Study on Fracture Characteristics of Asphalt Pavement with Longitudinal and Transverse Cracks under the Influence of Real Temperature Field

Kang Zhao¹, Guannan Yan¹, Jianfeng Li¹ and Linbing Wang²,³*

¹ National Center for Materials Service Safety, University of Science and Technology Beijing, Beijing, China
² Joint USTB-Virginia Tech Lab on Multifunctional Materials, University of Science and Technology Beijing, Beijing, China
³ Virginia Tech, Blacksburg, USA
Email: wangl@vt.edu

Abstract. In order to study the influence of the actual temperature field of asphalt pavement on the fracture characteristics of asphalt pavement structure, the finite element (FE) software ABAQUS is used to simulate the temperature field of asphalt pavement in summer and winter, and then the temperature field corresponding to specific time period is introduced into the thermal mechanical coupling analysis. The effects of different loading speeds (10, 20 m/s) and different loads sizes (0.7, 1.2 MPa) on the stress intensity factors (SIF) of top-down (longitudinal) and base reflective (transverse) cracks were studied, and the crack propagation characteristics were discussed. It is found that in summer, the top-down cracks in the surface layer mainly propagate in mode II, and the value increases with the increase of load. In winter, the low temperature promotes the propagation of mode I crack, and the sign of KⅢ value in winter is opposite to that in summer. For the reflection crack of base course, the coupled field promotes the propagation of mode II crack at high temperature in summer. However, in winter, the base is prone to mode I expansion, and increases with the increase of load. When there is no coupling field, the speed has little effect on crack propagation, but the location of SIF peak value changes in time. In the coupled field, the SIF value increases with the decrease of speed. Therefore, considering the real temperature field, heavy load and slow speed have the greater damage to the pavement.

Keywords. Actual temperature field, thermal mechanical coupling, stress intensity factor, top-down crack, base reflection crack.

1. Introduction

At present, semi-rigid base is mostly used in asphalt pavement base in China [1], but it is easy to produce temperature shrinkage and dry shrinkage cracks. Under the influence of traffic load and temperature stress, the pavement is also easy to form cracks near the wheel track belt on the surface. These cracks continuously expand down with time. These cracks are called "Top-Down cracking (TDC)" [2], the crack from top to bottom has been gradually considered as a main disease form of asphalt pavement by pavement workers at home and abroad [3]. As for TDC, Qiao et al [4] used ABAQUS software to build the temperature load coupling field asphalt pavement structure model, and analysed the SIFs of different asphalt base structures and the mechanical indexes of different positions of structural layers. Base reflection crack is the main form of initial cracking of semi-rigid base asphalt...
pavement. Zhao et al [5] studied the dynamic response of viscoelastic asphalt pavement containing cracks, and discussed the effect of vehicle speed, damping ratio and other related factors on the SIF at the crack tip. Fracture mechanics is a common method to analyse pavement structure with cracks. Because the mechanical properties of asphalt mixture in asphalt pavement structure are affected by temperature and driving speed, the change of mechanical properties of asphalt mixture will affect the stress distribution in the pavement structure and crack tip, and then affect the generation and expansion of cracks. In the current design method of asphalt pavement in China, the compressive resilient modulus is used as the basic mechanical parameter of asphalt mixture [6], but it cannot well reflect the influence of temperature and driving speed on the mechanical properties of asphalt mixture [7], which limits the objectivity of the analysis. At present, most of the studies on temperature are characterized by the change of modulus at different temperatures, and the real temperature field is not really introduced into the calculation, which is quite different from the actual situation.

In this paper, a FE model of asphalt pavement structure is established. The influence of temperature and vehicle load on mechanical parameters of asphalt mixture is comprehensively reflected by introducing real pavement temperature field and moving load. According to the fracture mechanics method, the cracking mechanism and fracture characteristics of top down and base reflective cracks of asphalt pavement under the coupling of temperature stress and moving load are analysed, which provides the basis for more scientific pavement structure analysis and design.

