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Reflective cracking viscoelastic response of asphalt concrete under dynamic vehicle loading

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Abstract: In order to investigate the mechanical response of reflective cracking in asphalt concrete pavement under dynamic vehicle loading, a finite element model is established in ABAQUS. The viscoelastic behavior is described by a prony series which is calculated through nonlinear fitting to the creep test data obtained in the laboratory. Based on the viscoelastic theory, the time-temperature equivalence principle, fracture mechanics and the dynamic finite element method, both the J-integral and the mix-mode stress intensity factor are utilized as fracture evaluation parameters, and a half-sine dynamic loading is used to simulate the vehicle loading. Finally, the mechanical response of the pavement reflective cracking is analyzed under different vehicle speeds, different environmental conditions and various damping factors. The results indicate that increasing either the vehicle speed or the structure damping factor decreases the maximum values of fracture parameters, while the structure temperature has little effect on the fracture parameters. Due to the fact that the vehicle speed can be enhanced by improving the road traffic conditions, and the pavement damping factor can become greater by modifying the components of materials, the development of reflective cracking can be delayed and the asphalt pavement service life can be effectively extended through both of these ways.

Key words: asphalt pavement; viscoelastic; finite element method; reflective cracking; dynamic vehicle loading

Asphalt concrete is widely used all over the world as a kind of pavement surface material. In several previous pavement research projects, asphalt concrete was regarded as a linear elastic material. The subsequent analysis of surface cracking and reflective cracking was based on linear elastic fracture mechanics. However, asphalt concrete at high temperature, room temperature, and even low temperature, exhibits viscoelastic and visco-plastic behaviors[1]. Thus, researchers have made efforts to analyze the asphalt concrete's viscoelastic and visco-plastic properties. Lu et al. [2] regarded asphalt concrete as a no damage and homogeneous viscoelastic-plastic material. Based on the Perzyna theory, numerical methods and analytical methods are utilized respectively to analyze the test results, and the analysis results show that these two methods have preferable coherence. Qian et al. [3] utilized a generalized Maxwell model to simulate the viscoelastic behavior of asphalt concrete and obtained the stiffness modulus in temperature and time domains through experiments and time-temperature equivalent principles. Huang et al. [4] established an increment-type viscoelastic constitutive relationship of asphalt concrete. They analyzed a semi-rigid base with an asphalt concrete overlay and included surface cracking and reflective cracking by using thermal viscoelastic fracture theory.

The finite element method (FEM) provides a good means to simulate the structural viscoelastic response of asphalt concrete pavement. Based on previous laboratory research, this paper provides a dynamic mechanism and time-temperature equivalent principle for asphalt concrete, and builds a viscoelastic FEM model of the pavement structure. The structural responses under different dynamic loadings and environmental conditions are analyzed.

1 Viscoelastic Fundamental Theory

The finite element commercial software ABAQUS assumes that the viscoelastic material is defined by a prony series expansion of the dimensionless relaxation modulus[5]. The formula of a prony series can be expressed as

$$g(t) = 1 - \sum_{i=1}^{n} g_i (1 - e^{-t/\tau_i}) \tag{1}$$

where g_i is the normalized relaxation modulus, $g(t) = E(t)/E_0$, $E_0 = E(0)$. Both g_i and τ_i are material constants, and they can be obtained by fitting the laboratory test data.

If creep test data are specified, ABAQUS will calculate the terms in the prony series automatically. Actually, the results obtained from the automatic transformation process are not very precise. Usually, the creep test data are converted to relaxation data through the convolution integrals as

$$\int_0^t j(t-s) g(s) \mathrm{d}s = t \tag{2}$$

where $g(t)$ is the normalized relaxation modulus and $j(t)$ is the normalized creep compliance. The relaxation data are fitting to prony series.

Viscoelastic materials obey the time-temperature equivalent principle, which can be expressed as

$$E(T, t) = E\left(T_0, \frac{t}{\alpha_T}\right) \tag{3}$$

where α_T is the shift factor, which is explained in the paragraph below. After obtaining the relaxation function and the shift factor expression of asphalt concrete under a reference temperature T_0 through laboratory testing, the relaxation functions at any time under any temperature can be obtained.

