Top-Down Crack Modeling of Asphalt Concrete based on a Viscoelastic Fracture Mechanics

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ABSTRACT

An energy based crack growth model is developed in this study to simulate the propagation of top-down cracking in asphalt pavements. A viscoelastic fracture mechanics approach, generalized J integral, is employed to model the crack growth of asphalt concrete. Laboratory fatigue crack propagation tests for three different asphalt mixtures are performed at various load levels, frequencies and temperatures. Disk-shaped specimens with a proper loading fixture and crack growth monitoring system are selected for the tests. It is observed from the tests that the crack propagation model based on the generalized J integral is independent of load levels and frequencies, while the traditional Paris' law model based on stress intensity factor is dependent of loading frequencies. However, both models are unable to take care of the temperature dependence of the mixtures. The fatigue crack propagation model proposed in this study has a good agreement between experimental and predicted crack growth lives, which implies that the energy based J integral could be a better parameter to describe fatigue crack propagation of viscoelastic materials such as asphalt mixtures.

Key Words: : fracture mechanics, viscoelastic, generalized J integral, stress intensity factor, top-down cracking

INTRODUCTION

Top-down (TD) cracks are longitudinal and/or transverse cracks that initiate at the pavement surface and propagate downward. Based on the location of the cracks, there are three types of longitudinal cracking: Wheel-path, center and left/right side cracks as shown in Figure 1. It is observed from several field cores that left/right and center cracks are mostly TD cracks. These cracks are typically located 0.6~0.8m away from the wheel path. Unlike the center and left/right cracks, sometimes, it is difficult to identify whether the wheel path cracks are TD or bottom-up (BU) cracks because the cracks completely penetrated into the bottom of asphalt base layer.

For the wheel path cracking, Myers et al. (1) reported that it appeared to initiate mostly in an opening mode because of the transverse stresses induced at the tire-pavement interface by radial truck ties and perhaps combined with thermal stresses and propagate deeper into the pavement largely by the action of high shear stresses under the edge of a tire.

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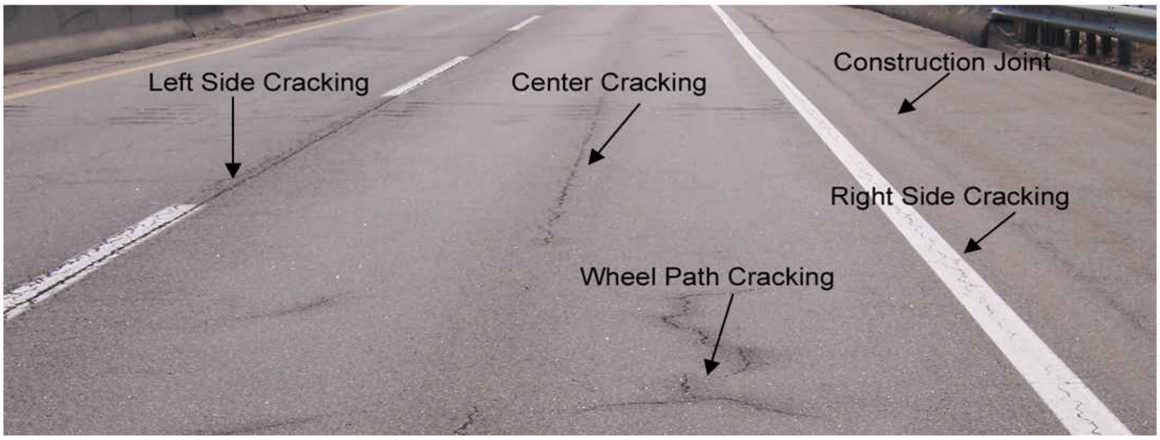


FIGURE 1 Asphalt pavement surface cracking observed in Korea

Based on the assumption that the TD cracking is Mode-I type (i.e., tensile opening mode), several researchers (1, 3, 4) have been studying the mechanisms of the initiation and propagation of TD cracking in pavement structure. Classical fatigue approach and continuum damage approach (2) may be reasonable to account for the crack initiation. But they may not be appropriate to describe the growth of cracks since they are almost impossible to consider the stresses redistribution developed at a crack tip as the crack propagates.

