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A fatigue damage model for asphalt mixtures under controlled-stress and controlled-strain modes

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Abstract: A fatigue damage model based on thermodynamics was deduced for asphalt mixtures under controlled-stress and controlled-strain modes. By employing modulus of resilience as the damage hardening variable, a damage variable related with dynamic modulus was extracted as the evaluation index. Then, the damage evolution law under two control modes was proposed, and it has a similar form to the Chaboche fatigue model with a nonnegative material parameter m related to its loading level. Experimental data of four loading levels were employed to calibrate the model and identify the parameter in both control modes. It is found that the parameter m shows an exponential relationship with its loading level. Besides, the difference of damage evolution under two control modes was explained by the law. The damage evolves from fast to slow under a controlled-strain mode. However, under a controlled-stress mode, the evolution rate is just the opposite. By using the damage equivalence principle to calculate the equivalent cycle numbers, the deduced model also interprets the difference of damage evolution under two control modes on the condition of multilevel loading. Under a controlled-strain mode, a loading sequence from a low level to a high level accelerates damage evolution. An inverse order under the controlled-stress mode can prolong fatigue life.

Key words: asphalt mixtures; fatigue model; control mode; continuum damage mechanics; dynamic modulus

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Fatigue failure due to repeated traffic load is a significant distress found in asphalt pavements[1−2]. The fatigue resistance is regarded as a main factor influencing the pavements' service life. Thus, establishing a suitable fatigue model for asphalt mixtures has been paid much attention to for many years.

It is shown that the existing research on fatigue of asphalt mixtures can be classified into three main types: the phenomenon models based on fatigue tests[3−4], the dissipated energy method which ignores the influence of path[5], the mechanical approach including the fatigue crack propagation models based on fracture mechanics and the fatigue damage evolution models based on damage mechanics[6]. Among the three categories, damage mechanics based on thermodynamics is given increasing attention due to its sufficient theoretical basis.

Whichever method is employed, it is acknowledged that the fatigue damage evolutions of asphalt mixtures are influenced by different control modes used during fatigue experiments. Stress control and strain control are two common control modes in laboratory fatigue tests. However, most of the present research emphasized the fatigue damage evolution law under only one of the two control modes, by employing a dynamic modulus, complex modulus or dissipated energy as the evaluation indices[7−9]. The definition of these damage evaluation indices was always artificial. In addition, only a few researchers have studied the mechanism of two control modes simultaneously. Castelo Branco et al.[10−11] demonstrated that no matter when derived from the controlled strain or the controlled-stress mode of loading, the values of the dissipated energy index of asphalt mixtures are similar. In the area of asphalt, Shan et al.[12] proposed a converting method for the interconversions of the fatigue damage evolution rule under different control modes. Nevertheless, the two investigations are both conducted on the theory of dissipated energy and fracture mechanics. A unified fatigue model was established and the difference of damage evolution under the two control modes was ignored[13]. Furthermore, the effect of multilevel loading on the fatigue damage under two different control modes is a subject of on-going research since whether asphalt has coaxing effects is still unclear.

The objective of this study is to compare the fatigue damage evolution mechanism of asphalt mixtures under two different control modes. A fatigue damage model for asphalt mixtures under controlled-stress and controlled-strain modes was established based on thermodynamics. A suitable dissipative potential function was chosen according to the fatigue characteristic of the asphalt mixtures. Specifically, the damage variable used here was deduced instead of being artificially defined. The difference in damage evolution under different control modes was compared after the model verification. Finally, the influence of multilevel loading on the fatigue damage un-

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der two different control modes was preliminarily interpreted using the model.

1 Theory of Damage Mechanics

The essence of damage is the flaw in micro-structures. The nucleation and development of micro-flaws are defined as the evolution of damage. Based on continuum mechanics, in damage mechanics, a field variable is introduced to describe a damage status. Damage constitutive equations and damage evolution laws are deduced from the laws of thermodynamics.

A damage variable can be directly defined as the volume percentage of microcracks and microvoids occupying the whole bulk[14]. Practically, researchers prefer employing the ratio of timely mechanical parameters, such as modulus and residual strength, to the original ones as a damage variable[8]. However, few of these damage variables are directly deduced from thermodynamics.

Under the condition of a constant temperature, the Helmholtz free energy of elastic materials with brittle failure can be expressed as

$$\varphi = \varphi(\varepsilon, D) \tag{1}$$

where φ is the Helmholtz free energy; ε is the present strain; and D is the damage variable.

