Influence of base-cracking inclination angle on reflection cracking in a low-temperature environment

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Abstract. The temperature crack is a principal disease of the subgrade sidewalk in northern China. Temperature and load affect reflective crack caused by a semi-rigid base, and its development mechanism needs further study. Based on numerical simulation technology, five presplitting inclination models of a base crack in a low-temperature environment are established, and the propagation laws of reflective crack, under different temperatures, are compared. The stress level, acoustic emission, and distribution rule of damage unit in the road structure, under various conditions, are analyzed and summarized. We found that with low-temperature load, the stress level in road material increases until the peak failure. The maximum stress in the model increases in a fluctuating manner with increasing inclination. The development of reflective cracks will deviate from the inclination direction of the preset crack. As the inclination angle of the preset crack increases, the offset of the reflective crack will become more obvious.

Keywords: Reflective Crack, Asphalt Sidewalk, Temperature Load, Crack Inclination

1 Introduction

In northern China, a low-temperature environment aggravates the appearance of reflection cracks, which affect road quality and durability. The study on this subject has a strong theoretical-reference value for curing road crack because the development of reflective cracks in a low-temperature environment is complicated.

Studies on sidewalk reflection crack has a long history [1]. Some scholars studied the antireflective cracking ability of surface layer, base course, antireflective crack interlayer, and interlayer contact surface by adding rubber particles, regenerated asphalt, and geotechnical materials [2-5]. Some scholars considered the effect of temperature, including the effect of cooling rate on reflective cracks at different temperatures and the effect of base modulus on sidewalk life [6,7]. It was concluded that setting stress-relief layer and geogrid has a good effect on antireflection crack [8-11]. In the aspect of theoretical analysis, Pirondi et al. [12] developed the damage mechanics model and
applied it to the finite element software, such as ABAQUS, which helps in the numerical technique. Wei Zeng et al. [13] established the attenuation model of bending modulus and used it to evaluate the remaining life of the semirigid base course. Based on numerical simulation technique, the adverse effect of interlayer bonding state and moving load on the sidewalk at high temperature and the influence of surface thickness on sidewalk cracking, in various temperature fields, are studied [14-16]. Wang et al. [17] considered the effect of the change in initial-crack inclination and length on the crack propagation, however, the crack-angle range is too small to reflect the effect of base-crack inclination on emission cracks of sidewalk. In the previous studies on the prevention of reflective cracks, little consideration was given to the influence of base cracking and cracking angle on the sidewalk-reflective crack in low-temperature conditions.

Given the shortcomings of existing studies, based on numerical simulations, considering different initial-crack inclinations during the uniform low-temperature drop, this study compares the acoustic emission (AE) characteristics and stress levels of the subgrade structure and analyzes the propagation of reflective cracks under different inclination cracks.

2 Numerical modeling

2.1 Basic assumptions of the model

The numerical model assumes the following: 1) Only the surface and semirigid base layers were simulated to increase the thickness of the semirigid layer and ignore the influence of the bottom-base layer. 2) Structural materials are isotropic and inhomogeneous. 3) Only the temperature load is considered. 4) The surface layer is brittle and has a high modulus.

2.2 Numerical model

The road-structure model is divided into surface and base layers; the thickness is 200 and 1000 mm, respectively; the length of each layer is 5 m. The left and right boundary and the lower boundary of the model are fixed, whereas the upper surface is free. The material mechanical parameters are shown in Table 1. Regarding the general modeling method for reflective cracks, cracks are present in the base of five identical models with a length, width, and spacing of 20, 2, and 750 mm, respectively. The inclination angles of each crack (the angle between the crack and vertical direction) are 0°, 30°, 45°, 60°, and 75°, respectively.

|          | Nonuniformity | Elastic modulus/MPa | Strength/MPa | Thermal expansion/°C | Thermal conductivity/(m°C) | Poisson ratio |
|----------|---------------|---------------------|--------------|-----------------------|-----------------------------|--------------|
| Surface layer | 3             | 1200                | 150          | 2 × 10⁻⁵              | 10                          | 0.25         |
| Base layer   | 10            | 100                 | 20           | 1 × 10⁻⁵              | 1                           | 0.25         |
To consider the effect of low-temperature conditions on the development of reflective cracks, temperature loads are applied, step by step, on the surface structure. The initial temperature is set at 0°C, which is reduced by 1°C in each step, and 40 steps are loaded. The specific model structure is shown in Fig. 1. The maximum tensile stress and Mohr–Coulomb criteria are used as damage thresholds for the constitutive relation of the elastic microunits to model and analyze road cracking.