Several researchers have addressed the crack propagation in asphalt concrete using the classical fracture mechanics approach. Stress intensity factor was considered as driving force for crack propagation in Jacobs' study (3) and Paris' law was employed to predict crack growth behavior. All the coefficients in the Paris' law were related to the material properties such as compliance curve, tensile strength and fracture energy and so on. However, stress intensity factor K is insufficient to describe the crack propagation behavior of viscoelastic materials, since the K is only related to loading magnitude and geometry of structure and does not change with the change of loading frequency.

An energy based parameter may be more suitable to describe the fracture behavior of viscoelastic materials. Bayomy (4) proposed energy release rate J_c as an indicator of resistance to fracture for asphalt mixtures, and Wagoner (5) utilized fracture energy G_c to represent the separation behavior of asphalt concrete. Recently, Song (6) adopted a cohesive zone approach to consider viscoelastic effects. All these studies gave great insights of the fracture properties of asphalt concrete, but their studies were limited to monotonic loading conditions and did not go further for fatigue propagation of cracking under a cyclic loading.

The major objective of this study is to develop a fatigue crack propagation model of asphalt concrete based on a generalized J integral approach (7). To accomplish this objective, a series of laboratory fatigue crack propagation tests were first conducted for three different types of asphalt concrete under varying loading magnitude, frequency and temperature conditions. The laboratory test results were then used to identify whether the generalized J integral is a suitable parameter to characterize the fracture behavior of asphalt concrete. A basic form of the fatigue crack propagation model was finally established. The model proposed in this study was verified by comparing the predicted fatigue lives with experimental data.

THEORY OF FRACTURE MECHANICS

Viscoelastic J Integral

Based on a nonlinear viscoelastic constitutive equation in the form of a hereditary integral, Schapery (7) developed a generalized J integral that is applicable to a wide range of viscoelastic materials. The correspondence principle of viscoelasticity makes it possible to define a generalized time-dependent J integral by forming a J_e (pseudo-elastic J integral) with the linear elastic case:

$$J = \int_{\Gamma}\left(wdy - T_i \frac{\partial u_i}{\partial x} ds \right) \tag{1}$$

$$J_e = \int_{\Gamma}\left(w^e dy - T_i \frac{\partial u_i^e}{\partial x} ds \right) \tag{2}$$

where,

T_i = components of the traction vector,

u_i = displacement vector components

u_i^e = pseudo displacement vector components,

ds = length increment along the contour Γ,

w w^e = strain energy density and pseudo strain energy density $w^e = \int \sigma d\varepsilon^e$, and

J_e = the pseudo-elastic J integral, which equals to energy release rate G.

With the pseudo stress and strain parameters, the viscoelastic problem can be converted to an elastic problem. Then the generalized J integral is given as

$$\begin{aligned} J &= E_R \int_{t_0}^{t} D(t-\tau) \frac{\partial J_e}{\partial \tau} d\tau \\ &= \int_{t_0}^{t} D(t-\tau) \frac{\partial K_I^2}{\partial \tau} d\tau \end{aligned} \tag{3}$$

where,

E_R =areferencemodulus,and
$D(t)$ =creepcompliance.

Damage Evolution Law for Crack Propagation under Repeated Loading

Under certain conditions, fatigue crack growth can be characterized by stress intensity factor. If the plastic zone is sufficiently small, the conditions at the crack tip are uniquely defined by the current stress intensity factor K, and crack is characterized by K_{min} and K_{max}. It is convenient to express the functional relationship for crack growth in the following form (9), known as Paris' law:

$$\frac{da}{dN} = C \cdot (\Delta K)^m \quad (4)$$

where,

$\Delta K = K_{\max} - K_{\min}$

a = crack length,

N = number of loading cycles, and

ds = length increment along the contour Γ,

C & m = regressed coefficients.

When fatigue crack propagation is accompanied by large-scale yielding, some researchers (10, 11) attempted to use the J integral instead of stress intensity factor K. They have assumed a growth law of the following form:

$$\frac{da}{dN} = A \cdot (\Delta J)^n \quad (5)$$

where,

ΔJ =contourintegralforcyclicloading,and

A & n = regressed coefficients.

