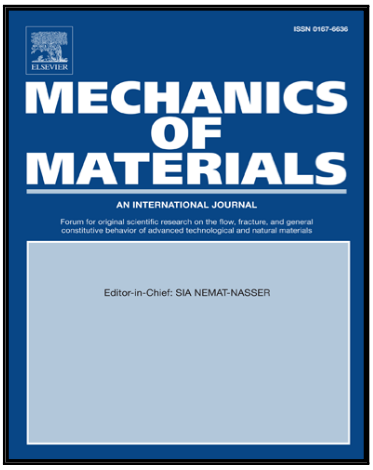

Energy-Based Mechanistic Approach for Crack Growth
Characterization of Asphalt Binder

Hui Li , Xue Luo , Weizhuo Yan , Yuqing Zhang

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The nonlinear viscoelastic critical strain level separating from damage is determined

A theoretical formula of the crack length is derived based on a pure mechanical method

A relationship between crack growth rate and material properties is established

Paris' law parameters are independent of strain levels and temperatures

Energy-Based Mechanistic Approach for Crack Growth Characterization of Asphalt Binder

Hui Li
College of Civil Engineering and Architecture
Zhejiang University
866 Yuhangtang Road, An-zhong Bldg.
Hangzhou 310058, Zhejiang, China
Email: huili94@zju.edu.cn
Xue Luo[1,2]
(corresponding author)
1. College of Civil Engineering and Architecture
Zhejiang University
866 Yuhangtang Road, An-zhong Bldg.
Hangzhou 310058, Zhejiang, China
2. National Engineering Laboratory of Highway Maintenance Technology,
Changsha University of Science & Technology, Changsha 410114, Hunan,
China
Phone: (86) 571-88206542
Email: xueluo@zju.edu.cn
Weizhuo Yan
College of Civil Engineering and Architecture
Zhejiang University
866 Yuhangtang Road, An-zhong Bldg.
Hangzhou 310058, Zhejiang, China
Email: yanwz14@zju.edu.cn
Yuqing Zhang
Aston Institute of Materials Research
Aston University
Aston Triangle, Birmingham, B4 7ET, U.K.
Phone: +44 (0) 121-204-3391
Email: y.zhang10@aston.ac.uk

ABSTRACT

The cohesive cracking within asphalt binders has a significant influence on fatigue cracking resistance of asphalt pavements. To more clearly understand the mechanism and accurately characterize the process of the cohesive cracking occurring within the asphalt binder. An energy-based mechanics (EBM) approach is applied to determine crack length and the pseudo J-integral is adopted to calculated crack growth rate in this study. First, a critical strain level separating nonlinear viscoelasticity from damage is determined based on statistical analysis approach, and result indicates that 0.7% is a critical nonlinear strain level for unmodified asphalt binder. Then, crack length of asphalt binders is derived based on a torque equilibrium equation and two energy balance equations, as well as crack length is measured and verified based on an image processing method. It is found that contact regions in cracked area of the asphalt binder are formed when performing a strain-controlled rotational shear load. There are two change stages of contact regions which first increase and then decrease with increase of loading time. Next, crack growth rate is formulated based on the pseudo J-integral *Paris' law* equation which considering nonlinear viscoelasticity. Linear relationship between crack growth rate and the function of material properties (such as shear modulus, phase angle) in double logarithm scale is proven and experimentally verified. *In addition, Paris' law parameters* (*n* and *A*) associated with crack growth rate are determined. Results show they are independent on strain levels and temperatures. For example, six *Paris' law parameter*s *n* of unmodified asphalt binder are approximately equal to 1.10 at 5%, 6%, 7% of strain level when test temperatures are 15°C and 20°C. They are inherent material properties for the asphalt binder.

Keywords: Fatigue cracking; Asphalt binder; Nonlinear viscoelasticity*; Paris' law;* Crack growth rate.

1 Introduction

Fatigue cracking resistance of asphalt mixtures plays a critical role in determining the fatigue cracking resistance of asphalt pavements. Fatigue cracking of asphalt mixtures is commonly caused by cohesive failure within the asphalt binder. Therefore, accurately characterizing and understanding the fatigue behavior of asphalt binder is of great significance in guiding the design of asphalt mixtures and extend the service life for asphalt pavement. Many fatigue characterization indicators have been proposed for asphalt binders, which are generally classified as: (1) empirical indicators; (2) indirect mechanical indicators; (3) direct mechanical indicators, like crack length and crack growth rate.

