Determination of Mixture Fracture Performance with the Help of Fracture Mechanics

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Abstract

Cracking is one of the most influential distresses that mostly affect the service life of asphalt concrete pavements. These cracks start as microcracks that later coalesce to form macrocracks, which propagate due to tensile and/or shear stress. As the cracks propagate, the pavement serviceability starts to reduce dramatically. In order to improve the cracking performance of asphalt pavements, it is important to acquire a good understanding of the cracking mechanism and to have a reliable system to determine mixture's resistance to crack development and propagation.

An HMA (Hot Mix Asphalt) fracture mechanics framework based on Superpave IDT (InDirect Tension test) has been developed in the US. The main ideology of this framework is the concept of the existence of a damage threshold. The dissipated creep strain energy (DCSE) limit and the fracture energy (FE) limit of asphalt mixtures are the lower and upper thresholds, respectively. According to this fracture mechanics framework, three types of testing are performed in the IDT testing device for predicting the fracture resistance of bituminous mixtures. Testing comprises resilient modulus, static creep and tensile strength. In this study, theory of this framework and application to field will be explained extensively.

Keywords: *Cracking; Fracture mechanics; Superpave IDT*

1 Introduction

Cracking is one of the most influential distresses that mostly affect the service life of asphalt concrete pavements. The cracking resistance of hot-mix asphalt (HMA) mixtures is directly related to the fatigue performance of flexible pavements. Fatigue cracking is observed as a longitudinal or hexagonal crack pattern in the wheel paths in the asphalt layer. The major distresses in asphalt concrete pavements are fatigue cracking, low temperature cracking and rutting. Fatigue cracking is resulting from the repeated loading while low temperature cracking and rutting depend on temperature changes. Good material selection for different layer and good construction mostly reduce the rutting problems. Thermal cracking mostly depends on the binder performance as bitumen is a temperature dependent viscoelastic material. Fatigue cracking is only the distress that required taking into account of actual structural response. Therefore, the laboratory characterization and modeling to understand the appearance and accumulation of fatigue cracking has been a topic of intensive study for many years. Investigation of material behavior under cyclic loading has continuously been an important issue during the past 150 years. Wöhler showed the cyclic-load effects increasing the fatigue life dramatically with the decreasing stress level (Wöhler, 1980).

Different test methods have been developed to simulate the fatigue behavior over the last couple of decay. Available test methodologies can be classified into the following categories: simple flexure, supported flexure, direct axial, diametral, triaxial, fracture mechanics, and wheel-track testing. Researchers evaluated each method for its potential use as a laboratory standard, the important criteria used were: (1) Ability to simulate field conditions; (2) applicability of test results for use in modeling pavement performance; and (3) simplicity. Among those the three most promising methods were simple flexure, diametral fatigue, and tests based on fracture mechanics principles (Matthews and Monismith, 1993). Therefore, fracture mechanics-based principle is focused to analyze the fatigue behavior in this paper.

The traditional and current fatigue approaches provide the basic ideas to understand fatigue performance of HMA pavements. They are either material dependent, or loading mode dependent, or both. These current approaches has been using in design application though none of these can deeply relate both material performance and loading history. Healing of the material needs to take into account to have a better fatigue model. On this purpose, there have been a lot of efforts to use the dissipated energy to describe HMA fatigue behavior (Van Dijk, 1975; Van Dijk and Vesser, 1977; Chomton and Valayer, 1972). Their hypothesis was all the dissipated energy cause damage of the material but some part of the energy will dissipated in form of heat, plasticity etc. which indicates further clear idea about dissipated energy is needed. To take into account of all of those rising problems, in recent years Roque et al. performed comprehensive studies to characterize the crack initiation and crack growth of asphalt mixtures which also can relate the fatigue behavior of the mixture (Roque et al., 1999; Zhang et al., 2001; Roque et al., 2002). They developed a viscoelastic fracture mechanics-based framework for measuring crack growth rate of asphalt mixtures by using three Superpave IDT tests (resilient modulus test, creep test and strength test). Also energy ratio (ER) was introduced into the HMA fracture mechanics model with the help of two thresholds (the dissipated creep strain energy (DCSE) limit and the fracture energy (FE) limit) for evaluating the cracking performance in asphalt mixtures (Roque et al., 2004).