Since asphalt concrete viscoelastic material, the J integral instead of the stress intensity factor seems to be more suitable to characterize conditions at the crack tip. On the other hand, using the J integral is easy to employ viscoelastic correspondence principle in fatigue crack propagation law. Thus the J integral was used in this study.

LABORATORY TESTING

Specimen Geometry

There are several specimen geometries available for tensile crack propagation test. But for a specimen geometry to be accepted in practice, several requirements should be considered as follows:

1) Geometry should be simple and readily fabricated from specimens made during the mixture design process,

2) Potential cracking area (initial ligament) should be wide enough to give a possible observation of cracking propagation, and

3) Stress intensity factor for the configuration of specimen could be calculated without difficulties.

With all the considerations above, Disk-Shaped Compact (DSC) specimen as shown in Figure 2 was selected (12) in this study.

Experimental Program

Specimen Preparation

Three different asphalt mixtures were used in the laboratory tests. Two (mixes A and B) of them were dense graded mixtures with 19mm nominal maximum aggregate size and PG 64-22 and PG 76-22 (modified) asphalt binders, respectively. The other one (mix C) was SMA mixture with 13mm nominal maximum size and PG 64-22 binder. All specimens were compacted using a Superpave gyratory compactor to 150mm of diameter and 130mm of height. The air void contents were in the range of 3.5 and 4.5% for Mixes A and B, 3 and 4% for Mix C. The gyratory compacted specimens were cut into two disk-shaped specimens with 150 mm in diameter and 50±1mm in thickness for the tests. After obtaining the viscoelastic properties of the specimens from dynamic modulus tests under indirect tensile (IDT) mode, specimens were then cut into disk-shaped compact geometry to perform fatigue crack propagation tests. The specimens were cut by water-jet machinery to form loading holes, initial crack notch and the flat edge at the notch mouth as shown in Figure 2.

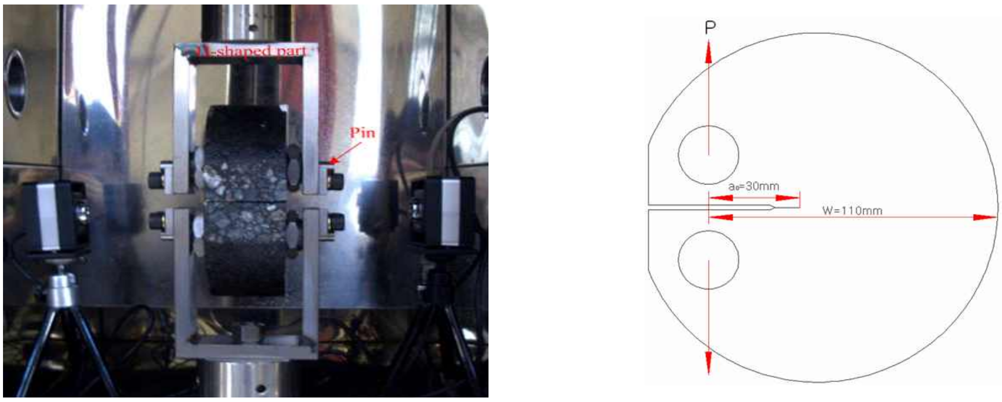


FIGURE 2 Webcam pair and loading fixture in testing set-up for disk-shaped specimen.

Testing Setup and Procedure

Two different types of tests were conducted: IDT dynamic modulus tests to obtain viscoelastic properties of the materials and fatigue crack propagation test.

- **IDT Dynamic Modulus Test**

Before the fatigue crack propagation tests, the viscoelastic properties of the specimens were obtained through the dynamic modulus tests under the IDT mode. The testing setup and analysis procedure proposed by Kim et al. (13) were employed in this study. Since the viscoelastic property needed in the J integral equation is creep compliance, dynamic modulus values were converted to creep compliance values following the inter-conversion procedure proposed by Park and Schapery (14, 15). Finally, the Prony series equation was used to mathematically represent the creep compliance curves.