Many empirical indicators have been proposed as fatigue failure criterions for asphalt binders. Such as, a 50% loss in stiffness and pseudo-stiffness criterion are established (Hicks et al.,1993; Kim et al.,1997). The peak of phase angle is defined as the critical fatigue failure point during fatigue tests (Reese, 1997). The peak of $S \times N$

(S is the stiffness, N is the number of loading cycles) is considered a fatigue failure point (Rowe and Bouldin, 2000). In addition, a fatigue factor denoted as $|G^*|sin$ ($|G^*|$ is shear modulus and is the phase angle) is proposed to characterize the fatigue behavior of asphalt binder in the Strategic Highway Research Program (SHRP) (Anderson & Kennedy, 1993). However, some researchers suggest that empirical indicators are not well correlated with the fatigue life of asphalt mixtures and asphalt pavements (Zhou et al.,2013).

In order to improve the usage of the empirical indicators. Indirect mechanical indicators have been proposed to reflect the fatigue behavior of asphalt binders from the perspective of dissipated energy ratio (DER) (Anderson et al.,2001; Martono et al., 2007; Wang et al., 2016) and the ratio of dissipated energy change (RDEC) (Shen et al., 2006; Shen et al., 2010; Subhy et al., 2017). These dissipated energy criterions are superior to the empirical criterions, because they are derived based on mechanical principles and material properties. However, these indirect mechanical indicators not provide explanations to the fatigue behavior and fatigue mechanisms for asphalt binders.

To better directly quantify the physical process of fatigue cracking. Some researchers focused on studying direct mechanical indicators of asphalt binders which include crack length and crack growth rate. Such as, crack length calculated by the theoretical formula and measured by the image processing method have been compared during a shear fatigue cracking process (Hintz and Bahia, 2013, Shan et al., 2017). In these studies, it is not rigorous for asphalt binders to use the linear viscoelastic constitutive equation at undamaged state to derive crack length at damage stage. For this reason, a damage mechanics-based crack length model has been established for asphalt binders under a rotational shear fatigue load (Zhang and Gao, 2019, Li et al., 2020). However, materials properties (such as shear modulus, phase angle) under linear viscoelastic condition are selected to calculated crack length under damaged condition.

In addition, there are some studies on the crack growth rate for asphalt binders. The relationship between energy release rate and crack growth rate is fitted and analyzed for asphalt binders (Hintz and Bahia, 2013, Gao et al., 2020), which indicated the fitting model parameters are independent on the magnitude of loading amplitude. However, the energy release rate of asphalt binders is calculated without taking the nonlinear viscoelasticity into consideration. Therefore, the viscosity of asphalt binders is incompletely eliminated, which make it impossible to accurately determine the model parameters of crack growth rate. Besides, Safaei and Castorena (2017) commented that the effect of material nonlinearity has been ignored in most of asphalt binders damage analysis and attributed all material integrity losses to damage for the sake of simplicity.

As a result, in order to further understand the physical process of fatigue cracking and better overcome the problems above-mentioned. It is necessary to fundamentally study the crack length and crack growth rate of asphalt binders by taking the nonlinear viscoelasticity into consideration under a rotational shear fatigue load. Hence, the objective of this work is that determining the crack length and crack growth rate based on a purely mechanical method, which can directly characterize the fatigue cracking behavior of asphalt binders.

This study is organized as follows. Firstly, test materials and methods are elaborated. Secondly, using the statistical analysis approach to determinate critical strain levels separating linear viscoelasticity and nonlinear viscoelasticity from damage. Thirdly, shear strain model, shear stress model and energy items are established under a rotational shear fatigue load. Then, a formula of crack length for asphalt binders is derived based on the EBM approach and verified by an image processing method. Next, the pseudo J-integral is obtained by taking the nonlinear viscoelasticity into account and crack growth rate is established based on the pseudo J-integral *Paris' law*. In addition, *Paris' law parameters associated with crack growth rate are determined at* different oscillation shear strain levels and temperatures. Finally, a summary section concludes this study with the main results.

