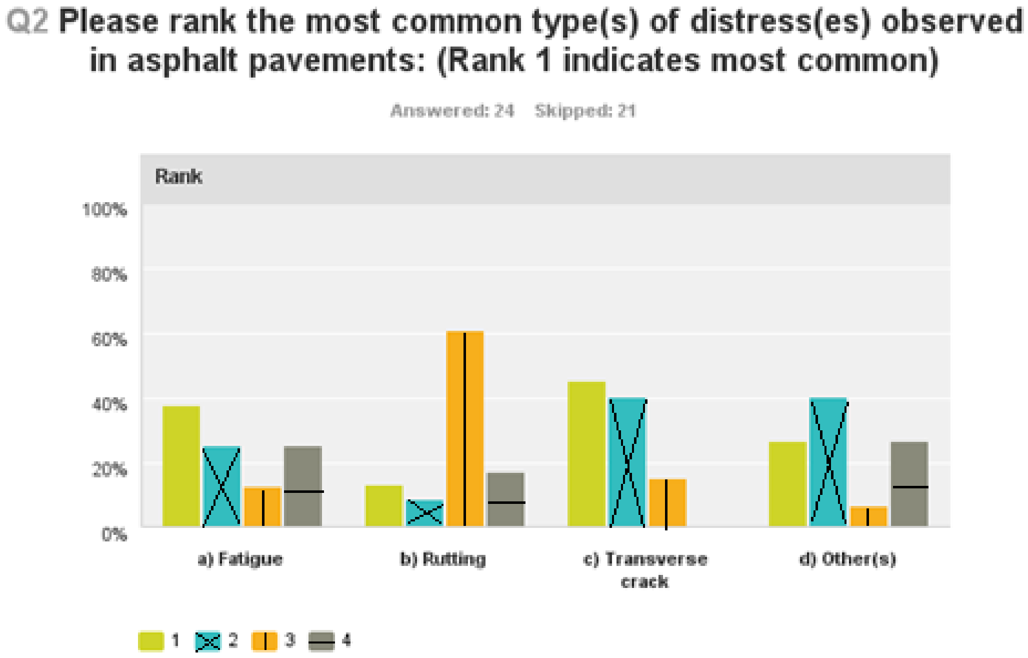


Figure 11. Most common type(s) of distress(es) observed in asphalt pavements.

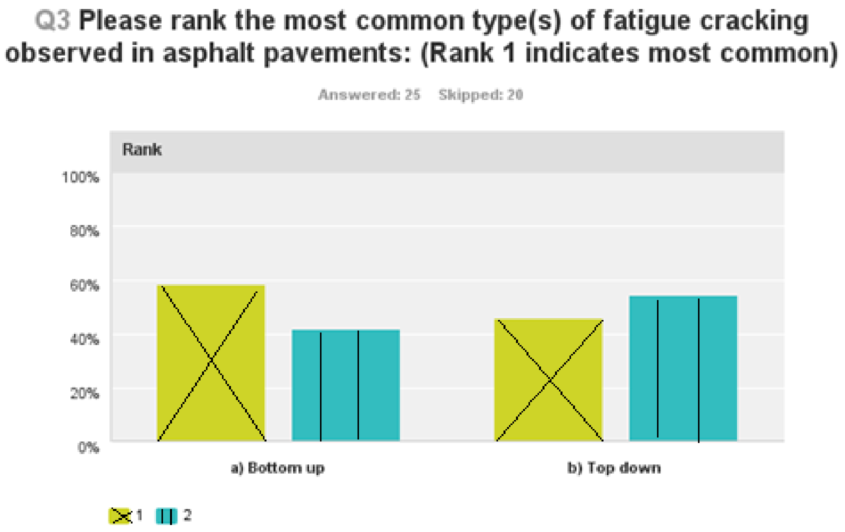


Figure 12. Most common type(s) of fatigue cracking observed in asphalt pavements.

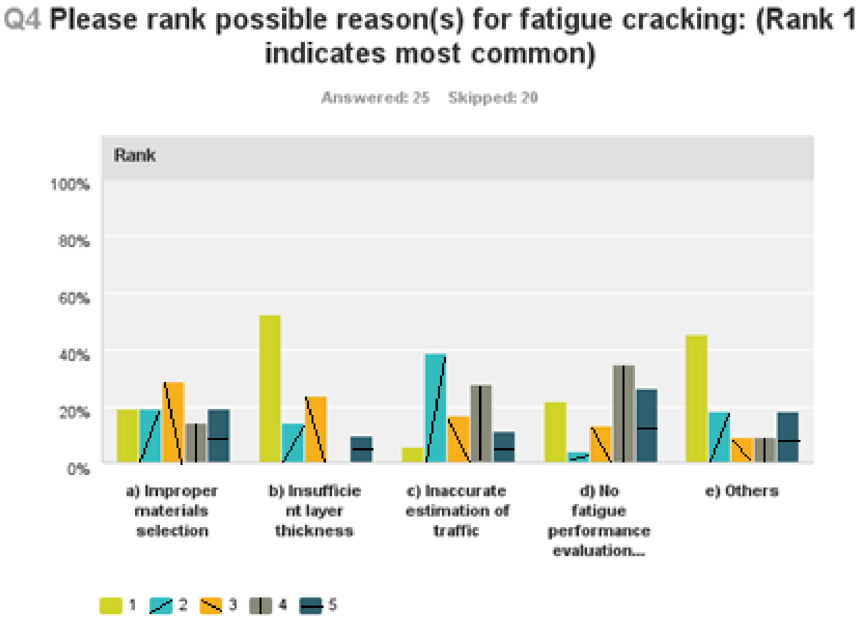


Figure 13. Possible reason(s) for fatigue cracking.

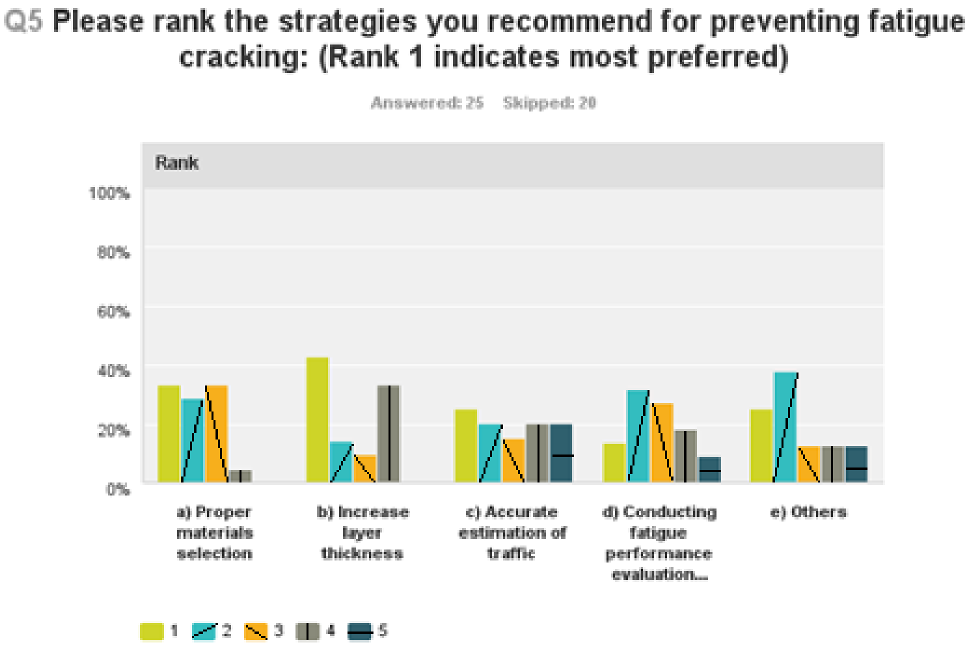


Figure 14. Strategies for preventing fatigue cracking.

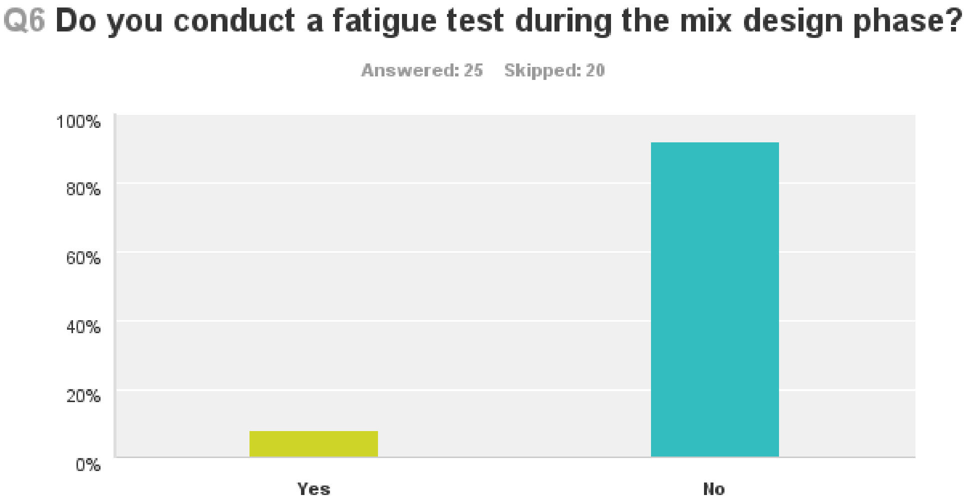


Figure 15: Use of fatigue test during the mix-design phase.

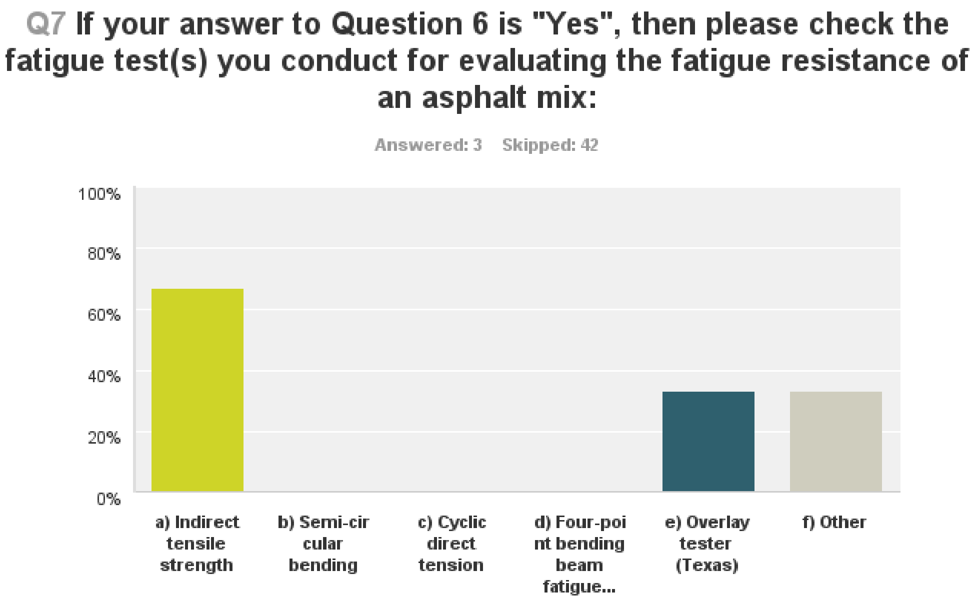


Figure 16: Test method(s) used for fatigue evaluation.

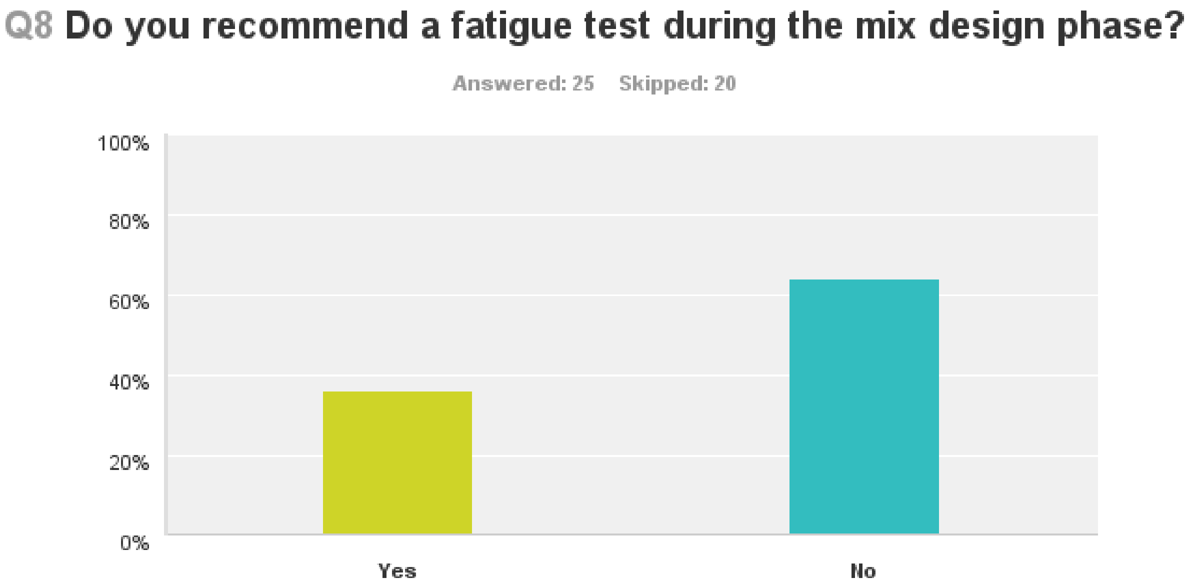


Figure 17: Recommendation about conducting fatigue test.

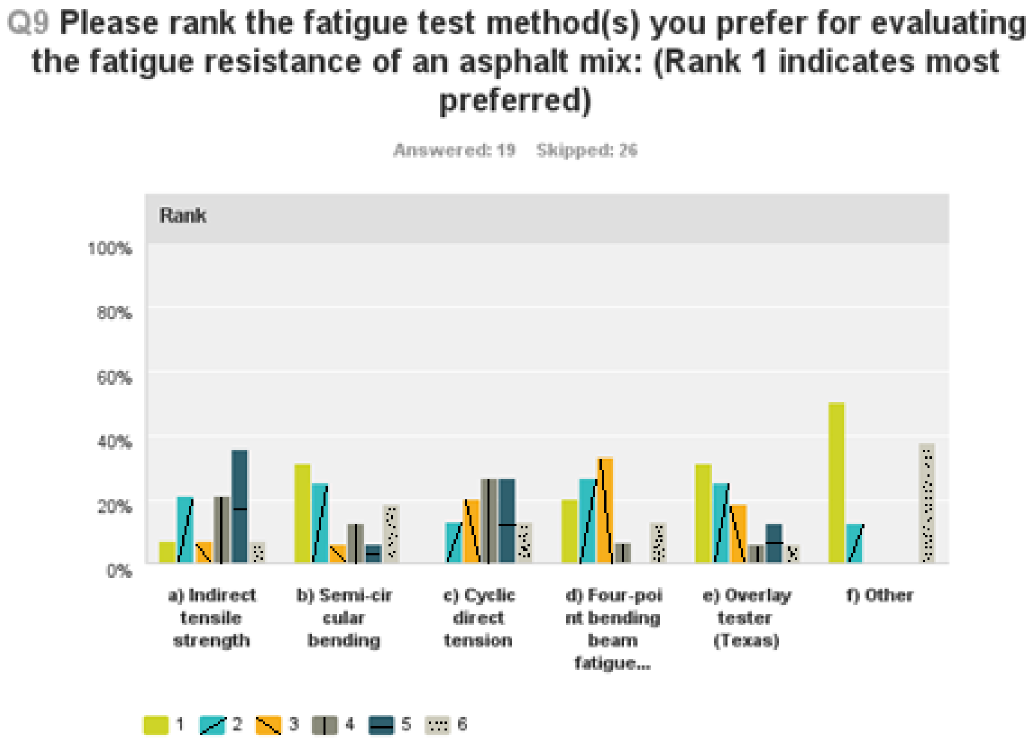


Figure 18. Preference of fatigue test methods.

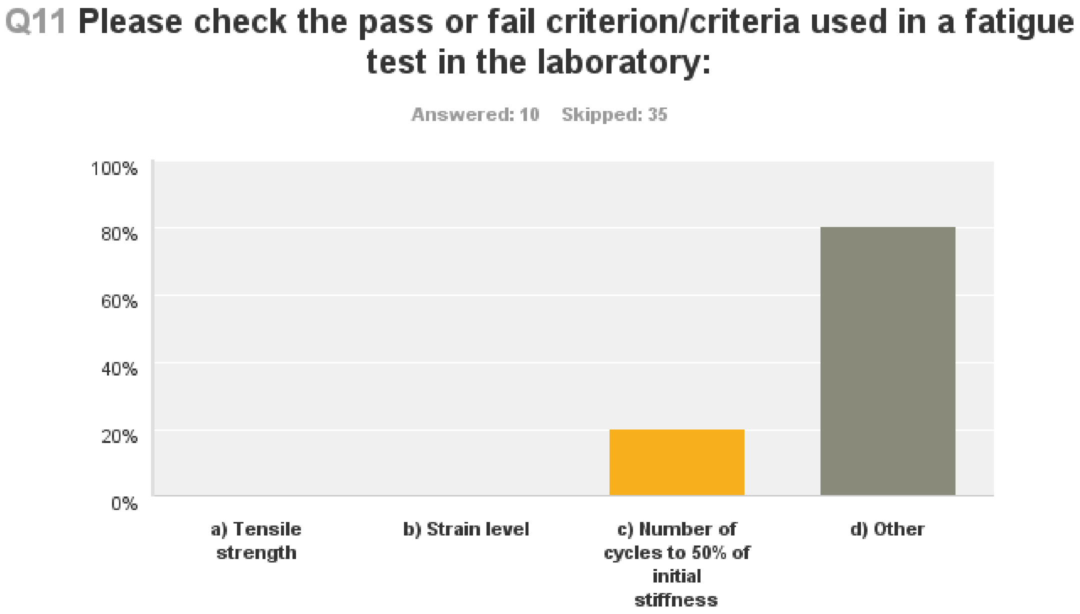


Figure 19: Pass or failure criterion/criteria used in the fatigue testing.

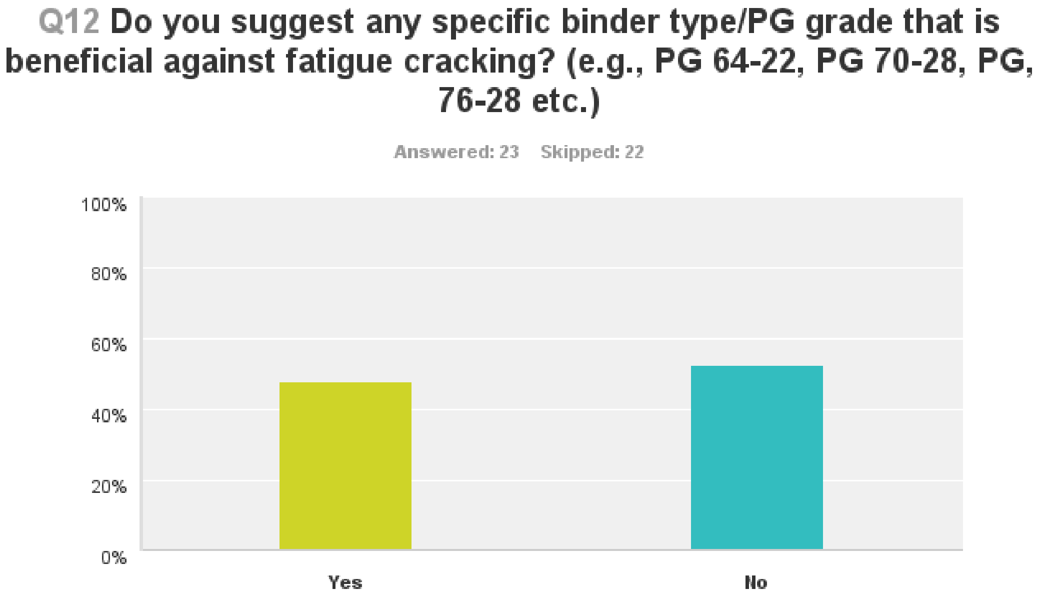


Figure 20: Beneficial role of binder type in addressing fatigue cracking.

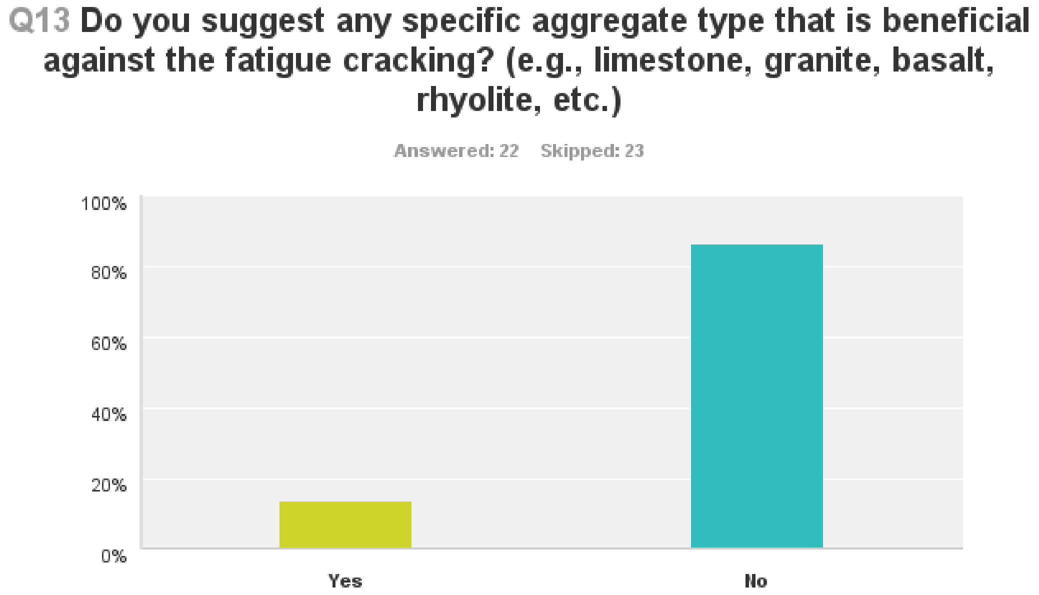
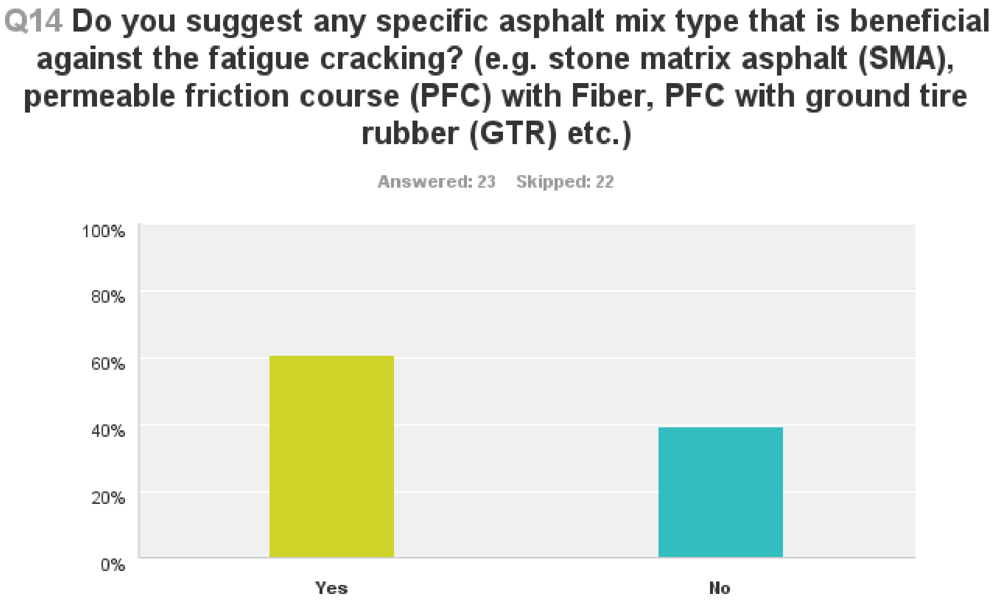


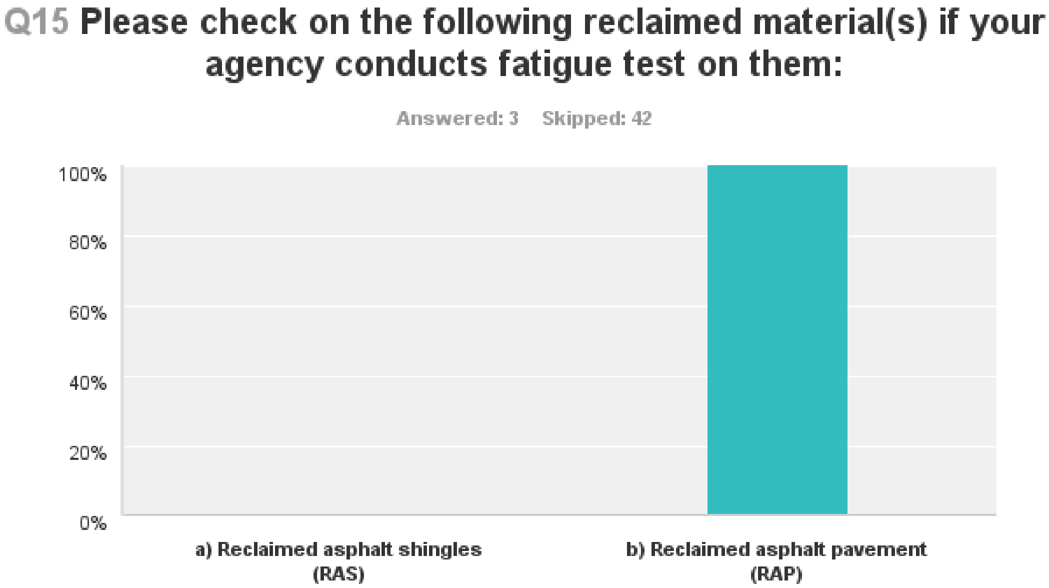
Figure 21: Beneficial role of aggregate type in addressing fatigue cracking.



Q14 Do you suggest any specific asphalt mix type that is beneficial against the fatigue cracking? (e.g. stone matrix asphalt (SMA), permeable friction course (PFC) with Fiber, PFC with ground tire rubber (GTR) etc.)

Answered: 23 Skipped: 22

Figure 22: Role of asphalt mix type in addressing fatigue cracking.



Q15 Please check on the following reclaimed material(s) if your agency conducts fatigue test on them:

Answered: 3 Skipped: 42

Figure 23: Fatigue testing on reclaimed asphalt mixes.