Employing the strain equivalence hypothesis, the expression of Helmholtz free energy for damaged materials is

$$\varphi = \varphi(\varepsilon, D) = \frac{1}{2}\,\frac{1}{\rho}(1-D)\varepsilon : E_0 : \varepsilon = (1-D)\varphi_0 \tag{2}$$

where ρ is the density of the material; E_0 and φ_0 are the initial elastic modulus and initial Helmholtz free energy, respectively.

Helmholtz free energy is taken into the Clausius-Duhem inequation:

$$\dot{\varphi} = \sigma : \dot{\varepsilon} - \rho\dot{\varphi} = \left(\sigma - \rho\frac{\partial \varphi}{\partial \varepsilon}\right) : \dot{\varepsilon} - \rho\frac{\partial \varphi}{\partial D}\dot{D} \geqslant 0 \tag{3}$$

where σ is the present stress; $\dot{\varepsilon}$, $\dot{\varphi}$ and $\dot{D}$ are the gradients of the corresponding parameters.

The damage constitutive model can be acquired from the first thermodynamical law:

$$\sigma = \rho\frac{\partial \varphi}{\partial \varepsilon} = (1-D)E_0 : \varepsilon \tag{4}$$

The releasing rate of the damage energy is

$$Y = -\rho\frac{\partial \varphi}{\partial D} = \frac{1}{2}\varepsilon : E_0 : \varepsilon$$

For the restriction $Y\dot{D} \geqslant 0$, the consistency condition is introduced: $F_{\mathrm{D}}(Y, D) = 0$.

The Lagrange multiplier method is employed to solve the consistency condition: $\pi = Y\dot{D} - \dot{\lambda}F_{\mathrm{D}}(Y, D)$. Thus,

$$\dot{D} = \dot{\lambda}\frac{\partial F_{\mathrm{D}}}{\partial Y} \tag{5}$$

where λ is the Lagrange multiplier, and $\dot{\lambda}$ is the gradient of λ.

2 Fatigue Damage Model for Asphalt Mixtures

In this section, a damage variable related to dynamic modulus was deduced from thermo-dynamic laws and a uniform fatigue model for damage under both controlled-stress and controlled-strain modes was established.

2.1 The dissipation potential

As Lemaître[17] promoted, ignoring visco-plasticity of asphalt mixtures, the dissipation potential of damage can be expressed as

$$w = \frac{1}{m+1}A\,Y^{m+1} \tag{6}$$

where w is the dissipation potential; m and A are the non-negative material parameters that characterize damage evolution, which can be determined by experimental data. A similar format was also used by Onifade et al[15].

An associated micro-crack formation and propagation criterion is introduced and expressed as

$$F_{\mathrm{D}} = w(Y) - R(r) = 0 \tag{7}$$

where $R(r)$ is the isotropic damage hardening function.

The resulting damage evolution law is given as a power-law type:

$$\dot{D} = \dot{\lambda}\frac{\partial F_{\mathrm{D}}}{\partial Y} = AY^m\dot{\lambda} \tag{8}$$

The damage hardening variable r can be obtained as a function of the Lagrange multiplier λ and expressed as[16]

$$\dot{r} = -\dot{\lambda}\frac{\partial F_{\mathrm{D}}}{\partial R} = \dot{\lambda} \tag{9}$$

In the previous research, the hardening variable r always had no practical senses[15-17]. Zhu et al. [18] proposed the cohesive force as the hardening variable of asphalt mixtures in the viscoelastic-viscoplastic damage constitutive model. In this damage model, the modulus of resilience μ was employed as the hardening variable to characterize the development of micro-plasticity, which is affected only by damage during a loading cycle. Since the dynamic modulus μ is negatively correlated with D, the damage evolution can be expressed as

$$\dot{D} = -AY^m\dot{\mu} \tag{10}$$

2.2 Damage variable

To simplify the derivation of damage variable, it is assumed that Y and μ are irrelevant. Thus,

$$\int_0^D \mathrm{d}D = \int_{\mu_0}^{\mu} -AY^m \mathrm{d}\mu = -AY^m \int_{\mu_0}^{\mu} \mathrm{d}\mu \tag{11}$$

where μ and μ_0 are the present and the original dynamic modulus, respectively. Then,

$$D = AY^m(\mu_0 - \mu) + c \tag{12}$$

The boundary conditions $\mu = \begin{cases}\mu_0 \to D=0, \\ \mu = \mu_{\min} \to D = 1\end{cases}$ are taken into Eq. (12). So,

$$AY^m = \frac{1}{\mu_0 - \mu_{\min}} \tag{13}$$

where $\mu_{\min}$ is the dynamic modulus at failure.