- **Fatigue Crack Propagation Test**

All the tests were conducted using a MTS with an environmental chamber capable of controlling the temperature between -20 and 40℃ within ±0.1℃. The load was monitored with a 10 kN load cell. Loading fixtures referred from (5) were dimensioned to ensure that the expected loads required for the test can be applied to specimen correctly. Of importance is the ability of the pins to provide frictionless loading. To do this, the interface between pin and Π-shaped part was designed to be frictionless as shown in Figure 2.

For each type of mixture, fatigue crack propagation tests were performed at different load levels, frequencies and temperatures as shown in Table 1. A haversine loading without rest period was applied to the specimens. Fatigue crack propagation process was monitored by two digital webcams. Propagation lengths at each side of the specimen were captured every one minute, and were recorded in JPG format with a resolution of 1600×1200 pixels. Every test was continued until a major crack propagated through the specimen completely. It should be noted here that the notched specimen (notch length is 27.5mm) was pre-cracked till the initial crack length reached 2.5mm to eliminate the effect of different notch tip sizes for different specimens.

TABLE 1 Testing Design

	Testing Description		
	Load Level	Load Frequency	Temperature
Step Ⅰ	High , Middle , Low	Constant (10Hz)	20℃
Step Ⅱ	Constant	High, Middle, Low	20℃
Step Ⅲ	High, Low	High, Low	10℃, 20℃, 30℃
Step Ⅳ	Repeat Step ⅠⅡⅢ for different Mixture		

ANALYSIS OF FATIGUE CRACK PROPAGATION TESTS

Determination of Crack Propagation Speed for a Specified Crack Length

Figure 3 presents crack propagation lengths with number of loading cycles. Since the images of crack propagation lengths were captured from two surfaces, small discrepancies between the crack lengths observed from two surfaces existed inevitably as shown in the figure. The following regression function was employed to fit the data:

$$\ln a = n \cdot \ln(A - N) + B \qquad (6)$$

$$a(t) = \exp[n \cdot \ln(A - f \cdot t) + B] \qquad (7)$$

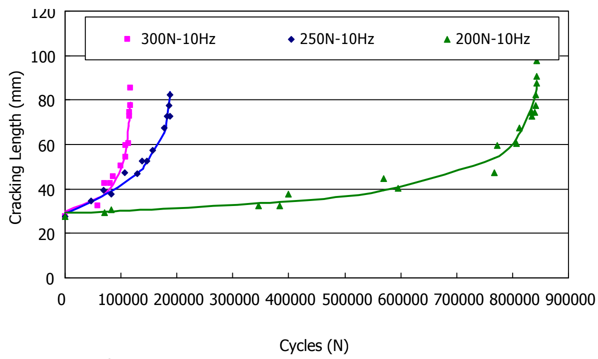


FIGURE 3 Crack propagation data and fitting curves

where, a, $a(t)$ = crack length (mm),
N = number of loading cycles,
t, f = loading time (sec) and loading frequency (Hz), and
B, n, A = least squares set of best fitting coefficients determined by Levenberg-Marquardt algorithm.

J Integral Calculation

1) Load Function

Since a haversine loading was used in the fatigue tests, the following form of the equation was used in the analysis to represent the loading.

$$P(t) = A_0 + A_0 \cdot \sin(2\pi f t - \frac{\pi}{2}) \qquad (8)$$

where, A_0 = loading amplitude, and

f = loading frequency

2) Stress Intensity Function for disk-shaped compact specimen (10)

$$K_I = \frac{P(t) \cdot f(\frac{a}{W})}{B\sqrt{W}} = P(t) \cdot G(a) \qquad (9)$$

where, B = thickness of specimen (mm),

W = crack ligament (mm), shown in Figure 2,

$f(a/W)$ = dimensionless geometry function.