2. Thermal Mechanical Coupling Model Considering Real Temperature Field of Asphalt Pavement

2.1. Coupling of Pavement Temperature Field and Force Field

When the pavement structure (thickness, thermal characteristics, etc.) is determined, the main environmental factors affecting the temperature field are daily maximum temperature $T_{\text{max}}^a$, daily minimum temperature $T_{\text{min}}^a$, daily total solar radiation $Q$, effective sunshine time $c$ and daily average wind speed $v_w$ [8]. In this study, the temperature field of road surface is simulated by ABAQUS software, in which solar radiation can be defined by load module in ABAQUS and realized by subroutine DFLUX; air temperature and convective heat exchange are realized by interaction module and subroutine FILM in ABAQUS [9]. Then, the temperature field data is coupled into the force field simulation. The pavement temperature field and pavement mechanics model should be consistent. In order to correctly import the temperature field data in thermal coupling, the number of units in the two models is also consistent. In this paper, the sequential coupling method is used [10]. Firstly, the temperature field data of asphalt pavement is calculated, and then the temperature field data file ODB is imported into the calculation process of force field. The specific method is shown in figure 1.

![Figure 1. Schematic diagram of thermal mechanical coupling analysis of Asphalt Pavement.](image-url)
2.2. Material Properties of Asphalt Pavement

In this study, viscoelasticity of materials is considered for asphalt pavement, which is input in the form of Prony Series in ABAQUS. The specific values refer to the research results of Dong [11]; the linear elastic constitutive relationship between base and soil base materials is selected, and the thermodynamic parameters of asphalt pavement are considered. The specific parameters are shown in tables 1 and 2 [12].

Table 1. Material properties of each layer of asphalt pavement.

| Pavement Structure Layer | Thickness cm | E MPa | Poisson’s ratio | Density kg·m⁻³ | Damping ratio | Thermal Conductivity k J·m⁻¹·h⁻¹·°C⁻¹ | Specific Heat C J·kg⁻¹·°C⁻¹ |
|--------------------------|--------------|-------|----------------|----------------|-------------|-----------------------------------|---------------------------|
| SMA-16                   | 5            | 1400  | 0.35           | 2400           | -           | 4600                              | 900                       |
| AC-20                    | 6            | 1300  | 0.35           | 2400           | -           | 4600                              | 850                       |
| AC-25                    | 7            | 1200  | 0.35           | 2400           | -           | 4600                              | 800                       |
| CSM                      | 35           | 1300  | 0.25           | 2100           | 0.05        | 5616                              | 910                       |
| LSM                      | 20           | 600   | 0.3            | 1900           | 0.05        | 5004                              | 921                       |
| SG                       | -            | 30    | 0.4            | 1800           | 0.05        | 5616                              | 1040                      |

Table 2. Thermal expansion coefficient of pavement materials.

| Structure Layer | Thermal expansion coefficient (×10⁻⁵) | Temperature °C | Structure Layer | Thermal expansion coefficient (×10⁻⁵) | Temperature °C |
|-----------------|--------------------------------------|----------------|-----------------|--------------------------------------|----------------|
| SMA-16          | 2.4                                  | 20             | AC-20           | 2                                    | 40             |
|                 | 2.5                                  | 30             |                 | 1.9                                  | 30             |
|                 | 2.7                                  | 40             |                 | 2                                    | 50             |
|                 |                                      | 50             | AC-25           | 1                                    | 60             |
|                 |                                      | 60             |                 | 2.2                                  | 20             |
| AC-25           | 1.2                                  |                | CSM             | 1                                    |                |
| LSM             | 30                                   |                | SG              | 20                                   |                |

2.3. Asphalt Pavement Model and Load Form and Actual Temperature Input

Asphalt pavement structure includes surface layer, base layer, subbase layer and soil foundation. The surface layer consists of 5 cm SMA-16, 6 cm AC-20 and 7 cm AC-25; the base course consists of 35 cm cement stabilized macadam (CSM) and 20 cm lime stabilized macadam (LSM).