Substituting Eq. (13) into Eq. (12), the damage variable definition is obtained:

$$D = \frac{\mu_0 - \mu}{\mu_0 - \mu_{\min}} \tag{14}$$

The related dynamic modulus in Eq. (14) can be measured by experiments.

2.3 Fatigue damage evolution

During the process of cyclic loading, the damage variable increases with the increase in the number of loadings. The kinetic law of D under the two control modes can be inferred from Eq. (10).

2.3.1 Fatigue damage evolution under a controlled-stress mode

During each cycle, the irreversible reduction of modulus only occurs during loading process. It is supposed that the gradient of the hardening variable and the gradient of stress is directly proportional[19-20]:

$$\dot{\mu} = -\dot{r} = -K\langle \dot{\sigma} \rangle \tag{15}$$

where K is a material parameter related to D; σ is the timely stress during a loading cycle; and $\langle \dot{\sigma} \rangle = (|\sigma| + \sigma)/2$.

Thus, according to Eq. (10), the damage rate is

$$\dot{D} = AK\left(\frac{1}{2}\frac{\sigma^2}{E(n)}\right)^m \langle \dot{\sigma} \rangle \tag{16}$$

where $E(n)$ is the dynamic modulus during the n-th cycle.

During each stress cycle, the dynamic modulus $E(n)$ is regarded as a constant and the decreasing $E(n)$ after the n-th stress cycle can be expressed as $E_0(1-D)$. The integral of one stress cycle is

$$\int_D^{D+\delta D/\delta n} \mathrm{d}D = \int_0^{\sigma_{\max}} AK\left(\frac{1}{2}\frac{\sigma^2}{E_0(1-D)}\right)^m \mathrm{d}\sigma \tag{17}$$

where $\sigma_{\max}$ is the peak stress and it is a constant.

Furthermore, D can also be regarded as a constant during a stress cycle. Thus,

$$\frac{\delta D}{\delta n} = \frac{AK\sigma_{\max}^{2m+1}}{(2m+1)(2E_0)^m(1-D)^m} \tag{18}$$

Then,

$$\int_0^{D_{nt}} (1-D)^m \mathrm{d}D = \int_0^{nt} \frac{AK\sigma_{\max}^{2m+1}}{(2m+1)(2E_0)^m}\mathrm{d}n \tag{19}$$

The boundary conditions $n = \begin{cases}0 \to D = 0 \\ N \to D = 1\end{cases}$ are taken into Eq. (19), and

$$N = \frac{(2m+1)(2E_0)^m}{(1+m)AK}\sigma_{\max}^{-(2m+1)} \tag{20}$$

where N is the fatigue life of the asphalt mixture under the stress loading level $\sigma_{\max}$.

Thus,

$$D = 1 - \left(1 - \frac{n}{N}\right)^{1/(m+1)} \tag{21}$$

2.3.2 Fatigue damage evolution under a controlled-strain mode

During each controlled-strain fatigue cycle, the irreversible reduction of the dynamic modulus only occurs during loading. According to Eq. (15), due to the simplification that the dynamic modulus during each loading cycle is constant, the gradient of the hardening variable can be expressed as

$$\dot{\mu} = -K\langle \dot{\sigma} \rangle = -K\langle \dot{\varepsilon} \rangle \tag{22}$$

where ε is the timely strain during a loading cycle, and $\langle \dot{\varepsilon} \rangle = (|\varepsilon| + \varepsilon)/2$.

Thus, according to Eq. (10), the damage rate is

$$\dot{D} = AK\left(\frac{1}{2}\varepsilon^2 E(n)\right)^m \langle \dot{\varepsilon} \rangle \tag{23}$$

And the integral of a loading cycle is

$$\int_D^{D+\delta D/\delta n} \mathrm{d}D = \int_0^{\varepsilon_{\max}} AK\left(\frac{1}{2}\varepsilon^2 E_0(1-D)\right)^m \mathrm{d}\varepsilon \tag{24}$$

where $\varepsilon_{\max}$ is the peak strain and it is a constant.