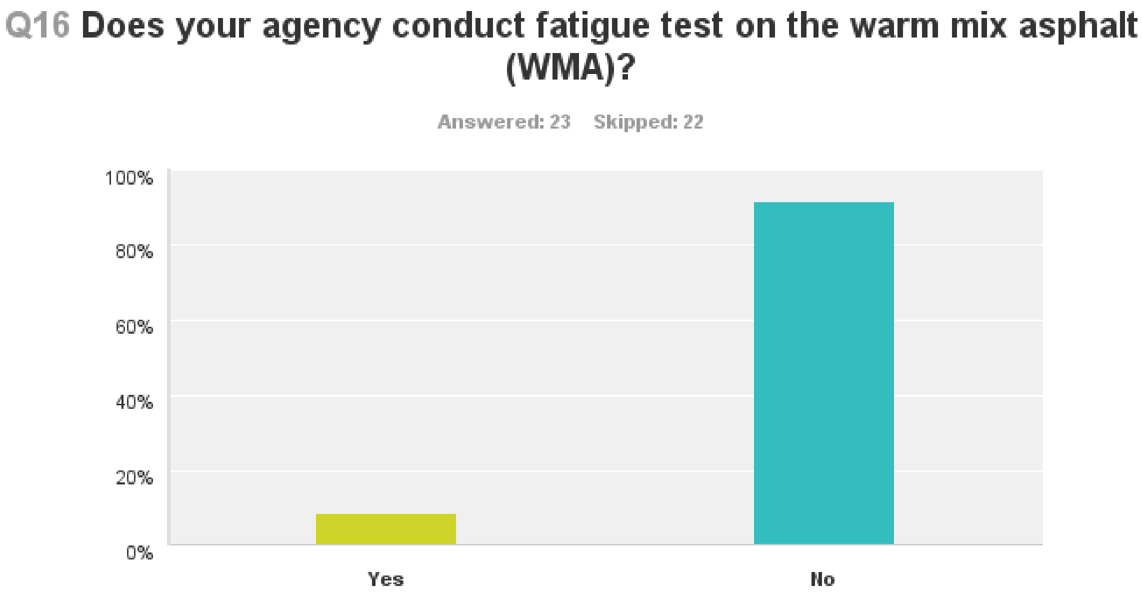


Figure 24: Fatigue testing on warm mix asphalt (WMA).

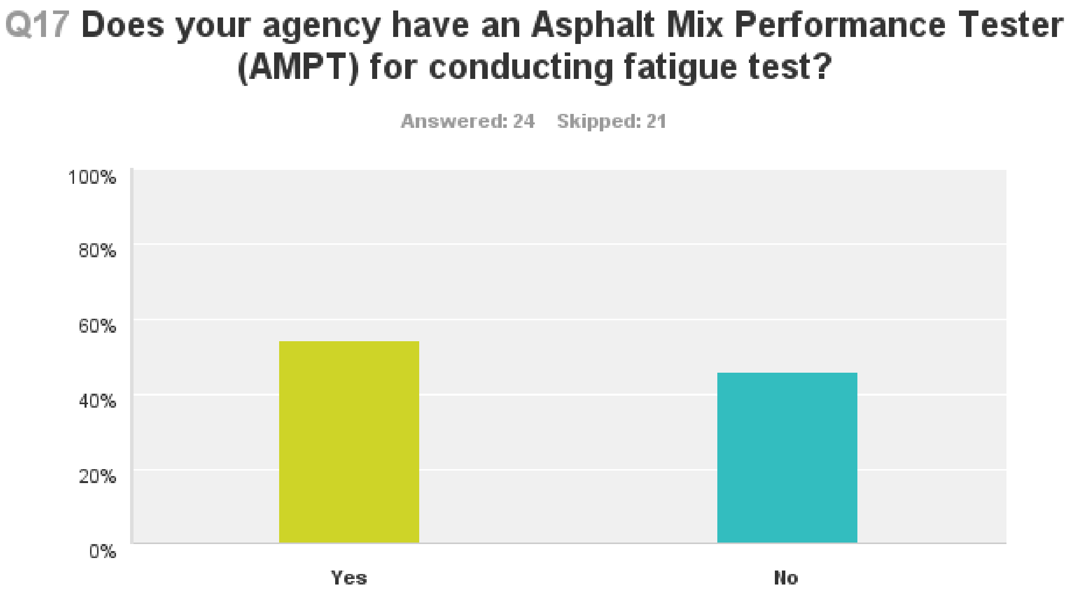


Figure 25: Availability of asphalt mix performance tester in DOTs.

4. MATERIALS AND SAMPLE PREPARATION

4.1 General

The identification and selection of materials were done in close cooperation with the ODOT Capital Programs Division and Materials and Research Division. Since the bulk specific gravity, Los Angeles abrasion value and other aggregate properties vary with the source, all the aggregates were collected from a same plant. Binders were collected from the different sources. This chapter includes a description on the types, source and characteristics of all the materials used in this study.

4.2 Aggregates

Aggregates were collected from same six stockpiles of a local asphalt plant, namely, Silver Star Construction Company, located at 2401 S Broadway St. in Moore, OK. The bulk specific gravities of the collected aggregates were determined in the laboratory as presented in Table 5. The job-mix formulas for both S3 (Nominal max. agg. Size, NMAS = 19.5 mm) and S5 (NMAS = 12.5 mm) gradations were obtained by blending the aggregates collected from these stockpiles. The 1-inch aggregates, 5/8-inch aggregates, screenings, manufactured sand, and natural sand were blended to obtain S3 gradation. In order to obtain S5 gradation, ½-inch aggregates, screenings, manufactured sand and natural sand were blended to achieve the job-mix formula gradation. Figure 26 and Figure 27 present the upper and lower limits and the gradations obtained for the S3 and S5 mixes, respectively.

Table 5: Bulk specific gravity of the aggregates collected for different mixes.

1"rock	5/8" chips	1/2" chips	Screenings	Man. sand	Nat. sand
2.733	2.742	2.730	2.703	2.655	2.639

Note: Man. – Manufactured; Nat. – Natural

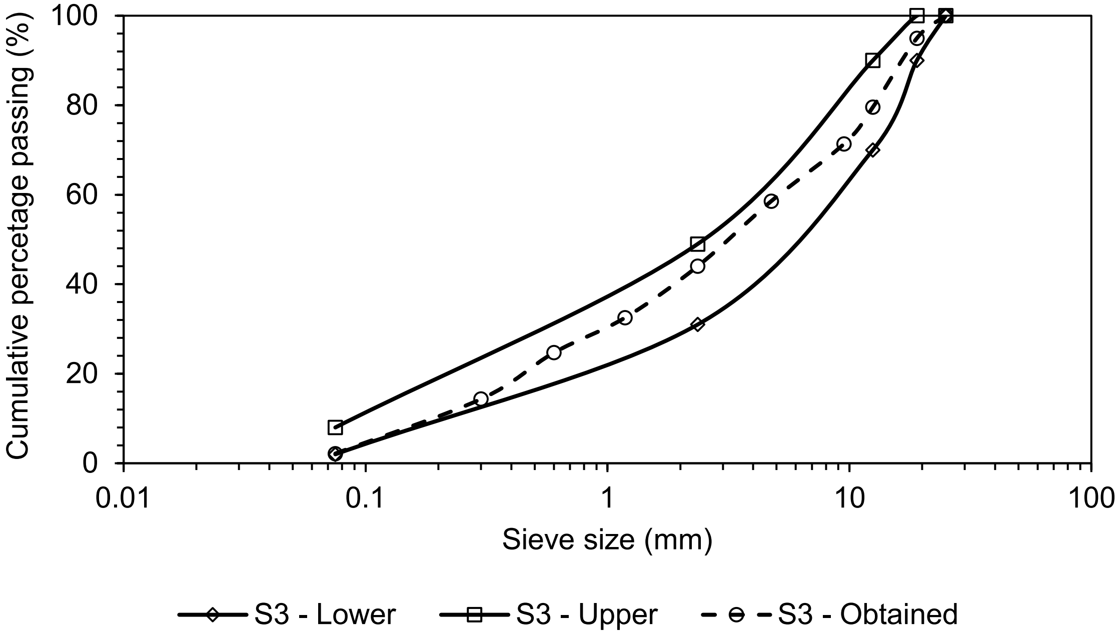


Figure 26: Upper and lower limits and the obtained gradation of the S3 mix.

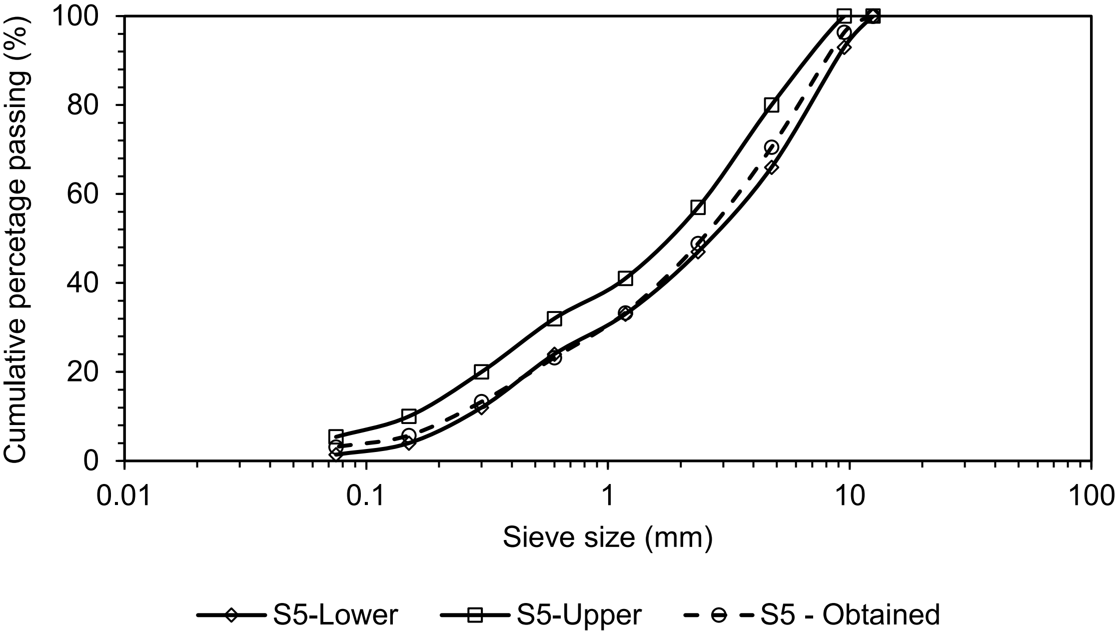


Figure 27: Upper and lower limits and the obtained gradation of the S5 mix.

4.3 Asphalt Binders

The PG 64-22 OK (Gary Williams) asphalt binder for production of the Mix-1 (S3-PG 64-22 OK) and Mix-6 were collected from the Silver Star Construction Company. The asphalt binder PG 76-28 OK required for the Mix-2 (S3-PG 76-28 OK) and Mix-4 (S5-PG 76-28 OK) was collected from the Valero Refinery Plant located in Ardmore, OK. The PG 76E-28 asphalt binder required for producing Mix-3 (S5-PG 76-28 E) which is a rich intermediate layer (RIL) mix was collected from Kraton Polymers U.S. LLC, Houston, TX. The raw binder for producing PG 76E-28 was collected from Lion Oil Company.

4.4 Plant Produced Asphalt Mix

Mix-5 (S3-F-PG 64-22 OK) is a foamed warm-mix asphalt (WMA) with S3 gradation and PG 64-22 OK asphalt binder. Since, the Broce Asphalt Laboratory at the University of Oklahoma was not equipped with an asphalt foamer during the reporting period for producing foamed WMA. This mix was collected from the Silver Star Company. The collected asphalt mix contained 25% reclaimed asphalt pavement (RAP) by the weight of aggregates. Approximately 400 kg of Mix-5 (S3-F-PG 64-22 OK) was collected. The mix was allowed to cool down to room temperature and was stored in a temperature-controlled room in the Broce Asphalt Laboratory. This mix was re-heated for preparation of test samples. Since Mix-5 (S3-F-PG 64-22 OK) was included in this study to represent a low fatigue resistant mix; the collected mix was found to be suitable to serve this purpose.

4.4 Asphalt Mix Design

The mix designs for Mix-1 (S3-PG 64-22 OK), Mix-2 (S3-PG 76-28 OK), Mix-3 (S5-PG 76E-28 OK), Mix-4 (S5-PG 76-28 OK) and Mix-6 (S3-C-PG 64-22 OK) were established as per AASHTO R35 and AASHTO M323. Mix-5 (S3-F-PG 64-22 OK), which is a foamed WMA, was designed and supplied by Silver Star Construction Company. The

Mix-6 (S3-C-PG 64-22 OK) is a chemical based WMA; Evotherm™ was added for producing this mix. The other four mixes were HMA. The mix design details for all the above-mentioned mixes are given in Table 6 to

Table 11. The optimum binder content for mixes 1 to 6 were determined to be 4.3%, 4.7%, 7.2%, 6.7%, 4.4%, and 4.3%, respectively. It shall be noted the aggregate gradations and binder contents for Mix-1 (S3-PG 64-22 OK) and Mix-6 (S3-C-PG 64-22 OK) were identical except that Mix-6 (S3-C-PG 64-22 OK) was a WMA, produced at a lower temperature using Evotherm™ as a chemical additive. The volumetric properties of these mixes were determined by performing necessary mix design-related tests, such as Rice density (AASHTO T 209) and bulk specific gravity (AASHTO T 166) on the asphalt mixes and compacted samples.

Table 6: Aggregate components of Mix-1 (S3-PG 64-22 OK), Mix-2 (S3-PG 76-28 OK), and Mix-6 (S3-C-PG 64-22)

No.	Aggregate	Producer/ Supplier	% Used
1	1”rock	Hanson 5008	25
2	5/8” chips	Hanson 5008	20
3	Screenings	Hanson 5008	25
4	Manufactured sand	Dolese Davis 5005	15
5	Natural sand	General Materials Inc. 1402	15

Table 7. Gradation (percent passing) of components of Mix-1 (S3-PG 64-22 OK), Mix-2 (S3-PG 76-28 OK), and Mix-6 (S3-C-PG 64-22).

Sieve size (mm)	1”rock	5/8” chips	Screenings	Man. sand	Nat. sand	Comb.
37.5	100	100	100	100	100	100
25	100	100	100	100	100	100
19	80	100	100	100	100	95
12.5	26	91	100	100	100	80
9.5	6	74	100	100	100	71
4.75	1	22	100	93	100	59
2.36	1	4	78	57	100	44
1.18	1	2	50	30	99	33
0.6	1	2	32	15	92	25
0.3	1	1	18	7	55	14
0.075	0.5	1.1	5.3	2.8	0.5	2

Table 8: Aggregate components of Mix-3 (S5-PG 76E-28 OK) and Mix-4 (S5-PG 76-28 OK).

No.	Aggregate	Producer/ Supplier	% Used
1	1/2” rock	Hanson 5008	37

No.	Aggregate	Producer/ Supplier	% Used
2	Screenings 33	Hanson 5008	40
3	Manufactured sand	Dolese Davis 5005	15
4	Natural sand	General Materials Inc. 1402	8

Table 9. Gradation (percent passing) of components of Mix-3 (S5-PG 76E-28 OK) and Mix-4 (S5-PG 76-28 OK).

Sieve size (mm)	1/2"rock	Screenings	Man. sand	Nat. sand	Comb.
37.5	100	100	100	100	100
25	100	100	100	100	100
19	80	100	100	100	100
12.5	100	100	100	100	100
9.5	90	100	100	100	96
4.75	23	100	93	100	70
2.36	3	78	57	100	49
1.18	2	50	30	99	33
0.6	2	32	15	92	23
0.3	2	18	7	55	13
0.075	0.5	5.3	2.8	0.5	3

Table 10: Aggregate components of Mix-5 (S3-F-PG 64-22 OK).

No.	Aggregate	Producer/ Supplier	% Used
1	#67" rock	Hanson 5005	15
2	5/8" Chips	Hanson 5008	22
3	Screenings	Hanson 5008	17
4	Manufactured sand	Davis 5005	10
5	Natural sand	General Materials Inc. 1402	11
6	Fine RAP	- -	25

Table 11. Gradation (percent passing) of components of Mix-5 (S3-F-PG 64-22 OK).

Sieve size (mm)	**#67 rock**	**5/8”chips**	**Scrns.**	**Man. sand**	**Nat. sand**	**Comb.**
37.5	100	100	100	100	100	100
25	100	100	100	100	100	100
19	91	100	100	100	100	100
12.5	53	81	100	100	100	99
9.5	34	52	100	100	100	94
4.75	3	17	80	92	99	74
2.36	2	3	52	52	99	54
1.18	1	3	36	30	97	41
0.6	1	2	26	18	92	34
0.3	1	2	19	10	60	25
0.075	0.8	1.7	10.47	3.4	1.7	9.5

4.5 Sample Preparation

The samples required for CDT, SCB, IDT and OT tests are cylindrical in shape. Rectangular-shaped samples are required for the BF tests. A Superpave gyratory compactor (SGC) was used for compaction of cylindrical samples and a linear kneading compactor (LKC) was used for preparation of rectangular samples. Rectangular samples were cut to obtain beam samples used for BF testing. Compacted samples were sawed and cored to the required size (Table 2) for preparing samples for different tests. A large number of samples were prepared for each test. The test samples were selected after conducting volumetric analysis (AASHTO T 166). All the test samples were selected based on the target air voids of 7± 0.5%. Figure 28 to Figure 35 show photographic views of samples prepared for different tests. The pictures of the initial samples and the test-ready samples obtained from the initial samples are presented in these figures. Test samples were prepared throughout the duration of the project.

Figure 28. SCB test specimen preparation.

Figure 29. Beam Fatigue test specimen preparation.

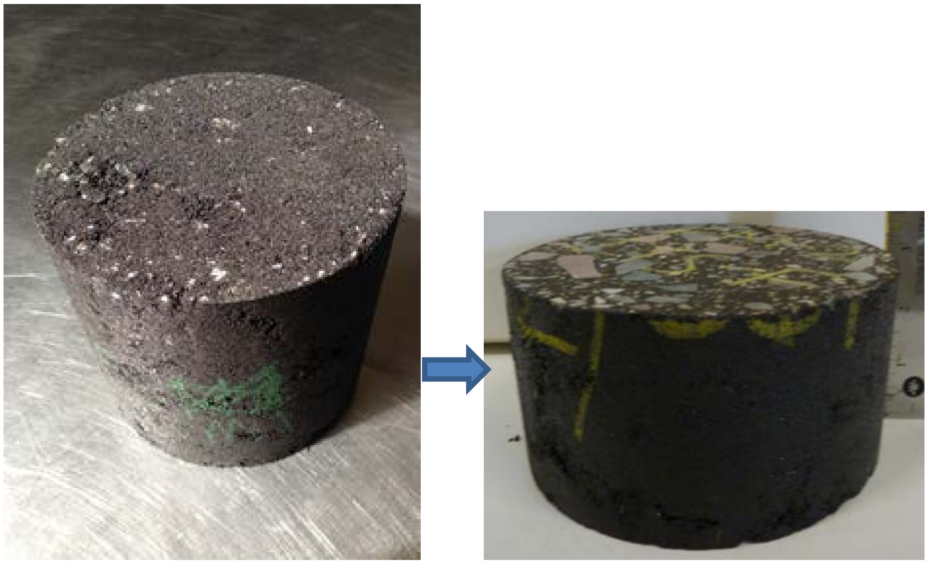


Figure 30. IDT test specimen preparation.

Figure 31. CDT test specimen preparation.

Figure 32. DM test specimen preparation.

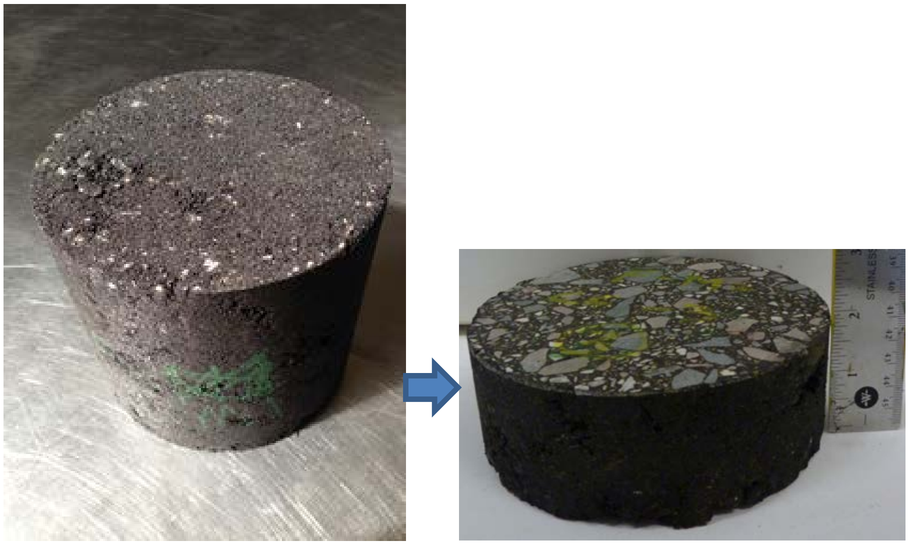


Figure 33. CC test specimen preparation.

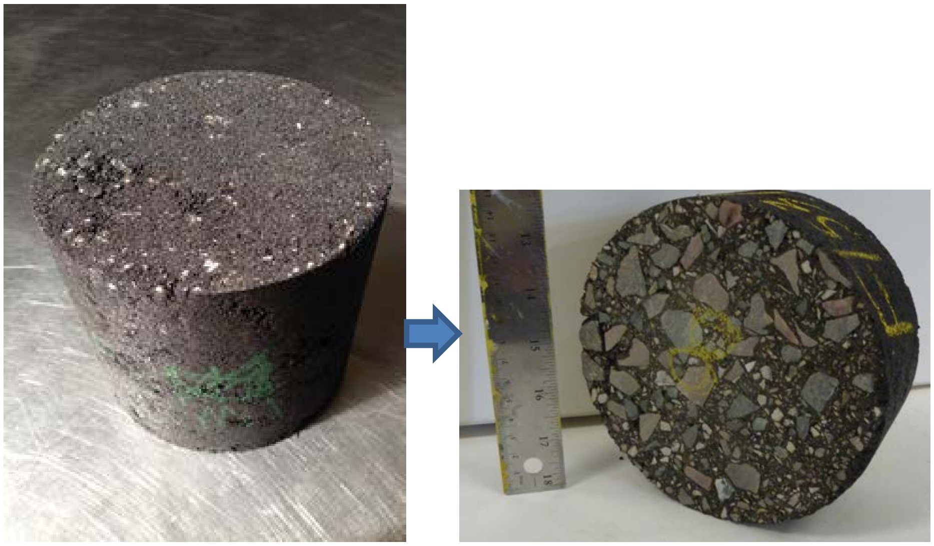


Figure 34. M_r test specimen preparation.

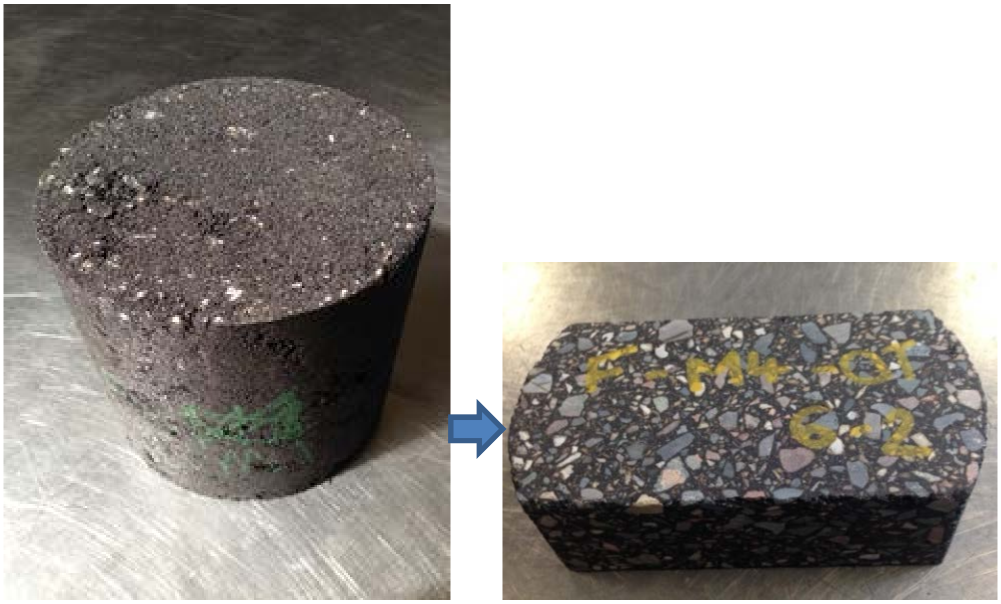


Figure 35. OT test specimen preparation.

Table 12 to Table 17 present summaries of samples prepared for Mix-1 (S3-PG 64-22 OK) through Mix-6 (S3-C-PG 64-22 OK). At least three samples with air voids in the range of 7± 0.5% were prepared for each test except SCB and CDT tests. For the SCB test, three sets of samples, each consisting of three samples, were prepared. Each set of samples were cut with a notch of a specific depth. Therefore, a total of nine SCB samples were prepared for each mix. At least five CDT samples with air voids in the range of 7± 0.5% were prepared for each mix and were tested at three different strain levels (300 micro-strain and two other strain levels based on the number of cycles at failure for the sample tested at 300 micro-strain as per AASHTO TP 107, 2014). Two additional samples were also tested at 300 micro-strain in order to verify the repeatability of the test results. Results of three CDT samples tested at 300 micro-strain were compared for verification of the repeatability.

The OT test equipment was not available at OU Broce Asphalt Laboratory during the reporting period. The OT samples prepared using Mix-1 (S3-PG 64-22 OK), Mix-2 (S3-PG 76-28 OK) and Mix-4 (S5-PG 76-28 OK) were tested at Texas A&M

Transportation Institute (TTI). Eight samples were prepared for each of the above-mentioned mixes and then transported to TTI asphalt laboratory for testing.

Table 12: Summary of sample preparation and testing for Mix-1 (S3-PG 64-22 OK).

Test	**No. of specimens required**	**No. of specimens prepared with 7.0±0.5% air void**	**No. of specimens tested**
Semi-circular bend (SCB)	9	12	12
Beam fatigue (FTG)	3	5	5
Indirect tensile strength (ITS)	3	3	3
Cyclic direct tension (CDT)	5	6	5
Dynamic modulus (DM)	3	3	3
Creep compliance (CC)	3	3	3
Resilient modulus (Mr)	3	3	3
Overlay Tester (OT)	8	8	8

Table 13: Summary of sample preparation and testing for Mix-2 (S3-PG 76-28 OK).

Test	**No. of specimens required**	**No. of specimens prepared with 7.0±0.5% air void**	**No. of specimens tested**
Semi-circular bend (SCB)	9	9	9
Beam fatigue (FTG)	3	6	6
Indirect tensile strength (ITS)	3	3	3
Cyclic direct tension (CDT)	5	5	5
Dynamic modulus (DM)	3	4	4
Creep compliance (CC)	3	3	3
Resilient modulus (Mr)	3	3	3
Overlay Tester (OT)	8	8	8

Table 14: Summary of sample preparation and testing for Mix-3 (S5-PG 76E-28 OK).

Test	No. of specimens required	No. of specimens prepared with 7.0±0.5% air void	No. of specimens tested
Semi-circular bend (SCB)	9	9	3
Beam fatigue (FTG)	3	4	4
Indirect tensile strength (ITS)	3	3	3
Cyclic direct tension (CDT)	5	5	5
Dynamic modulus (DM)	3	4	3
Creep compliance (CC)	3	3	3
Resilient modulus (Mr)	3	3	3
Overlay Tester (OT)	8	0	0

Table 15: Summary of sample preparation and testing for Mix-4(S5, PG 76-28 OK).

Test	No. of specimens required	No. of specimens prepared with 7.0±0.5% air void	No. of specimens tested
Semi-circular bend (SCB)	9	9	9
Beam fatigue (FTG)	3	3	3
Indirect tensile strength (ITS)	3	3	3
Cyclic direct tension (CDT)*	5	5	5
Dynamic modulus (DM)	3	4	3
Creep compliance (CC)	3	3	3
Resilient modulus (Mr)	3	3	3
Overlay Tester (OT)	8	8	8

Table 16: Summary of sample preparation and testing for Mix-5 (S3-F-PG 64-22 OK).

