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# Research on the Propagation Law of Temperature-Induced Reflective Cracks in Semi-Rigid Base Asphalt Pavement

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**Abstract:** In order to solve the problem of reflection cracks in semi-rigid base asphalt pavement, a study of temperature-type reflection crack expansion is carried out according to the typical climatic characteristics of Guilin, Guangxi Province. According to the theory of fatigue fracture mechanics, the stress intensity factor analysis at the crack tip is carried out, the reflection crack propagation life under single-factor and multi-factor changes is calculated using the Paris fatigue growth formula, and the prediction model of the propagation life of reflected crack under the action of a temperature gradient is established. The results show that the propagation life of temperature-type reflective cracks increases with an increase in the thickness of the middle course and bottom course, and decreases with an increase in the surface course modulus, base course modulus, base course thickness, and temperature decrease. The prediction model includes the factors that have a great influence on the reflection crack extension and provides a theoretical supplement and reference for the design and calculation of asphalt pavement structure in areas with large temperature differences.

**Keywords:** asphalt pavement; temperature gradient; reflection crack; propagation law



**Citation:** Chen, F.; Yue, A. Research on the Propagation Law of Temperature-Induced Reflective Cracks in Semi-Rigid Base Asphalt Pavement. *Buildings* **2024**, *14*, 3586. https://doi.org/10.3390/buildings14113586

Academic Editors: Mijia Yang and Huayang Yu

Received: 22 August 2024
Revised: 21 October 2024
Accepted: 21 October 2024
Published: 12 November 2024



## 1. Introduction

When the temperature drops, the plate-shaped pavement structure course will experience warping deformation with both ends rolling upwards, which will make the temperature shrinkage and dry shrinkage cracks of the semi-rigid base gradually expand to the asphalt surface course and finally form reflection cracks running through the asphalt surface course [1,2]. The latest study by Xiaoying Wang et al. [3] investigated the formation mechanism of reflective cracks under the combined action of temperature and mobile traffic, but did not study the extension life of reflective cracks; Jiang Xi et al. [4] conducted research on the numerical response of inverted pavement structures but were unable to completely solve the problem of reflection cracks. A reflection crack is the most important defect of semi-rigid base asphalt pavement, which not only causes a large number of visible cracks on the road surface but also induces water damage and greatly reduces the service life of asphalt pavement. The main measure to deal with the reflection crack internationally is to use the special properties of the structural course materials to slow down, such as adding a fatigue joint course capable of resisting fatigue, a macroporous graded macadam capable of dispersing tensile force, geotextiles with high tensile strength between asphalt courses and semi-rigid bases, or others. However, there are few measures to resist temperature-type reflection cracks from the perspective of structural combination. The main reason is that the law of the temperature-type reflection cracks expanding with the thickness and modulus of the structural layer is not clear at present, and the structural combination of temperature-type reflection cracks lacks corresponding theoretical support. Based on this situation, this paper is based on the building materials from the Guilin–Huangshahe section of National Highway 322 in Guangxi and the climate characteristics of Guilin City to carry out research on the propagation of temperature-type reflective cracks in semi-rigid base asphalt pavement, and analyze the propagation law of reflective cracks under the action of temperature gradient cycles.

The reflection crack propagation caused by a temperature gradient is actually a kind of crack propagation resulting from the repeated action of temperature stress, which conforms to the theory of fatigue crack mechanics [5] and can be calculated by the Paris fatigue propagation formula.

According to the different forms of crack propagation under load, crack propagation can be divided into three basic types: open crack (type I), sliding crack (type II), and tearing crack (type III). The research results of Wu Ganchang et al. [6–8] show that under the action of temperature gradient, the pavement structure layer is warped due to the temperature difference between the top and the bottom. The stress intensity factor is the tensile stress intensity factor $K_I$. Therefore, this paper only analyzes crack extension caused by the opening stress intensity factor.