The objective of this study is to explain HMA fracture mechanics model and evaluate the fatigue performance of HMA mixtures based on the results of IDT tests.

2 HMA Fracture Mechanics

"HMA Fracture Mechanics" (Zhang et al., 2001) developed at the University of Florida can be able to describe the fracture properties of HMA mixtures. It is a fundamental framework that could predict the micro- and macrodamage in mixtures resulting by changes in the visco-elastic properties of mixtures, as well as strength and stiffness. In this framework, the development of macro-cracks at any time during either crack initiation or propagation described by lower and upper thresholds: Dissipated Creep Strain Energy ($DCSE_f$) limit and Fracture Energy (FE), respectively. DCSE limit is associated with continuous repeated loading and FE corresponds to that threshold required to fracture the mixture with a single load application (Birgisson et. al., 2007). Once the energy threshold is exceeded, non healable macro-cracks develop and propagate along the mixture.

The rate of damage growth under the energy threshold is governed by the creep properties of the mixture. The creep compliance of the mixture can be fitted by the following power function:

$$D(t) = D_0 + D_1 t^m \tag{1}$$

The power law parameters D_0, D_1, and m were obtained from creep tests. Based on the concepts and HMA fracture model, dissipated creep strain energy (DCSE limit) and parameter governing the creep strain rate (m-value and D1) are the key parameters to control the cracking performance of asphalt mixtures.

As shown in the Figure 1 with the stress strain response, the dissipated creep strength energy ($DCSE_f$) was determined by deducting from fracture energy (FE) to elastic energy (EE). Fracture energy is the area under the stress strain curve to the failure strain.

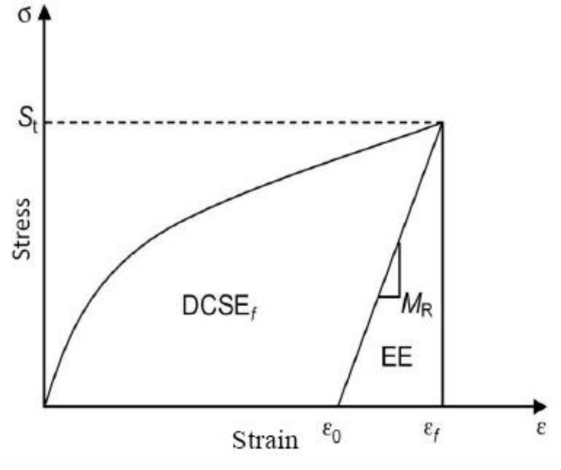

Figure 1. Graphical illustration of lower and upper threshold (Birgisson et. al., 2003).

An analysis was performed by researchers on the pavement sections to identify the key mixture properties that affect cracking performance. The various mixture properties for each section including binder viscosity, effective asphalt content, theoretical film thickness, percent air voids and VMA were determined besides of creep compliance, tensile strength, failure strain, m-value and DCSE. They found that no clear relationship exists between any of these properties and the relative cracking performance (Jajliardo, AP., 2003). A further parameter named Energy Ratio (ER) introduced by Roque et al. (Roque et. al., 2004; Birgisson et. al., 2007) into the HMA fracture mechanics model to predict fracture performance of the mixture in the field. This parameter is a measure of the fracture resistance of mixtures, and can be expressed as:

$$ER = \frac{DCSE_f}{DCSE_{\min}} = \frac{a \times DCSE_f}{m^{2.98} D_1} \tag{2}$$

$$a = 0.0299\sigma^{-3.1}(6.36 - S_t) + 2.46 \times 10^8 \tag{3}$$

where $DCSE_f$ is the dissipated creep strain energy limit (KJ/m^3) and $DCSE_{min}$ is minimum dissipated creep strain energy for adequate cracking performance (KJ/m^3). DCSEmin is a function of the creep compliance power low parameters (m and D_1). For a known maximum tensile stress in the asphalt layer $DCSE_{min}$ can be calculated by the tensile stress (σ) of the asphalt layer (psi), and the tensile strength (S_t) of the material (MPa). For a good field performance of the mixture ER>1 is required. Generally, higher ER indicates better cracking resistance of the mixture.