2 Materials and Laboratory Tests

2.1 Materials

Two types of asphalt binders commonly used in China are selected in this study, which represent unmodified asphalt binders and SBS modified asphalt binders. Three replicates for each type of the asphalt binder are tested based on the method in the specification (China, 2010a; 2010b; 2011; 2014). The requirement and measured average results of basic properties (penetration, softening point and ductility) of the unmodified asphalt binder and SBS modified asphalt binder are showed in Table 1. Basic properties of asphalt binders can meet the requirement in the specification.

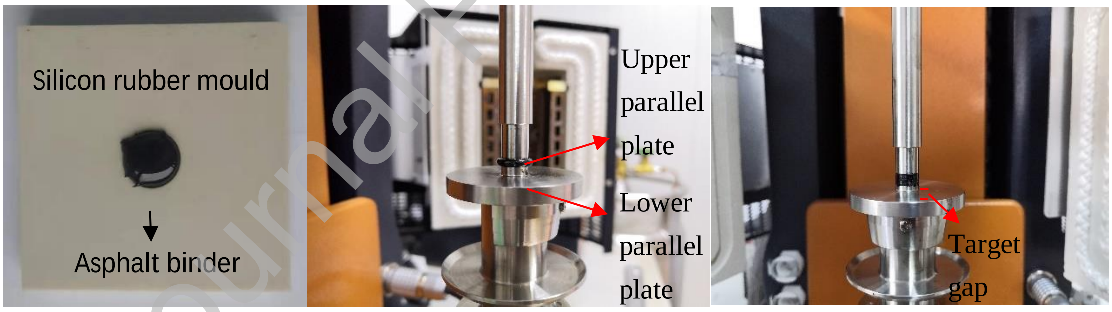
Table 1. Basic properties of unmodified asphalt binders and SBS modified asphalt binders

Properties	Unit	Unmodified asphalt binders			SBS modified asphalt binders		
		Method	Requirement	Result	Method	Requirement	Result
Penetration at 25℃	0.1mm	T 0604 (China, 2011)	40-60	56	GB/T 4509 (China, 2010b)	60-80	74
Softening point	℃	T 0606 (China, 2011)	*60*	88.4	GB/T 4507 (China, 2014)	44-57	47.3
Ductility at 5℃	cm	T 0605 (China, 2011)	*20*	36.5	GB/T 4508 (China, 2010a)	*100*	>150

2.2. Equipment and Sample Preparation

Discovery Hybrid Rheometer (Figure 1a) from TA Instruments is adopted to conduct tests for asphalt binders. In this study, an 8-mm diameter parallel plate geometry is employed by forming a specimen 8 mm in diameter, 2 mm in height. Specimens are prepared by pouring the hot asphalt binder that can flow into the silicon rubber mould (Figure 1b), and cool them to room temperature for a period time. Then, the specimen is removed by flexing the rubber mould and adhered to the lower parallel plate by gently pressing the top surface of the pellet. After that, the upper parallel plate is lowered close to the asphalt binder until the gap is equate to the trim gap *(2050μm)* and then rock the rotating lever (Figure 1c). A heated trimming tool is employed to trim the excess asphalt binder around the edges of the plates so that the asphalt binder is the same as the outer diameter of the plates. When the trimming step is complete, the upper parallel plate is lowered to the target gap (2*000μ*m), which is shown in Figure 1d. T*he extra 50μm can* ensure that a proper lateral bulge is formed at the outside face of the asphalt binder specimen. Finally, to avoid uneven temperature distribution throughout the entire asphalt binder specimen volume, the specimen is heated to the testing temperature and keep it for 5 min before loading.

a. Discovery Hybrid Rheometer



b. Asphalt binder specimen c. Trim gap d. Target gap

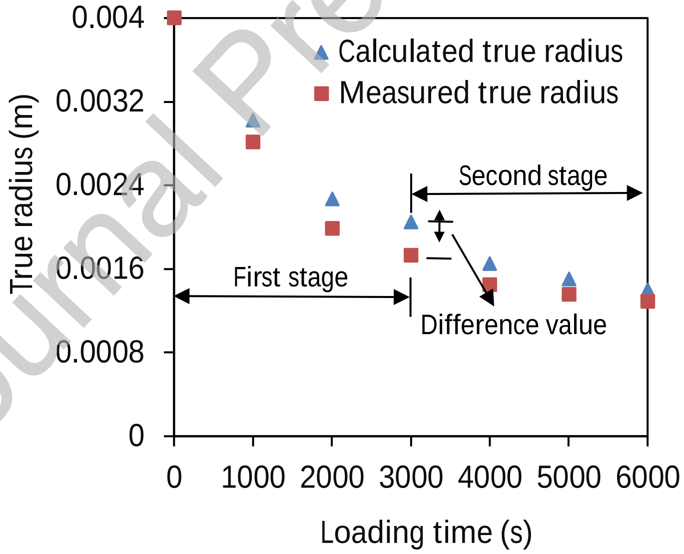
Figure 1. Equipment and sample preparation of the test