## 2. Reflection Crack Analysis Model and Parameters

### *2.1. The Basic Assumptions*

In this paper, the following basic assumptions are made in the analysis and calculation of the reflection crack:

1. It is assumed that there is a penetrating crack in the semi-rigid base.
2. It is assumed that there is a tiny initial crack at the bottom of the asphalt course and that it is connected with the penetrating crack of the semi-rigid base course, and the initial crack length is 8 mm.
3. It is assumed that the asphalt mixture is uniform and free of impurities and that the reflection crack expands vertically.
4. Because it is the change in stress intensity factor that leads to crack propagation, the size of the stress intensity factor at the starting temperature of the material crack is ignored, and its size is regarded as 0, and we only focus on the amplitude $\triangle K_I$ of the stress intensity factor at a certain temperature drop.

### *2.2. Structure Model and Parameters*

#### 2.2.1. Basic Structure and Simplified Structure

Basic Structure

According to the design and the experience of using typical semi-rigid basic asphalt pavement in China, the structural form shown in Table 1 is used as the basic structure of asphalt pavement for analysis.

**Table 1.** The basic structure of semi-rigid base asphalt pavement.

| Structure Course | Material Type | Thickness, cm |
|---|---|---|
| Surface course | SMA-13 | 4 |
| Middle course | AC-20 | 6 |
| Bottom course | AC-25 | 8 |
| Base course | 4% cement stabilized | 36 |
| Subgrade | - | |

Note: stone mastic asphalt (SMA)-13 and asphalt concrete (AC)-16.

Simplified Structure

In order to simplify the calculation, according to Chinese standards [9], all asphalt courses of the pavement structure were simplified into one course, so that the basic structure was simplified into three courses: surface course, subgrade course, and road base. The structure before and after the simplification of the basic structure is shown in Table 2.

**Table 2.** Pavement structure before and after being simplified.

| Basic Structure Before Simplification | Simplified Basic Structure |
|---|---|
| 4 cm SMA + 6 cm AC20 + 8 cm AC25 + 36 cm cement-stabilized macadam | 18 cm bituminos mixed surface course + 36 cm semi-rigid base |

#### 2.2.2. Material Parameters of Temperature Field Model

##### Thermal Characteristic Material Parameters

Because the thermal characteristics of dense gradation asphalt mixture vary little with the type of mixture [10–12], the thermal characteristic parameters of different types of dense gradation asphalt mixture can be set to the same value in the analysis of pavement temperature field. The thermal characteristic parameters of the structural course materials used for pavement temperature field analysis in this paper are shown in Table 3.

**Table 3.** The thermal parameters of structural course materials.

| Parameter | Dense Gradation Hot Asphalt Mixtures | Cement-Stabilized Macadam Base | Subgrade |
|---|---|---|---|
| Pyroconductivity k, J/(m·h·°C) | 5480 | 5616 | 5616 |
| Density ρ, kg/m$^3$ | 2300 | 2200 | 1800 |
| Thermal capacity C, J(kg·°C) | 842.5 | 911.7 | 1040.0 |
| Absorption factor of solar radiation $\alpha_s$ | | 0.90 | |
| Heat exchange coefficient, W/(m$^2$·°C) | | $h_c = 3.7v_w + 9.4$ | |
| Road emissivity ε | | 0.81 | |
| Absolute zero value $T^Z$, °C | | −273 | |
| Stefan–Boltzmann constant σ, J/(h·m$^2$·K$^{4)}$ | | $2.041092 \times 10^{-4}$ | |

##### Meteorological Parameters

After investigation, measurement, and reference to the meteorological data released by the Guilin Meteorological Bureau, the average meteorological parameters of Guilin City, Guangxi Province, from May to September in the past 5 years are shown in Table 4.

**Table 4.** The average meteorological parameters of Guilin City from May to September in the past 5 years.

| Month | Maximum Daily Average Temperature, °C | Minimum Daily Average Temperature, °C | Average Daily Total Solar Radiation, MJ/m$^2$ | Average Number of Hours of Sunshine per Day, h | Average Wind Velocity per Day, m/s |
|---|---|---|---|---|---|
| 5 | 28.2 | 20.2 | 15.2 | 13.0 | 6.5 |
| 6 | 32.5 | 24.3 | 16.7 | 13.0 | 5.0 |
| 7 | 34.2 | 26.0 | 19.4 | 13.0 | 4.0 |
| 8 | 33.0 | 24.1 | 19.7 | 13.0 | 4.5 |
| 9 | 32.2 | 23.0 | 17.8 | 12.0 | 7.0 |
| Average | 32.0 | 23.5 | 17.8 | 12.8 | 5.4 |

#### 2.2.3. Material Parameters of Fracture Propagation Model

##### Material Mechanical Parameter

Since the temperature change process is slow and the temperature acting on the structural course is close to the static load, the asphalt course should adopt the dynamic modulus of static modulus or the dynamic modulus of low-frequency loading (below 0.01 Hz). After the laboratory test, the dynamic modulus of the asphalt mixture at 0.01 Hz is shown in Table 5.