There are two common methods to calculate the shift factor: the WLF equation and the Arrhenius equation. In the research of the low-temperature cracking problem of asphalt concrete, the Arrhenius equation is utilized more frequently.

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Its expression is as follows:

$$\alpha_T = \exp\left[\delta H \frac{(1/T - 1/T_0)}{R}\right] \quad (4)$$

where T is the temperature, δH is the activation energy, and R is the molar gas constant, 8. 314 J/(mol·K).

Activation energy is required when the Arrhenius equation is applied. Zheng et al. [6] expressed the formula of the shift factor of an asphalt mixture when the reference temperature $T_0 = 15$ ℃,

$$\alpha_T = \exp\left[\frac{40\ 000 \times 4.18}{8.314}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \quad (5)$$

2 Finite Element Model

The semi-rigid base pavement is simulated as a plane-strain multilayer system[7]. The purpose of this study is to investigate the reflective cracking viscoelastic response of asphalt concrete pavement under periodic loadings. Thus, the interlayer contact conditions are assumed to be continuous, and the calculation model of the reflective cracking under vehicle loading is shown in Fig. 1.

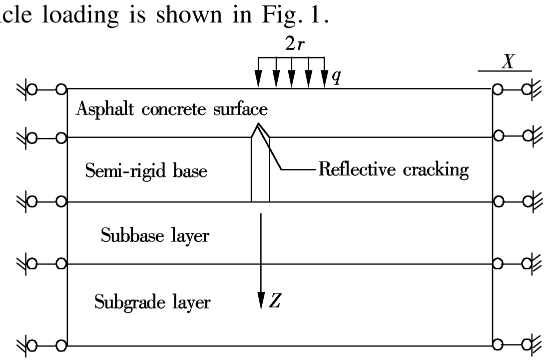

Fig. 1 Schematics for pavement under dynamic loading

The distributed load is set at $q = 0.707$ MPa with a contact range of $2r = 2 \times 10.65$ cm. The width of the existing crack in the base layer is 4 mm, and the length of the reflective cracking in the asphalt concrete layer is 4 cm.

A prony series with six terms is used to describe the relaxation behavior of asphalt concrete. This paper utilizes the fitting method of viscoelastic parameters presented by Lü et al[8]. The viscoelastic parameters of common 70# asphalt concrete AC-20 is shown in Tab. 1.

Tab. 1 Asphalt concrete AC-20 fitting values of prony series

g_i	τ_i
0. 140 66	4. 626 49
0. 092 68	1 080. 488 51
0. 151 78	0. 376 00
0. 368 30	44 856. 874 72
0. 123 99	28. 637 78
0. 122 14	181. 403 86

The fitting correlation coefficient between the parameters in Tab. 1 and the test data is 0. 999 98, providing a suitable accuracy for implementation into ABAQUS for the pavement simulation.

The pavement dimensions and properties are shown in Tab. 2[9].

Tab. 2 Standard structure parameters

Pavement layer	Thickness/cm	Modulus/MPa	Poisson ratio
Asphalt concrete layer	18		0. 35
Semi-rigid base	30	5 000	0. 15
Subbase layer	30	1 000	0. 20
Subgrade		60	0. 35

3 Dynamic Vehicle Loading

In this paper, the vehicle load is considered dynamic, and the simplified form of the dynamic load presented in the Kenlayer programme developed by Huang[10] is utilized. The vehicle dynamic load is a semi-sinusoidal distributed load on an equivalent circular. The loading formula is

$$q(t) = q_{\max}\sin^2\left(\frac{\pi}{2} + \frac{\pi t}{T}\right) \quad (6)$$

where T is the loading period, and $q_{\max}$ is the amplitude of the distributed load, set at 0. 7 MPa.