Test	No. of specimens required	No. of specimens prepared with 7.0±0.5% air void	No. of specimens tested
Semi-circular bend (SCB)	9	12	12
Beam fatigue (FTG)	3	4	3
Indirect tensile strength (ITS)	3	3	3
Cyclic direct tension (CDT)	5	5	5
Dynamic modulus (DM)	3	3	3
Creep compliance (CC)	3	3	3
Resilient modulus (Mr)	3	3	3
Overlay Tester (OT)	8	0	0

Table 17: Summary of sample preparation and testing for Mix-6 (S3-C-PG 64-22 OK).

Test	**No. of specimens required**	**No. of specimens prepared with 7.0±0.5% air void**	**No. of specimens tested**
Semi-circular bend (SCB)	9	9	9
Beam fatigue (FTG)	3	4	3
Indirect tensile strength (ITS)	3	0	0
Cyclic direct tension (CDT)	5	5	5
Dynamic modulus (DM)	3	3	3
Creep compliance (CC)	3	0	0
Resilient modulus (Mr)	3	0	0
Overlay Tester (OT)	8	0	0

5. LABORATORY TESTING AND ANALYSIS OF TEST RESULTS

5.1 General

Dynamic modulus (DM), SCB, BF, ITS, CDT tests were conducted on all the mixes and three of the six mixes were tested for OT. The DM test is an associated test for CDT test; DM test results are required for mechanistic evaluation of the CDT test results to develop the damage characteristics curves. The tests were conducted as per the pertinent AASHTO and ASTM standards. The test temperature for all the fatigue related tests was 20°C (68°F). Furthermore, standard test temperatures ranging from 4 to 54°C (39.2 to 129.2°F) were used for dynamic modulus testing (AASHTO TP 79). This chapter provides a comprehensive discussion of the results of different tests conducted in this project.

5.2 Semi-Circular Bend (SCB) Test

The SCB tests were conducted on samples with three different notch depths: 25.4 mm, 31.8 mm and 38 mm. Figure 36 presents the typical load vs deformation curves for the SCB samples tested at 25.4-mm notch depth; the test results of Mix-3 (S5-PG 76E-28 OK) were used to generate these graphs. Three samples were tested at each notch depth, and the average of the results is used for comparison between the notch depths.

5.2.1 Load at Failure (P_f)

The load at failure for the samples tested at different notch depths for all the six mixes are presented in Figure 37. Error bars indicate the single standard deviation of the results of the three samples. From Figure 37, it was observed that the difference between the P_f values of the mixes were not consistent when comparing them at a given crack width. The Mix-3 (S5-PG 76E-28 OK), which is a RIL mix prepared with 76E-28 OK binder, and Mix-5 (S3-F-PG 64-22 OK) and Mix-6 (S3-C-PG 64-22 OK), which were WMA mixes, failed at relatively lower loads when compared to other three mixes.

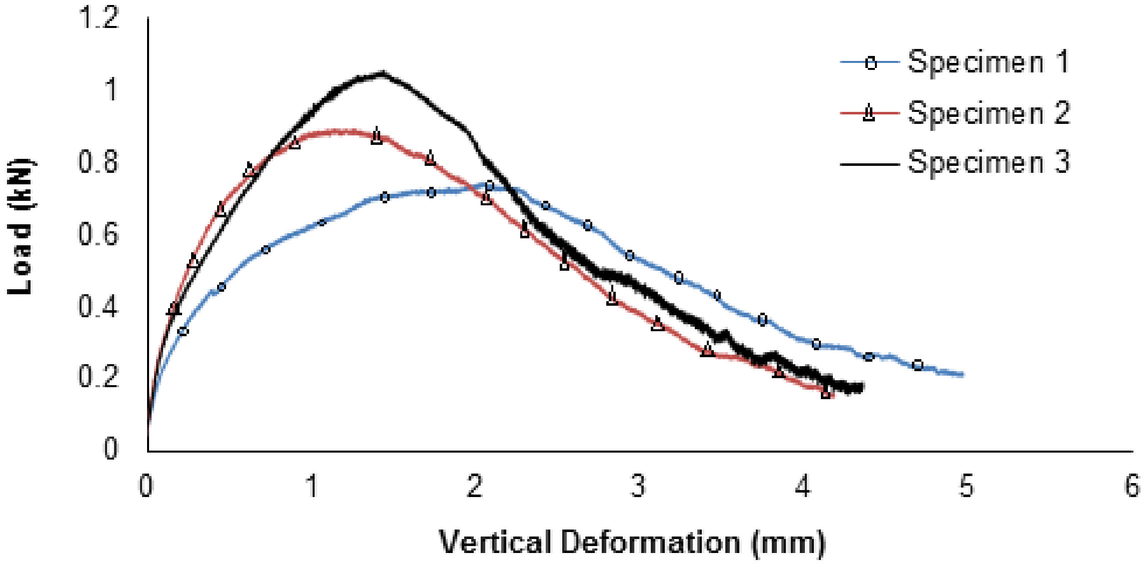


Figure 36. Load vs deformation curves for the SCB samples tested at 25.4 mm notch depth for Mix-3 (S5-PG 76E-28 OK).

5.2.2 Vertical Deformation at Failure (d_f)

The vertical deformations at failure for all of the six mixes are presented in Figure 38. As anticipated, the mixes with modified asphalt binder sustained higher vertical deformations at the failure. The Mix-3 (S5-PG 76E-28 OK) resulted in the highest and the Mix-5 (S3-F-PG 64-22 OK) resulted in the lowest vertical deformation at failure. The Mix-1 (S3-PG 64-22 OK) and Mix-6 (S3-C-PG 64-22 OK) which were prepared with same aggregate gradation and binder sustained similar vertical deformation at failure. Between the two WMA mixes, Mix-6 (S3-C-PG 64-22 OK) sustained a greater vertical deformation at failure as compared to the Mix-5 (S3-F-PG 64-22 OK).

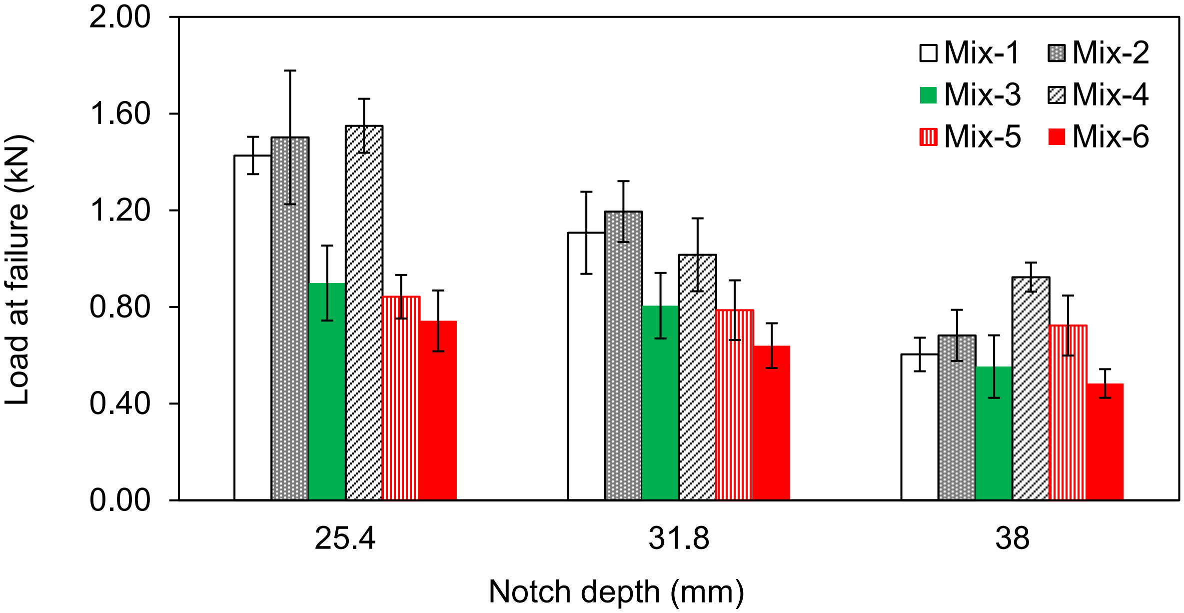


Figure 37: Comparison of loads at failure at different notch depths between the six mixes for SCB test.

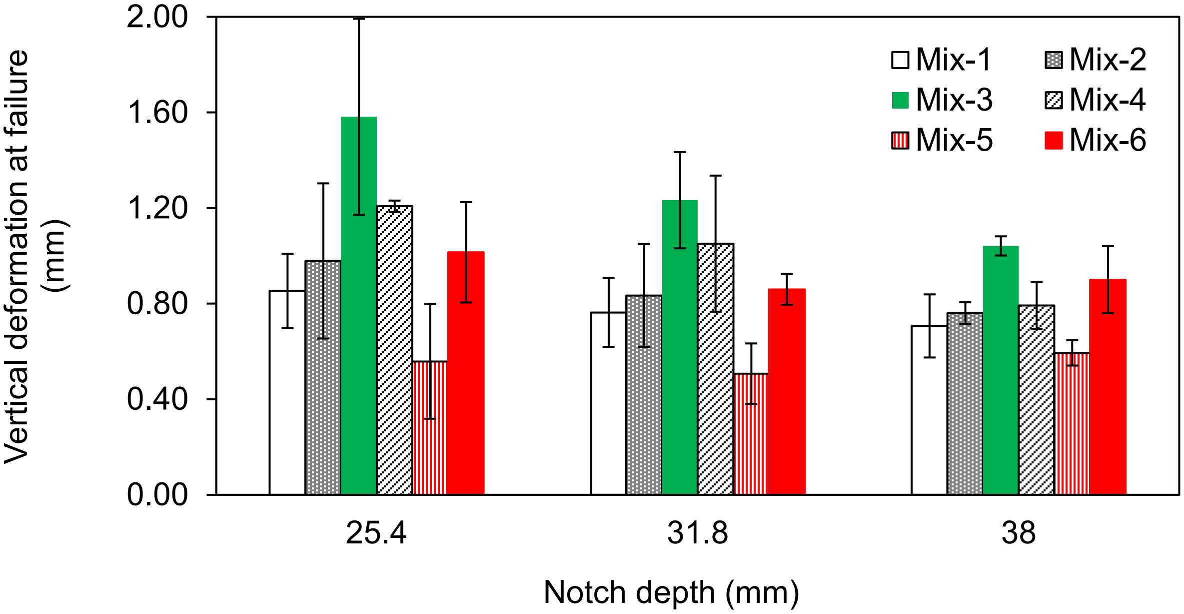


Figure 38: Comparison of vertical deformations at failure at different notch depths between the six mixes for SCB test.

5.2.3 Strain Energy at Failure (U_f)

The strain energy at failure was estimated by calculating the area under the load-deformation curve, up to the peak load. Figure 39 presents a comparison of the strain energies at peak loads (U_f) for the six mixes. It can be seen that the variation in U_f between the mixes follow similar trends at all the three notch depths. The Mix-3 (S5-PG 76E-28 OK) and Mix-5 (S3-F-PG 64-22 OK) resulted in the highest and lowest U_f values, respectively. Between the two WMA mixes, Mix-6 (S3-C-PG 64-22 OK) resulted in greater strain energy at failure than the Mix-5 (S3-F-PG 64-22 OK).

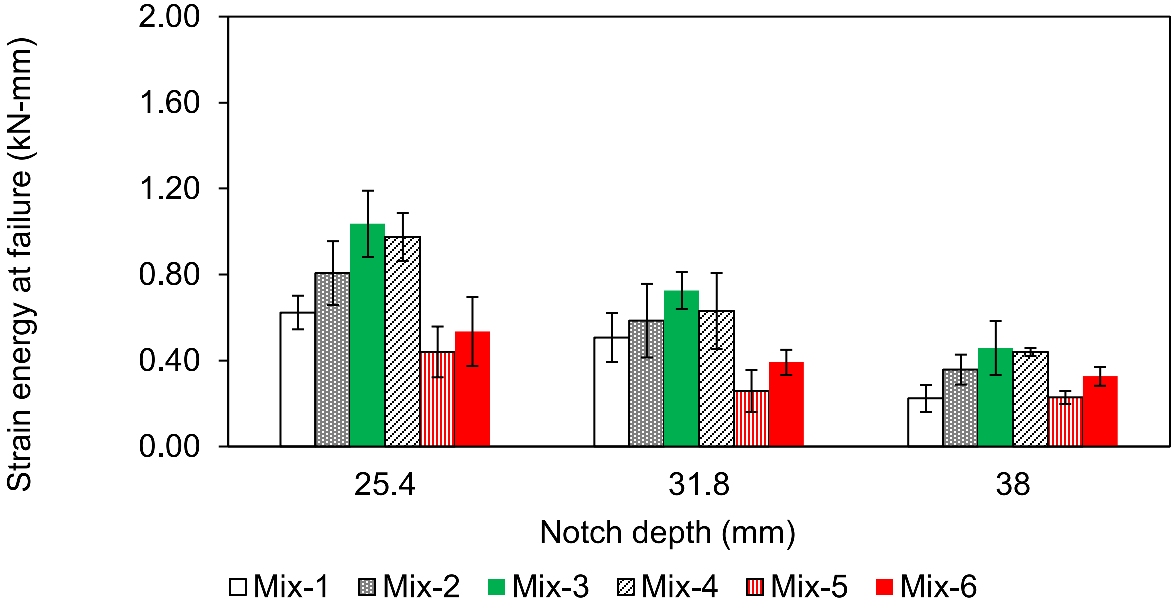


Figure 39: Comparison of strain energies at failure at different notch depths for the six mixes.

5.2. 4 Critical Strain Energy Release Rate (J_c)

The fatigue resistance of asphalt mixes is evaluated by comparing the critical strain energy release rate (J_c) in the SCB test method. The higher the J_c value, the higher the fatigue resistance (Wu et al., 2005). The relationships for strain energy at failure and notch depth for all the six mixes are shown in Figure 40. A linear regression correlation was developed and plotted as a straight line between the strain energies and notch depths for each mix. The slope of the linear regression line, which is always negative, was used to determine the critical strain energy release rate. It was found that the coefficient of determinations (R^2) of the linear regression lines developed for the four mixes lie between 0.86 and 0.99. These high R^2 values indicate good correlation between the strain energy at failure vs notch depth.

As shown in Figure 41, the values of J_c for Mix-1(S3, PG 64-22 OK) through Mix-6 (S3-C-PG 64-22 OK) were found to be 0.634, 0.712, 1.084, 0.850, 0.336 and 0.332 kJ/m², respectively.

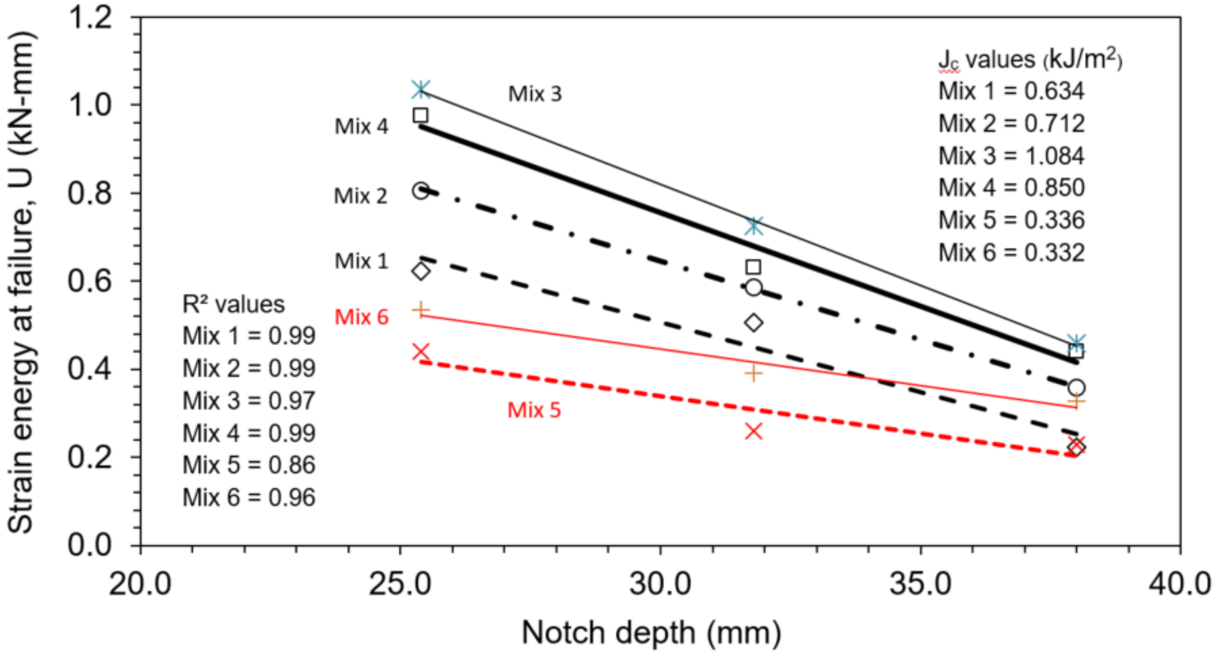


Figure 40. Comparison of strain energies at failure vs notch depths between the six mixes

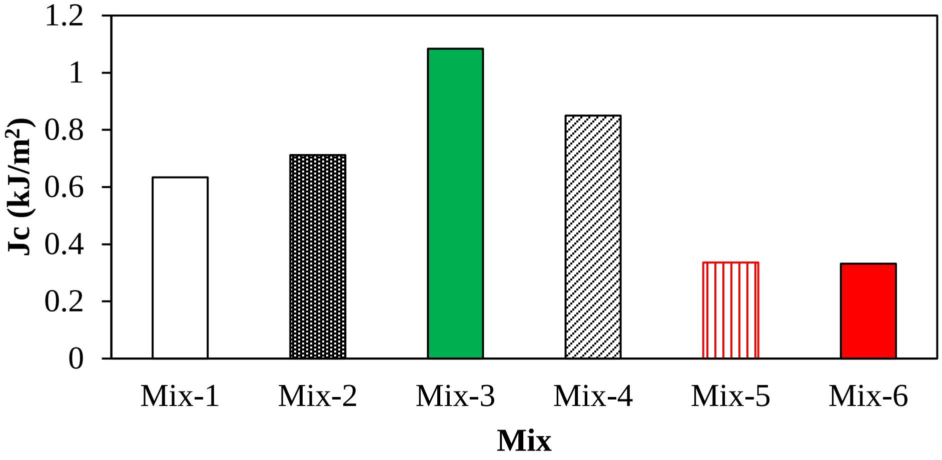


Figure 41. Bar chart showing the values of J_c for six mixes.

5.2.5 Comparison of the Fatigue Performance between the Six Mixes

While comparing the fatigue performance of the six mixes, it is interesting to see that the SCB test could distinguish the differences in fatigue performances between these mixes. Mix-5 (S3, PG 64-22 OK, F- WMA), which is a foamed WMA mix and contains 25% RAP resulted in the least fatigue resistance, had the lowest value of J_c. The relatively higher strain energy at failure for Mix-4 (S5, PG 76-28 OK) as compared to Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK), Mix-5 (S3-F-PG 64-22 OK) and Mix-6 (S3-C-PG 64-22 OK) indicated that the asphalt mix with a finer aggregate gradation exhibits a higher fatigue resistance. Also, use of modified binder helped increase the fatigue resistance. As anticipated, the highest value of J_c was obtained for Mix-3 (S5-PG 76E-28 OK). This is a RIL mix and contains the highest binder content among the five mixes. Therefore the ranking of these six mixes based on their fatigue resistance is as follows: Mix-3 > Mix-4 > Mix-2 > Mix-1 > Mix-6 > Mix-5. This ranking is completely in agreement with the anticipated fatigue resistance.

5.3. Four-Point Beam Fatigue (BF) Test

The BF test was conducted on all the mixes. At least three samples were tested for each of these mixes. The comparison of the initial stiffness, number of cycles at failure and cumulative dissipated energy at failure for each mix are provided in the following subsections.

5.3.1 Stiffness

Figure 42 presents a comparison of the initial stiffness (measured at 50th cycle) of each of the three beams tested for the five different mixes. Typically, the stiffness decreases with the load cycles, as shown in Figure 43. The stiffness ratio (in Figure 43) is the ratio of the stiffness at a given cycle to the initial stiffness.

The average initial stiffness of Mix-1(S3, PG 64-22 OK) through Mix-6 (S3, C, PG 64-22 OK) were 4610 MPa, 3940 MPa, 2247 MPa, 3430 MPa, 3290 MPa and 3286 MPa, respectively. It appeared that a mix with a relatively coarser aggregate gradation and unmodified binder resulted in a higher stiffness when compared to the mix with a finer aggregate gradation and modified binder. However, this was not true when the coarser mix was a foamed WMA and/or contained a considerable amount of RAP. The Mix-3 (S5-PG 76E-28 OK) which is a RIL mix resulted in lowest initial stiffness.

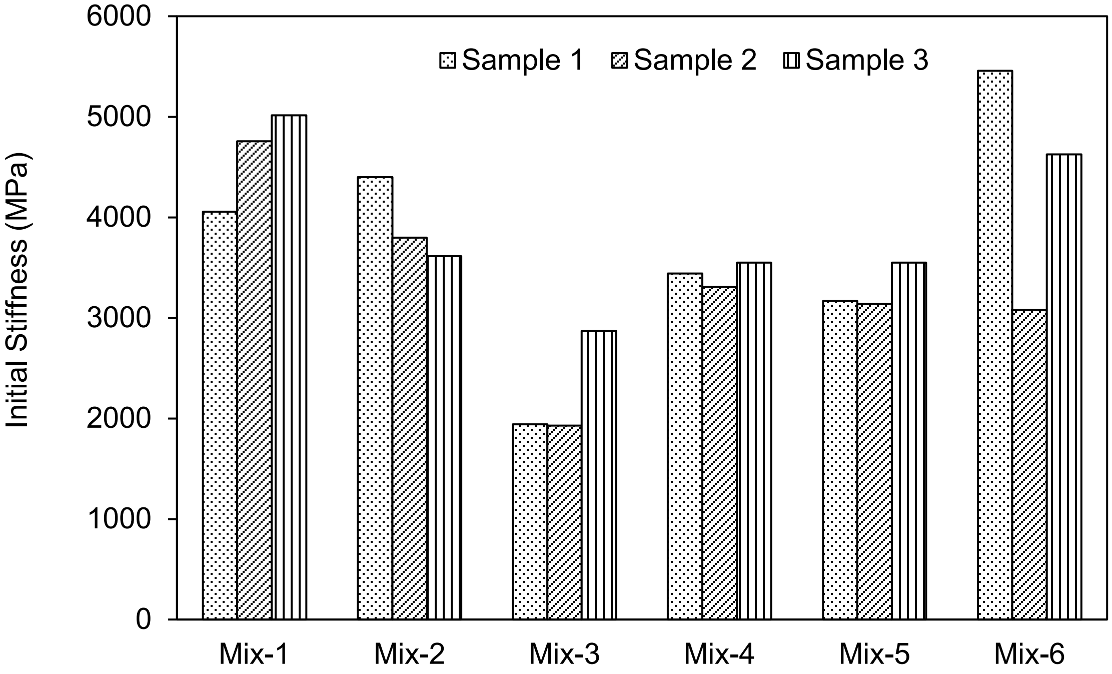


Figure 42: Comparison of initial stiffness for the six mixes.

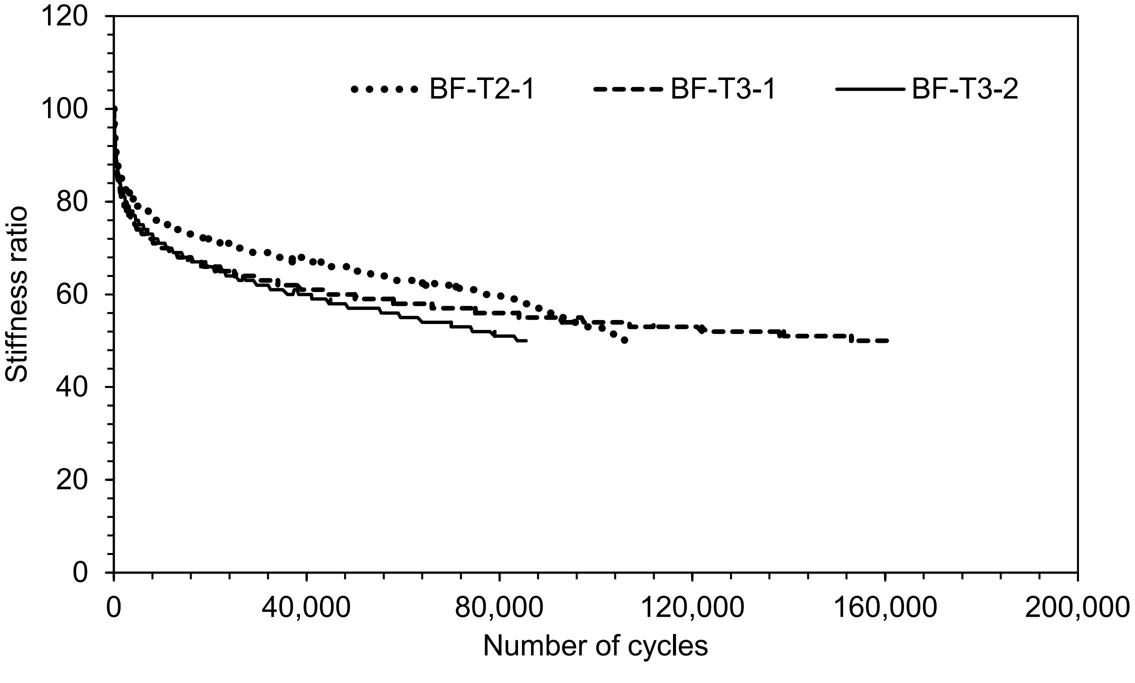


Figure 43: Typical trend of stiffness ratio vs number of load cycles relationship (Mix-1 (S3-PG 64-22 OK)).

5.3.2 Number of Cycles at Failure (N_f)

Figure 44 presents the comparison of the number of cycles of the three beams tested for the six different mixes. The average N_f of Mix-1(S3, PG 64-22 OK) through Mix-5 (S3-C-PG 64-22 OK) were found as 117,660; 303,390; 4,855,000; 1,445,000; 94,160, and 62,065, respectively. The number of cycles at which the stiffness drops to 50% of the initial stiffness was considered as failure load cycle (AASHTO T 321). As anticipated, the mix with a relatively coarser aggregate gradation and unmodified asphalt binder provided a lower fatigue life as compared to that of the mix with a finer aggregate gradation and modified asphalt binder. The higher fatigue life (N_f) of Mix-2(S3, PG 76-28 OK) as compared to Mix-1(S3, PG 64-22 OK) indicated that the modified asphalt binder contributed to increasing the fatigue life. The higher performance of Mix-4 (S5, PG 76-28 OK) as compared to the Mix-2(S3, PG 76-28 OK) indicated that finer gradations helped in improving the fatigue life. The relatively lower fatigue life of Mix-5 (S3-F-PG 64-22 OK) and Mix-6 (S3-C-PG 64-22 OK) indicated that use of a WMA mix may lead to a low fatigue life. The highest fatigue life provided by Mix-3 (S5-PG 76E-28 OK) is much higher than all other mixes. It can be seen that the average number of cycle at failure for this mix is 4.86 million. This test method is probably not very suitable for RIL types of mixes; otherwise, it will take a long time.