**Table 5.** Summary of 0.01 Hz dynamic modulus of asphalt mixtures.

| Materials | SMA13 | | | | | AC20 | | | | | AC25 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature, °C | 4 | 10 | 21 | 37 | 55 | 4 | 10 | 21 | 37 | 55 | 4 | 10 | 21 | 37 | 55 |
| Dynamic modulus, MPa | 6890 | 2619 | 766 | 172 | 81 | 8355 | 3378 | 1558 | 407 | 203 | 9414 | 4102 | 2630 | 446 | 251 |

The temperature at different depths of pavement structure is not the same, so the modulus of asphalt mixture at different depths is also different. This article calculates the average temperature of the structural layers and determines the modulus of the asphalt mixture at this temperature using the interpolation method.

The modulus of the roadbed was obtained using a load-bearing plate test on the in situ soil base of the test section, and the test result was 60 MPa. The modulus of the 4% cement-stabilized gravel was obtained according to the method of determining the elastic modulus of materials by graded loading using Chinese testing standards [13], and the test result was 1200 MPa.

Due to the limitation of test conditions, it is difficult to determine Poisson's ratio of each structural course of pavement. The empirical value is taken, and the specific value is shown in Table 6.

**Table 6.** Poisson's ratio of the structural course materials.

| Materials | Poisson's Ratio |
|---|---|
| Bituminous mixture | 0.30 |
| Cement-stabilized macadam | 0.25 |
| Subgrade | 0.40 |

The modulus and Poisson's ratio of the simplified pavement structure are obtained by the conversion formula of the modulus and Poisson's ratio derived by Wu Hongling according to the membrane force equivalence [14]. The conversion formula is as follows:

$$v = \frac{\sum_{i=1}^{n} E_i h_i v_i / \left(1 - v_i^2\right)}{\sum_{i=1}^{n} E_i h_i / \left(1 - v_i^2\right)} \tag{1}$$

$$E = \frac{1 - v}{h} \sum_{i=1}^{n} \frac{E_i h_i}{1 - v} \tag{2}$$

The terms in the formula are defined as follows: $E$—The structural course modulus after structure simplification;

$v$—The structural course using Poisson's ratio after structure simplification;
$h$—The total thickness of structural courses;
$E_i$—The structural course modulus before structure simplification;
$v_i$—Poisson's ratio of each structural course before structure simplification;
$h_i$—The thickness of each structure course before structure simplification.

Coefficient of Linear Expansion

The linear expansion coefficient of the structural course material is shown in Table 7.

**Table 7.** The linear expansion coefficient of the structural course materials.

| Structure Course | Coefficient of Linear Expansion $\alpha$, $10^{-5}$/°C |
|---|---|
| Bituminous mixed surface course | 2.0 |
| Cement-stabilized base | 1.0 |
| Subgrade | 0.5 |

## 3. Finite Element Model

In order to calculate the internal force of pavement structure caused by temperature change, it is necessary to determine the temperature range of the structure course caused by temperature change, so as to determine the temperature field of pavement structure and the modulus of the asphalt course at different temperatures. The finite element model of the ABAQUS 2016 temperature field established in this paper has exactly the same size as the finite element model of reflection crack propagation. The subgrade thickness is 7 m and the model width is 10 m, as shown in Figure 1.

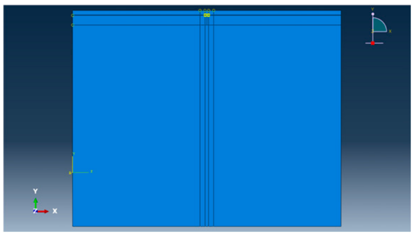

**Figure 1.** Finite element model of temperature field and reflection crack propagation.

The element type used in the temperature field model is the secondary heat conduction axisymmetric element DCCAX4. The crack propagation unit type adopts the quadratic reduction integral unit CPE8R, and the mesh division at the crack is shown in Figure 2.