The hypothesis here is that if D keeps constant during each strain cycle, the integral is

$$\frac{\delta D}{\delta n} = \frac{AKE_0^m(1-D)^m\varepsilon_{\max}^{2m+1}}{(2m+1)2^m} \tag{25}$$

Then,

$$\int_0^{D_m} \frac{1}{(1-D)^m}\mathrm{d}D = \int_0^{nt} \frac{AKE_0^m\varepsilon_{\max}^{2m+1}}{(2m+1)2^m}\mathrm{d}n \tag{26}$$

The boundary conditions $n = \begin{cases}0 \to D = 0 \\ N \to D = 1\end{cases}$ are considered, and

$$N = \frac{(2m+1)2^m}{(1-m)AKE_0^m}\varepsilon_{\max}^{-(2m+1)} \tag{27}$$

Thus,

$$D = 1 - \left(1 - \frac{n}{N}\right)^{1/(1-m)} \tag{28}$$

From Eqs. (21) and (28), the fatigue damage evolutions under two different control modes can be generalized with the restriction $m \geqslant 0$.

$$D=\begin{cases}1-\left(1-\dfrac{n}{N}\right)^{1/(1+m)} & \text{controlled stress mode}\\ 1-\left(1-\dfrac{n}{N}\right)^{1/(1-m)} & \text{controlled strain mode}\end{cases} \tag{29}$$

3 Model Calibration and Parameter Identification

To ensure that the fatigue failure mode of asphalt mixtures can be classified into quasi-brittle damage, the experimental data used in this paper are from the following situations: 1) Under the controlled-stress mode at a moderate temperature of 20 ℃, visco-plastic deformation is insignificant and resilient strain occupies the most during the process of fatigue[8]; 2) Under the controlled-strain mode at a moderate temperature of 15 ℃, the mode belongs to high-cycle fatigue, which means that the fatigue life of asphalt mixtures is greater than 10 000 cycles[9]. For both experiments, the loading rate was set to be 10 Hz and the load form is half-sinusoidal wave. The properties of the asphalt mixtures used in the experiments can be found in the original dissertation.

3.1 Fatigue damage model under a controlled-stress mode

The fatigue damage model for asphalt mixtures under a controlled-stress mode was calibrated using the experimental data from Liu[8]. The direct tension test was employed for controlled-stress fatigue experiment under five different stress levels. The specimens were cut from rutting plates to the following dimensions: 250 mm × 50 mm × 50 mm. The fatigue test equipment was MTS-810. No fewer than three specimens were tested under each stress level. The average dynamic modulus during the cyclic loading process was recorded as shown in Fig. 1. As shown in Tab. 1, when the fatigue life ratio is 0. 1, the dynamic modulus was chosen as the initial modulus. The average dynamic modulus of the last 5 cycles was chosen as the critical modulus of rupture.

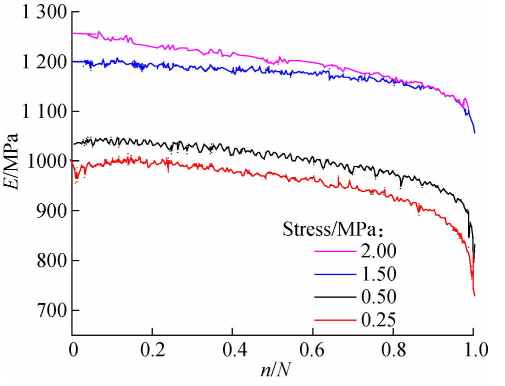

Fig. 1 The dynamic modulus attenuation rule under controlled-stress mode

The static loading strength f is 1. 228 MPa. The dynamic resilient modulus is used to calculate the damage variable as Eq. (14). The results are shown in Fig. 2. The damage variables are calculated and the damage evolution laws are predicted under different stress levels.

To determine m, it is supposed that $a=\dfrac{1}{m+1}$ is a power function of the stress level. The stress level is described as $S=\dfrac{\sigma_{\max}}{f}$. The fitting result is shown in Fig. 3.