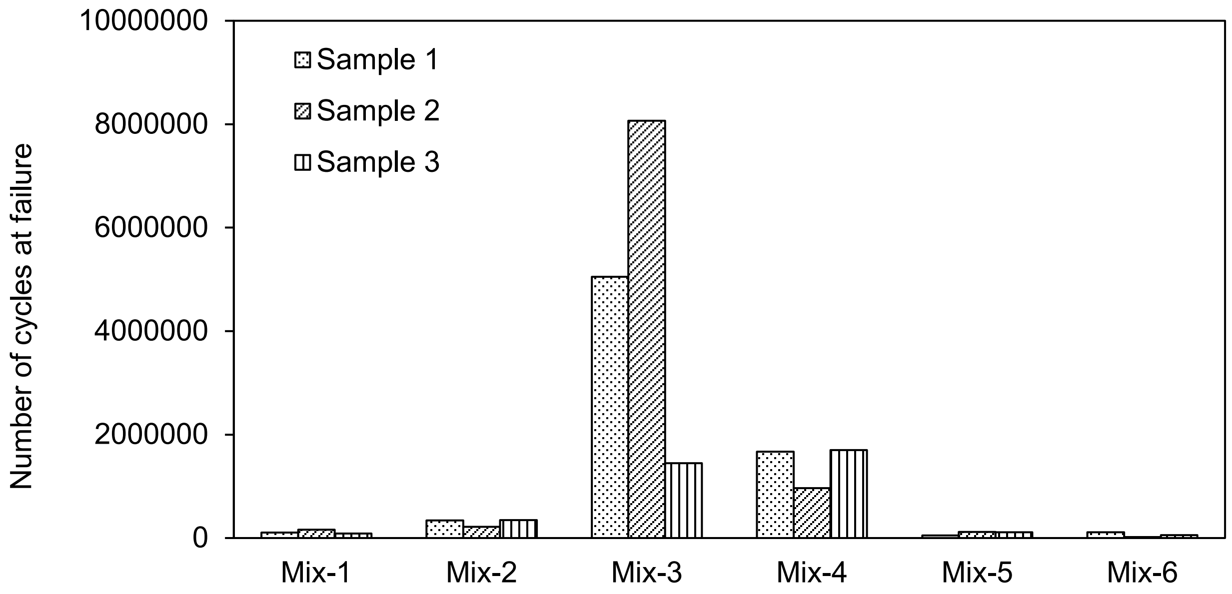


Figure 44: Comparison of number of cycles at the failure (N_f) for the six mixes.

5.3.3 Cumulative Dissipated Energy (W_N).

The BF test results of all of the samples were analyzed to determine the cumulative dissipated energies of each mix. Many researchers (Carpenter et al. 2003; Tayebali et al., 1993; Van Dijk and Vesser, 1977) studied the correlation between dissipated energy and the number of load cycles to failure. Also, in this study the relationship between the cumulative dissipated energy and number of the failure load cycles were studied. Figure 45 presents a typical curve for cumulative dissipated energy vs. number of loading cycles. From Figure 45, it was observed that the energy continuously dissipated with an increase in load cycles.

Figure 46 presents a comparison of the W_N of the three beams tested for the four different mixes. The average W_N of Mix-1(S3, PG 64-22 OK) through Mix-6 (S3-C-PG 64-22 OK) were 91,250 kPa; 221,990 kPa; 2,150,000 kPa; 749,100 kPa, 69,131 kPa, and 50,825 kPa, respectively. Interestingly, a similar trend was also observed in the case of N_f. This implies that a mix with a better fatigue performance fails after a large amount of energy dissipation.

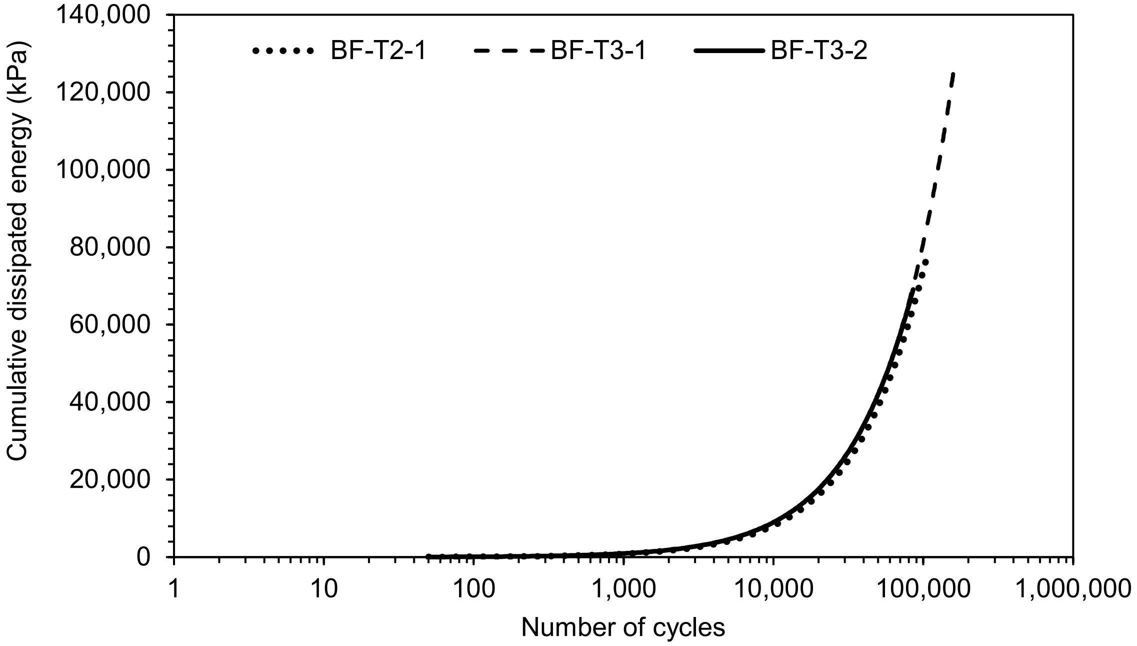


Figure 45: Typical curve for cumulative dissipated energy vs number of load cycles (Mix-1(S3, PG 64-22 OK)).

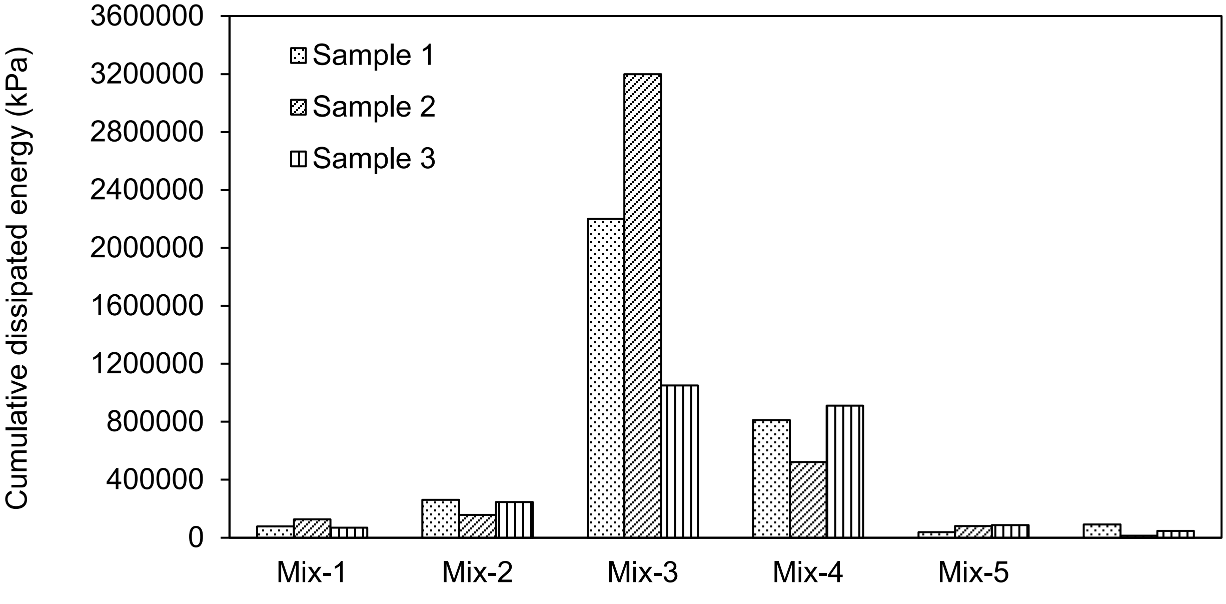


Figure 46: Comparison of cumulative dissipated energy at the failure for the six mixes.

5.4 Indirect Tension (IDT) Test

The IDT test results can be used to determine the toughness index (TI) and fracture energy ratio (ER) (Wen, 2013; Yin et al., 2008; Roque et al., 2004) in order to characterize the fatigue resistance of asphalt mixes. Fracture toughness index is determined directly from the load vs. vertical deformation curve obtained in the IDT test. Figure 47 shows a typical load vs. vertical deformation curve obtained in the IDT test. This load vs. vertical deformation relationships are used to determine the normalized indirect tensile strength (ITS) vs. strain curve, as shown in Figure 48. As previously mentioned, the toughness index is computed using the normalized indirect tensile strength (ITS) vs. strain curve. It may be stated that the results of five mixes are included in this report, the ITS results of sixth mixes were erroneous because of incorrect air voids percentage of the test specimens.

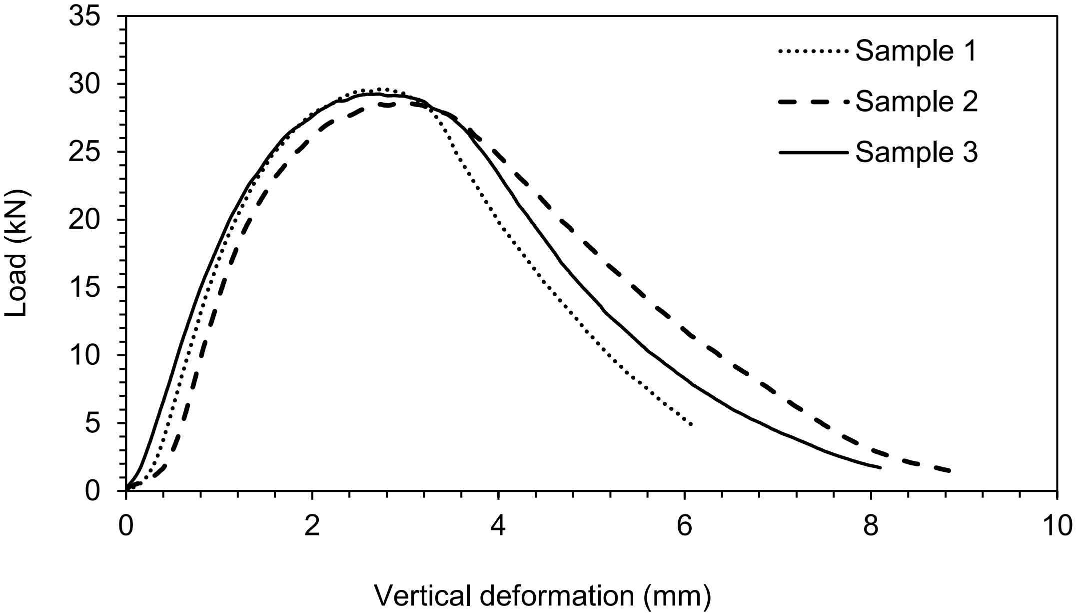


Figure 47: Typical load vs vertical deformation in IDT test (Mix-4 (S5, PG 76-28 OK)).

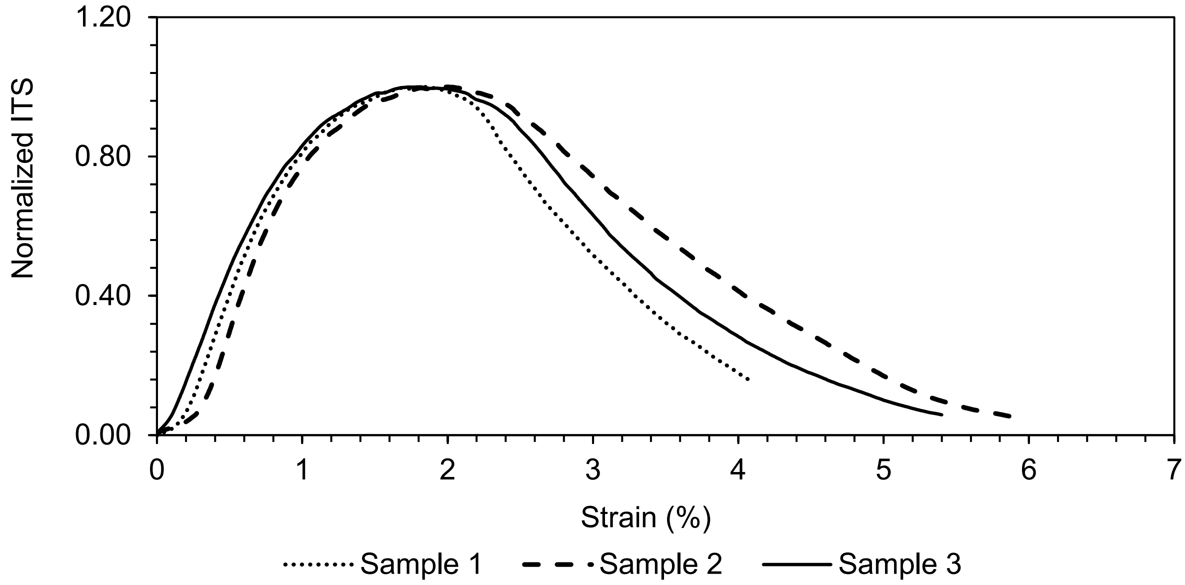


Figure 48: Typical normalized ITS vs strain (%) in IDT test (Mix-4 (S5, PG 76-28 OK)).

5.4.1 Peak load at failure (Pf)

Figure 49 presents the comparison of the peak loads at failure of the three samples of the five mixes. The average peak load measured for Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK), Mix-3 (S5-PG 76E-28 OK), Mix-4 (S5, PG 76-28 OK) and Mix-5 (S3-F-PG 64-22 OK) were found to be 15.47 kN; 24.47 kN; 15.96 kN; 29.15 kN and 15.21 kN, respectively.

5.4.2 Indirect tensile strength (ITS)

Figure 50 presents a comparison of the ITS of the three samples of the five different mixes tested. The average ITS of the Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK), Mix-3 (S5-PG 76E-28 OK), Mix-4 (S5, PG 76-28 OK) and Mix-5 (S3-F-PG 64-22 OK) were 876 kPa, 1385 kPa, 897 kPa, 1650 kPa and 861 kPa, respectively. The Mix-5 (S3-F-PG 64-22 OK) which is a warm mix resulted in the lowest ITS value.

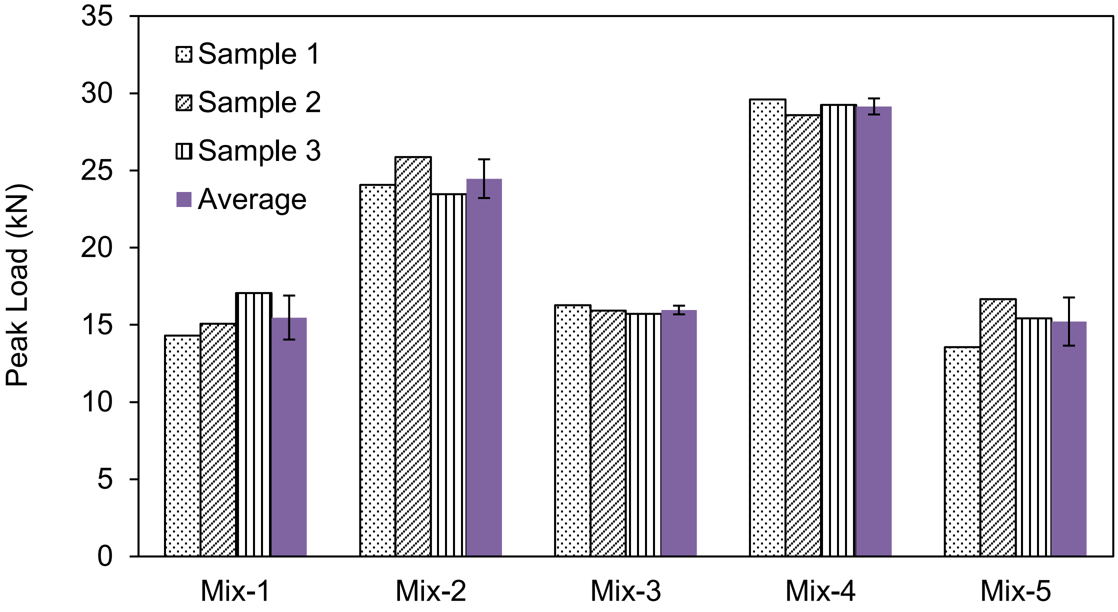


Figure 49: Comparison of peak load at failure for all the six mixes.

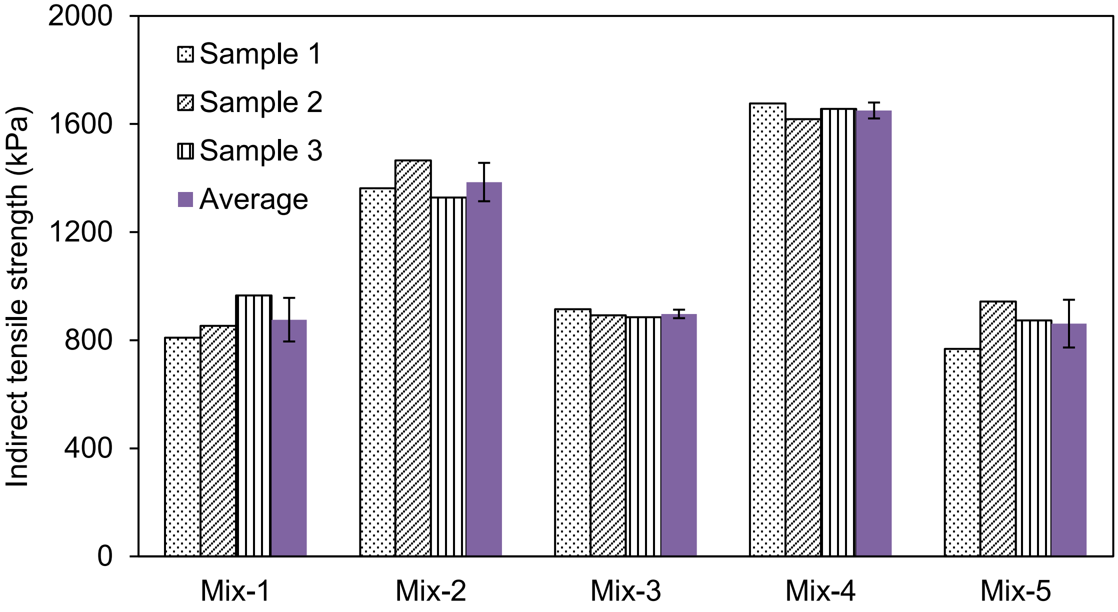


Figure 50: Comparison of Indirect tensile strength for all the six mixes.

5.4.3 Vertical deformation

Figure 51 presents the comparison of the vertical deformations of the three samples tested for the five different mixes. The average vertical deformations of Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK), Mix-3 (S5-PG 76E-28 OK), Mix-4 (S5, PG 76-28 OK) and Mix-5 (S3-F-PG 64-22 OK) were 2.38 mm, 2.50 mm, 4.53 mm, 2.82 mm and 2.42 mm, respectively. It appears that a mix with finer aggregate gradation and modified asphalt binder sustained a higher deformation at failure as compared to mix with coarser aggregate gradation and unmodified binder. The vertical deformation at failure for the Mix-3 (S5-PG 76E-28 OK) was significantly higher than other mixes; a similar trend was also observed in SCB test results.

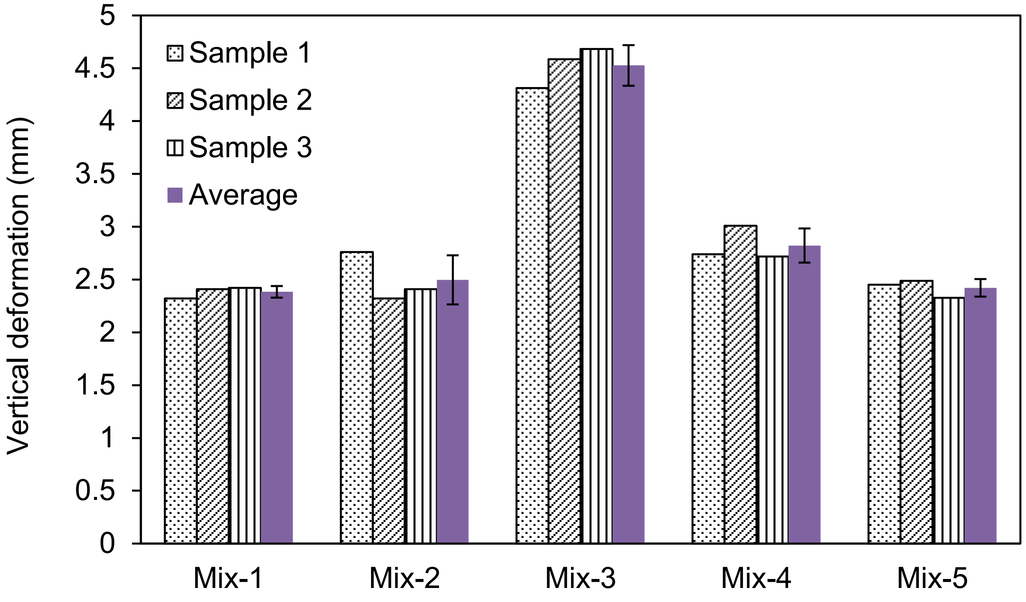


Figure 51: Comparison of vertical deformation for all the six mixes.

5.4.4 Toughness index

Figure 52 presents the comparison of the toughness indices of the three samples tested for the five different mixes. The average toughness indices of the Mix-1(S3, PG 64-22

OK), Mix-2(S3, PG 76-28 OK), Mix-3 (S5-PG 76E-28 OK), Mix-4 (S5, PG 76-28 OK) and Mix-5 (S3-F-PG 64-22 OK) were 0.79, 0.83, 1.00, 0.86 and 0.78, respectively. As anticipated, Mix-3 (S5-PG 76E-28 OK) which is a RIL mix resulted in higher toughness index as compared to the other four mixes.

The SCB and BF test methods had shown a similar rank of the fatigue resistance for these mixes. However, the difference in the TI values between the five mixes is quite low, when a same terminal strain value is considered for all the mixes (3% in this study). A relatively lower terminal strain value (e.g., 3%) for the weaker mixes and a higher terminal strain value (e.g.,10%) for the high fatigue resistance mixes can also be considered to determine TI values for different mixes; but in that case, drawing a comparison of the fatigue resistances between the mixes would be difficult. So, from the IDT test results for the five mixes, it can be concluded that even though the correct rank of the fatigue resistance of mixes could be identified, the quantitative difference between fatigue lives may not be properly captured by using the IDT test results when TI values are used to characterize the fatigue resistance.

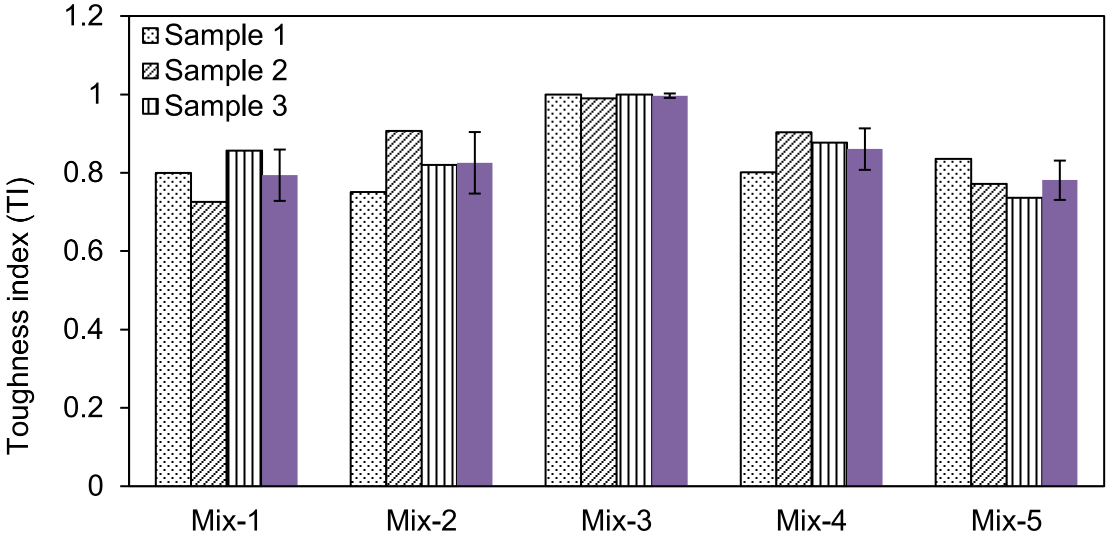


Figure 52: Comparison of toughness index for all the six mixes.

5.5. Cyclic Direct Tension (CDT) Test

The CDT tests were conducted as per AASHTO TP 107, 2014. At least five CDT samples were tested for each mix at three different strain levels. Among the five CDT samples, the first sample was tested at 300 micro-strain as suggested by AASHTO TP 107, 2014. Based on the number of cycles at which the first samples failed, the strain levels for next two samples were selected so that the first three samples represent three different level of fatigue lives: low, moderate and high. As the first three samples were tested at three different strain levels, the repeatability of the test results could not be determined based on the results of these three samples. That is why the last two samples were tested at 300 micro-strain so that at least three samples could be tested at same strain levels. The results of the first sample and the last two samples (all tested at 300 micro-strain) were intended to use to verify the repeatability of the test results. CDT tests were performed on all the mixes, however, the variability between the results for most of the samples were a concern.

The CDT test results were used to develop the damage characteristic curve (pseudo stiffness vs. damage). Dynamic modulus results of the corresponding mixes used for analyzing CDT test results in Simplified Visco-Elastic Continuum Damage (S-VECD) platform. The ALPHA Fatigue software was used for the analysis.