![Crack diagram](image1)

![FE Model](image2)

Figure 2. Model diagram.

The FE model of semi-rigid asphalt pavement with longitudinal and transverse cracks is established by ABAQUS software. The length, width and height of the model are 5 m, 3 m and 6 m respectively.
There is one top-down crack penetrating the longitudinal pavement model on the surface layer, and one reflective crack penetrating the transverse pavement in the base course. The width of the two cracks is 1cm (figure 2(a)). In this study, two models are established, one is temperature field model, the other is temperature moving load coupling model. The element types of the two models are inconsistent. The temperature field is DC3D8 and the coupling field is C3D8R. The FE model is shown in figure 2(b). The load form of this study is moving load, considering the time history change of load amplitude, spatial distribution change and the movement of its action position, so as to reflect the real stress status of pavement structure as much as possible. The dynamic load is 0.7 and 1.2 MPa respectively. The basic assumptions of the calculation model are: the displacement of each layer of pavement structure is continuous; the boundary conditions of the model are normal constraints around, so the bottom is fully constrained due to the large depth of the model.

Under the influence of environmental factors, the temperature of actual pavement structure changes with the depth and time of pavement, and its temperature field is transient temperature field [13]. The 24 h temperature of August 7 and December 14, 2019 in Changping District of Beijing is taken as the input, which is defined as the external temperature varying with time (the third boundary condition).

3. Results

3.1. Analysis of Asphalt Pavement Temperature Field
The 24 h temperature variation curve and depth variation of each layer in summer are shown in figure 3, and those in winter are shown in figure 4. The simulation results show that the temperature in the pavement changes with the change of the ambient temperature. At 7:14:00, it increases with the increase of the ambient temperature, and then gradually decreases and tends to be stable. In one day, the pavement temperature changes greatly, which will produce greater temperature stress on the pavement, so this part of the impact cannot be ignored in the actual research. At the same time, the temperature fluctuation gradually decreases with the increase of depth, and the time to reach the maximum temperature is also delayed. The temperature fluctuation at the top of the upper layer is the largest. The maximum temperature difference in summer can reach 30.7 ℃ and that in winter is 7.5 ℃. This is mainly because the surface of the upper layer is directly exposed to the environment, so the change range is large. The surface crack is located in the upper layer with large temperature difference, so it will be subject to large temperature stress, and its crack propagation characteristics will be greatly affected. Based on this, we select the temperature field at 13:00 in summer and 5:00 in winter as the imported temperature of thermal coupling.

![Figure 3. Simulation results of pavement temperature field in summer.](image-url)
Figure 4. Simulation results of pavement temperature field in winter.

3.2. Calculation Point Selection
Because of the 3D model established in this paper, it is necessary to select the crack calculation point. With the movement of load, the time history of SIF reaching the peak value at each point on the transverse reflection crack is the same, but the numerical value is different. The calculation point is located in the middle of the pavement. The TDC is a longitudinal crack, and the crack direction is consistent with the load movement direction. With the load movement, the time history law of SIF at different sections will be different. Ai [13] found that the $K_{\text{eff}}$ of the longitudinal middle section of the crack is obviously larger than that of other points, which indicates that this section is the most prone place for crack growth on the whole TDC. Therefore, the calculation section of the TDC is taken as the middle section, and the model diagram is shown in Figure 5.

Figure 5. Schematic diagram of crack calculation point.

3.3. Effect of Seasons and Different Loads on Crack Propagation
In this part, the variation of SIF with time in different seasons (winter and summer) and different axial loads (0.7, 1.2 MPa) is calculated. The speed of load is taken as 10 m/s.

3.3.1. Influence on Top-Down Crack Growth. The time history curves of mode I, II and III SIF of TDC are shown in Figure 6. When $K_I$ is positive, it can promote mode I crack growth, but when $K_I$ is negative, it does not promote crack growth; both $K_{II}$ and $K_{III}$ can promote crack growth no matter whether they are positive or negative.