Thus, the fatigue damage evolution law of the asphalt mixtures under a controlled-stress mode can be expressed as follows:

Tab. 1 Initial and critical moduli under controlled-stress mode

Stress level σ/MPa	Number of failure cycle N_f	Initial modulus			Critical modulus		
		μ_0/MPa	Mean value of μ_0/MPa	C_v	$\mu_{\min}$/MPa	Mean value of $\mu_{\min}$/MPa	C_v
0. 25	154 449	1 056	1 080	0. 02	597	586	0. 13
	200 337	1 073			491		
	61 705	1 078			670		
	72 032	1 114			584		
0. 5	6 874	1 163	1 092	0. 09	623	639	0. 03
	5 447	1 021			631		
	22 454	1 085			663		
1. 5	552	1 177	1 199	0. 02	1 045	1 043	0. 01
	406	1 200			1 051		
	469	1 221			1 033		
2. 0	223	1 210	1 224	0. 02	1 053	1 077	0. 02
	227	1 208			1 074		
	180	1 253			1 105		

Note: C_v is the coefficient of variance.

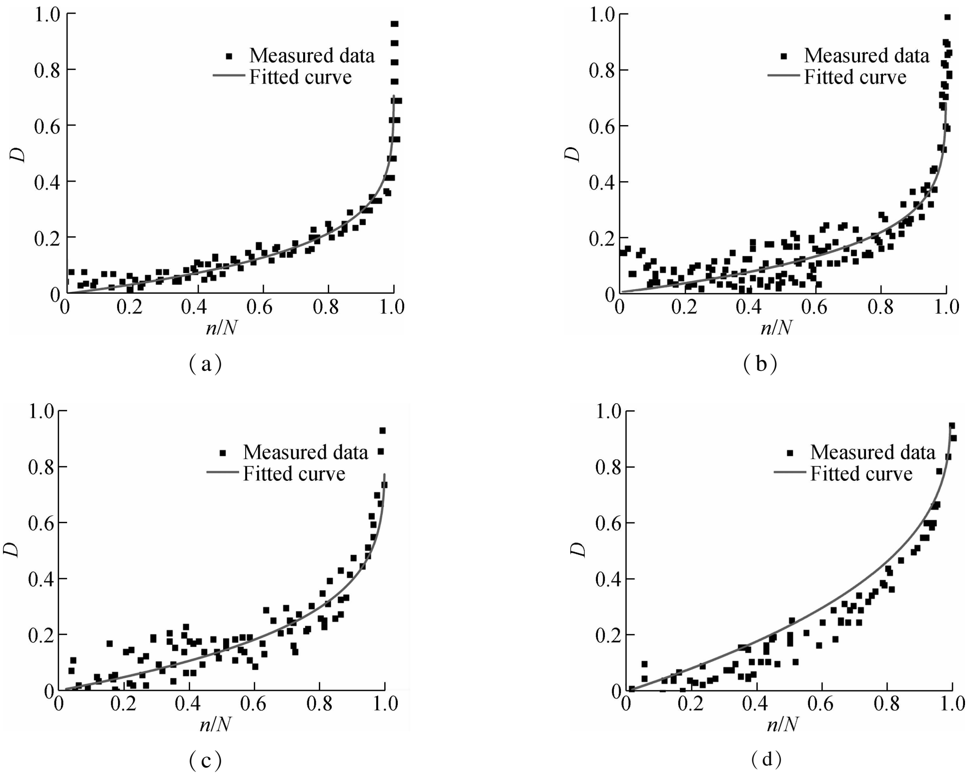

Fig. 2 The damage evolution laws under different stress levels. (a) $\delta = 0.25$ MPa, $m = 5.620$, $R^2 = 0.807\ 8$; (b) $\delta = 1.00$ MPa, $m = 4.812$, $R^2 = 0.986$; (c) $\delta = 1.50$ MPa, $m = 3.525$, $R^2 = 0.985$; (d) $\delta = 2.00$ MPa, $m = 1.600$, $R^2 = 0.800$

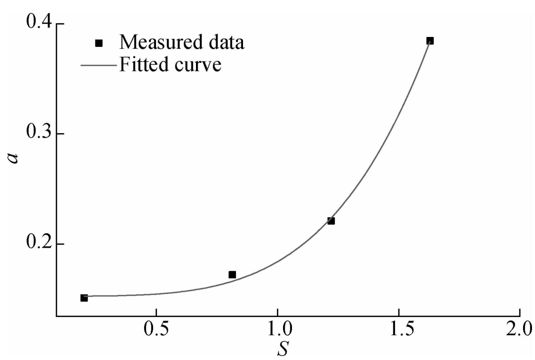

Fig. 3 The relationship between a and S under $a = 0.152\ 7 + 0.31\ 23S^{4.105\ 0}$, $R^2 = 0.999$

$$D = 1 - \left(1 - \frac{n}{N}\right)^{0.152\ 7 + 0.031\ 23S} \tag{30}$$

where $S = \sigma_{max}/1.228$.