4 Pavement Structure Vibration Analysis

In order to analyze the pavement response under dynamic vehicle loading, the governing equation is expressed as[11]

$$\boldsymbol{M}\ddot{\boldsymbol{u}} + \boldsymbol{C}\dot{\boldsymbol{u}} + \boldsymbol{K}\boldsymbol{u} = \boldsymbol{F}(t) \quad (7)$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ represent the mass matrix, the damping matrix and the stiffness matrix, respectively; $\ddot{\boldsymbol{u}}, \dot{\boldsymbol{u}}, \boldsymbol{u}$ are the acceleration vector, the velocity vector and the displacement vector, respectively; $\boldsymbol{F}(t)$ expresses the dynamic loading vector that acts on nodes. The consistent mass matrix is used in the FEM calculation of this paper and it can be expressed as

$$\boldsymbol{C} = \alpha\boldsymbol{M} + \beta\boldsymbol{K} \quad (8)$$

where α and β are the constant coefficients related to the inherent frequencies and the damping factors of the structure. These coefficients can be determined by the inherent frequencies and the damping ratio of any two vibration modes,

$$\alpha = \frac{2\omega_i\omega_j(\omega_j\zeta_i - \omega_i\zeta_j)}{\omega_j^2 - \omega_i^2}, \quad \beta = \frac{2(\omega_j\zeta_j - \omega_i\zeta_i)}{\omega_j^2 - \omega_i^2} \quad (9)$$

where ω_i, ω_j are the natural cyclic frequencies of these two modes; ζ_i, ζ_j are the corresponding damping factors.

5 Influence of Vehicle Speed

Stress and strain are not suitable for evaluating the mechanical response around the tip of cracking in a structure. Thus, the stress intensity factor and J-integral are used in this paper. Both parameters are the basic parameters in fracture mechanics[12].

Fig. 2 shows that the reflective cracking parameters change as the dynamic vehicle loading moves on the pavement under the reference temperature 15 ℃.

The results indicate that there is a similar trend between the reflective cracking parameters and the loading function. As the vehicle speed increases, the time history curve of the parameters gradually moves forward. The J-integral and the mixed-mode stress intensity factor K^* changes in a similar fashion since they all decrease as the speed increases. As a representative value, the maximum value of K^* is reduced from 0.080 2 to 0.058 09 MPa·m$^{1/2}$ while the speed increases from 20 to 120 km/h. There is a decrease of 27.6%.

According to the above data, there is an optimal speed for maintaining pavement performance while allowing for driver safety. Most of the roads in China have an upper-limit speed to ensure the safety of vehicles and passengers. The upper-limit speed can be enhanced by improving the road conditions. One effective method is to build freeways. Therefore, building more freeways and making more vehicles run on freeways can well relieve the reflective cracking damage on asphalt concrete pavements.

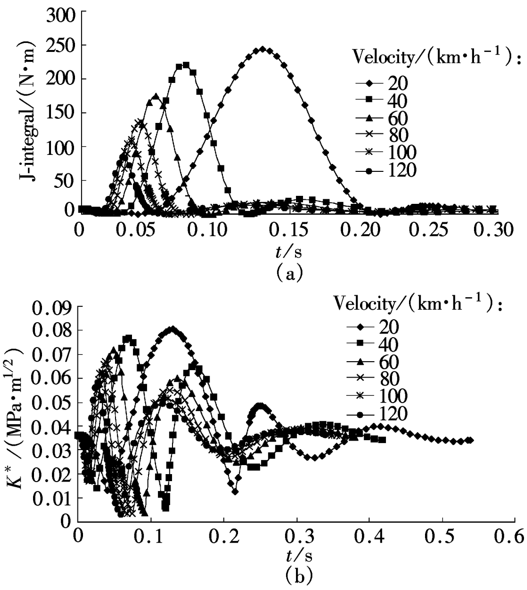

Fig. 2 Time-history curves of reflective cracking parameters under different vehicle speeds. (a) J-integral; (b) Mix-mode stress intensity factor K^*

6 Response of Dynamic Loading Under Various Temperatures

In this section, the temperature influence on the properties of asphalt concrete is considered, but thermal stress is not considered. The vehicle speed is taken as 80 km/h.

The analysis results are shown in Fig. 3. At different reference temperatures, the cracking parameters exhibit periodic variation and the time history curves are similar. In fact, the maximum value of the cracking parameters and the moments at which they appear are very similar. This phenomenon explains that the reflective cracking parameters induced by dynamic loadings cannot be significantly influenced by the variations in material properties induced by temperature differences.

The results show that no matter whether in winter or in summer, the reflective cracking damages induced by vehicle loadings do not have significant differences. Researches on temperature influence must be focused on the thermal stress analysis.