Figure 6 (a) shows that $K_I$ is negative in the analysis step time, and the probability of mode I crack propagation is small in summer; in winter, the value of $K_I$ fluctuates slightly at the beginning, but changes suddenly at the midpoint, and then tends to be flat. The results show that the lower air temperature in winter promotes the mode I crack, while the higher the ambient temperature in summer, the asphalt mixture is not prone to mode I crack due to its viscoelastic effect. It can be seen from figure 6 (b) that in winter and in the case of no real temperature field, the change trend of $K_{II}$ is basically consistent with the movement of load; in summer, $K_{II}$ presents the phenomenon of negative positive alternation with the movement of load, and the peak value is significantly greater than the other two cases. It can be seen from figure 6 (c) that in summer, the $K_{III}$ value increases first and then decreases with the load movement, then increases again, and finally tends to be gentle, but it is always
positive and larger than that in winter and without temperature field. It can be seen that high temperature in summer has great influence on mode III crack of pavement, and the pavement is easy to shear fracture.

With the increase of load, the overall trend of SIF changes little, and there is a certain increase in numerical value. It can be seen from Figure 6 (c) that the increase of load has the greatest impact on mode III crack. For the top-down cracks of pavement, considering the real temperature field, low temperature in winter can promote the growth of mode I crack, while in summer with high temperature, mode II and III cracks are more likely to occur. At the same time, $K_{III}$ is less than $K_{II}$ by one order of magnitude, so the top-down crack propagation is mainly mode II in summer.

![Figure 6](image6.png)

**Figure 6.** Time history curves of SIF of mode I, II and III of top-down cracks.

3.3.2. Influence on Reflection Crack Propagation. The reflection crack at the bottom of the base layer is transverse crack, which does not produce transverse shear effect with the movement of load, so it is a mode I + II composite crack. Figure 7 shows the time history curve of SIF of reflection crack under different conditions.

![Figure 7](image7.png)

**Figure 7.** Time history curve of SIF of reflection crack.
It can be seen from figure 7 (a) that in winter and without real temperature field, $K_I$ increases first and then decreases, and the peak value increases with the increase of load. When the load acts directly above the reflection crack, $K_I$ reaches the peak value; because $K_I$ is generally positive, the load promotes the mode I propagation of reflection crack. However, in summer, $K_I$ decreases to a negative value at first, increases gradually with the movement of load, and finally tends to be gentle, which has little effect on type I expansion. It can be seen from figure 7 (b) that in summer, $K_{II}$ increases gradually with the movement of load, and finally tends to be stable. The numerical value is an order of magnitude larger than that in winter and without real temperature field, and the change range is not large with the increase of load, which indicates that mode II propagation of base reflection crack is easy to occur under the joint action of moving load and temperature stress in summer.

3.4. Effect of Different Vehicle Speeds on Crack Propagation

In this study, the SIF of pavement cracks under different speeds (10 and 20 m/s) at low temperature in winter were compared.

3.4.1. Top-Down Crack. It can be seen from figure 8 (a) that the speed has little effect on mode I crack, but the peak position changes in time, while the low temperature has a more obvious effect; it can be seen from figure 8 (b) that in both cases, the $K_{II}$ value at the speed of 10 m/s is significantly greater than that at 20 m/s. It can be seen from figure 8 (c) that the velocity has little effect on mode III crack.

3.4.2. Reflective Cracks. It can be seen from figure 9 that the velocity has little effect on the value of SIF, but the time to reach the peak value changes. It can be seen from figure 9 (a) that the $K_I$ value increases after the temperature field is added. It can be seen from figure 9 (b) that the $K_{II}$ value has a similar rule with the $K_I$ value. When the low temperature is slow, the peak value of the SIF under the
real temperature field is obviously greater than that without the real temperature field. Therefore, the effect of the real temperature field on the pavement should be considered in the study of similar problems. There may be a big gap between the previous simplification and the actual situation.