3) J integral function for viscoelastic material

By plugging Equation (9) into Equation (3), one can obtain the following equation,

$$\begin{aligned} J &= \int_{t_0}^{t} D(t-\tau) \frac{\partial (P(\tau) \cdot G(a))^2}{\partial \tau} d\tau \\ &= 2G^2(a) \int_{t_0}^{t} D(t-\tau) P(\tau) P'(\tau) d\tau \end{aligned} \qquad (10)$$

where P' is the first derivative of P in Equation (8). The J integral can be computed by a numerical method and one of the typical analysis results is presented in Figure 4. It is observed in this figure that the J integral value is continuously increasing with harmonic change in each cycle. The difference between the maximum and minimum values of the J integral of each cycle is defined as △J.

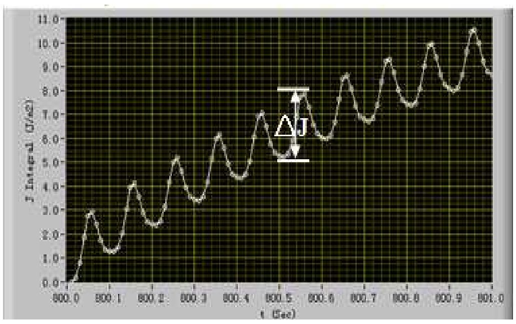
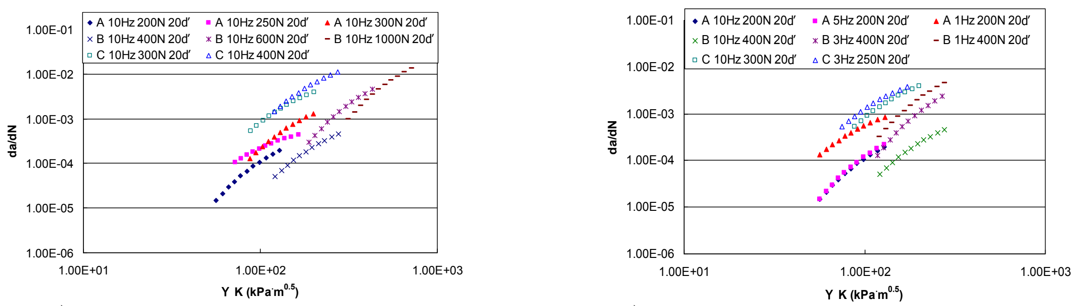


FIGURE 4 J integral curve.

TESTING RESULTS

In this section, the analysis results obtained from the traditional Paris' law and energy based crack propagation law are compared for various load levels and frequencies at 20℃.



a) Cases of different load levels b) Cases of different load frequencies

FIGURE 5 Crack propagation speed versus △K

Figures 10 showed the change in crack speed with △K. One can observe that the △K data of different load levels converged into one fitting curve for each mixture. This may imply that the △K could take care of load level dependence. It suggests that the regressed C and m values could be constant regardless of the change of load levels. On the other hand, this phenomenon did not exist for the cases of different frequencies as shown in Figure 5 b). It is observed in this figure that the lower frequency data located at upper position for the same △K value of each mixture. It can be concluded from the observation made in those two figures that the regressed C and m values for the traditional Paris' laware dependent not only on the material properties but also on the loading frequency.

The damage evolution law in Equation (5) was used to characterize the crack growth behavior of each mixture and the results were presented in Figure 6. Compared to the traditional Paris' law, the advantage of △J integral based crack propagation law is that crack speed versus △J integral curves for different load levels and frequencies formed a unique relationship for each mixture. A regression analysis was performed to obtain model coefficients A and n in Equation (5) and the result was given in Table 2.

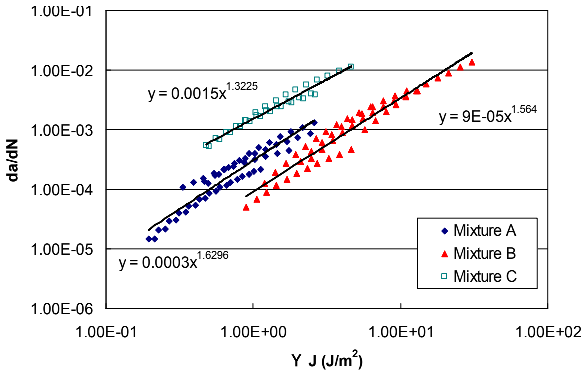


FIGURE 6 Uniform regression regardless of loading frequencies and levels.