2.3 Test Methods

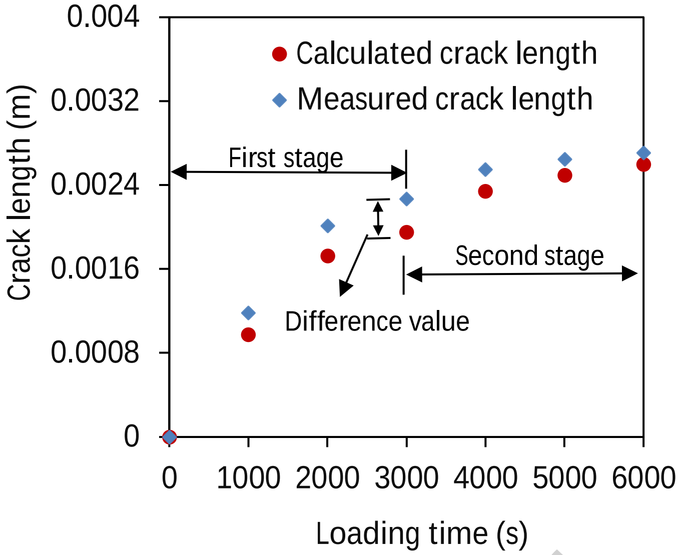
In this study, three types of tests including linear amplitude sweep test, time sweep test under low and high oscillation shear strain level are performed. Two types of asphalt binders (unmodified asphalt binders and SBS modified asphalt binders) are tested. Besides, all tests are conducted at two temperatures (15°C and 20°C) and one loading frequency (10 Hz).

(1) Linear amplitude sweep test

energy dissipated by these contact regions; (2) the reason for observation 2 is that fewer contact regions make the calculated values and the measured values match well during the initial and later loading process. The reasons for the small proportion of contact regions is that contact regions start to germinate during the initial loading process as well as the uncracked area decreases and torque is transferred to the weaker contact regions during the later loading process, which accelerates the failure of contact regions; and (3) the reason why the difference value has two stages is that contact regions have two change stages. First stage: contact regions increase with the increase of loading time before the difference value reached the peak value; and second stage: contact regions decrease with the increase of loading time after the difference value reached the peak value. Besides, a similar result is found in the polystyrene and polyethylene. T*he "drop-like shape" crack* and contact regions are formed and proved when performing a time sweep test (Mattes et al., 2008).



a. Calculated and measured true radius



b. Calculated and measured crack length

Figure 11. Calculated and measured true radius or crack length of unmodified asphalt binders at 5%, 20°C and 10 Hz

5.2 Determination of Crack Growth Rate for Asphalt Binders

Paris' law is the most widely used model to characterize crack growth rate of materials (Paris and Erdogan 1963), which relates crack growth to the stress intensity factor or the J-integral. For the viscoelastic materials, large-scale yielding of crack growth occurs. Schapery (1984) proposed that substituting the pseudo J-integral for the stress intensity factor or the J-integral. Therefore, the pseudo J-integral Paris' law is adopted to predict the crack growth rate for asphalt binders, as shown in Equation 26.

$$\frac{dc}{dt} = A\left(J_R\right)^n \tag{26}$$

where A and n *are Paris's law parameters associated with the evolution of crack growth,* and J_R is the pseudo J-integral, which represents the energy dissipation rate caused by damage, which can be calculated as below:

$$J_R = \frac{\partial\left(\int_0^t DPSE^A(t)\,dt\right)}{\partial V^c} = \frac{\partial\left(\int_0^t DPSE^A(t)\,dt\right)/\partial t}{\partial V^c/\partial t} = \frac{DPSE^A(t)}{\partial V^c/\partial t} \tag{27}$$

in which $DPSE^A(t)$ is $DPSE^A$ at any loading time t; V^c is the crack volume of the asphalt binder, which calculated by the following expression:

$$\frac{\partial V^{c}}{\partial t} = 2\pi r^{T}\frac{\partial c}{\partial t} \tag{28}$$