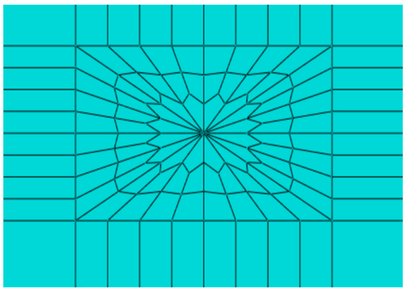

**Figure 2.** The unit division of the crack.

## 4. Stress Intensity Factor Analysis Under Temperature Gradient

In general, the daily temperature difference across the country is about 10 °C. Except for extreme weather and a few areas, it rarely exceeds 20 °C. The normal temperature in Guangxi Province is 20 °C, which can be used to reduce the temperature by 15 °C for the unfavorable climatic conditions of the road surface. The stress intensity factor formula is as follows:

$$K_1 = \frac{\sqrt{2\pi}E}{4(1-\mu^2)}\frac{v}{\sqrt{r}} \tag{3}$$

The terms in the formula are defined as follows: $E$—Modulus of structural course:

$\mu$—Poisson's ratio of structural courses;
$v$—Displacement in direction of cracks;
$r$—Crack radius length.

Under such adverse climatic conditions, the influence law of each influencing factor on the change amplitude of stress intensity factor $\triangle K_I$ is shown in Figures 3–9.

From Figures 3–9, it can be seen that at the same crack length, $\triangle K_I$ increases with an increase in the base course modulus, surface course modulus, base course thickness, and temperature drop range, and decreases with an increase in the middle surface course thickness and bottom course thickness. Subgrade modulus has little effect on $\triangle K_I$, which can be ignored. This means that when the base modulus, surface modulus, base thickness, and temperature drop amplitude increase, the stress field at the crack tip inside the asphalt course will increase, the tensile stress on both sides of the crack will increase, and the crack will easily expand upward. When the thickness of the middle and bottom course increases, the stress field at the crack tip inside the asphalt course decreases, the tensile stress on both sides of the crack decreases, and the crack will not easily expand upward. When the modulus of the subgrade increases, the stress field at the crack tip of the asphalt course changes little and has little influence on the crack propagation speed.