3.2 Fatigue Damage Model under a Controlled-Strain Mode

The experimental data under four different strain levels were used to calibrate the fatigue damage model under a controlled-strain mode[9]. The four-point bending test method was adopted. The dimension of the specimen is 380 mm × 50 mm × 65 mm. The fatigue test equipment is Cooper NU-14. The average dynamic modulus during the cyclic loading process is recorded as shown in Fig. 4. Tab. 2 is the mean value of the critical modulus. The dynamic modulus at the 100th cyclic loading is chosen as the initial modulus. The inflection point on the curve of dynamic modulus is set as the critical modulus of rupture. The damage variables calculated and the damage evolution laws predicted are shown in Fig. 5. It can be seen that the fitting effect is not in competition with that under the stress-controlled mode.

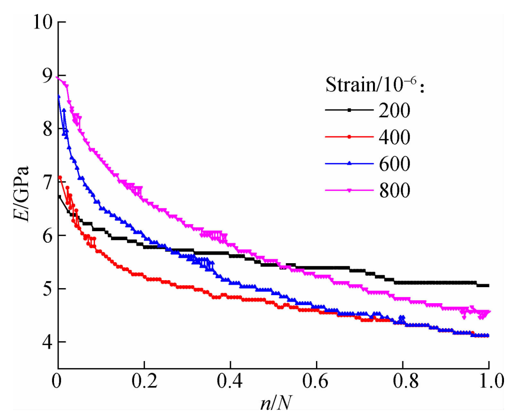

Fig. 4 The dynamic modulus during the loading process under controlled-strain mode

Tab. 2 Mean value of initial and critical moduli under controlled-strain mode

σ/MPa	N_f	μ_0/MPa	μ_{min}/MPa
200	769 560	7 169	5 685
400	177 917	7 061	4 500
600	28 667	7 825	4 263
800	10 540	8 997	4 726