![Figure 9. Time history curves of mode I, II stress intensity factors of base reflective cracks under different velocities in winter.](image)

In summary, heavy load and slow speed of vehicles in winter cause the greater damage to asphalt pavement. Therefore, for expressways, we should limit overload and specify the minimum driving speed, so as to reduce the damage of vehicle load on the pavement and improve the pavement durability.

4. Conclusion
(1) In summer, the probability of mode I propagation of top-down crack under moving load is small, while in winter with low temperature, mode I propagation is easy to occur, which is mainly due to viscoelastic effect of asphalt mixture under high temperature. At the same time, $K_{II}$ is less than 1 order of magnitude of $K_{I}$. Therefore, the propagation of top-down cracks is mainly mode II in summer and mode I in winter.

(2) In winter and without real temperature field, the load promotes the mode I propagation of reflection crack. However, in summer, it has little effect on mode I expansion. In the summer high temperature period, the load promotes the mode I propagation of reflection crack under the action of temperature stress.

(3) With the increase of load, the overall trend of SIF changes little, and the numerical value has a certain increase; without considering the real temperature field, the influence of vehicle speed on mode I crack is not obvious, but the peak position changes in time. After adding temperature field, the value at low speed is obviously greater than that at high speed. Therefore, the coupling field can more truly reflect the actual situation of pavement.

(4) Considering the real temperature field, heavy load and slow speed have the greatest damage to the road surface. Therefore, we should limit the overload and the minimum driving speed to reduce the damage of vehicle load on the road surface and improve the pavement durability.

Acknowledgments
The research performed in this paper is supported by Beijing major science and technology projects (No. Z191100008019002) and National Key Research and Development Program of China (No. 2017YFF0205600).

Reference
[1] Xi L Y, Shi P Z, Yan L, et al. 2016 Analysis of temperature field of asphalt pavement by site
measurement in full-depth *Journal of Chang’an University: Natural Science Edition* **36**(1) 1-7.

[2] Zhao Y Q, Tan Y Q, Zhou C H, et al. 2008 Analysis of Top-Down Cracking of Asphalt Pavements Based on Fracture Mechanics Approach *Journal of Tongji University (Natural Science)* **38**(2) 218-222.

[3] Roque R, Birgisson B, Drakos C, et al. 2004 Development and field evaluation of energy-based criteria for top-down cracking performance of hot mix asphalt *Journal of the Association of Asphalt Paving Technologists* **73** 229.

[4] Qiao J G, Wang W, Cheng C, et al. 2019 Analysis on Crack Resistance of Asphalt Pavement Based on Temperature Load Coupling Field *Highway* (8).

[5] Zhao Y Q, Xue Q and Huang R H 2007 Comparison of Compressive Resilient Modulus and Dynamic Modulus of Asphalt Mixtures *Journal of Wuhan University of Technology* **029**(012) 105-107 111.

[6] Ministry of communications of the people's Republic of China 2006 *JTG D50-2006 Code for Design of Highway Asphalt Pavement* Beijing: People's Communications Press.

[7] de Araújo P C, Soares J B, de Holanda Á S, et al. 2010 Dynamic viscoelastic analysis of asphalt pavements using a finite element formulation *Road Materials and Pavement Design* **11**(2) 409-433.

[8] Yan Z R 1984 Analysis of the Temperature field in layered pavement system *Journal of Tongji University (Natural Science)* (03) 79-88.

[9] Liao GY and Huang XM 2014 *Application of Abaqus Finite Element Software in Road Engineering* 2nd Edition Southeast University Press.

[10] Wang X and Zhong Y Temperature fatigue reflective crack in asphalt pavement using extended finite element method

[11] Dong ZJ and Tan YQ 2015 *Dynamic Response of Asphalt Pavement* Science Press.

[12] Si C, Chen E, You Z, et al. 2019 Dynamic response of temperature-seepage-stress coupling in asphalt pavement *Construction and Building Materials* **211** 824-836.

[13] Ai C F, Xu C, Ren D Y, et al. 2018 Characterization of vertical and horizontal propagations of double cracks in asphalt pavements under moving loads *Journal of Southwest Jiaotong University* **53**(001) 128-135.