In order to evaluate mixture cracking performance using the HMA Fracture Mechanics Model, resilient modulus (M_R), creep compliance power law parameters (D_1 and m-value), tensile strength (S_t), dissipated creep strain energy to failure ($DCSE_f$) and fracture energy are required.

3 Superpave IDT tests

The Superpave Indirect Tensile Test (IDT) is used to determine resilient modulus, creep compliance, m-value, D_1, tensile strength, failure strain, fracture energy and dissipated creep strain energy to failure (Roque et. al., 2004). Resilient modulus (M_R), Creep Compliance, and Strength tests were carried out using the Superpave IDT by following the procedures developed by Roque and Buttlar (Roque and Buttlar, 1992; Buttlar and Roque, 1994). Experiments were carried out at 0 ^{0}C which is fairly critical temperature under Swedish conditions. In this test cylindrical specimens with 150 mm in diameter and 50 mm in thickness with 7 ± 1% air voids were used. The experimental setup of the Superpave IDT test is shown in Figure 2.

Figure 2. The experimental setup of the Superpave IDT test.

Two strain gauges (with a length of 38.1 mm for 150 mm diameter specimens and 25 mm for 100 mm diameter specimens) are placed at the center of the specimen to measure vertical and horizontal deformations during loading. To take into account 3D effects, correction factors are needed to correct the measured horizontal and vertical deformation to fit the deformation in a flat plane (Roque and Buttlar, 1992, 1994; Birgisson et al. 2003). The average strain is the value obtained from correction factors divided by the gauge length GL. Finally, center correction factors are used to correct the strain values at the center of specimen (Birgisson et. al., 2007).

3.1 Resilient modulus test

The resilient modulus and Poisson's ratio are calculated based on three dimensional finite element analyses (Roque and Buttlar, 1992, 1994) in the resilient modulus test. The ratio of the applied stress to the recoverable strain under applied repeated loads is known as resilient modulus. The resilient modulus test was conducted in load control mode by applying a repeated haversine waveform load to the specimen for a 0.1 second followed by 0.9 seconds rest period resulting in horizontal strain within the range of 200 to 300 micro-strains. The resilient modulus calculated using the following equations:

$$M_R = \frac{P \times GL}{\Delta H \times t \times D \times C_{comp}} \tag{4}$$

where, M_R= Resilient modulus; P = Maximum load; GL = Gauge Length; ΔH = Horizontal Deformation; t= Thickness, D= Diameter of specimen; C_{comp} = Nondimensional creep compliance factor; $C_{comp} = 0.6354(X/Y)^{-1}-0.332$ and (X/Y) = Ratio of horizontal to vertical deformation.

3.2 Static creep test

As creep compliance is a function of time-dependent strain over stress so the time-dependent behavior of asphalt mixture can be represent by the creep compliance curve. Thus, it can be used to evaluate the rate of damage accumulation of asphalt mixtures. The creep compliance test is carry out by applying a constant load for 1000 seconds resulting in horizontal strain within the range of 200 to750 micro-strains. If the horizontal deformation was greater than 180 micro-inches at 100 seconds, the load immediately removed from the specimen and before reloading at a lower load level specimen was allowed to recover for a minimum 3 minutes.