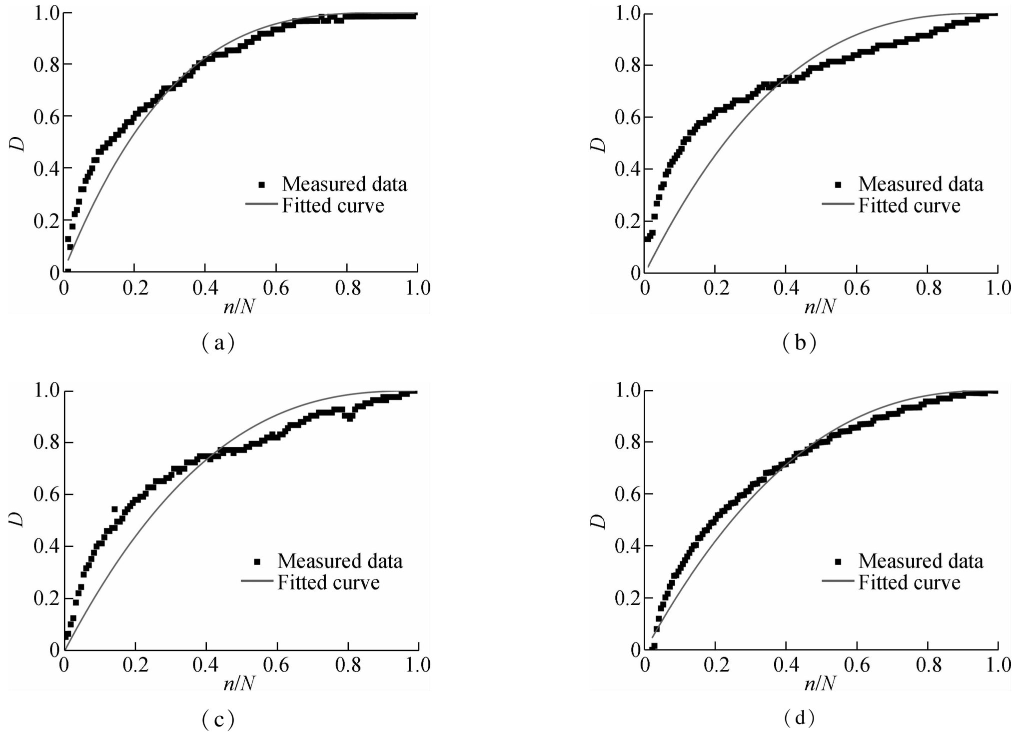

Fig. 5 The damage evolution laws under different strain levels. (a) $\varepsilon = 2\times10^{-4}$, $m = 0.7064$, $R^2 = 0.996$; (b) $\varepsilon = 4\times10^{-4}$, $m = 0.6627$, $R^2 = 0.975$; (c) $\varepsilon = 6\times10^{-4}$, $m = 0.6147$, $R^2 = 0.983$; (d) $\varepsilon = 8\times10^{-4}$, $m = 0.5934$, $R^2 = 0.958$

As shown in Fig. 5, the measured damage evolution is faster than that of the predicted result in the initial. The gap between them becomes smaller when the cycle number increases. It is because only the flexural modulus is used in representation of damage. The flexural modulus is calculated by the maximum tensile stress and the maximum strain of the beam during the bending test. However, the stress state is more compressive than that in the direct tensile test. According to Ref. [21], the attenuation laws of tensile modulus and compressive modulus are different. Thus, a more accurate damage model considering complex stress state should be established for the bending test in the future. Employing the deduced model, the correlation between m and strain level is shown in Fig. 6.

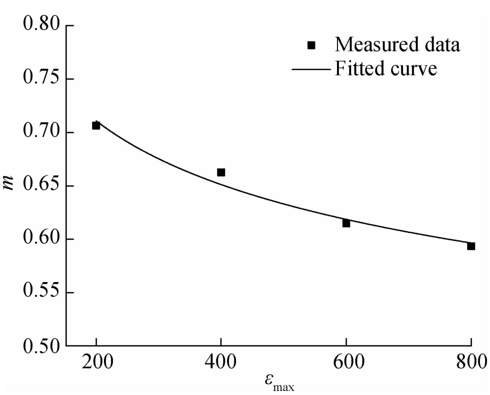

Fig. 6 The relationship between m and strain level under $m = 0.391\varepsilon_{max}^{-0.127}$, $R^2 = 0.965$

Thus, the fatigue damage evolution law of the asphalt mixture under a controlled-strain mode can be expressed as

$$D = 1 - \left(1 - \frac{n}{N}\right)^{1/(1-1.391\varepsilon_{max}^{-0.127})} \tag{31}$$

3.3 Discussion

Considering the condition that $m \geqslant 0$, $D \geqslant 0$ and $\dot{D} \geqslant 0$, the characteristic curves of damage evolution with the increasing number of loading cycles are shown in Fig. 7.

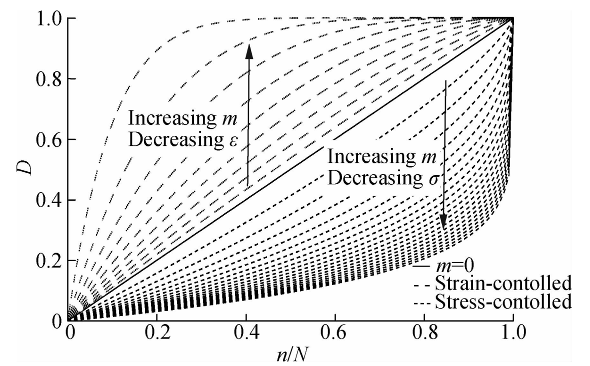

Fig. 7 The damage evolution laws under two control modes

As shown in Fig. 7, the fatigue damage model interprets the kinematic laws of damage under two different control modes. During the processes of stress-controlled loading, damage evolves slowly in the initial stage while it increases abruptly before fracture. Inversely, under a strain-controlled mode, the damage evolution rate is high at first. A relatively stable platform appears in the latter part of the evolution curve.

When $m=0$, the fatigue damage model is the same as the Miner fatigue theory. It corresponds to the situation when a loading level is a specific value or large enough to destroy the specimen at once.