The $DPSE^{A}(t)$ can be determined as follows:

$$DPSE^{A}(t) = \iiint_{V^{A}} DPSE^{A}(t,r,z) \tag{29}$$

Then, substitute Equation 27, Equation 28, Equation 29 into Equation 26 and arrange it, yielding:

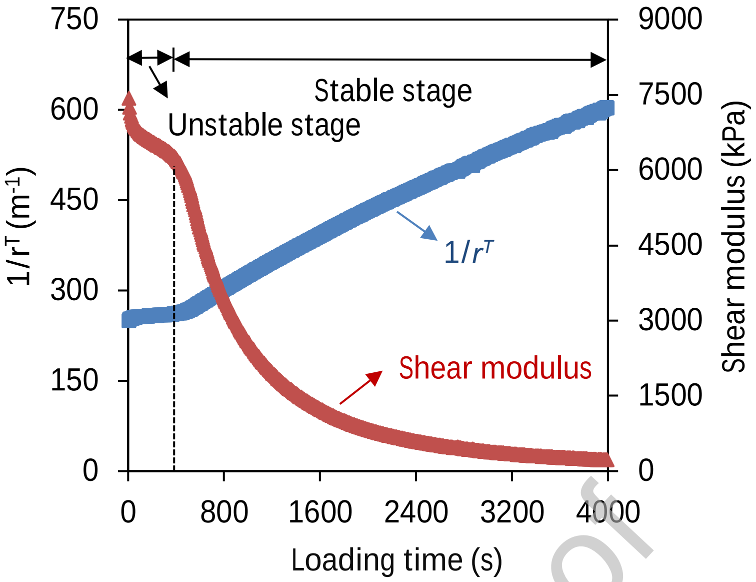
$$\frac{dc}{dt} = A^{1/(n+1)}\left[\frac{1}{4}\pi^{A}\left|G^{*T}\right|^{1/4}\left({}^{A}_{0}\gamma\right)^{2}\left|G^{*A}\right|^{3/4}\sin\left({}^{A}\delta - {}^{A}_{NLVE}\delta\right)\right]^{n/(n+1)} \tag{30}$$

in which ${}^{A}_{NLVE}\delta$ is the apparent phase angle at the nonlinear viscoelastic critical point of the asphalt binder, which is identified in the section 3.

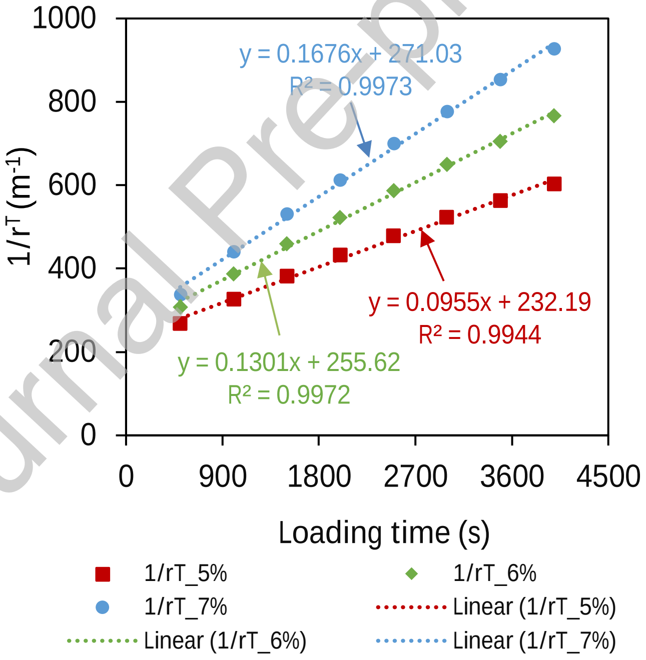
Next, take the logarithm of both sides of Equation 30, whose result is:

$$\ln\left(\frac{dc}{dt}\right) = \frac{1}{n+1}\ln A + \frac{n}{n+1}\ln\left[\frac{1}{4}\pi^{A}\left|G^{*T}\right|^{1/4}\left({}^{A}_{0}\gamma\right)^{2}\right] + \frac{n}{n+1}\ln\left[\left|G^{*A}\right|^{3/4}\sin\left({}^{A}\delta - {}^{A}_{NLVE}\delta\right)\right] \tag{31}$$