7 Influence of Damping Factors

In this section, the influence of damping on the response of pavement structure is investigated. The reference temperature is set as 15 ℃ and the vehicle speed is 80 km/h. As shown in Fig. 4, the reflective cracking parameters decrease and the maximum value moves backward as the damping ratio increases when $\zeta = 0$. At this point, the pavement structure has a high vibration, but the decay rate is very small. Because of the pavement vibration after dynamic loading, J-integral and K^* reach high initial values, which promote the development of the reflective cracking. As the damping ratio increases, the pavement structure vibration attenuates rapidly and the maximum value of K^* decreases from 0.114 1 to 0.036 2 MPa·m$^{1/2}$. In addition, when ζ increases from 0 to 0.2, the maximum value of K^* decreases by 68.3%.

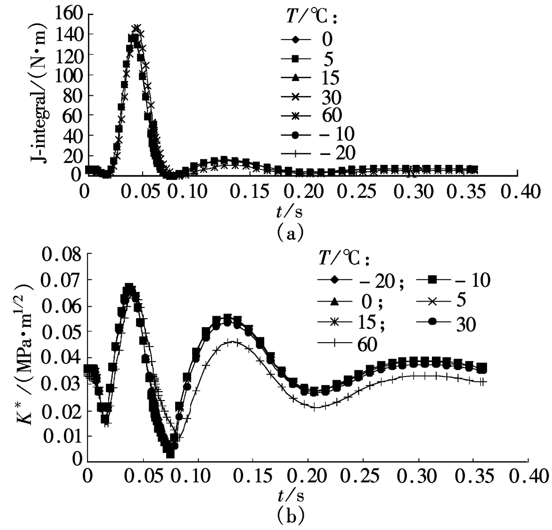

Fig. 3 Time-history curves of loading fracture parameters under different reference temperatures. (a) J-integral; (b) Mix-mode stress intensity factor K^*

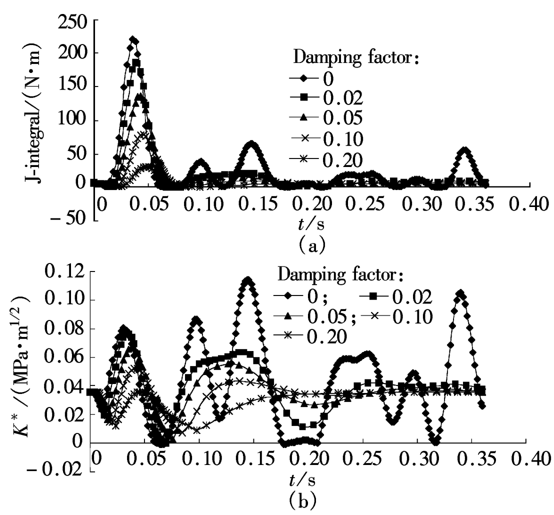

Fig. 4 Time-history curves of reflective cracking parameters with different damping factors. (a) J-integral; (b) Mix-mode stress intensity factor K^*

According to the above results, it is obvious that improving the damping ratio of materials can effectively reduce the values of reflective cracking parameters. Thus, adding materials with a high damping factor into asphalt concrete can be very helpful to delay the development of reflective cracking.

8 Conclusion

The primary purpose of this study is to investigate reflective cracking of asphalt concrete under periodic vehicle loading. The finite element method (FEM) and the viscoelastic theory are used to simulate the response of the pavement structure. The results indicate that the reflective cracking parameters J-Integral and K^* represent periodic variation as the load changes. The time-history curve of cracking parameters moves forward and the maximum value decreases as the vehicle speed increases. Also, increasing the vehicle speed is beneficial to extending the service life of the pavement. Due to the high upper-limit speed, freeways should well reduce the reflective cracking damage to asphalt concrete pavement. Thus, it may be an effective method to extend the pavement service life by building a road as a freeway.

Temperature variations can hardly influence the reflective cracking parameters which are caused by vehicle dynamic loadings. This result indicates that no matter whether in winter or in summer, the reflective cracking damages induced by vehicles does not have any significant differences. Researches on temperature influence should be focused on the thermal stress analysis.