4 Interpretation in Multilevel Loading

The fatigue damage model can also interpret the effect of different loading sequences on the fatigue life of asphalt mixtures under two different control modes. The damage equivalence principle is used here to calculate the equivalent cycle numbers.

As shown in Fig. 8, suppose that stress σ_1 has been cyclically loaded for n_1 times, the fatigue life of the second stress level σ_2 needs to be predicted. To reach the same damage level under σ_2, the equivalent cycle numbers of n_1 is

$$D(n_e)=1-\left(1-\frac{n_1}{N_1}\right)^{1/(1-m_1)}=1-\left(1-\frac{n_e}{N_2}\right)^{1/(1-m_2)} \tag{32}$$

$$n_e=N_2\left[1-\left(1-\frac{n_1}{N_1}\right)^{(1-m_2)/(1-m_1)}\right] \tag{33}$$

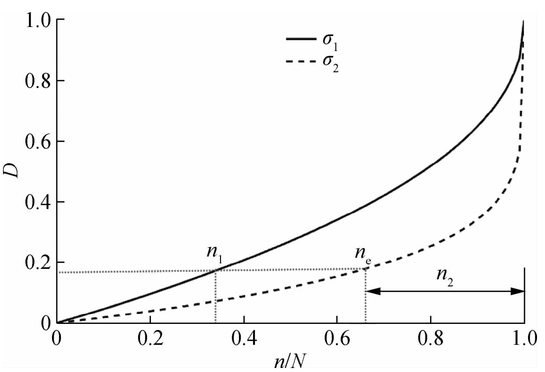

Fig. 8 Prediction of fatigue life under multilevel loading

The number of residual cycle is $n_2=N_2-n_e$. The calculation process is the same as that under a controlled-strain mode.

The results $\frac{n_1}{N_1}+\frac{n_2}{N_2}$ predicted under two control modes is shown in Tab. 3.

Tab. 3 Normalized fatigue life under two control modes

Loading sequence	Controlled-stress mode	Controlled-strain mode
Low→High level	>1	<1
High→Low level	<1	>1

The model interprets the fact that under a controlled-stress mode, a sequence from a low loading level to a high level can prolong fatigue life, which is similar to the training effect of metal. While under a controlled-strain mode, a sequence from a low level to a high loading level accelerates the damage evolution[9]. Further experimental validation will be conducted in the future.

5 Conclusions

1) A uniform fatigue damage model under two control modes is established based on thermodynamic laws. The damage variable related with dynamic modulus is deduced: $D=\frac{\mu_0-\mu}{\mu_0-\mu_{\min}}$.

2) The damage evolution law of asphalt mixtures under controlled-stress and controlled-strain modes can be interpreted by the model $D=1-\left(1-\frac{n}{N}\right)^{1/(1\pm m)}$. As the loading level decreases, the value of m increases.

3) The sequence of multilevel loading has inverse effects on the fatigue damage evolution under two control modes. A sequence from a low loading level to a high level can prolong fatigue life under a controlled-stress mode while it can accelerate the damage evolution under a controlled-strain mode.

4) The fatigue damage model for asphalt mixtures is simple enough for engineering use. However, in future research, the viscous dissipated energy and heat dissipation should be considered in the whole free energy.

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应力、应变控制模式下沥青混合料疲劳损伤模型

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摘要:推导了应力控制和应变控制模式下沥青混合料的热力学疲劳损伤模型. 选取回弹模量作为损伤硬化参数,提取出一个与动态模量相关的损伤变量作为评估指标. 所获得的2种控制模式下的损伤演化规律中保留了一个与加载水平有关的非负材料参数 m,具有与Chaboche疲劳模型相似的形式. 在每种控制模式下,采用4组加载水平所获得的疲劳损伤试验数据校核模型并确定参数. 由此发现参数 m 与荷载水平呈指数关系. 利用所获得的演化方程可阐述2种控制模式下的损伤演化差异,即在应变控制模式下,疲劳损伤演化由快变慢,在应力控制模式下情况则相反. 通过利用损伤等效原理计算等效荷载循环次数,该模型还解释了在多级加载条件下,2种控制模式的疲劳演化差异:在应变控制的疲劳模式下,所加荷载等级按照从低荷载到高荷载的顺序会加速损伤演化,而在应力控制的疲劳模式下,相反的荷载施加顺序可延长疲劳寿命.

关键词:沥青混合料; 疲劳模型; 控制模式; 连续损伤力学; 动态模量

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