However, Equation 31 only applies to the stable stage of crack growth. It is necessary to determine the stable stage of crack growth for asphalt binders in this study. Based on the test data and calculation results, Figure 12a presents two stages (unstable crack growth stage and stable crack growth stage) of crack growth of asphalt binders: (1) in unstable crack growth stage: the inverse of true radius slowly increases (crack length rapidly increase) with increases of loading time, which is caused by unstable flow at the edge of asphalt binder sample when performing a strain-controlled rotational shear load; (2) in stable crack growth stage: the inverse of true radius linearly increases with the increase of loading time, which indicates the unstable flow of the edge of the asphalt binder disappears and crack stably growth. In addition, unmodified asphalt binders are presented as an example. Figure 12b shows relationship between the inverse of true radius and loading time in the stable crack growth stage at different oscillation shear strain levels (5%,6%,7%), 20°C and 10 Hz. Results show that a linear relationship between the inverse of true radius and loading time is presented, and high values of goodness of fit are obtained (R^2>0.99). The similar results are obtained in other conditions or other asphalt binders.



a. Two stages of crack growth



b. Relationship between the inverse of true radius and loading time in stable crack growth stage at different oscillation shear strain levels, 20°C and 10 Hz

Figure 12. Unstable crack growth stage and stable crack growth stage of unmodified asphalt binders

Therefore, the inverse of true radius in stable crack growth stage can be expressed by the following linear equation:

$$\frac{1}{r^T} \quad k_1 t \quad k_2 \tag{32}$$

where, k_1, k_2 are fitting parameters.

Take the partial derivative of to the loading time t:

$$\frac{1}{r^T} \S^{2} \frac{dr^T}{dt} \quad k_1 \tag{33}$$

Substitute Equation 25 into Equation 33, the crack growth rate can be determined as follows:

$$\frac{dc}{dt} \quad \frac{d \quad r^A \quad r^T}{dt} \quad \frac{dr^T}{dt} \quad k_1 \quad r^T \quad ^2 \tag{34}$$

Figure 13 presents some examples of plotting crack growth rate and the function of material properties (shear modulus and phase angle) in double logarithm scale under different oscillation shear strain levels and temperatures. 20_5% standing for the test temperature is 20°C and the oscillation shear strain level is 5%, and other legends have similar interpretations. Two conclusions can be drawn from Figure 13: (1) crack growth rate and the function of material properties (shear modulus and phase angle) in double logarithm scale is linear under different oscillation shear strain levels and temperatures, because of high goodness of fit (R^2>0.999); (2) crack growth rate increases with increase the function of material properties (shear modulus and phase angle) in double logarithm scale, that is slopes of these straight lines are positive. In addition, the slopes are almost identical under different oscillation shear strain levels and temperatures.