In regards to loading periods, the vibration attenuates more rapidly as the pavement damping factor increases. In addition, the maximum value of each cracking parameter becomes smaller as the pavement factor increases, so the addition of materials with a large damping factor can delay the development of reflective cracking.

References

[1] Zhang Xiaoning. *The theory and application of viscoelastic mechanics for asphalt and asphalt concrete* [M]. Beijing: China Communications Press, 2006: 1 − 6. (in Chinese)

[2] Lu Y, Wright P J. Numerical approach of visco-elastoplastic analysis for asphalt mixture [J]. *Computer and Structures*, 1998, **69**(2): 139 − 147.

[3] Qian Guoping, Guo Zongyin, Zheng Jianlong, et al. Calculation for thermal stress of asphalt pavement under environment conditions based on thermal viscoelastic theory [J]. *Journal of Tongji University: Natural Science*, 2003, **31**(2): 150 − 155. (in Chinese)

[4] Huang Zhiyi, Wang Jinchang, Zhu Xiangrong. Viscoelastic fracture analysis of asphalt concrete pavement with cracks [J]. *China Journal of Highway and Transport*, 2006, **41**(1): 114 − 119. (in Chinese)

[5] Hibbitt, Karlsson, Sorensen, Inc. *ABAQUS/Standard user's manual*; *ABAQUS/CAE user's manual*; *ABAQUS keywords manual*; *ABAQUS theory manual* [M]. Hibbitt, Karlsson, Sorensen, Inc, 2002.

[6] Zheng Jianlong, Zhou Zhigang, Ying Ronghua. Numerical analysis of asphalt pavement thermal stress [J]. *Journal of Changsha Communications University*, 2001, **17**(1): 29 − 32. (in Chinese)

[7] Li Qiang. Research on the design indexes of reflective cracking in semi-rigid base asphalt pavements [D]. Nanjing: School of Transportation of Southeast University, 2007. (in Chinese)

[8] Lü Songtao, Tian Xiaoge, Zheng Jianlong. Test of viscoelastic parameters of bituminous mixture and its application in the constitutive model [J]. *Journal of Changsha Communications University*, 2005, **21**(1): 37 − 42. (in Chinese)

[9] Zhao Yanjing. Research on anti-cracking performance of bottom layer for semi-rigid base asphalt pavements [D]. Nanjing: School of Transportation of Southeast University, 2008. (in Chinese)

[10] Huang Yangxian. *Pavement analysis and design* [M]. Beijing: China Communications Press, 1994: 63 − 64. (in Chinese)

[11] Zhang Wenyuan. *Dynamic mechanics analysis of finite element method in ABAQUS* [M]. Hong Kong: China Tushu Publishing Limited, 2005: 49 − 58. (in Chinese)

[12] Ramsamooj D V, Lin G S. Stress at joints and cracks in highway and airport pavements [J]. *Engineering Fracture Mechanics*, 1999, **60**(6): 507 − 518.

动载作用下沥青混凝土路面反射裂缝粘弹性响应分析

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摘要：为研究沥青混凝土路面内部反射裂缝在动态荷载作用下的力学响应，采用 ABAQUS 有限元软件建立分析模型．通过对沥青混凝土蠕变试验曲线进行非线性拟合，得到 Prony 级数以赋予模型中面层粘弹性材料属性．基于粘弹性理论、时温等效原理、断裂力学及动力学有限元方法，利用半正弦荷载模拟动荷载作用，以断裂参数 J 积分以及复合应力强度因子作为裂缝扩展评价指标，对路面反射裂缝在不同车速、不同环境温度以及不同材料阻尼系数等条件下的力学响应进行分析．计算结果表明：反射裂缝断裂参数值随车辆行驶速度的增加而减小；不同结构温度下的断裂参数差异不明显；断裂参数曲线随阻尼比的增大而逐渐后移，且最大值逐渐减小．因此，通过改善车辆行驶条件以提高车辆行驶速度，以及通过改进材料组成来增大沥青混凝土阻尼系数，都能够有效延缓反射裂缝扩展速度，延长路面的正常使用寿命．

关键词：沥青路面；粘弹性；有限元方法；反射裂缝；动态荷载

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