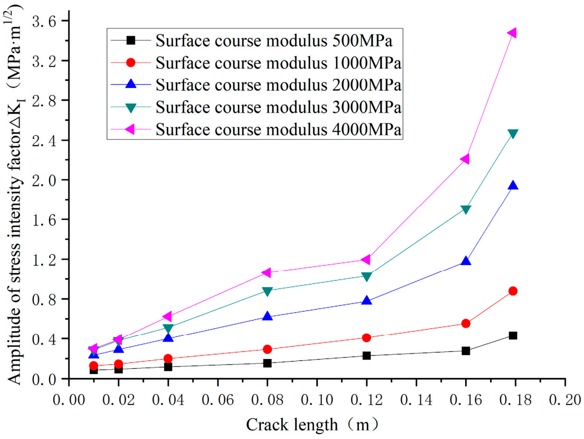


**Figure 3.** Law of $\triangle K_I$ with surface course modulus.

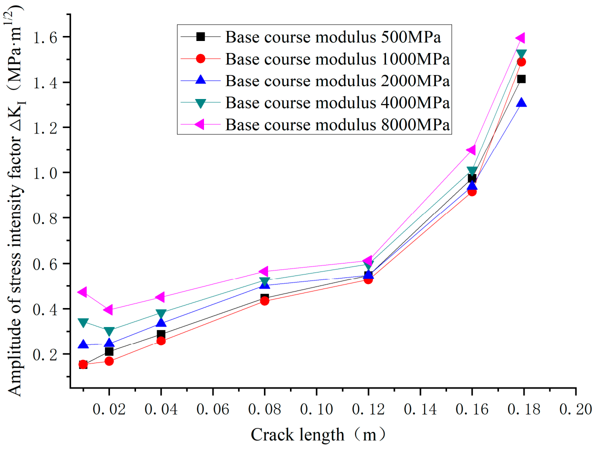


**Figure 4.** Law of $\triangle K_I$ with base course modulus.

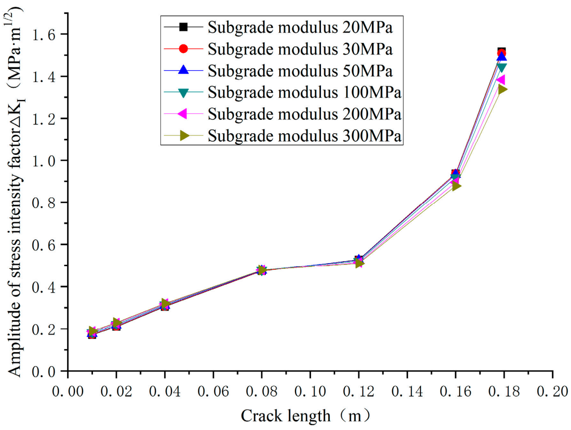


**Figure 5.** Law of $\triangle K_I$ with subgrade modulus.

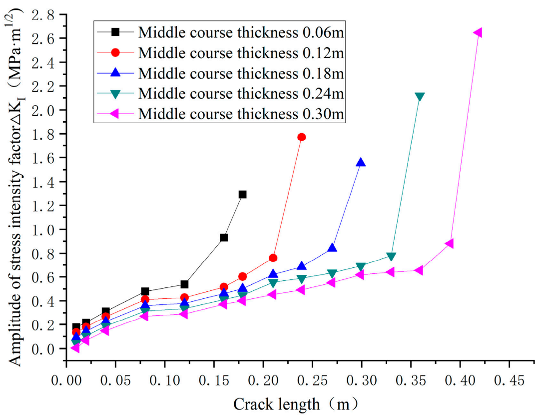


**Figure 6.** Law of $\triangle K_I$ with middle course thickness.

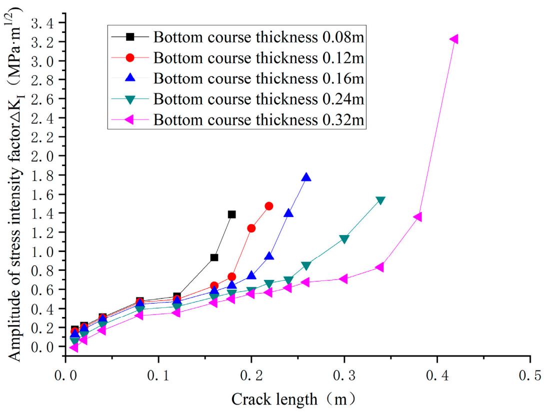


**Figure 7.** Law of $\triangle K_I$ with bottom course thickness.

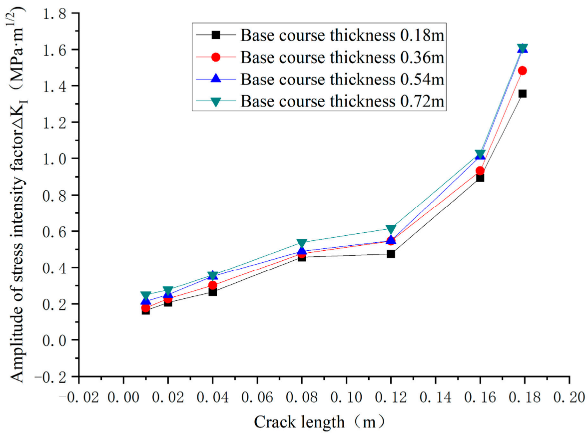


**Figure 8.** Law of $\triangle K_I$ with base course thickness.

According to the calculation results of the temperature field, if the thickness of the middle and bottom course increases, the distance between the crack tip of the same crack length and the top surface of the road becomes longer and the temperature field decreases under the influence of air temperature. When the air temperature drops, the deformation or stress change in the crack tip decreases, and $\triangle K_I$ decreases, resulting in the difficulty of upward propagation of the crack.

When the surface course modulus and base course modulus increase, the overall stiffness of the pavement structure course will increase, while the deformation capacity of the large stiffness material is poor. When the temperature drops, materials with the same thermal characteristics and linear expansion coefficient will produce the same size of buckling deformation. Materials with large stiffness values will inevitably generate greater tensile stress and $\triangle K_I$ at the crack tip. Therefore, the larger the surface modulus and the base modulus, the easier it is for the crack to expand upward.