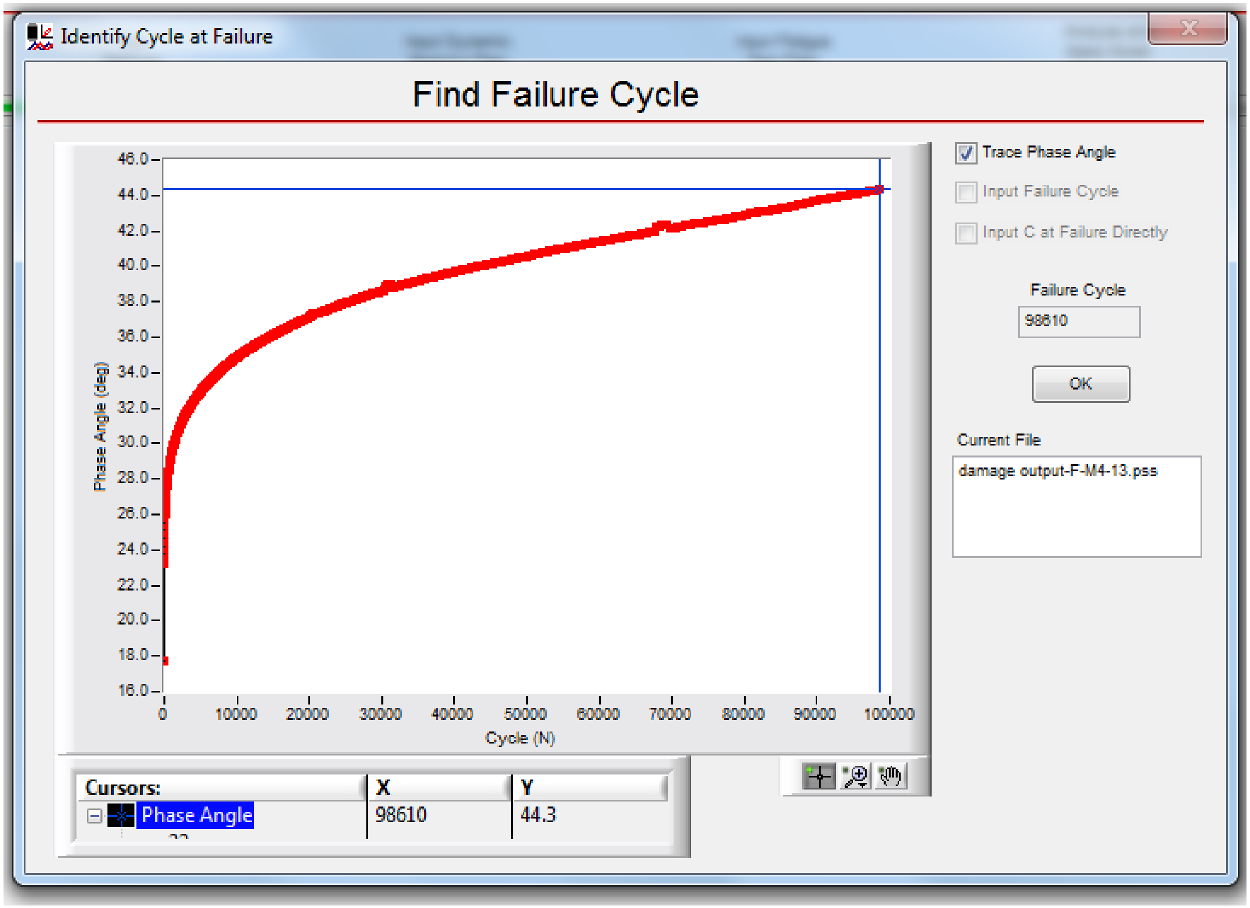
The CDT test results Mix-4(S5, PG 76-28 OK) and Mix-5(S3, F, PG 64-22 OK,) were analyzed and presented in this report. It may be noted that this test was the most complex among the five tests discussed. The variations of the results between the samples were also large and inconsistent. The data analyses for other three mixes were hence not included in this report.

Mix-4(S5, PG 76-28 OK)

As per the requirement, the first sample was tested at 300 micro-strain. It can be seen in Figure 53 that the phase angle continued to increase even at 100,000 cycles. However, the modulus dropped from 3771 MPa (initial modulus) to 517 MPa at the

100,000th cycle. So, it was assumed that the sample failed at a cycle slightly more than 100,000 cycles. Based on this failure-cycle, the peak-to-peak strains for second and third samples were decided as 450 and 400-micro-strain. It can be seen in Figure 54 that the second sample, a representative of short range fatigue life, failed at 10,983th cycle when the phase angle reached its peak angle of 45.9 degrees. The third sample, a representative of medium range fatigue life, failed at 3,735th cycle (Figure 55) at peak phase angle of 38.5 degrees. It was surprising that the third sample which was tested at a lower (400 micro-strains) strain as compared to the second sample (450 micro-strain) failed at lower number of load cycles. Unfortunately, this same phenomenon was observed for many other sets of specimens.

Using the test results, damage characteristic curves were drawn, as shown in Figure 56. These damage characteristic curves provide a relationship between the relative modulus (C) and the damage parameter (S). The fitting parameters of these kinds of curves are used to estimate the fatigue life of the asphalt mix, for given values of strain, temperature and loading frequency. A fatigue analysis was performed for the Mix-4(S5, PG 76-28 OK) and the results are given in Table 18. The fatigue analysis was performed for five different strain values 250, 300, 350, 400 and 450 micro-strains. The estimated fatigue lives for the five strain levels are: 90.37, 21.11, 6.17, 2.13 and 0.83 million cycles, respectively.



☑ Trace Phase Angle

☐ Input Failure Cycle

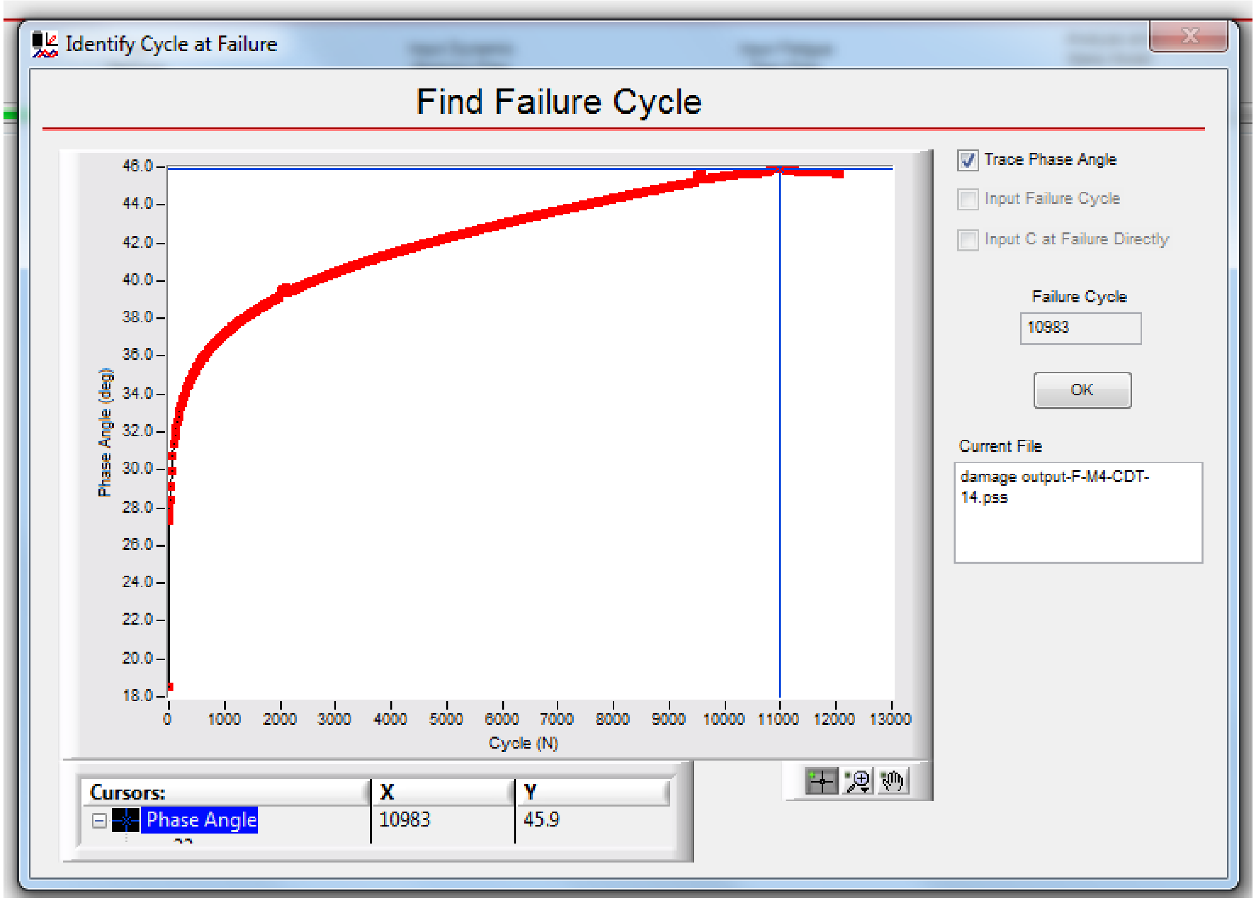
☐ Input C at Failure Directly

Failure Cycle: 98610

Current File: damage output-F-M4-13.pss

Cursors:	X	Y
Phase Angle	98610	44.3

Figure 53. Phase angle vs number of cycles for the first CDT sample for the Mix-4 (S5, PG 76-28 OK), tested with 300 micro-strain.



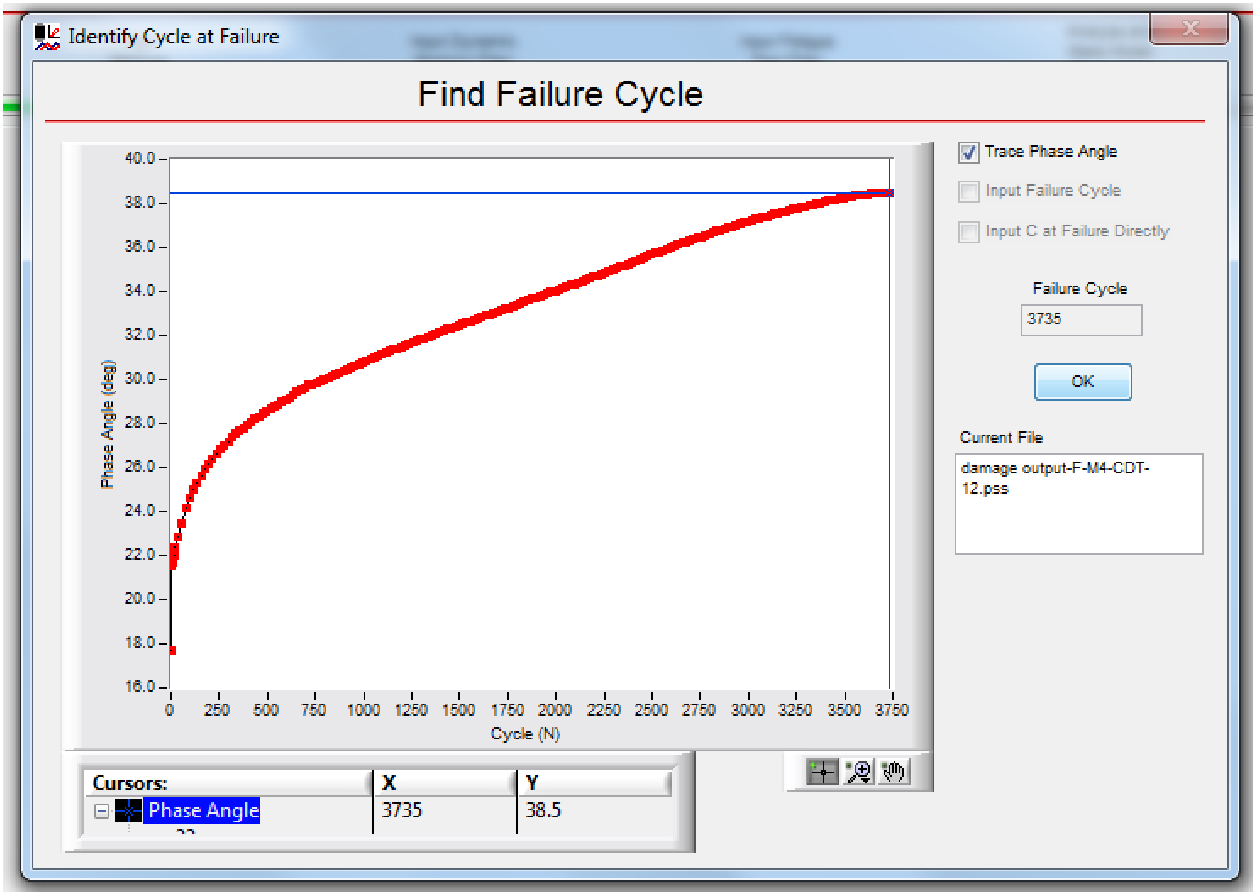
☑ Trace Phase Angle
☐ Input Failure Cycle
☐ Input C at Failure Directly

Failure Cycle: 10983

Current File: damage output-F-M4-CDT-14.pss

Cursors:	X	Y
Phase Angle	10983	45.9

Figure 54: Phase angle vs number of cycles for the second CDT sample for the Mix-4 (S5, PG 76-28 OK), tested with 450 micro-strain.



☑ Trace Phase Angle

☐ Input Failure Cycle

☐ Input C at Failure Directly

Failure Cycle: 3735

Current File: damage output-F-M4-CDT-12.pss

Cursors:	X	Y
Phase Angle	3735	38.5

Figure 55: Phase angle vs number of cycles for the third CDT sample for the Mix-4 (S5, PG 76-28 OK), tested with 400 micro-strain.

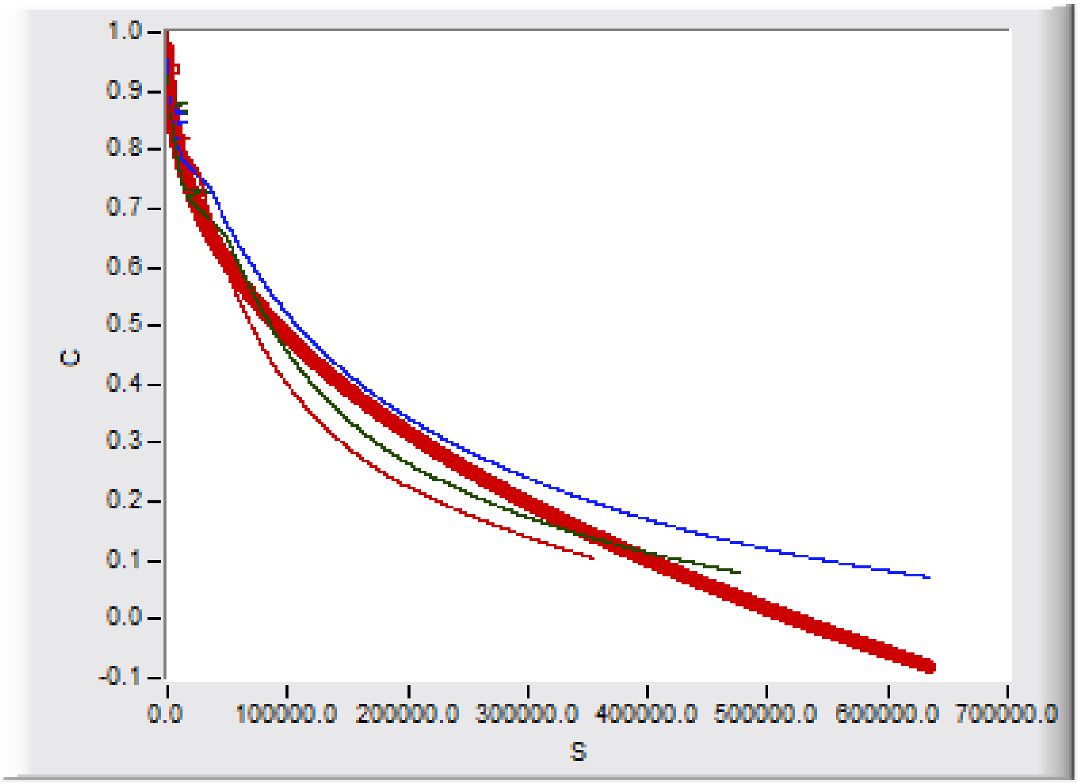


Figure 56: Damage characteristic curve for the Mix-4 (S5, PG 76-28 OK).

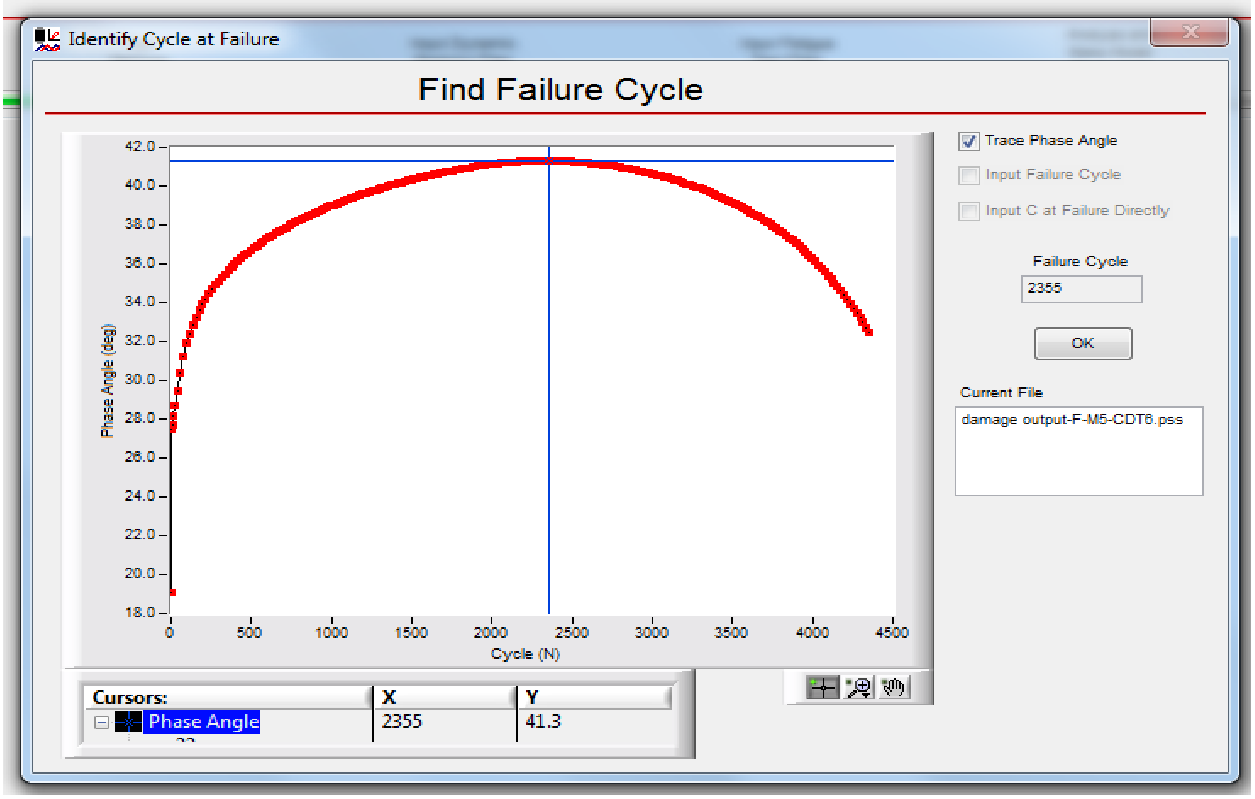
Table 18. Estimated fatigue life for Mix-4 (S5, PG 76-28 OK).

Micro-strain/ anticipated fatigue life range	Temperature (C)	Frequency (Hz.)	Fatigue life, N_f (million)
250/large	21	10	90.37
300/large	21	10	21.11
350/medium	21	10	6.17
400/medium	21	10	2.13
450/short	21	10	0.83

Mix-5(S3, F, PG 64-22 OK)

As per the requirement, the first sample was tested at 300 micro-strain. This sample failed at 2,355th cycle, as shown in Figure 57, when the phase angle reached to its peak at 41.3 degrees. Based on this failure-cycle, the peak-to-peak strains for second and third samples were tested at 250 and 300-micro-strains. It can be seen in Figure 58 that the second sample, a representative of medium range fatigue life, failed at 5,595th cycle when its peak phase angle reached to 43.4 degrees. The third sample, a representative of long range fatigue life, failed at 43,045th cycle (Figure 59) when the phase angel reached to 42 degrees.

Data collected from the CDT tests were used to construct a damage characteristic curve, as shown in Figure 60. A fatigue analysis was performed for the Mix-5(S3, F, PG 64-22 OK), the results are given in Table 19. The fatigue analysis was performed for three different strain values 300, 250 and 200 micro-strains, representing short, medium and large range of fatigue lives, respectively; the estimated fatigue lives for these three ranges of fatigue lives were 0.13, 0.37 and 1.37 million cycles, respectively.



☑ Trace Phase Angle

☐ Input Failure Cycle

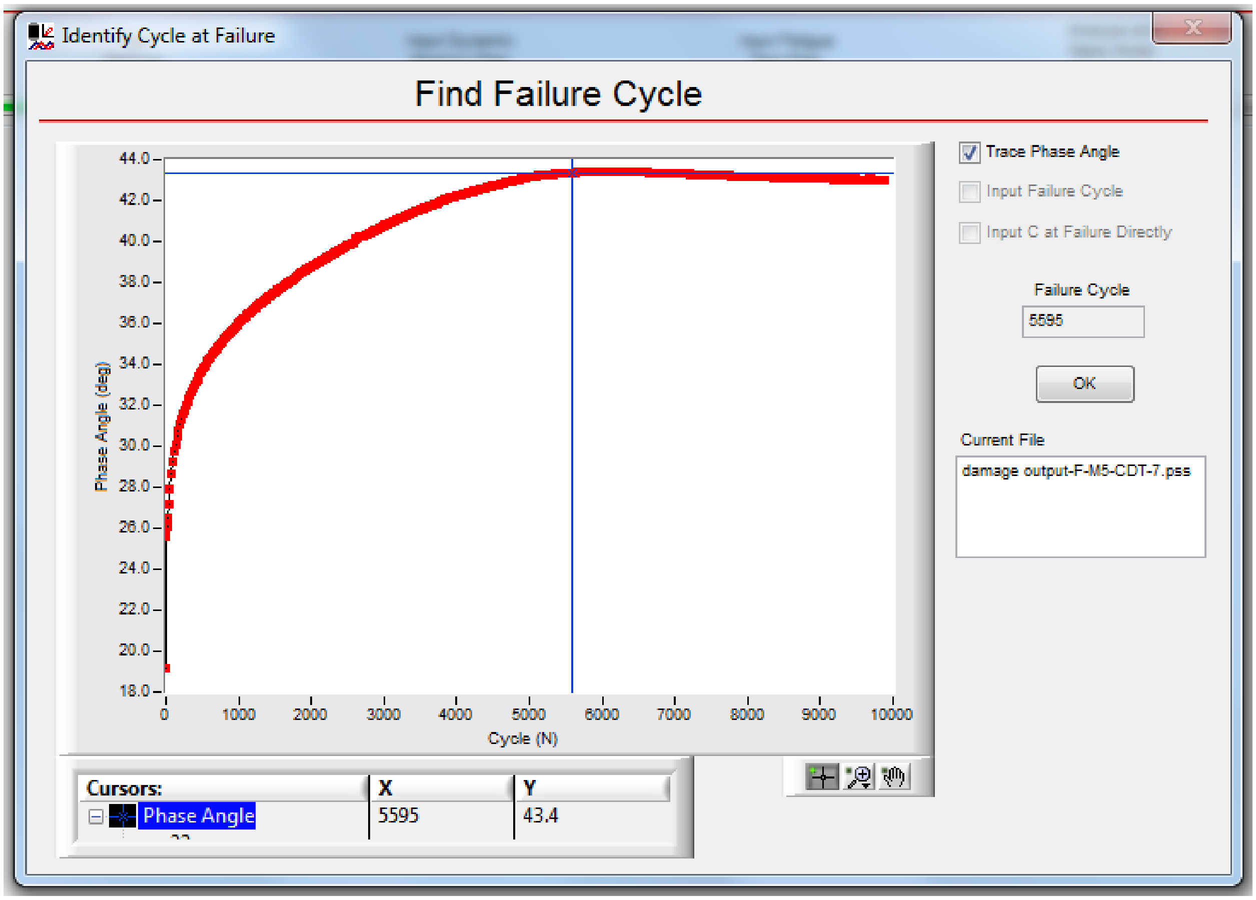
☐ Input C at Failure Directly

Failure Cycle: 2355

Current File: damage output-F-M5-CDT6.pss

Cursors:	X	Y
Phase Angle	2355	41.3

Figure 57: Phase angle vs number of cycles for the first S-VECD sample, tested with 300 micro-strain, Mix-5(S3, PG 64-22 OK, F-WMA).



☑ Trace Phase Angle

☐ Input Failure Cycle

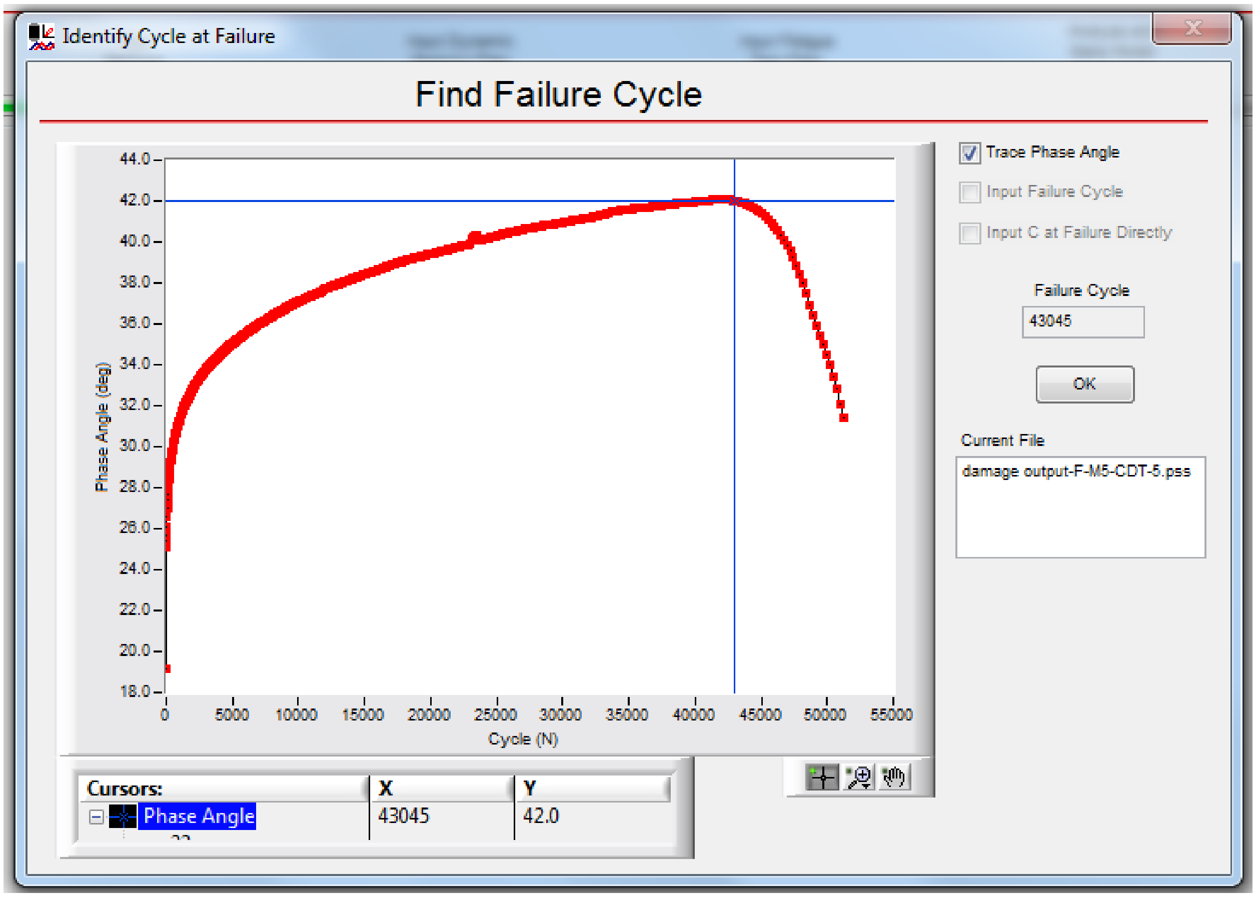
☐ Input C at Failure Directly

Failure Cycle: 5595

Current File: damage output-F-M5-CDT-7.pss

Cursors:	X	Y
Phase Angle	5595	43.4

Figure 58: Phase angle vs number of cycles for the second S-VECD sample, tested with 250 micro-strain, Mix-5(S3, PG 64-22 OK, F-WMA).