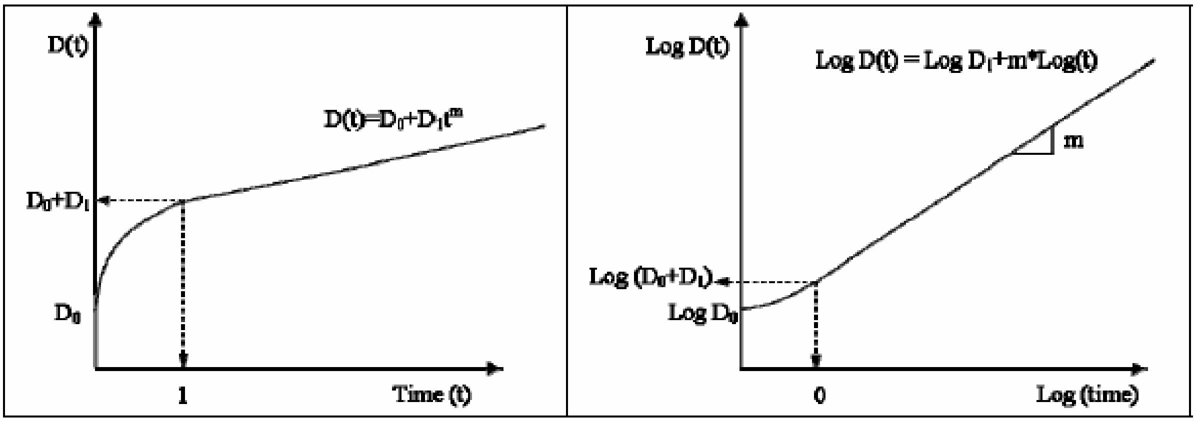

Figure 3. Power model of creep compliance (Birgisson et. al., 2007).

As shown in the figure, three mixture parameters (D_0, D_1, and m-value) can be obtained from creep compliance tests. D0 describes the instantaneous elastic response; D_1 gives idea about the initial portion of the creep compliance curve, while m-value expresses the longer-term portion of the same curve. An asphalt mixture with a low m-value exhibits a low rate of damage accumulation (Kim et al., 2003).

3.3 Indirect tensile strength test

The IDT strength test was conducted to determine the strength and strain of the sample in a displacement control mode by applying a constant rate of 50.8 mm/min until the specimens failed. With the stress strain response, the dissipated creep strength energy ($DCSE_f$) was determined by deducting from fracture energy (FE) to elastic energy (EE). Fracture energy is the area under the stress strain curve to the failure strain (Fig. 2).
Strength tests are conducted in a displacement control mode and used to determine failure limits as tensile strength, failure strain, fracture energy and dissipated creep strain energy. The test is performed loading monotonically the IDT specimen applying a constant stroke of 50mm/min until the specimens failed (Roque and Buttlar, 1992, 1994; Birgisson et al. 2007). The tensile strength is calculated as:

$$S_t = \frac{2PC_{sx}}{\pi Dt} \qquad (5)$$

where: St = indirect tensile strength; P = load of the specimen; D = diameter of the specimen; t = thickness of the specimen; Csx = horizontal stress correction factor.
Csx = 0.948 - 0.01114(t/D) - 0.2693ν + 1.436(t/D)ν
ν = Poisson's ratio, $\nu = 0.1 + 1.480(X/Y)^2 - 0.778(t/D)^2(X/Y)^2$
(X/Y)= ratio of horizontal to vertical deformation

4 Experimental

The laboratory study was carried out to explain the fracture mechanics model.

4.1 Binder, Aggregate and Asphalt Mixtures

In this study, 70/100 penetration grade binder was used. Traditional index tests were performed on binder and the results are shown in Table 1. Based on the superpave binder test results, the performance grade of the binder was found to be PG 58-22.

A dense graded asphalt concrete mixture according to Swedish road standards (ATB VÄG, 2004) with maximum aggregate size of 11 mm was prepared. Two types of crushed granite aggregate which were denoted as AG1 and AG2 were used in this study. The gradation given in Table 2 was used mixtures. The binder contents were 6.2% for AG1 and 6.4% for AG2 by weight. The air void contents for the Superpave IDT tests were 7±1% by volume.

Table 1. Properties of binder.

Characteristics	Units	Results
Softening Point	^{0}C	46
Penetration	dmm	81
Brookfield visc. at 135 ^{0}C	mPas	345
Brookfield visc. at 165 ^{0}C	mPas	101

Table 2. Aggregate gradation for AG1 and AG2.

Sieve size, mm	Grading passing, %		Specification limits	
	AG1	AG2		
0.063	7.8	7.9	6	9
0.125	10.6	10.8	8	15
0.25	15.7	14.9	11	22
0.5	21.8	20.7	16	31
1	29.7	29.2	23	42
2	43.3	42.4	33	52
4	57.0	63.2	48	66
5.6	67.2	69.9	58	75
8	78.6	83.0	70	88
11.2	92.2	98.4	85	99
16	99.1	100.0	98	100
22.4	100.0	100.0	100	100

Specimens which have 150 mm diameter and approximately 100 mm thickness were produced using a gyratory compactor (Model ICT-150R/RB from Finland). The compacted specimens were extruded from moulds and allowed to cool at room temperature for 24 hours. For each mixture, four samples were prepared and air voids were measured. Then, specimens were cut, by a wet saw, into 50 mm thick specimens for IDT tests.