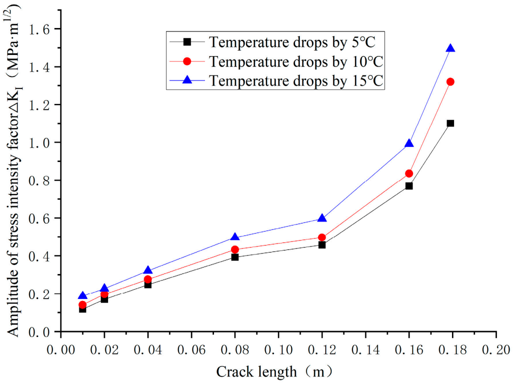


**Figure 9.** Law of $\triangle K_I$ with temperature drop.

When the thickness of the surface course is unchanged and the thickness of the grassroots level increases, as the temperature decreases, the warping deformation of the surface course remains unchanged, but the warping deformation of the grassroots level decreases. Since the contact between the grassroots level and the surface course is always continuous, it will inevitably hinder the warping deformation of the surface course, leading to an increase in the stress field at the tip of the cracks, after which the $\triangle K_I$ increases, and the cracks easily expand upwards.

The subgrade is far away from the top of the pavement, and the deformation caused by the change in air temperature is very small. Therefore, the influence of the change in subgrade modulus on the stress intensity factor at the crack tip is very small, and the change in $\triangle K_I$ is very small, so it cannot be considered when calculating the crack propagation life.

## 5. Analysis of the Propagation Life of Reflection Cracks Under the Action of Temperature Gradients

When the temperature drops, the change amplitude of the stress intensity factor is $\triangle K_I$. The integral calculation of $\triangle K_I$ according to the Paris formula can obtain the extended life of the reflection crack under the temperature gradient. In this paper, cylindrical specimens of indoor structural course materials were cut and then subjected to a semicircular bending fatigue test. The Paris formula is the most commonly used fatigue crack propagation model at present. If the crack propagation is $\triangle$a after the stress cycle $\triangle$N times, then the crack propagation is da/dN (mm/time) for each stress cycle, which is called the "crack propagation rate". Under the limit condition, it is expressed by differential da/dN [15–17].

$$\frac{da}{dN} = C(\Delta K_1)^n \tag{4}$$

For further integration, the following is calculated:

$$N = \int_0^h \frac{da}{C(\Delta K_1)^n} \tag{5}$$

The terms in the formula are defined as follows: $\Delta K_1$—The amplitude of the stress intensity factor under a given load;

$C$—The fracture parameters of the given material;
$a$—Crack length;
$N$—Cumulative fatigue times of the standard axle load;
$h$—Pavement thickness.

The Paris formula parameters of three asphalt mixtures were obtained through data processing, as shown in Table 8.

**Table 8.** Paris parameters for structural course materials.

| Type of Bituminous Mixture | n | C |
|---|---|---|
| SMA13 | 3.36 | $7.18 \times 10^{-6}$ |
| AC20 | 2.18 | $1.29 \times 10^{-5}$ |
| AC25 | 1.46 | $2.31 \times 10^{-5}$ |

Under unfavorable climatic conditions where the temperature drops from 20 °C to 15 °C, the influence rule of the propagation life of the reflection crack is shown in Figures 10–15.