Find Failure Cycle

☑ Trace Phase Angle

☐ Input Failure Cycle

☐ Input C at Failure Directly

Failure Cycle: 43045

Current File: damage output-F-M5-CDT-5.pss

Cursors:	X	Y
Phase Angle	43045	42.0

Figure 59: Phase angle vs number of cycles for the third S-VECD sample, tested with 200 micro-strain, Mix-5(S3, PG 64-22 OK, F-WMA).

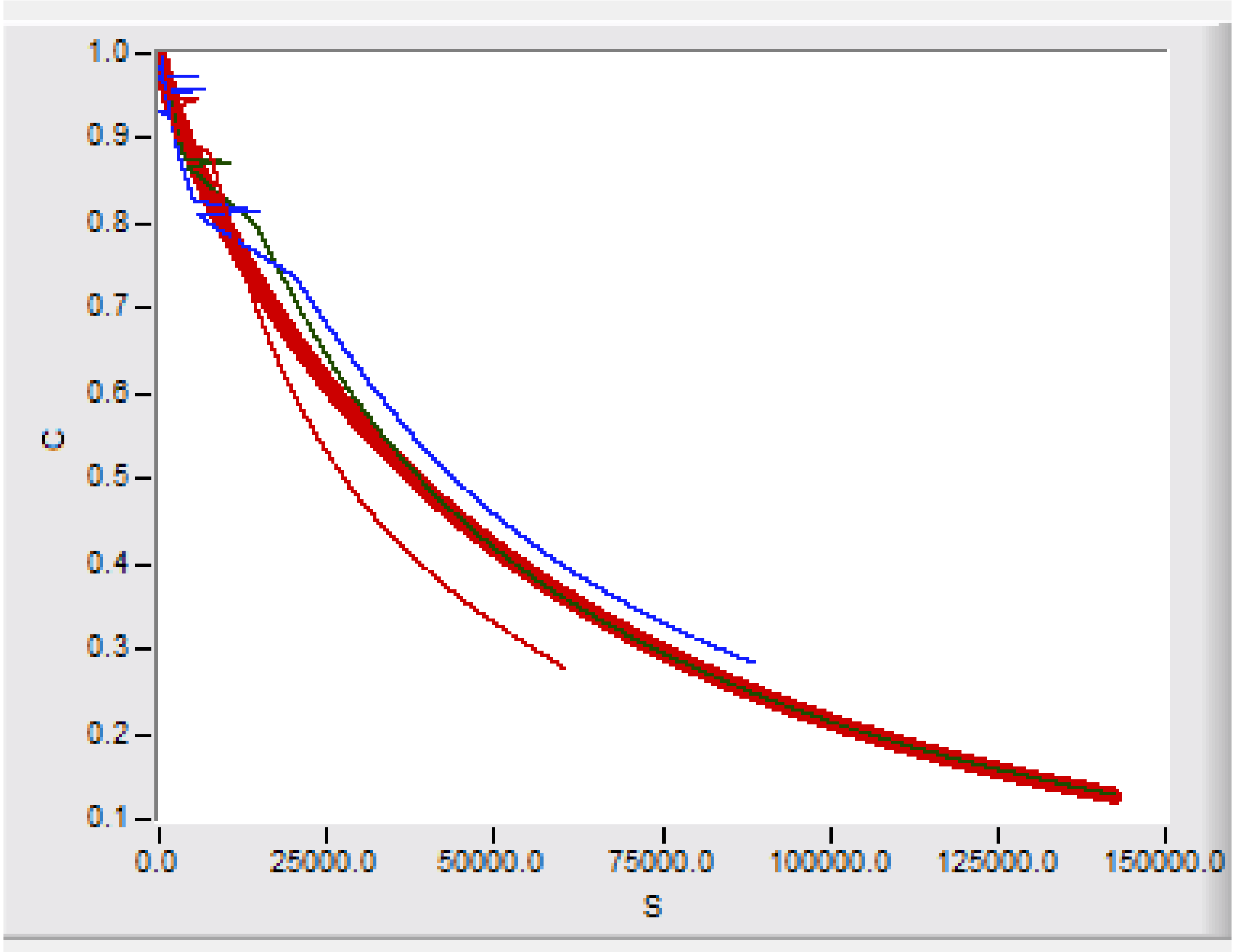


Figure 60: Damage characteristic curve for the Mix-5(S3, PG 64-22 OK, F-WMA).

Table 19. Estimated fatigue life for Mix-5(S3, F, PG 64-22 OK).

Micro-strain/ anticipated fatigue life range	Temperature (C)	Frequency (Hz.)	Fatigue life, N_f (million)
300/short	21	10	0.13
250/medium	21	10	0.37
200/large	21	10	1.37
400/short*	21	10	0.025

5.6 Overlay Tester (OT) Test

This subsection includes the overlay test results for Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK) and Mix-4(S5, PG 76-28 OK). As mentioned before, OT samples were tested at TTI. A total of eight samples were sent for each of three mixes. It may be noted that TTI was not provided with any details about mixture composition. Results from the three representative replicates were considered for the statistical analysis. Other samples were discarded in order to eliminate outlying results. A few samples were also discarded since they were falling outside the dimensional tolerances as per the Texas T-248-F specification (TxDOT, 2014).

5.6.1 First-cycle Peak Loads (P)

Figure 61 presents the first-cycle peak loads (P) of the three samples for each of the three mixes. The average P values for the Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK) and Mix-4(S5, PG 76-28 OK) were 911, 752 and 711 lbs, respectively. The P value for the unmodified mix, Mix-1(S3, PG 64-22 OK) was found to be higher than that of the polymer-modified mixes (Mix-2(S3, PG 76-28 OK) and Mix-4(S5, PG 76-28 OK).

5.6.2 OT cycles at failure (N_f)

Figure 62 presents the number of load cycles at failure (N_f) for the three mixes. The N_f is the number of the load cycles at which the load drops to 7% of its peak load. The average N_f for the Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK) and Mix-4(S5, PG 76-28 OK) were found to be 17, 12 and 122, respectively. As anticipated, the Mix-4 (S5, PG 76-28 OK) which comprises of finer aggregate gradation, higher binder content and polymer-modified asphalt binder, showed the best fatigue performance. The Mix-1(S3, PG 64-22 OK) and Mix-2(S3, PG 76-28 OK) failed at almost equal number of load cycles. It may be noted that the number of cycles at which the Mix-2(S3, PG 76-28 OK) failed was 2.5 times higher than that of Mix-1(S3, PG 64-22 OK) in the BF test procedure. This implies that OT test could not capture the contribution of modified binder in the Mix-2(S3, PG 76-28 OK).

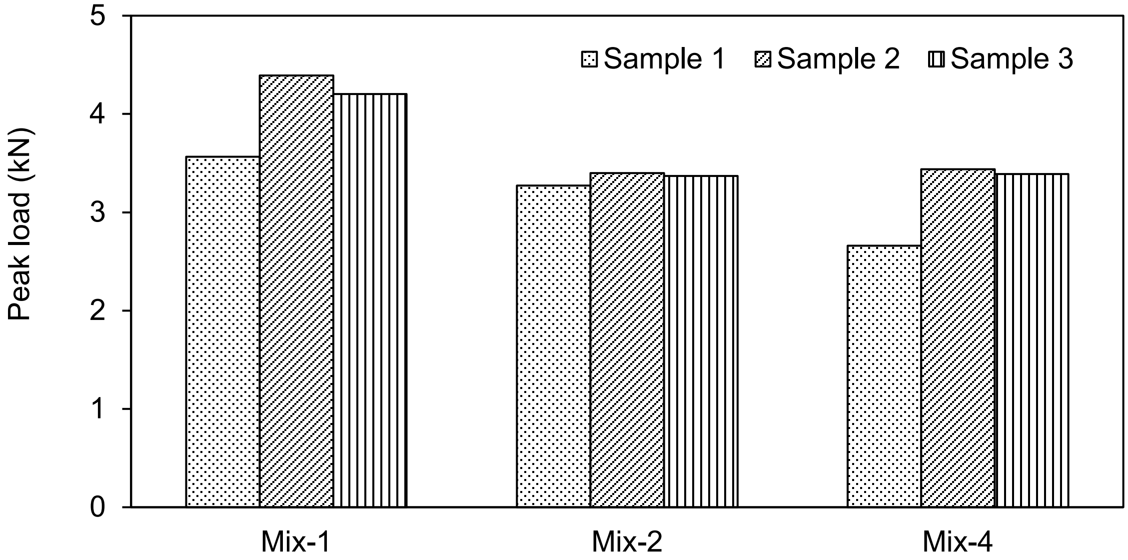


Figure 61: First-cycle peak load for the Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK) and Mix-4 (S5, PG 76-28 OK).

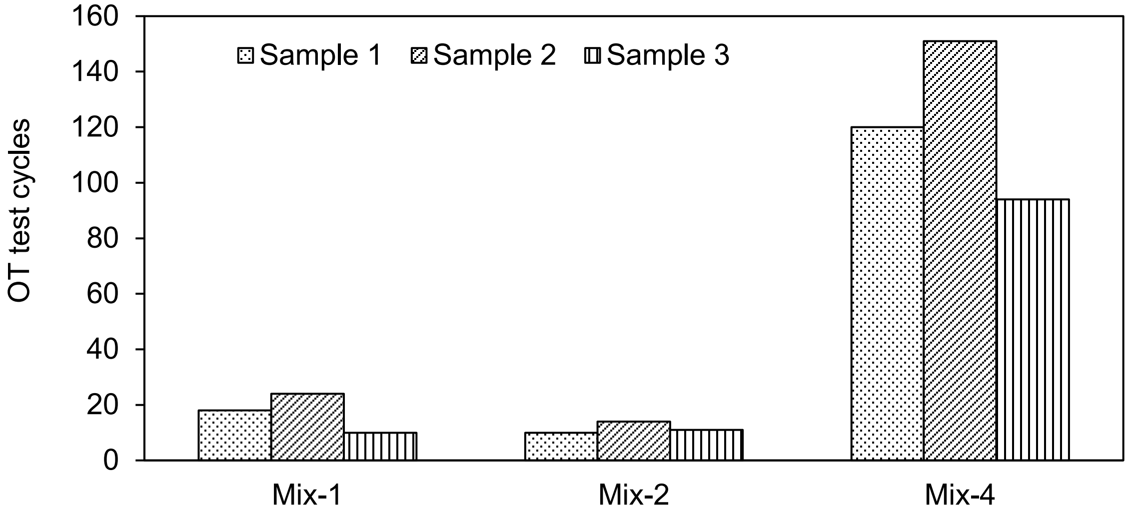


Figure 62: Number of cycles at failure for the Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK) and Mix-4 (S5, PG 76-28 OK).

6.1 General

The repeatability of the results for the BF, SCB, IDT and OT test methods is presented here. CDT test results are not shown but variability was extremely high. For that reason and the complexity of the test and analysis, further investigation as a recommended fatigue test method for ODOT was not pursued. The coefficient of variations (COVs) of the test results were used to understand the repeatability of the test methods.

6.2 SCB Test Method

The strain energy at failure (U_f) at various notch depths is presented in Table 20. The COVs calculated for the SCB fatigue test results for Mix-1(S3, PG 64-22 OK) through Mix-6 (S3-C-PG 64-22 OK) are presented in Table 21. It was seen that the COV varies between 2 and 37%.

6.3 BF Test Method

The repeatability of the BF test results was studied for Mix-1(S3, PG 64-22 OK) through Mix-6 (S3-C-PG 64-22 OK). The COVs obtained for initial stiffness, number of cycles at failure and cumulative dissipated energy at failure are given in Table 22. The COVs of these parameters varied between 6 and 68%.

Table 20. Strain energy at failure (U_f) at various notch depths (kN-mm).

Mix Designation	**Notch depth = 25.4 mm**	**Notch depth = 31.8 mm**	**Notch depth = 38 mm**
Mix-1 (S3, PG 64-22 OK)	0.62	0.51	0.22
Mix-2 (S3, PG 76-28 OK)	0.88	0.7	0.31
Mix-3 (S5-PG 76E-28 OK)	1.04	0.73	0.46
Mix-4 (S5, PG 76-28 OK)	0.98	0.63	0.44
Mix-5 (S3, C, PG 64-22 OK,)	0.44	0.26	0.23
Mix-6 (S3, C, PG 64-22 OK,)	0.53	0.39	0.33

Table 21. Repeatability (COV (%)) of SCB test results for the six mixes.

Mix Designation	**Notch depth = 25.4 mm**	**Notch depth = 31.8 mm**	**Notch depth = 38 mm**
Mix-1 (S3, PG 64-22 OK)	13	23	28
Mix-2 (S3, PG 76-28 OK)	2	9	19
Mix-3 (S5-PG 76E-28 OK)	15	9	13
Mix-4 (S5, PG 76-28 OK)	11	28	4
Mix-5 (S3, C, PG 64-22 OK,)	27	37	13
Mix-6 (S3, C, PG 64-22 OK,)	30	15	13

6.4 IDT Test Method

The repeatability of the results of the IDT test method was studied for Mix-1(S3, PG 64-22 OK), Mix-2(S3, PG 76-28 OK) and Mix-4(S5, PG 76-28 OK) as presented in the Table 23. The COVs calculated for the strain energy values at peak load, toughness indices and indirect tensile strength values were compared for the above three mixes. The COVs of these parameters varies between 2 and 16%. The repeatability of TI values was quite good, but the considerably low variation of these values among different mixes is a disadvantage.

Table 22: Repeatability of BF test results for the six mixes.

Mix Designation	Initial stiffness (MPa)		Numbers of cycles at failure (N_f)		Cumulative dissipated energy (kPa)	
	Average	COV (%)	Average	COV (%)	Average	COV (%)
Mix-1	4,609	11	117,000	33	91,251	34
Mix-2	3,937	11	303,386	24	221,990	25
Mix-3	2,245	24	4.87	68	2,150,000	50
Mix-4	3,490	6	1,445,027	29	749,100	27
Mix-5	3,286	7	94,157	38	69,131	38
Mix-6	4,387	22	62,065	63	50,826	63

Table 23: Repeatability of ITD test results for five different mixes.

Mix Designation	Strain energy at peak load (kN-mm)		Toughness Index (TI)		Indirect tensile strength (kPa)	
	Average	COV (%)	Average	COV (%)	Average	COV (%)
Mix-1 (S3, PG, 64-22 OK)	26.08	7	0.81	7	865	7
Mix-2 (S3, PG 76-28 OK)	43.26	16	0.83	8	1385	4
Mix-3 (S5-PG 76E-28 OK)	54.66	2	1	1	897	2
Mix-4 (S5, PG 76-28 OK)	53.16	2	0.86	5	1650	2
Mix-5 (S3, PG 64-22 OK, F-WMA)	23.72	10	0.78	5	861	8

6.4 OT Test Method

The repeatability of the OT test results is presented in Table 24. The COV computed for the peak load at first cycle and number of cycles at failure are presented in Table 24. It was observed that the COV varies between 18 and 41%. It should be noted that total eight OT samples were tested and three best results were picked for computing the COV values.

Table 24. Repeatability of OT test results for three different mixes

Mix ID	**Peak load at first cycle (kN)**	**COV (%) of Peak load at first cycle**	**Number of cycles at failure**	**COV (%) of Number of cycles at failure**
Mix-1	4.05	11	17	41
Mix-2	3.35	2	12	18
Mix-4	3.16	14	122	23

6. SELECTION OF TEST METHOD AND EQUIPMENT

The most suitable test method was selected based on (i) the repeatability of test results, (ii) sample preparation and testing time, (iii) rigor in sample preparation and testing, (iv) tediousness in the computational procedure, and (v) required personnel training level.

Table 25 presents a comparison of different fatigue test methods based on the experiences gained during the course of the present project. The COVs of the test results in SCB method are generally below 30%, except one particular result for Mix-4 (S5, PG 76-28 OK) when COV was found to be 37%. The COV in toughness index (TI) in IDT method was lower than 30%. However, the variations in the TI values between the different mixes were quite low when the TI values were computed considering a same terminal strain for all the mixes. Therefore, a quantitative estimation of fatigue life may be difficult based on the TI values. The COVs of BF and OT tests were found to be higher than 30%. The initial analysis of the CDT test results also indicated a higher value for COV.

Sample preparation for SCB, IDT and its associated tests are comparatively easier than those for the other tests. Computation of fatigue resistance parameters in SCB, BF and OT tests are relatively simple. The most tedious computational procedure is involved with the CDT test method. All the tests require training; however, extensive level of training is required for conducting BF, and CDT test. Based on afore-mentioned findings, it appears that the SCB test method may be the best overall fatigue test for screening of asphalt mixes in terms of the fatigue resistance.

Table 25. Comparison between different fatigue test methods.

Name of fatigue test	Repeatability (COV, %)	Sample preparation and testing time	Rigor in sample preparation and testing	Tediousness in the computational procedure	Required training level
SCB	<30	Less time consuming	Relatively easy	Easy	Moderate
BF	< 60	Very much, takes weeks	Difficult	Moderate	Extensive
IDT	<20*	Less time consuming	Easy	Moderate	Moderate
CDT	To be determined	Needs considerable amount of time.	Difficult	Moderate	Extensive
OT	< 40	Needs considerable amount of time for sample preparation	Sample preparation is difficult, testing is easy	Easy	Moderate

* Difference in the value of TI between different mixes is low.

7. PURCHASE OF EQUIPMENT FOR ODOT

An Asphalt Mixture Performance Tester (AMPT) was purchased during September 2014. The manufacturer of this equipment is IPC Global Co.®, Australia and is distributed in U.S. by InstroTek Co.®, North Carolina, USA. A photographic view of this equipment is shown in Figure 63. Different fatigue tests such as SCB, CDT and OT can be conducted using this new equipment. The necessary test fixtures for conducting the CDT and OT tests were purchased from the IPC Global Co.®. Since, a readily usable SCB test fixture for the AMPT was not available, commercially; an SCB test fixture was designed. The Associated Technologies & MFG. (ATM), Baton Rouge, Louisiana helped with fabrication of this SCB test fixture. Additional modification and tuning of the fixture was performed at OU. It may be mentioned here that a number of different manufactures presently supply stand-alone SCB test apparatuses as well; Figure 64 provides examples of two such SCB test apparatus.

Figure 63: Newly purchased AMPT for conducting fatigue tests.

IPC Global's SCB

(https://www.ipcglobal.com.au/products/product-range/scb-tester-stand-alone/#frbprettyphoto/1/)

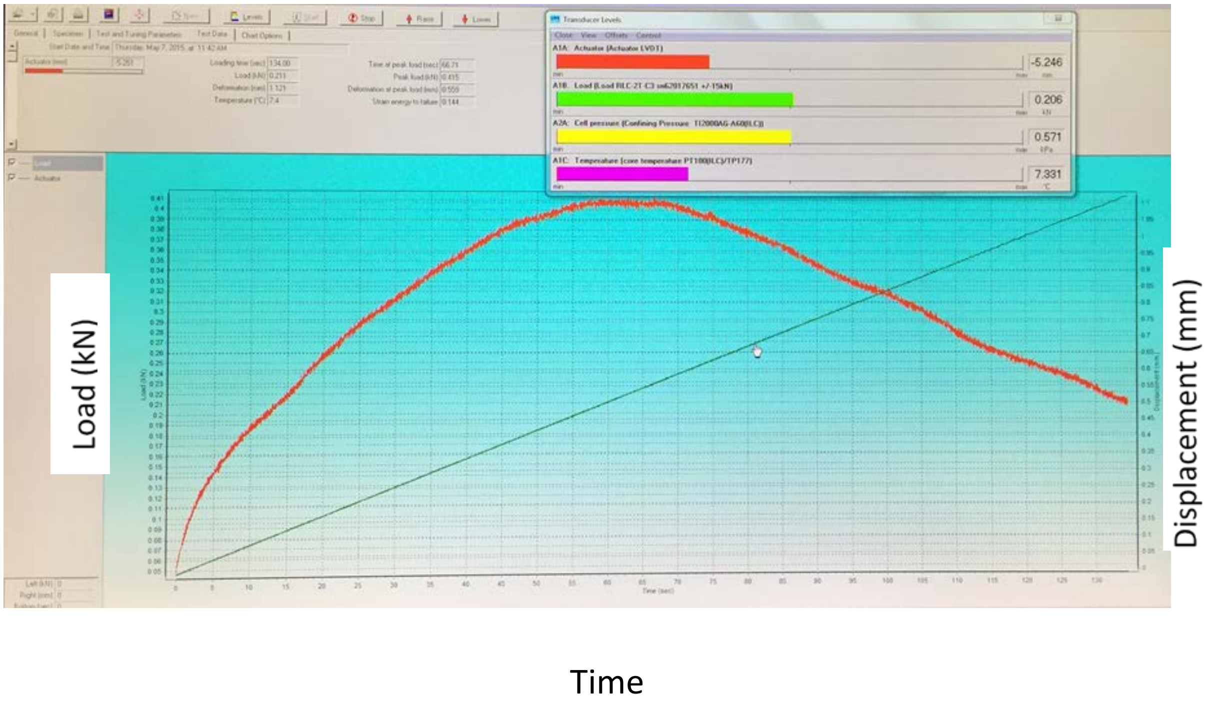
InstroTek's Auto SCB

(https://www.instrotek.com/products/auto_scb?variant=18789943299)

Figure 64: Stand-alone SCB test apparatus, available commercially.

8. DEVELOPMENT OF SCB TEST PROTOCOL AND METHOD

A procedure/program was developed to conduct the SCB test using the AMPT. A monotonic load at a rate of 0.5 mm/min (Kim et al., 2012) was applied to perform the test. The procedure displays the load and displacement vs. time or load vs. displacement in real-time (Figure 65 and Figure 66). The procedure records load, displacement and temperature data on a time scale, and saves data file in “csv” format. This data file can be used for computation of the fracture properties of the asphalt mix such as the critical strain energy release rate, J_c. An excel spreadsheet was developed for computing the J_C. The test procedure/software can also produce a printable test report as shown in Figure 67.



Start Date and Time: Thursday, May 7, 2015, at 11:42 AM

Loading time (sec): 134.00
Load (kN): 0.211
Deformation (mm): 1.121
Temperature (°C): 7.4

Time at peak load (sec): 66.71
Peak load (kN): 0.415
Deformation at peak load (mm): 0.559
Strain energy to failure: 0.144

A1A: Actuator (Actuator LVDT): -5.246 mm
A1B: Load (Load RLC-2T-C3 sn62017651 +/-15kN): 0.206 kN
A2A: Cell pressure (Confining Pressure TI2000AG-A60(LC)): 0.571 kPa
A1C: Temperature (core temperature PT100(LC)/TP177): 7.331 °C

Figure 65. Load and displacement on time scale, displayed during the SCB test in real-time.

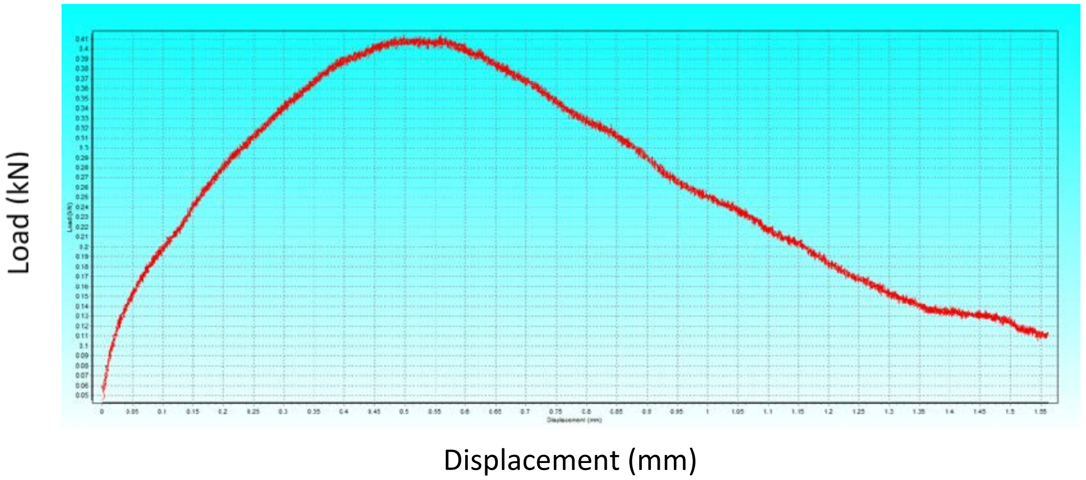
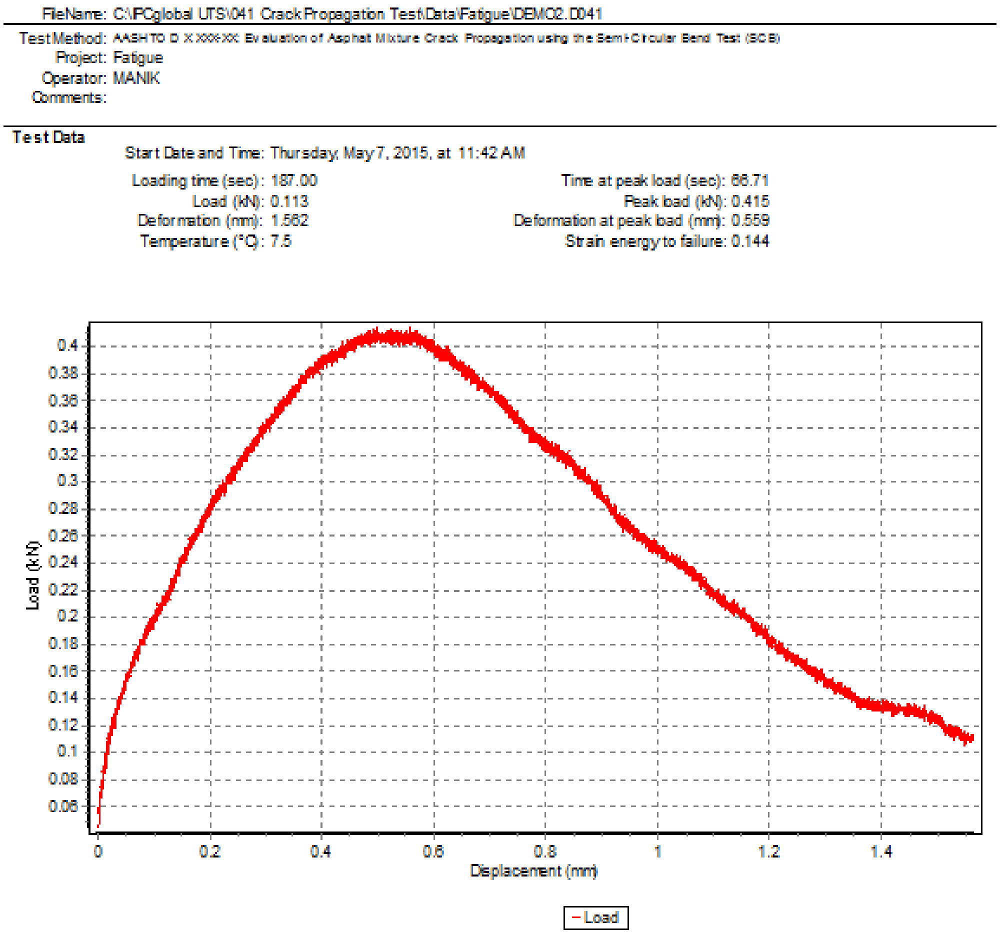


Figure 66: Load vs displacement curve, displayed during the SCB test in real-time.