![Fig. 1. Model schematic for numerical simulation](image)

3 Stress and acoustic emission analysis at different crack inclinations

3.1 Stress and acoustic emission results

The relevant data of AE and tension stress are obtained with temperature loading on the model. Using the data, the cylindrical figure of AE quantity and the break-line diagram of tension stress corresponding to different crack inclinations are drawn (Fig. 2). The number of AE can reflect the number of units destroyed in the road structure, while tensile stress is the cause of road cracking. Therefore, the number of AE and the change of stress can be used as an important analysis basis for the propagation mechanism of reflective cracks (Fig. 2):

Comparing the AE changes of five inclination conditions, we found that there is a maximum value in the process of AE changes, meaning that the loading step corresponds to the structural damage. The corresponding steps for the first four kinds of structural damage are about 20 steps, thus, the structural damage occurs in this model at −20°C. However, when the crack inclination is 75°, the destruction temperature required for the structure is reduced.

![Fig. 2. Stress and acoustic emission analysis](image)
The road-structural damage and the explosive increase in the AE amount correspond to the increase in the tensile stress of surface structure. Since the acoustic emission indirectly reflects the stress state in the material, the loading step of the peak tensile stress in the model is earlier than that of the maximum AE number.

The stress maximum values for five models are counted and the curves of maximum stress values with inclination are plotted (Fig. 3); the change of the maximum tensile stress in this model and the inclination angle of the crack in the base layer fluctuate. The smaller the maximum tensile stress, the easier the occurrence of a reflective crack in the structure. The initial inclination angle of the crack in this calculation model is 30° and 60°, which are unfavorable conditions.

Fig. 2. Load step-tension-acoustic emission curves of the model at different inclination angles

Fig. 3. Stress maximum versus inclination angle
3.2 Analysis

The generation of tensile stress is the main cause of road cracking. Under low-temperature load, both the surface layer and the base material of the road will shrink. The two layers of material produce uneven shrinkage deformation because the thermal expansion coefficient of the surface layer is larger than that of the base layer. At the same time, the bond between the surface and base layers is strong, and the effect of bond and friction will aggravate the nonuniform tension of the surface layer material and further concentrate the tension stress at the preset cracks in the base layer.

4 Analysis of reflective-crack development at different crack inclinations

The final destruction modes of the five-crack inclination models are shown in Fig. 4, and the reflective cracks are indicated by a red box. The diagram shows that all five models have reflective cracks formed just above one preset crack. The location of the reflective crack is random due to the nonuniformity in the model material.

(a) Inclination 0°  (b) Inclination 30°
(c) Inclination 45°  (d) Inclination 60°
(e) Inclination 75°

Fig. 4. Final destruction mode diagram

To observe the formation and propagation of reflective cracks at different inclination angles, the AE distribution of five models is compared and analyzed, as shown in Fig. 5. In the figure, the red circle shows that the unit is being destroyed, and the black circle shows that the unit has been destroyed. The size of the circle represents the amount of energy released during the destruction.

(a) Inclination 0°  (b) Inclination 30°
(c) Inclination 45°  (d) Inclination 60°
From Fig. 5, when the preset crack angle is 0°, reflective cracks propagate toward the preset cracks. The damage range of the sidewalk is from 22° on the left to 30° on the right, in the vertical direction.

When the preset crack angle is 30°, the failure range of the surface layer is from 14° on the left to 11° on the right in the vertical direction. The development range of the reflective crack is narrower than that of the preset crack at 0°.

Reflective cracks at preset crack inclinations of 45°, 60°, and 75° have similar development processes. Reflective cracks occur on the left side of the preset crack. Reflective-crack path and preset crack form a fold line, and the degree of bending increases with the increase in preset crack angle. The corresponding failure ranges of the three models are 24°, 28°, and 35° on the left side in the vertical direction. This range angle is roughly half of the preset crack angle, which may be related to the thermal expansion coefficient of the surface layer and the base material.

5 Conclusion

In this study, the effect of base-crack inclination on the reflective-crack formation process in the sidewalk structure, under low temperature, is studied using numerical simulation. Five preset conditions of crack inclination (0°, 30°, 45°, 60°, and 75°) are selected, and the development process of reflective crack under each condition, as well as the AE phenomena and stress levels, are compared and analyzed. The main conclusions are as follows:

(1) The formation of reflective cracks is the result of the development of tensile stress in the surface structure. With the low-temperature load, the stress level in road material increases, reaching the peak value and then destroying and decreasing. The temperature range corresponding to the stress extremes under each calculation condition is (−20°C)–(−30°C).

(2) The trend of the development path of reflective crack is roughly following the inclination direction of preset crack. With the increase in the inclination of the preset crack, the offset of the propagation path of reflective crack becomes obvious. When the ratio of thermal expansion coefficient between surface and base layers is 2, the deviation between the development direction of reflective crack and the vertical direction is about half of the preset crack inclination.

(3) The maximum stress value of model structure fluctuates with the increase of crack inclination, and the unfavorable conditions with lower maximum tensile stress value are inclination angles 30° and 60°. The calculation model with preset crack inclination of 75° needs the most temperature-loading steps and the latest time for tensile failure. It shows that when the preset cracks in the base layer tend to be horizontal, the
restraint of the surface layer has a certain mitigating effect on the expansion of reflective cracks.

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