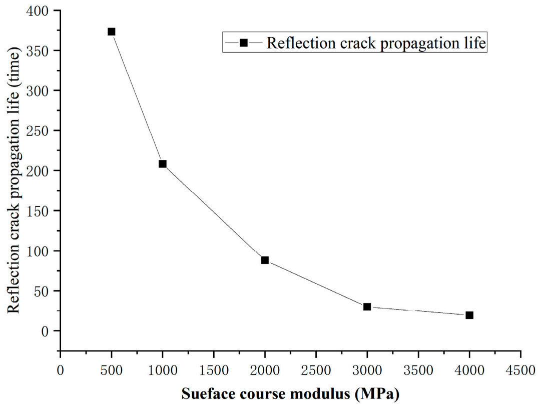


**Figure 10.** Law of reflection crack growth life with surface course modulus.

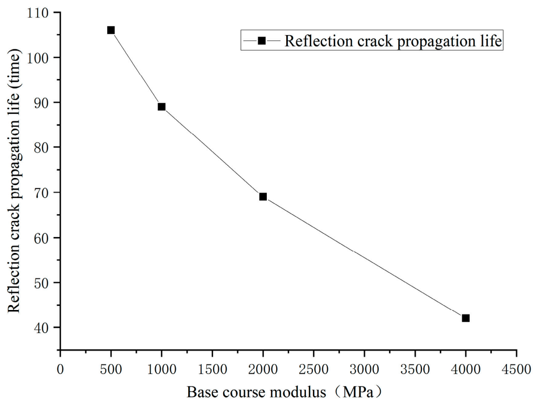


**Figure 11.** Law of reflection crack growth life with base course modulus.

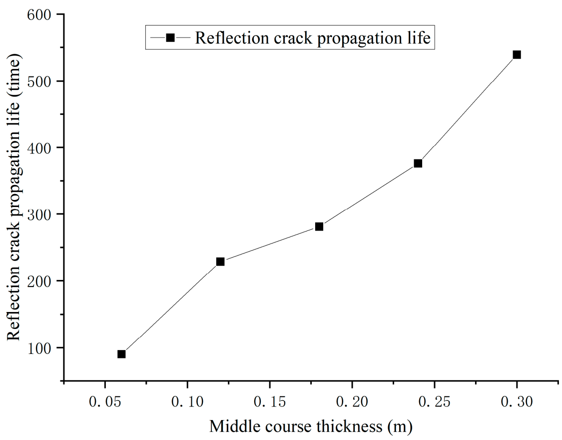


**Figure 12.** Law of reflection crack growth life with middle course thickness.

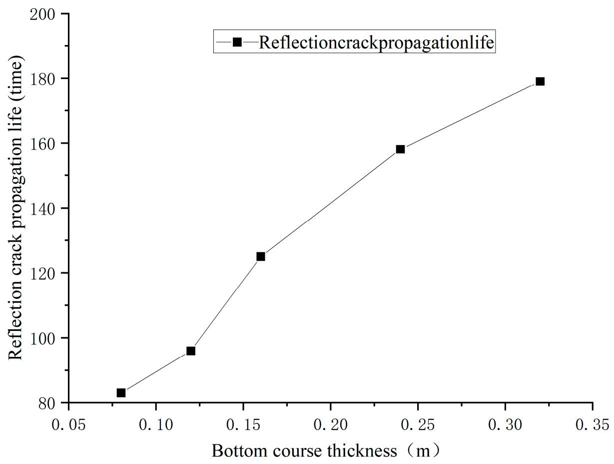


**Figure 13.** Law of reflection crack growth life with bottom course thickness.

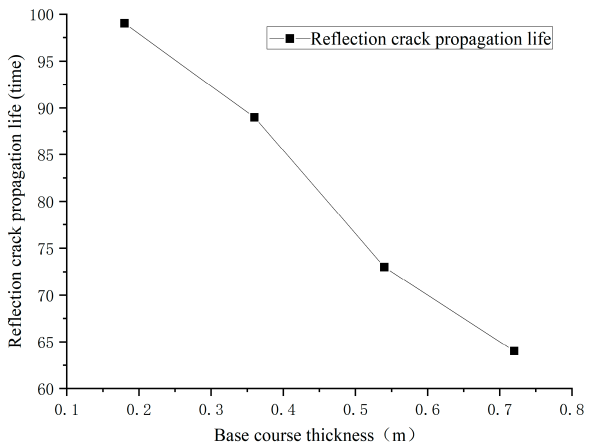


**Figure 14.** Law of reflection crack growth life with base course thickness.

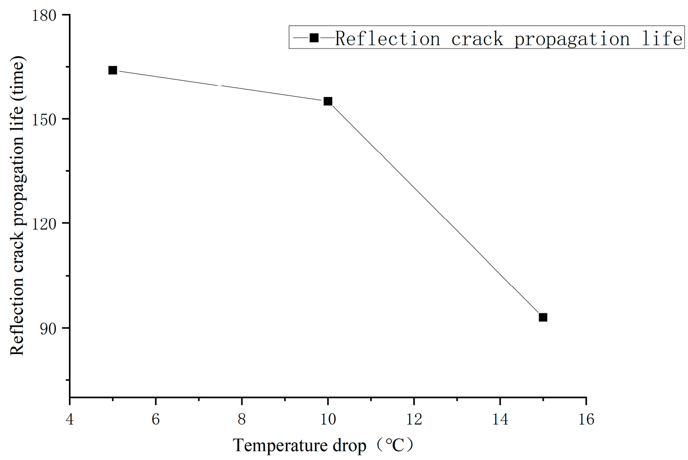


**Figure 15.** Law of reflection crack growth life with temperature drop.

As can be seen from Figures 10–15, the reflection crack propagation life increases with an increase in the thickness of the middle course and the thickness of the bottom course and decreases with an increase in the surface course modulus, base course modulus, subgrade modulus, base course thickness, and amplitude of temperature drop.

According to the stress intensity factor analysis of the reflection crack tip under the action of a temperature gradient, it is difficult for the crack to expand upward when the thickness of the middle and bottom course increases. At the same time, the thickness of the middle and bottom course determines the path length of the reflection crack. When the thickness of the middle and bottom course is greater, the path of the reflection crack extending from the bottom of the asphalt course upward is longer, the length interval of the integral of the Paris formula is longer, and the crack propagation life is longer. When the surface modulus, base modulus, base thickness, and the scale of the drop in temperature increase, the crack tends to expand upward. Therefore, the crack propagation life decreases with an increase in these factors.

## 6. Sensitivity Analysis of Factors Influencing Propagation Life of Reflection Crack

In order to screen out the unnecessary factors affecting the propagation life of the reflection crack, sensitivity analysis was carried out. Sensitivity analysis can determine the significance of the influence of each factor on the reflection crack. The basis of the judgment is the sensitivity coefficient, and the calculation formula is as follows:

$$S_{AF} = \frac{\Delta A/A}{\Delta F/F} \tag{6}$$

The terms in the formula are defined as follows: $S_{AF}$—Sensitivity coefficient;