FileName: C:\PCglobal UTS\041 Crack Propagation Test\Data\Fatigue\DEMO2.D041

Test Method: AASHTO D X XXX-XX: Evaluation of Asphalt Mixture Crack Propagation using the Semi-Circular Bend Test (SCB)
Project: Fatigue
Operator: MANIK
Comments:

Test Data

Start Date and Time: Thursday, May 7, 2015, at 11:42 AM

Loading time (sec): 187.00
Load (kN): 0.113
Deformation (mm): 1.562
Temperature (°C): 7.5

Time at peak load (sec): 66.71
Peak load (kN): 0.415
Deformation at peak load (mm): 0.559
Strain energy to failure: 0.144

Figure 67: Screenshot of the printable test report of the SCB test results.

9. TRAINING AND WORKSHOP FOR ODOT PERSONAL

A demonstration session and three separate hands-on training sessions were conducted under the scope of this project. Participants from the ODOT attended these sessions. Participants learned general use of AMPT, and conducted DM, SCB and CDT tests using the AMPT purchased for this project. Figure 68 presents some pictures taken during the demonstration and training sessions.

Figure 68. Different activities in AMPT demonstration and training sessions.

10. CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

The survey conducted under the scope of this study indicated that a large number of asphalt pavements fail due to fatigue cracking. However, most of the DOTs, including the Oklahoma DOT, currently do not screen asphalt mixes based on their resistance to fatigue cracking. The primary objective of this study was to evaluate different fatigue test methods and to recommend the most suitable one to Oklahoma Department of Transportation (ODOT). Most of the fatigue test methods that were used in NCHRP 9-57 project were also included in this study. The following methods were in used the current study: Semi-Circular Bend (SCB), (ii) Four-Point Beam Fatigue (BF), (iii) Indirect Tension (IDT), (iv) Cyclic Direct Tension (CDT) and (v) Overlay Tester (OT). Six different asphalt mixes were tested in this study to evaluate the abovementioned five fatigue test methods. These mixes include representation of different asphalt binder types (modified vs. unmodified), different aggregate gradations (coarse (S3) vs. fine (S5)), and different mix types (hot mix vs warm mix). These selected mixes represent high, medium and low fatigue resistant mixes. Fatigue test methods were evaluated with respect to the following criteria: (i) repeatability of test results; (ii) time spent for sample preparation and testing; (iii) training level needed for sample preparation and testing; and (iv) personnel expertise level and complexities involved in the data analysis and computational procedure.

The repeatability of the test methods were evaluated based on the COV of the test results. It was found that the COVs of the SCB test results are generally around 30%. The COV in toughness index (TI) in IDT method was lower than 30%. However, the variations in the TI values between the mixes were quite low. The COVs of BF and OT tests were found to be higher than 30%. The analysis of the CDT test results also indicated a higher value for COV.

Sample preparation for SCB, IDT and its associated tests are comparatively easier than those for the other tests. Computation of fatigue resistance parameters in

SCB, BF and OT tests are relatively simple. The most tedious computational procedure is involved with the CDT test method. All the tests require training; however, extensive level of training is required for conducting BF, and CDT test. Based on afore-mentioned findings, it appears that the SCB test method may be the best overall fatigue test for screening of asphalt mixes in terms of the fatigue resistance.

An Asphalt Mixture Performance Tester (AMPT) was purchased in this project which has been handed over to the ODOT in the fourth year of the study. The manufacturer of this equipment is IPC Global Co.®, Australia and is distributed in U.S. by InstroTek Co.®, North Carolina, USA. Different fatigue tests such as SCB, CDT and OT can be conducted using this new equipment. Since, a readily usable SCB test fixture for the AMPT was not available, commercially; an SCB test fixture was designed and manufactured under the current project. A procedure/program was developed to conduct the SCB test using the AMPT.

11.2 Recommendations

Based on all the factors considered in this study which include most considered in NCHRP 9-57, we recommend that ODOT fully adopt SCB (ASTM D 8044) as a their standard mix design fatigue test. However, the target limits of the critical strain energy release rate (J_c) shall be established before implementation this test method for screening asphalt mixes based on their fatigue resistance. These limits can be function of traffic volume, material types (e.g., virgin mix, mix with RAP/RAS, HMA mix, WMA mix) and class of roadways. Although all the tests in the current projects were conducted at 20^{o}C (71.6 ^{o}F), the test temperature for the asphalt mixture screening can be decided based on the asphalt binder grade. However, based on the types of the binder grades that are used in Oklahoma, a test temperature of 77 ^{o}F is logical.

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PART B

FATIGUE PERFORMANCE OF ASPHALT MIXES AND OVERLAYS IN THE LTPP PROJECT IN OKLAHOMA

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1. INTRODUCTION

1.1 General

Fatigue cracking is a major distress in asphalt pavements in Oklahoma. Occurrence of fatigue cracking depends on many factors such as pavement structure, traffic, environment, and most importantly fatigue performance of asphalt mixes used in construction. Recognizing the need for screening of asphalt mixes based on their fatigue performance, the Oklahoma Department of Transportation (ODOT) funded two research projects: (i) SPR Item 2243, which is focused on identifying a suitable test method that can be used by the agency for screening of asphalt mixes for fatigue before construction; and (ii) SPR Item 2246, which was focused on characterizing the fatigue performance of asphalt mixes containing Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS). Both of these projects have generated very useful laboratory data that can be used by ODOT to develop Special Provisions/Testing Criteria for screening of asphalt mixes for fatigue. Both of these projects, however, involved testing of laboratory designed and compacted specimens only instead of specimens prepared from field cores and field mix. Since fatigue properties may be different from those of laboratory compacted specimens during the mix design phase, it is important to undertake a study in which the fatigue properties of designed mixes (i.e., mixes submitted by the contractor for approval), field mix, and field cores can be compared and correlated. The present study is an effort to address this important comparison and correlation through a unique field project outlined below.

The Long-Term Pavement Performance (LTPP) program, which is known as the largest pavement study ever conducted, is an important source of pavement quality data for the pavement community. So far, this program has monitored and gathered data from more than 2,500 pavement sections on in-service highways located throughout the United States and Canada. Specific Pavement Studies-10 (SPS-10), “Warm Mix Asphalt (WMA) Overlay of Asphalt Pavements”, located in Canadian County, Oklahoma, is one of the most recent LTPP experiments. Oklahoma Department of Transportation (ODOT) in collaboration with the Federal Highway Administration (FHWA) constructed this project in November 2015. Six types of asphalt mixes were used in this project including one control HMA, four WMA mixes, and a stone matrix asphalt (SMA) mix. In the present study, the cracking resistance of these mixes were investigated using the Semi-Circular Bend (SCB) test. For all of these mixes, tests were conducted on laboratory-produced mixes, plant-produced mixes and field cores. The findings of this study are expected to add to the knowledge base in the area of the long-term performance of green asphalt pavements and facilitate their use in Oklahoma and nationwide.

1.2 Objectives

The primary objectives of the proposed study, through one-year extension to SPR Item 2243, are:

(i) Compare and correlate fatigue properties of field cores and laboratory compacted samples from the field mix, if needed, and the designed mixes (mixes submitted by the contractor for approval) for six different mixes ODOT used in the LTPP SPS-10 sections.

(ii) Investigate changes in fatigue properties with traffic, environmental conditions, and age and compare with initial properties.

1.3 Problem Statement

Fatigue and rutting are the two most common distresses observed in roadway pavements. Designing a fatigue resistant asphalt mix with an acceptable rutting performance is essential for having a sustainable pavement with a long service life. Rapidly-increasing demand for application of eco-friendly materials, such as RAP and RAS, and construction alternatives, such as Warm Mix Asphalt (WMA) technologies, in the asphalt pavement industry has made this task even more important but challenging. Although the application of highly aged materials is found to improve the rutting resistance of asphalt mixes, there are serious issues regarding their resistance to fatigue cracking. Furthermore, there is a need for research to correlate the cracking resistance of the laboratory produced mixes and field mixes. Focus of investigation in the current study was the fatigue cracking resistance of asphalt mixes containing RAP and RAS and to compare and correlate cracking resistance of field cores and laboratory-compacted samples from the laboratory-produced and plant-produced mixes.

2. LITERATURE REVIEW

A comprehensive review of literature for this project was submitted to Oklahoma Department of Transportation in the final report of ODOT project (SPR 2243: Recommended Fatigue Test for the Oklahoma Department of Transportation). A brief literature review on application of WMA technologies and recycled materials (RAP and RAS) in asphalt mixes and Semi-Circular Bend (SCB) test method is presented below.

2.1 Warm Mix Asphalt

Warm mix asphalt, which was developed about fifteen years ago in Europe, is a group of technologies to produce asphalt mixes at lower mixing and compaction temperatures with workability, strength, and durability equivalent to or better than traditional hot mix asphalt (HMA). The most commonly used WMA technologies in the U.S. can be classified into two groups: Group 1 - process-driven technologies, such as plant foaming like Double Barrel Green® and Low Energy Asphalt, and Group 2 - Chemical or organic additives such as Evotherm®, Rediset WMX, REVIXTM, and Sasobit®, among others . The first experience of WMA technology application on a test track in the U.S. was the Evotherm® test sections at the National Center for Asphalt Technology (NCAT) Pavement Test Track at Auburn University in September 2005.

Many asphalt technologists, design engineers, and agency personnel were quick to recognize the fact that, by reducing temperatures of production and construction enabled by WMA technologies, the binder was less oxidized resulting in asphalt mixes with higher cracking resistance compared to traditional HMA mixes. Performance evaluation of additive-based and foaming-based WMA mixes indicated that WMA mixes produced with chemical additives performed similar to conventional HMA mixes in terms of rutting, while foaming-based WMA mixes had higher rutting potential compared to the HMA mixes. Haggag et al. (2011) evaluated the performance of three WMA mixes produced with Advera, Evotherm®, and Sasobit® and concluded that there is no significant difference between dynamic modulus and fatigue characteristics of WMAs and those of the corresponding HMA. In a similar laboratory study, it was shown that performance of WMA mixes produced with Advera, Sasobit®, and Evotherm® was comparable to that of traditional HMA. Comparison of mixes placed in three sections of the NCAT Test Track indicated that WMA mixes produced using Evotherm® had in-place densities equal to or better than HMA and rutting performance of WMAs were similar to that of the control HMA mix. A laboratory study conducted on two different asphalt mixes produced with addition of Rediset WMX and Sasobit® to the asphalt binder indicated that by utilization of these additives one can reduce the compaction temperature by 40ºC without significant changes in stiffness and permanent deformations compared to reference HMA. A field study was performed in Washington State to examine different WMA technologies including Sasobit® and three water foaming technologies, Gencor® Green Machine Ultrafoam GX®, Aquablack™ and water injection. The field data showed that WMA mixes are comparable with their corresponding control HMA mix in terms of rutting, roughness, and cracking resistance.

2.2 Asphalt Mixes Containing RAP and RAS

In the last few years, RAP and RAS have been widely used in the U.S. since they significantly reduce the initial cost of the construction in addition to their benefits for the environment. However, utilization of these materials presents a concern about the performance of the resulting mix, specifically fatigue performance due to highly aged RAP/RAS binder incorporated in the mix. Mogawer et al. (2015) evaluated the effect of long-term aging on fatigue performance of high-RAP mixes modified with rejuvenators. They concluded that long-term aging did not have any significant effect on fatigue characteristics of the high-RAP mixes with or without rejuvenators. Furthermore, it was shown that fatigue performance comparable to control mix with no RAP can be achieved for high-RAP mixes by application of rejuvenators. In a recent study, the effect of Evotherm® were studied on WMA mixes incorporating RAP contents ranging from 0 to 70%. It was shown that although rutting resistance of WMA with 0% RAP is similar to that of control HMA; WMA showed worse fatigue performance than HMA. The addition of RAP stiffened the mixes and improved the rutting resistance significantly, while reducing the fatigue resistance of mixes. It was also indicated that utilization of Evotherm® greatly improved the moisture resistance of WMA-RAP mixes. In another study, Sabouri et al. (2015) investigated the fatigue performance of twelve plant-produced mixes with RAP contents ranged from 0% to 40% by total weight of the mix. It was concluded that, in general, utilization of RAP in the asphalt mix increases its stiffness, which leads to a reduction in fatigue resistance. It was shown that lowering the virgin binder PG grade improves the fatigue properties. In general, there are at least four approaches to improve the cracking resistance and durability of RAP/RAS mixes and balance their performance: reducing RAP/RAS amount, lowering design air voids, utilization of Rejuvenating Agent, and using soft virgin binders.

2.3 Semi-Circular Bend (SCB) Test

The Semi-Circular Bend (SCB) test method for identification of asphalt mixes prone to fatigue has been studied and favored by many researchers (Pirmohammad and Ayatollahi, 2015; Tang, S., 2014; Aragao and Kim, 2012; Biligiri et al., 2012a; Biligiri et al., 2012b; Kim et al., 2012; Huang et al., 2011; Mohammad et al., 2011; Liu, 2011; Hassan et al., 2010; Perez-Jimenez et al., 2010; Li et al., 2010a; Li et al., 2010b; Huang et al., 2009; Tarefder et al., 2009; Wu et al. ,2005; Lie et al., 2004). It was found that the SCB test is a reliable and relatively simple test method for assessment of cracking performance of HMA. An important advantage of this test is that it can be conducted on laboratory compacted samples as well as on cores extracted from the field. Given these advantages, the SCB test method was selected in this study to evaluate the cracking resistance of the WMA mixes containing RAP and RAS.

In the past ten years, researchers have tried to examine the potential of SCB test as a candidate test method for characterizing cracking resistance of asphalt mixes in the mix design phase. Although these studies are valuable resources for design crack-resistant mixes, the SCB tests were mostly conducted on field cores and not laboratory-produced specimens. For instance, in a recent study conducted by Mohammad et al. (2015), it was shown that there is a good correlation between critical strain energy release, SCB Jc, values of field cores and Random Cracking Index (RCI) of the corresponding pavement. It was indicated that SCB test can measure the cracking performance of an asphalt mix. It was suggested that the minimum SCB J_c values be between 0.5 and 0.6 kJ/m^2 at 25℃ as tentative criteria to avoid crack related issues in asphalt pavements. The laboratory test results in the present study have been used to bridge the gap in this area by studying the correlation between SCB J_c values of field cores, laboratory-produced mixes, and plant-produced mixes. This correlation is helpful for introducing the SCB test for screening of mixes for their fatigue performance in the mix design stage. The most common WMA technologies, i.e., foaming and chemical-based technologies are compared. Furthermore, different approaches to offset the higher binder stiffness in WMA mixes containing RAP and RAS were investigated.

3. PREPARATION OF SGC CYLINDERS FROM DESIGNED MIXES

The research team from the University of Oklahoma (OU) attended the LTPP project pre-work meeting on September 22, 2015, at the El Reno residency. During the meeting, it was revealed that six different asphalt mixes were to be used in the construction of the test section, including one HMA mix, four WMA mixes, and one stone matrix asphalt (SMA). The OU research team was able to collect all the mix design sheets from the Contractor, T. J. Campbell, by end of October 2015. A summary of the aforementioned mixes is presented in Table 26. According to Table 26, Mix 1 was the HMA control mix containing a PG 70-28 with 4.9% total asphalt binder content. Mix 2 was a WMA prepared with a foaming technology containing a PG 70-28 asphalt binder. In the foaming process, a small amount of water (2% by weight of asphalt binder) was added to the virgin binder using a nozzle foaming device. Application of nozzle while adding water to the binder creates water steam which results in a volume increase of the binder and facilitates the mixing and compaction at lower temperatures. Typically, this type of WMA technology does not require any modification in the mix design process. Mixes 3, 4, 5, and 6 were prepared using PG 70-28, PG 64-22, PG 58-28, and PG 70-28 asphalt binder, respectively. These mixes were prepared using additive-based technologies. The chemical additive used in this study was a package that included cationic emulsification agents, anti-stripping agents, and additives to enhance aggregate coating and mix workability. The additive dosage blended with virgin binder was 0.7% for Mixes 3, 4, and 5 and 1.0% for Mix 6 by the weight of binder. In order to compensate for the hardening effect of the highly aged RAP and RAS binders in the mixes, the high temperature PG grades in Mixes 4 and 5 were dropped by 1 and 2 levels, respectively. In addition to dropping the high temperature PG grade by one level in Mix 4, a Rejuvenating Agent (RA) with an amount of 11% by the total weight of asphalt binder was used to counteract the effect of highly aged binders.

Table 26. Summary of the mixes used in the construction project.

Mix ID	**Mix 1**	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**	**Mix 6**
LTPP Section ID	40AA01	40AA02	40AA03	40AA61	40AA62	40AA63
Description	HMA Control	WMA Foam	WMA Chemical	WMA Chemical + PG Drop + RA	WMA Chemical + 2 × PG Drop	SMA Chemical
Virgin binder PG	70-28	70-28	70-28	64-22	58-28	70-28
WMA Dose Rate, %	NA	2.0	0.7	0.7	0.7	1.0
Virgin binder content (%)	3.7	3.7	3.8	3.8	3.8	6.6
Total binder content (%)	4.9	4.9	5.0	5.0	5.0	6.6
Mix Temperature, ℃	163	135	141	141	141	141
Compaction Temperature, ℃	152	127	129	129	129	129
RAP, %	12	12	12	12	12	NA
RAS, %	3	3	3	3	3	NA

The Mixes 1, 2, 3, 4, and 5 were designed with a same aggregate gradation (Figure 69) containing 12% RAP and 3% RAS representing approximately 13% and 14% binder replacement, respectively, while, the SMA mix was produced with a coarse aggregate gradation shown in Figure 69.

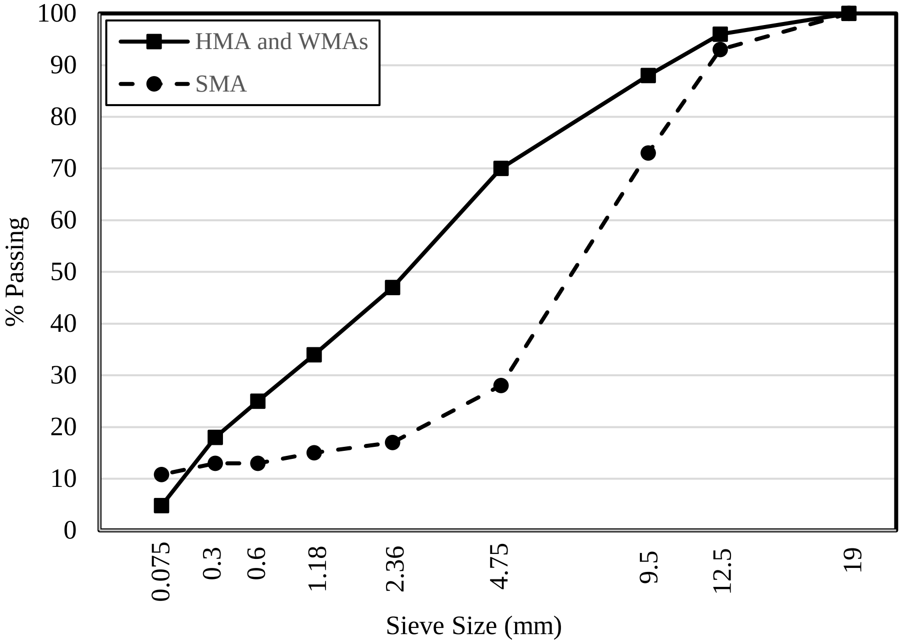


Figure 69. Aggregate Gradation of the Mixes

Since the fracture properties of asphalt pavements constructed in the field can be different from those of laboratory compacted specimens, it is important to evaluate and compare the cracking properties of laboratory-produced mixes, plant-produced mixes, and field cores. This difference becomes even more important when the objective is developing a test method for screening asphalt mixes for their fatigue performance at the mix design stage. Therefore, required aggregate stones, RAP and RAS materials, and asphalt binders were collected from T. J. Campbell and laboratory-produced mixes were prepared by batching them according to their respective mix designs and short-term aged in accordance with AASHTO R 30 mix conditioning procedure. All the laboratory-produced loose mixtures were compacted to 7± 0.5% air voids content.

4. PREPARATION OF SGC CYLINDERS FROM FIELD MIXES

The research team attended the LTPP project job site in Yukon, Oklahoma, to collect the plant-produced mixtures used in this project (Figure 70). The hot loose mixes were transferred to the laboratory and cooled down to the room temperature and then stored in sealed bags at 20℃ in order to minimize the mixture aging prior to compaction.

According to Table 26, six types of asphalt mixes were used for construction of the test section. Each mix covered approximately 0.15 miles of the overlay project. Required amounts of plant-produced loose mixtures were placed in an oven for two hours to reach the desired compaction temperature prior compaction using the Superpave® Gyratory Compactor (SGC). All the plant-produced loose mixes were compacted to 7 ± 0.5% air voids content.

(a) (b) (c) (d)

Figure 70. LTPP SPS-10 Project Located in Canadian County, Oklahoma. (a) Laying of the Asphalt Mixture (b) Compaction of Asphalt Mixture with Smooth Drum Vibratory Compactor (c) Collection of the Plant-Produced Materials (d) Constructed Pavement

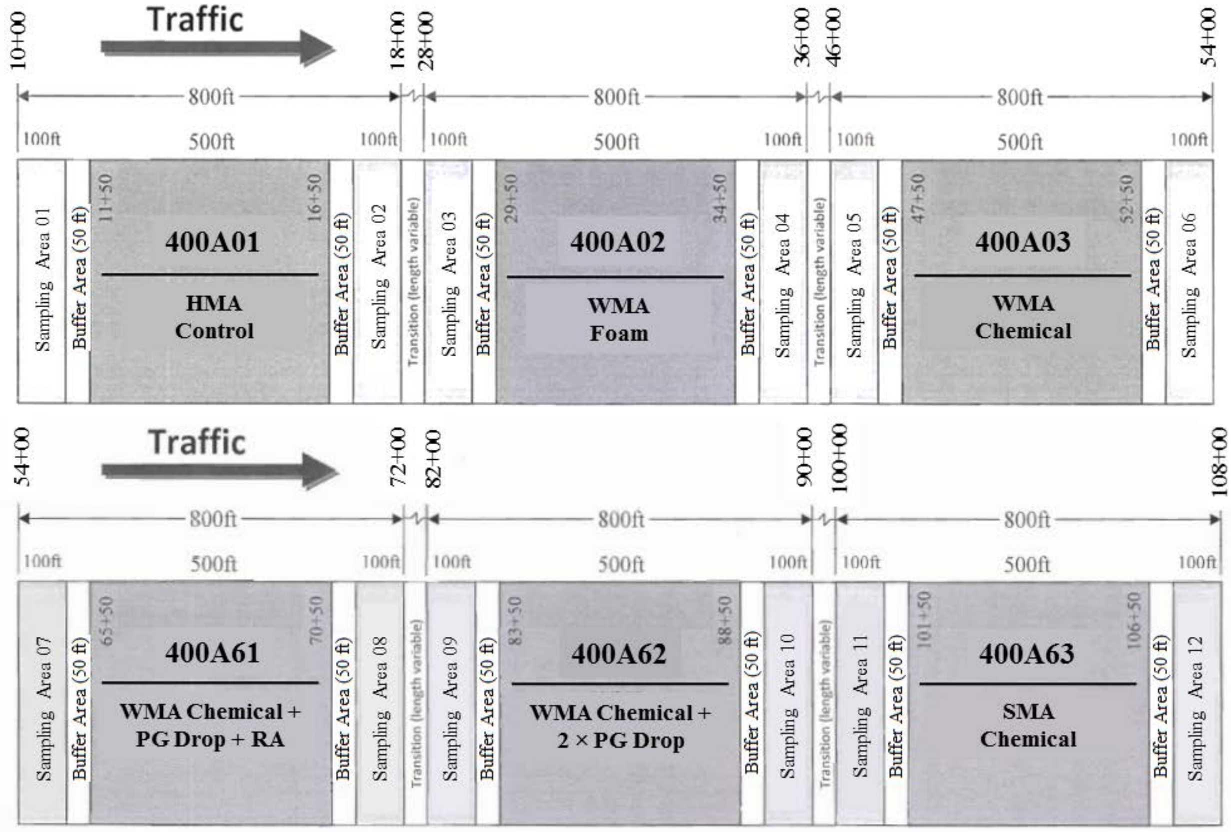


Figure 71. Test Sections Layout.

5. COLLECTION OF FIELD CORES

5.1 Collection of the Cores One Day after Construction

The 6-inch diameter field cores were drilled and collected by ODOT and the contractor one day after construction of the overlay. A total of six cores were collected for each one of the mixes used in the LTPP sections. The field cores were transferred to the Broce lab and stored in an environmentally controlled room at 25℃. The performance testing on field cores was completed in three weeks after collection them in order to minimize the oxidation and environmental effects.

5.2 Collection of the Cores Six Months after Construction

Similar to the cores that were collected one day after construction, the OU research team visited the job site on May 25, 2016, to collect field cores of the LTPP sections after being subjected to the traffic load and environment for 6 months (Figure 72). The performance testing on field cores was completed three weeks after collection in order to minimize the oxidation and environmental effects.

Figure 72. Collection of the Field Cores from the Construction Site

6. SPECIMEN PREPARATION

6.1 SCB Specimen Preparation from Laboratory Compacted Samples

Cylindrical shape specimens are required for SCB test. A Superpave® gyratory compactor (SGC) was used for compaction of 6-inch cylindrical samples. Compacted samples were sawed to the required size for preparing test specimens (Figure 73). All the test samples were selected based on the target air voids of 7± 0.5%. Each SGC cylinder was used to prepare four SCB specimens (Figure 74). A summary of SCB specimen preparation for laboratory produced mixes (L) and plant produced mixes (P) is given in Table 27 and Table 28, respectively.

Figure 73. Test Sample Prepared for SCB Test.

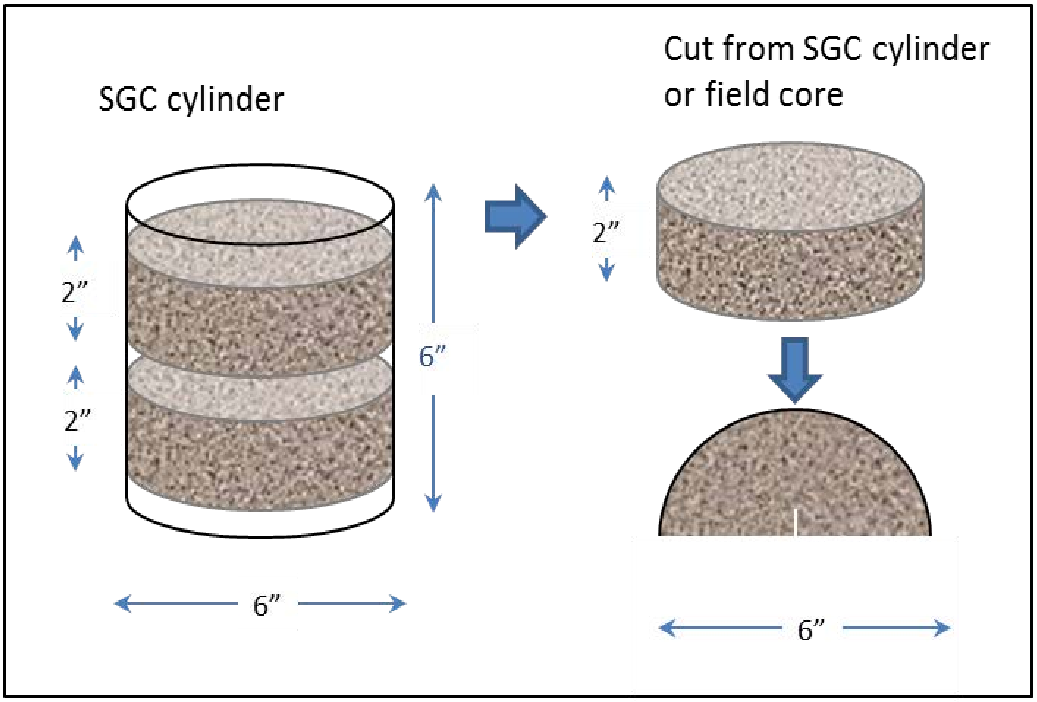


Figure 74. SCB Test Sample Preparation Steps.