5 Experimental Results

The fracture resistance of the mixtures is evaluated and a summary of the mixture fracture properties obtained from the Superpave IDT are shown in Table 3.

Table 3. Summary of mixtures fracture properties.

Sample ID	Resilient Modulus, M_R (Gpa)	D_1 (1/GPa)	m-value	Tensile Strength, S_t (Mpa)	Fracture Energy (KJ/m^3)	$DCSE_f$ (KJ/m^3)	D'(1000)	Energy Ratio, ER
AG1-O	12.95	0.0920	0.629	2.40	2.51	2.27	0.0045	0.93
AG2-O	13.61	0.1316	0.616	2.57	2.72	2.47	0.0057	0.74

The material's elastic stiffness is known as the resilient modulus (M_R). For the two mixtures, M_R is quite similar. This indicates that, the mixture's response will not affect at small strain and/or short loading times. Creep compliance is measures of material's relaxation stresses. The higher the slope of the creep compliance curve at 1000 seconds is the higher the rate of permanent deformation (Zhang et al., 2001). As shown in Figure 4, the creep compliance curves varied significantly from AG2-O to AG1-O. The AG1-O mixture has lower rate of creep, D'(1000), this means that the rate of damage accumulation due to the repeating loading will be lower as compared to AG2-O. On contrary, AG2-O mixtures show the higher fracture strength and fracture energy than AG1-O mixtures. So, it is not possible to conclude by comparing only one parameter.

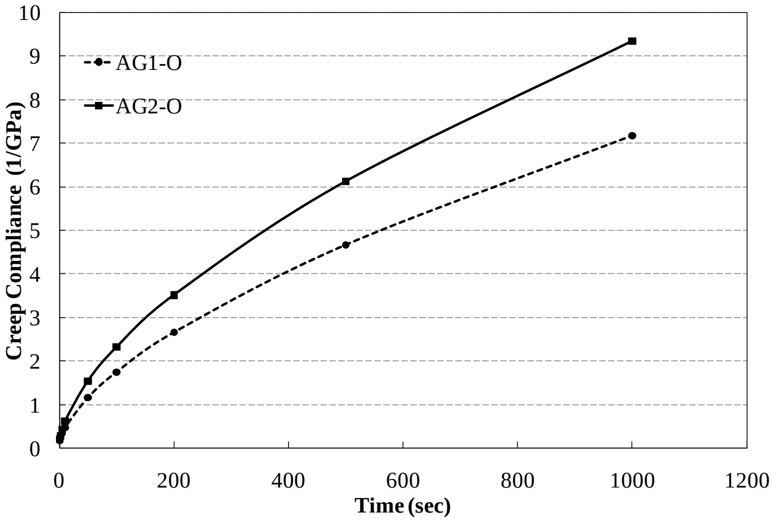

Figure 4. Power model of creep compliance (Birgisson et. al., 2007).

Finally, the energy ratio defines a single criterion for top-down cracking performance of all mixtures in pavement structures. The greater is the energy ratio the higher is the mixture resistance. AG1-O mixtures has higher energy ratio compared to AG2-O mixtures, indicating the higher fracture resistance than the AG2-O mixtures.

6 Conclusions

Cracking is the one of the important performance characteristics and should be taken in the account in mixture design. A fundamental failure mechanism for evaluating the cracking performance of asphalt mixtures using the indirect tension test were proposed by Zhang et al. 2001a,b, Birgisson et al. 2002, and Roque et al. 2002. Generally, higher the values of DCSE or FE, the longer the fatigue life of HMA mixtures. But these single parameters will give the initial information not the final picture how the mixture will serve. Therefore ER defines a single criterion for cracking performance of all mixtures in pavement structures.

Based on the results obtained in this study, compare to AG1-O mixtures, AG2-O mixtures show the higher DCSE limit, fracture energy but creep compliance support that AG1-O is better than AG2-O. For a reliable mixture performance multiple parameters (like Energy Ratio) study is necessary. From the energy ratio concept, it can be concluded that the AG1-O mixture has better resistance to crack initiation and propagation.

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