In order to inspect whether the △J integral was also able to take care of the temperature dependence, additional fatigue tests were conducted at 10℃ and 30℃. The results showed that the crack propagation speed was influenced by temperature significantly even the loading condition kept constant. Table 2 shows the regressed A and n values for all the mixtures at different temperatures. It is found that the A values are strongly dependent on mixture type and testing temperature. The A value increases as the temperature increases for each mixture due to the change of material properties. However, there is a slight change in n values for different temperatures. According to Schapery (7), this n value is closely related to the slope of the creep compliance curve of a linear range in logarithmic scale.

TABLE 2 Regressed A and n Values for AllMixtures at Different Temperatures

	Temperature	A-Value	n-Value
A Mixture	10℃	5.00E-06	1.5725
	20℃	3.00E-04	1.6296
	30℃	5.40E-03	1.5976
B Mixture	10℃	4.00E-06	1.5626
	20℃	9.00E-05	1.5648
	30℃	3.00E-04	1.6028
C Mixture	20℃	1.50E-03	1.3225

The advantage of using the J integral compared to the classical Paris' s law is that the J integral can take care of loading time and temperature dependencies of the viscoelastic materials because the viscoelasticity of the materials can be considered through the creep compliance function in Equation (10). However, the J integral could not take care of the temperature dependence of the crack speed completely as shown in Table 2. The creep compliance is a linear viscoelastic material property. Both the viscoelastic property and the fracture characteristics of the material change when the testing temperature changes. However, the creep compliance can consider only the changes in viscoelastic properties of the material.

Prediction of Crack Propagation Life

Integrating the both sides of Equation (5), an expression for fatigue life can be derived as:

$$\int dN = \int_{a_0}^{a} \frac{1}{A(\Delta J)^n}\, da \qquad (11)$$

Using Equation (11) with the coefficients A and n in Table 2, fatigue life regarding any specified crack propagation length can be predicted. For a0 and a values of 30 and 60mm, respectively, the predicted and measured fatigue lives were compared in Figure 7. The predicted lives have a good agreement with the experimental results that verifies the energy based △J integral could be a fundamental parameter to describe fatigue crack propagation of asphalt mixtures.

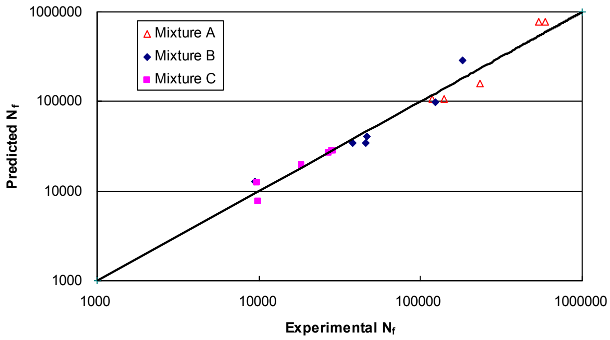


FIGURE 7 Experimental and predicted crack propagation lives.

CONCLUSION

The following observations and conclusions are made in this study:

· Disk−shaped compact specimen is suitable to perform fatigue crack propagation test with proper loading fixture and image monitoring system.

· The Paris' law with stress intensity factor is able to take care of the load level dependence of the asphalt concrete but is dependent on the loading frequency.

· Unlike the Paris's law, the △J integral can take care of both load level and frequency dependences of the crack speed. However, it is impossible to eliminate the temperature dependence of the crack speed completely.

· The J integral considers the time and temperature dependences of a material through the use of creep compliance which is a linear viscoelastic material property. Both the viscoelastic property and the fracture characteristics of the material change when the testing temperature changes. However, the creep compliance can consider only the changes in viscoelastic properties of the material.

· The prediction of crack propagation lives for different types of mixtures and loading conditions can be made using Equation (11) with coefficients in Table 2. The predicted lives have a good agreement with the experimental results that verifies the energy based △J integral could be a fundamental parameter to describe fatigue crack propagation of asphalt mixtures.

· A further study is needed to validate the findings in this study and to study the effects of temperature on the fracture characteristics of asphalt concrete.

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