Table 27. Summary of Laboratory Produced Sample Preparation.

Mix ID	No. of specimens required	No. of specimens prepared with7.0 ± 0.5% air void	No. of specimens tested
Mix-1 (L)	9	12	12
Mix-2 (L)	9	10	10
Mix-3 (L)	9	9	9
Mix-4 (L)	9	15	15
Mix-5 (L)	9	9	9
Mix-6 (L)	9	9	9

Table 28. Summary of Plant Produced Sample Preparation

Mix ID	No. of specimens required	No. of specimens prepared with7.0±0.5% air void	No. of specimens tested
Mix-1 (P)	9	15	15
Mix-2 (P)	9	15	15
Mix-3 (P)	9	9	9
Mix-4 (P)	9	11	11
Mix-5 (P)	9	18	18
Mix-6 (P)	9	9	9

6.2 SCB Specimen Preparation from Field Cores

As mentioned previously, six field cores were collected for each one of the mixes. Field cores were sawed to the required size for preparing test specimens. Each field core was used to prepare two SCB specimens. A summary of SCB specimen preparation for field cores (C) is given in Table 29.

Table 29. Summary of Field Core Sample Preparation

Mix ID	No. of specimens required	No. of specimens prepared	No. of specimens tested
Mix-1 (C)	9 , 9	12 , 12	12 , 12
Mix-2 (C)	9 , 9	12 , 12	12 , 12
Mix-3 (C)	9 , 9	12 , 12	12 , 12
Mix-4 (C)	9 , 9	12 , 12	12 , 12
Mix-5 (C)	9 , 9	12 , 12	12, 12
Mix-6 (C)	9 , 9	12 , 12	12 , 12

12 , 12 → 12 SCB specimens from the cores collected right after the construction and 12 SCB specimens from the cores collected after 6 months being subjected to traffic.

6.3 SCB Specimens Air Voids Content

All of the prepared SCB specimens were tested to measure their air voids content. Table **30** shows the range of air voids content for each group of SCB specimens.

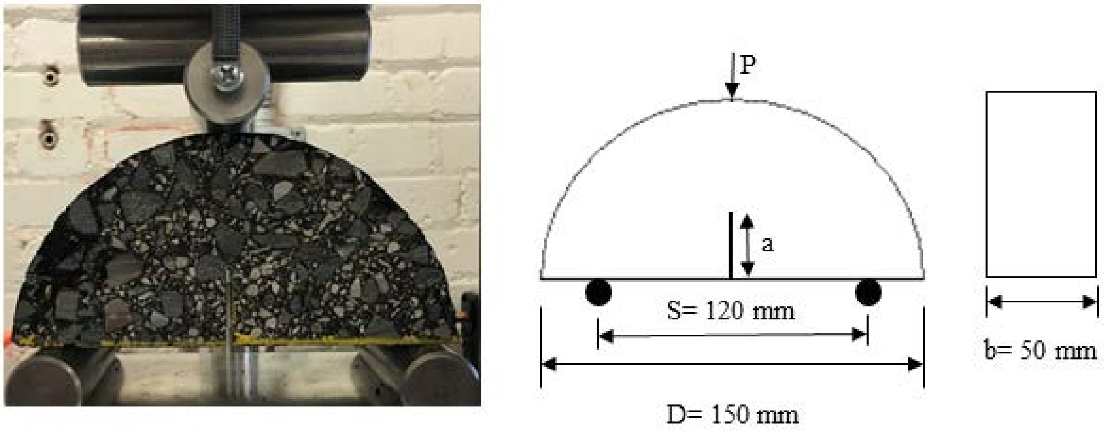
Table 30. Air Voids Content of SCB Specimens

Mix ID	***Description***	***Air Voids Range (%)***
Mix 1	Laboratory-Produced	6.5-7.5
Mix 1	Plant-Produced	6.5-7.5
Mix 1	Field Core (1 Day Old)	5-7
Mix 1	Field Core (6 Months Old)	5-7
Mix 2	Laboratory-Produced	6.5-7.5
Mix 2	Plant-Produced	6.5-7.5
Mix 2	Field Core (1 Day Old)	6-10
Mix 2	Field Core (6 Months Old)	5-7
Mix 3	Laboratory-Produced	6.5-7.5
Mix 3	Plant-Produced	6.5-7.5
Mix 3	Field Core (1 Day Old)	6.5-10
Mix 3	Field Core (6 Months Old)	7-9
Mix 4	Laboratory-Produced	6.5-7.5
Mix 4	Plant-Produced	6.5-7.5
Mix 4	Field Core (1 Day Old)	3-4.5
Mix 4	Field Core (6 Months Old)	2.5-4
Mix 5	Laboratory-Produced	6.5-7.5
Mix 5	Plant-Produced	6.5-7.5
Mix 5	Field Core (1 Day Old)	5-8
Mix 5	Field Core (6 Months Old)	5-6.5
Mix 6	Laboratory-Produced	6.5-7.5
Mix 6	Plant-Produced	6.5-7.5
Mix 6	Field Core (1 Day Old)	10-13
Mix 6	Field Core (6 Months Old)	9-11

7. TESTING

Using SCB test to characterize the cracking resistance of asphalt mixes, is relatively new. The SCB test procedure characterizes the cracking resistance of asphalt mixes at an intermediate temperature (20℃ in this study) in terms of the critical strain energy release rate, J_c, as discussed in Part A.

In this study, SCB tests were conducted on half-disk-shaped specimens having a diameter of 150 mm and thickness of 50 mm (Figure 75). In order to determine the critical value of J-integral (J_c) using Equation 1, Part A, the SCB test should be performed on 50 mm-thick samples with at least two different notch depths. Three different notch depths of 25.4 mm, 31.8 mm, and 38 mm, based on the ASTM D 8044, were selected in this study to increase the measurement accuracy by developing a linear regression correlation for the strain energies versus notch depths for each mix. Three SCB specimens were prepared for each notch depth. The specimens were loaded monotonically at a rate of 0.5 mm/min using a three-point flexural apparatus. The applied load and the vertical deformation were continuously recorded and the strain energy at failure was determined by calculating the area under the load versus deformation curve, up to the peak load. Typical load vs deformation curves for three asphalt mix SCB samples tested at 25.4 mm notch depth is shown in Figure 76.



(a) (b)

Figure 75. SCB Test Method: (a) Test in Progress (b) Schematic of Test Specimen

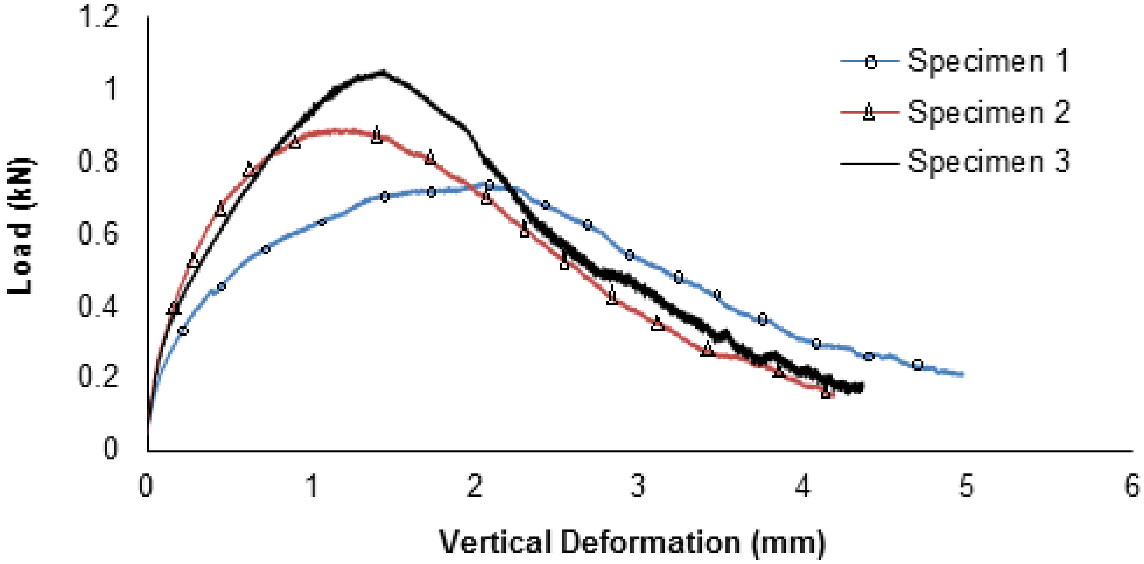


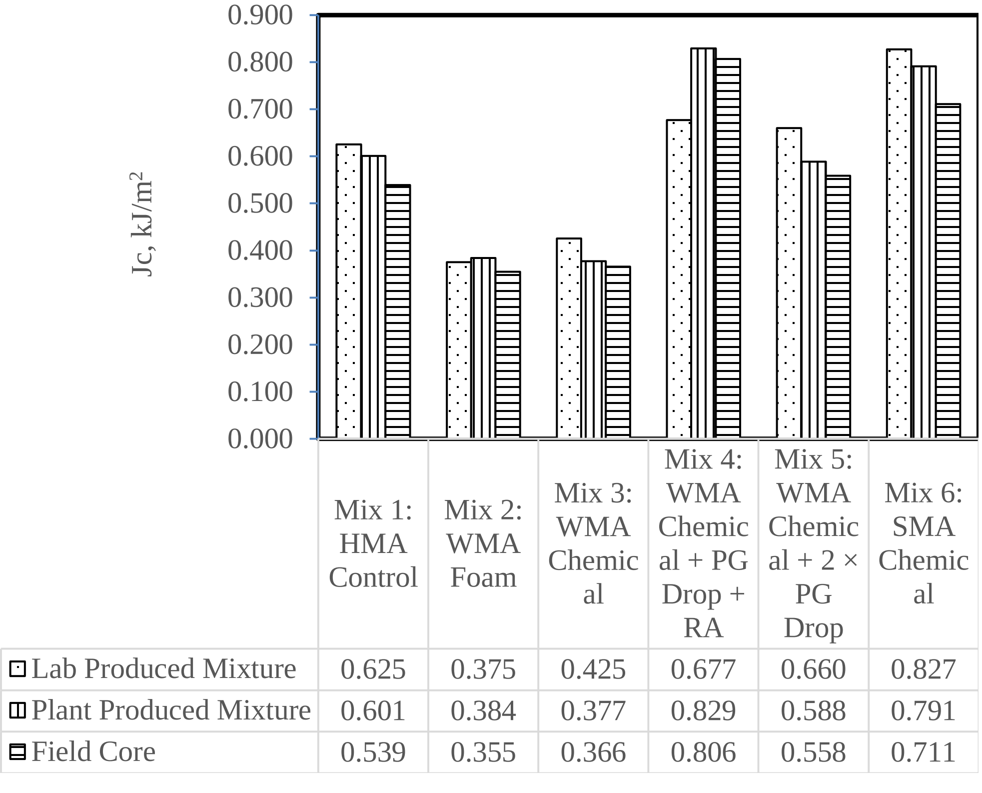
Figure 76. Load vs Deformation Curves for the SCB Samples Tested at 25.4 mm Notch Depth.

8. MECHANISTIC CHARACTERIZATION OF FATIGUE

The SCB tests were conducted on specimens of asphalt mixes to obtain the Jc value. The critical strain energy release rate for each mix was calculated using Equation 1, PART A. It was found that the coefficient of determinations (R2) of the linear regressions developed for Jc versus notch depths for the mixes lie between 0.93 and 0.99. The high R2 values indicate a good correlation between the strain energy at failure versus notch depth. Figure 77 presents the Jc values for all of the mixes evaluated in this study. From Figure 77. it is evident that the SCB test method ranks the laboratory-produced and plant-produced mixes similar to the field cores with respect to their Jc values. As shown, using WMA technologies without any method to adjust the effect of highly aged RAP and RAS binders results in a significant reduction in asphalt mix cracking resistance compared to the traditional HMA. For example, the Jc value calculated for the laboratory-produced HMA was found to be 0.625. However, it was reduced to 0.375 and 0.425 for laboratory-produced foam-based and additive-based WMAs, respectively. This reduction was attributed to lower mixing temperature of WMA mixes and consequently lower amounts of binder released from RAP and RAS, which resulted in a lower effective binder content. Also, it was found that using chemical additives resulted in a WMA mix with slightly higher cracking resistance compared to the WMA mixes prepared with the foaming process as was seen in mixes discussed in Part A as well. This can be due to the fact that a better adhesion between aggregate and asphalt binder can be achieved as a result of using a chemical additive processes as found in Part A and Part B mixtures. This finding may be true due to water being present in the mix by using foaming process which likelyrfesulted in a weaker bond between aggregate and asphalt binder.

As noted earlier, mixes 3, 4, and 5 were additive-based warm mix asphalt with an additive amount of 0.7% by the weight of asphalt binder. As shown in Figure 77, mixes 4 and 5 exhibited higher J_c values compared to the control HMA produced using a PG 70-28 asphalt binder. As anticipated, indicates that application of softer virgin binder or addition of recycling agent in presence of RAP and RAS in a mix improves the cracking resistance of the asphalt mix. It is important to note that application of softer virgin binder and/or rejuvenating agent softens the blend of the binder present in a mix which results in mixes with higher cracking resistance. Furthermore, the results of this study support the idea that using a softer virgin binder and/or recycling agent will allow incorporating more recycled material in an asphalt mix.

A comparison of laboratory-produced and plant-produced mixes indicates that the stone matrix asphalt had a better cracking resistance compared to the control HMA and warm mix asphalts. This better performance can be due to higher binder content in SMA mix compared to other mixes and lack of highly aged RAP and RAS binders in the SMA. As shown in Figure 69, there is a meaningful difference between critical strain energy release rate of laboratory-produced SMA and its field mixes. As indicated, the J_c value of laboratory-produced specimens dropped from 0.827 to 0.711 for field cores. It could be attributed to the air voids content of the asphalt mixes. All the laboratory-produced and plant-produced SCB specimens were tested at 7 ± 0.5% air voids content. However, the SMA field cores had air voids content of 11.5 ± 1.5%.



	Mix 1: HMA Control	Mix 2: WMA Foam	Mix 3: WMA Chemical	Mix 4: WMA Chemical + PG Drop + RA	Mix 5: WMA Chemical + 2 × PG Drop	Mix 6: SMA Chemical
⊡ Lab Produced Mixture	0.625	0.375	0.425	0.677	0.660	0.827
◫ Plant Produced Mixture	0.601	0.384	0.377	0.829	0.588	0.791
⊟ Field Core	0.539	0.355	0.366	0.806	0.558	0.711

Figure 77: Semicircular Bend Test Results

As shown in Figure 70 the J_c values obtained from laboratory-produced mixes are generally higher than those obtained from plant-produced specimens and field cores. However, this pattern was observed to change in Mix 4. In an effort to find the reason of this observation, the research team found that the amount of RA used in the plant-produced mixes was 11% by weight of the virgin binder, by error. However, the RA amount used in the laboratory was 11% by the weight of the total weight of asphalt binder. A higher J_c values observed in the laboratory-produced mixes suggests developing a correction factor to find the equivalent J_c values of laboratory-produced mixes with those in the field. It becomes highly important if the SCB test is sought to be used as a screening method for fatigue performance of the asphalt mixes in the mix design process.

Figure 78 shows a comparison of J_c values measured for the laboratory-produced mixes and plant-produced mixes. As shown in Figure 78, there is a good correlation between J_c values of laboratory-produced mixes and plant-produced mixes. It is interesting to note that generally, the points on Figure 78 are below the equity line which means that the specimens prepared using laboratory-produced mixes have higher cracking resistance compared to plant-produced mixes. As mentioned earlier, the hot plant-produced mixtures were collected from the job site, transferred to the laboratory and kept at room temperature before heating them to the compaction temperature. It is speculated that lower cracking resistance of plant-produced mixes compared to laboratory-produced mixes is due to a higher aging that the plant-produced mixes experienced in the mixing drum, storage silos, and at the back of the truck before placement and compaction or more compaction in the lab than the field or a combination of these factors.

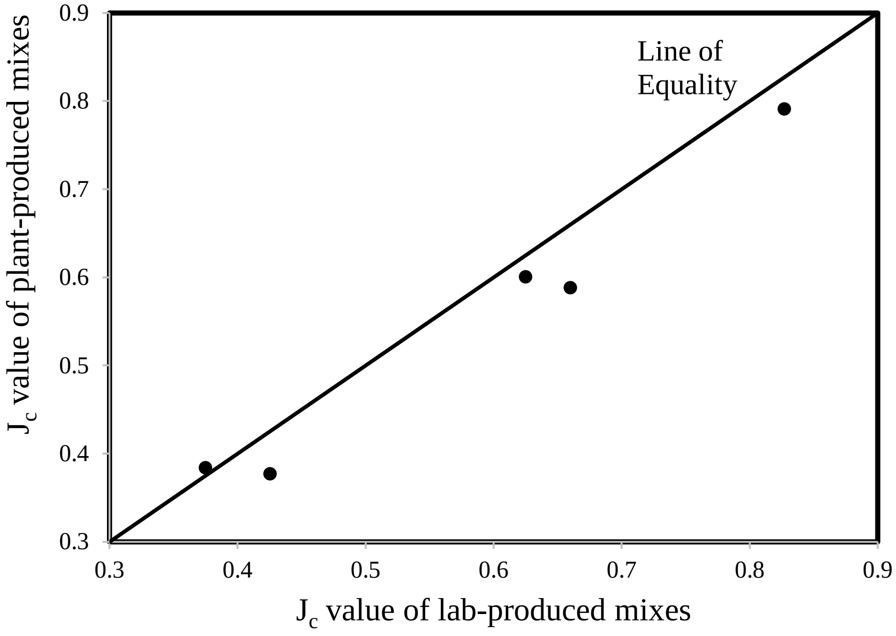


Figure 78. Comparison of Cracking Resistance of Laboratory-produced Mixes and Plant-produced Mixes.

Figure 79 shows a comparison between the J_c values measured for the laboratory-produced mixes and field cores. From Figure 79, it was observed that there is a very good correlation between cracking resistance of field and laboratory mixes (R^2 value of 0.99). However, the J_c values calculated for the field cores were found to be lower than those of laboratory-produced specimens (Figure 79). This difference in J_c values was attributed to a higher aging in the plant, the difference in compaction methods used in the field and laboratory, and lower thickness of the asphalt layer in the field which may result in a different aggregate structure than the specimens compacted in the laboratory. The results of this study indicate that in order to achieve a specific J_c value for the field mix, higher J_c values should be obtained from the corresponding laboratory-produced mixes. In this study, the J_c values measured for the laboratory-produced specimens were found to be higher than those of field cores in the range of 0.02 to 0.1 kJ/m^2. More studies are needed to accurately relate the field core J_c value to that of the laboratory-produced specimen.

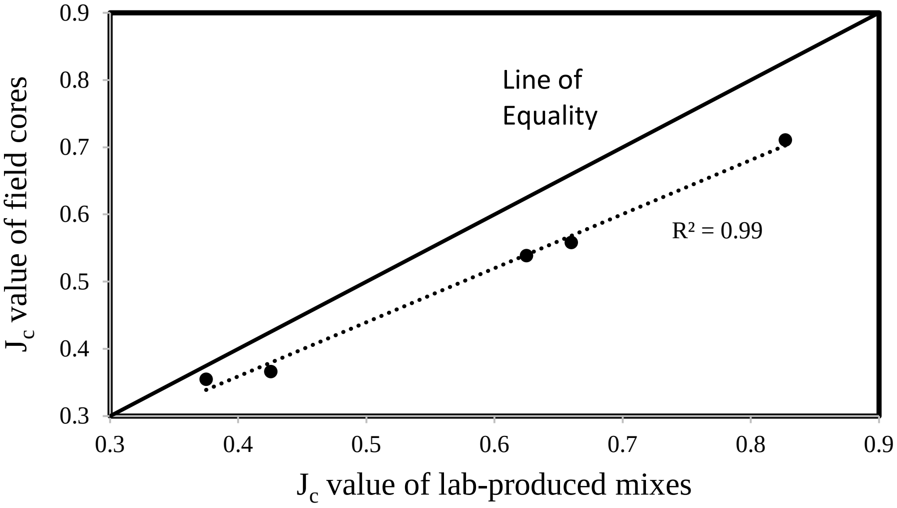


Figure 79. Comparison of Cracking Resistance of Laboratory-produced Mixes and Field Cores

As mentioned earlier, in addition to the field cores collected one day after construction, the research team collected the field cores six months after being subjected to traffic and environmental conditions. The cracking resistance of the mixes were determined by conducting SCB test. As shown in Figure 80, the difference between J_c value of the one-day old mixes and 6-months old mixes ranged between 4% and 13% for all mixes. It was found that although the cracking resistance of the control mix was reduced by 7% after being subjected to traffic loading for six months; the cracking resistance of the rest of the mixes improved. It is speculated that the improvement of the cracking resistance of these mixes is attributed to their air voids content reduction over time. As indicated in Table **30**, the air voids content of mixes 2 through 6 reduced after being subjected to traffic for 6 months. More study on field cores is needed to accurately address the aging effect on cracking resistance of asphalt mixes for time, environmental, binder oxidation, and traffic consolidation effects.

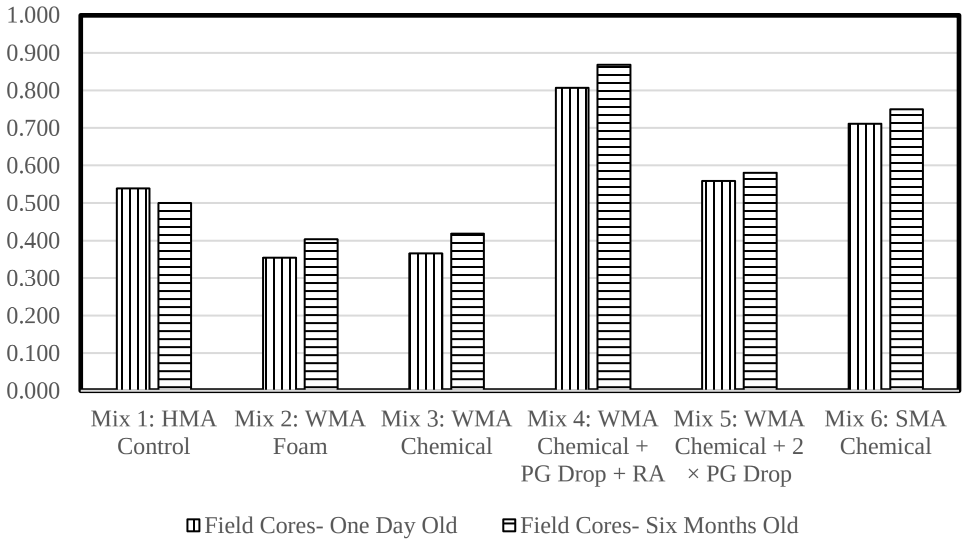


Figure 80. Comparison of Critical Strain Energy Rate of one-day old mixes and 6-months old mixes

The repeatability of the test results for the laboratory-produced, plant-produced and field mixes was studied by determination of the coefficient of variation (COV) of the J_c values measured by using SCB tests for different specimens (Table 31). From Table 31 it was observed that COV values varied from 8 to 22, 16 to 30, and 16 to 36% for laboratory-produced mixes, plant-produced mixes, and field cores, respectively. In general, the COV values were found to be 16, 22, and 24% for laboratory-produced mixes, plant-produced mixes and field cores, respectively. It was also found that COV values increase as the notch depths increase. For instance, the average COV values for field cores with 25.4, 31.8, and 38 mm, were found to be 19, 24, and 31%, respectively. It should be noted that at higher notch depths it is more likely that the notch interferes with large aggregate particles. This likely explains the observation of higher COVs as the notch depth increases.

Table 31. Coefficient of Variation (%) of J_c Values Measured for Asphalt Mixes.

Mix ID	***Description***	***25.4 mm Notch Depth***	***31.8 mm Notch Depth***	***38.0 mm Notch Depth***
Mix 1	Laboratory-Produced	8	21	21
Mix 1	Plant-Produced	22	19	21
Mix 1	Field Core	18	24	36
Mix 2	Laboratory-Produced	18	20	22
Mix 2	Plant-Produced	21	19	30
Mix 2	Field Core	22	18	30
Mix 3	Laboratory-Produced	12	15	18
Mix 3	Plant-Produced	27	21	20
Mix 3	Field Core	21	31	27
Mix 4	Laboratory-Produced	14	10	19
Mix 4	Plant-Produced	16	18	23
Mix 4	Field Core	16	18	27
Mix 5	Laboratory-Produced	21	17	17
Mix 5	Plant-Produced	20	29	24
Mix 5	Field Core	18	16	35
Mix 6	Laboratory-Produced	14	18	20
Mix 6	Plant-Produced	22	23	22
Mix 6	Field Core	29	20	32

9. CONCLUSIONS AND RECOMMENDATIONS

Semi-Circular Bend test was used in this study to investigate the cracking resistance of six different asphalt mixes including one traditional hot mix asphalt, four warm mix asphalts produced using different technologies, and one stone matrix asphalt. A test section was also constructed to monitor the long-term performance of the abovementioned mixes in the field. The tests were conducted on laboratory-produced mixes, plant-produced mixes, and field cores collected from the construction site. The main findings of this research are listed as follows:

- SCB J_c values measured for laboratory-produced specimens were higher than those of plant-produced mixes and the corresponding field cores. A higher J_c value observed in the laboratory-produced mixes suggests developing a correction factor (offset or linear regression correction) similar to what is used for density compaction gauges to find the equivalent J_c values of laboratory-produced mixes with those in the field. Such correlations would be useful if the SCB test is ever used as a pay factor for acceptance. As a screening tool, ranking is sufficient for mix design purposes but shadow testing over at least a year time is recommended prior to full adoption by ODOT. The results show that application of a softer virgin binder and/or rejuvenating agent improves the cracking resistance of the WMA mixes containing recycled materials (RAP and RAS).
- Higher binder content in SMA mix compared to other mixes and lack of highly aged RAP and RAS binders in the SMA resulted in an asphalt mix with higher cracking resistance compared to the other mixes.
- For most of the mixes, the cracking resistance improved after six months being subjected to traffic and environment. Likely, the increase in density due to traffic consolidation was the biggest factor that increased cracking resistance in the first six months for these mixes. Repeatability analyses of the test results indicated that the laboratory-produced mixes result in a lower coefficient of variation (COV)

compared to that of plant-produced mixes and field cores. The SCB test results conducted on field cores showed the highest COV values.

COV values increase as the notch depths increase in the SCB specimens. More SCB tests and analysis are needed for a multitude of mixes before ODOT should consider setting mix design specification limits and even more so should results be considered as a pay factor for acceptance.

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