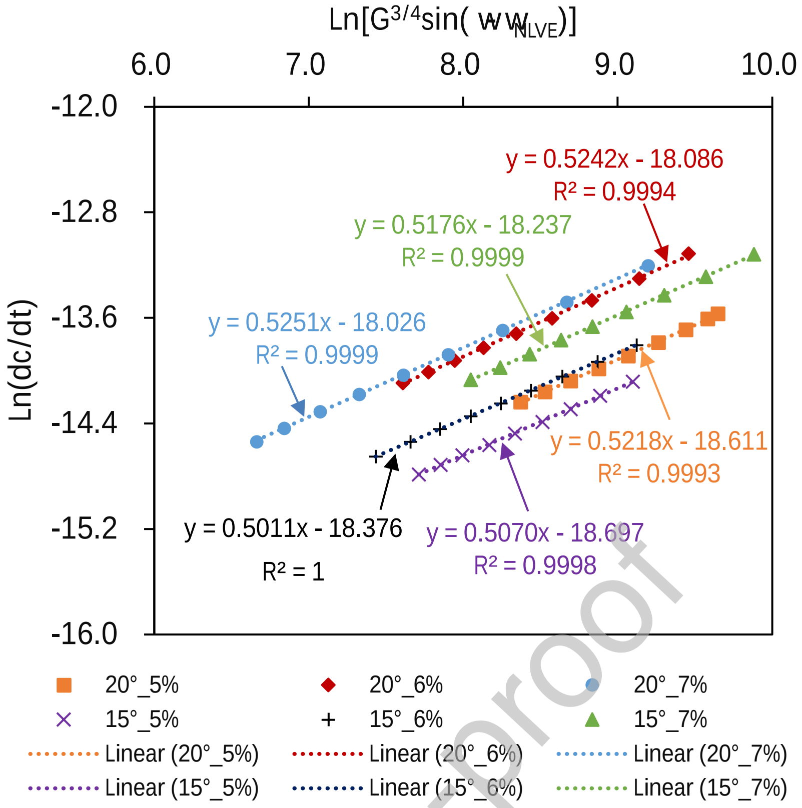


Figure 13. Relationship of crack growth rate and the function of material properties (shear modulus and phase angle) in double logarithm scale under different oscillation shear strain levels and temperatures

Finally, Paris's law parameters n and *A* can be determined by the slope and intercept in Figure 13. Table 6 presents *Paris's law parameters n* and *A* of unmodified asphalt binders and SBS modified asphalt binders at different oscillation shear strain levels and different temperatures. It is found that *Paris's law parameters n* and *A* do not significantly vary with oscillation shear strain levels and temperatures regardless of unmodified asphalt binders or SBS modified asphalt binders. For example, six *Paris'* law parameters *n* of unmodified asphalt binder are approximately equal to 1.10 at 5%, 6%, 7% of oscillation shear strain level when test temperatures are 15°C and 20°C. *Therefore, Paris's law parameters n* and *A* are independent on oscillation shear levels and temperatures. Thus, *n* and *A* can be determined by one oscillation shear strain level and temperature. Then, it can be used to characterize crack growth rate of asphalt binders at any oscillation shear strain level and temperature.

Table 6. *Paris's law parameters of unmodified asphalt binders* and SBS modified asphalt binders at different oscillation shear strain levels and different temperatures

Materials	Oscillation shear strain level	*Paris's law parameters*			
		20°C		15°C	
		n	*A*	*n*	*A*
Unmodified asphalt binders	5%	1.09	4.17E-13	1.05	4.08E-13
	6%	1.10	8.00E-13	1.03	9.93E-13
	7%	1.10	6.41E-13	1.10	4.86E-13
SBS modified asphalt binders	7%	1.51	2.77E-17	1.54	7.97E-18
	8%	1.58	1.83E-17	1.57	7.61E-18
	9%	1.57	2.68E-17	1.63	2.98E-18

6. Conclusions

Targeting the challenge that accurately characterizing the fatigue cracking process of the asphalt binder. An energy-based mechanics approach is applied to determine the crack length and crack growth rate is modeled by the pseudo J-integral in this study. The main findings of this study are listed as follows:

- The linear viscoelastic critical strain level separating linear viscoelasticity from nonlinear viscoelasticity, and the nonlinear viscoelastic critical strain level separating nonlinear viscoelasticity from damage are determined. Results of unmodified asphalt binders as an example, the linear viscoelastic critical strain level is 0.3% and the nonlinear viscoelastic critical strain level is 0.7%.
- A theoretical formula of crack length is derived based on a pure mechanical method. The crack length of asphalt binders can be determined by true shear modulus, apparent shear modulus and apparent radius. Crack length increases and growth rate decreases with the increase of loading time, and larger oscillation shear strain level can increase crack length under the same conditions.
- Contact regions in cracked area of asphalt binders are formed and a part of strain energy is dissipated by friction among these regions when performing a strain-

controlled rotational shear load. In addition, there are two change stages of contact regions, which first increase and then decrease with the increase of loading time.

- Crack growth rate is modeled by the pseudo J-integral Paris' law which considering nonlinear viscoelasticity. Linear relationship between crack growth rate and the function of material properties (shear modulus and phase angle) in double logarithm scale is proven. Slopes of these straight lines are positive and almost identical under different oscillation shear strain levels and temperatures.
- *Paris' law* parameters (*A* and *n*) associated with the evolution of crack growth are determined. They are independent on oscillation shear strain levels and temperatures, which indicate that they are inherent material properties for asphalt binders.

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CRediT author statement

Hui Li: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing. **Xue Luo:** Funding acquisition, Supervision, Resources, Project administration, Writing - review & editing. **Weizhuo Yan** Investigation, Methodology. **Yuqing Zhang:** Supervision, Writing - review & editing.