$\Delta F/F$—The rate of change of uncertainty F, %;
$\Delta A/A$—When the uncertainty factor $F$ changes by $\Delta F$, the change rate of evaluation index A,%.

The sensitivity of each factor to the effect of individual variation in a certain range on the reflective crack propagation life caused by $\triangle K_I$ is shown in Table 9.

**Table 9.** Sensitivity of influence factors on propagation life of reflection crack.

| Sensitivity Coefficient, % | | | | | |
|---|---|---|---|---|---|
| **Middle Course Thickness** | **Bottom Course Thickness** | **Base Course Thickness** | **Surface Course Modulus** | **Base Course Modulus** | **Amplitude of Temperature Drop** |
| 1.247 | 0.386 | −0.118 | −0.136 | −0.088 | −0.217 |

As can be seen from Table 9, under the effect of temperature, within the range of influencing factors consistent with the actual situation of the road surface, the thickness of the middle course and the thickness of the bottom course change in the same direction as the extended life of the temperature reflection crack, while the thickness of the base course, the modulus of the surface course, the modulus of the base course, and the drop in temperature change in the opposite direction as the extended life of the temperature reflection crack.

The order of significance of the influence factors on the temperature reflection crack propagation life is as follows: middle course thickness > bottom course thickness > amplitude of temperature drop > surface course modulus > base course thickness > base course modulus.

## 7. Prediction Model of Reflection Crack Propagation Life

The parameters of the final retained prediction model were the thickness of the middle course, the thickness of the bottom course, the thickness of the base course, the surface course modulus, and the temperature drop range.

1. The estimated model form.

On the basis of ensuring the physical significance of the formula, Formula (7) is used as the prediction formula for the propagation life of the reflection crack:

$$N = a \times \frac{\left(h_{p2}^{b} + h_{p3}^{c}\right)}{h_{b}^{d}} \times E_{p}^{e} \times \Delta T^{f}. \tag{7}$$

The terms in the formula are defined as follows: $N$. —Reflection crack propagation life;

$E_p$—Surface composite modulus, MPa;
$h_{p2}$—Thickness of middle course, m;
$h_{p3}$—Thickness of bottom course, m;
$h_b$—Thickness of basement course, m;
$\Delta T$—Range of temperature drop, °C;
$a, b, c, d, e, f$—Coefficient;

2. The estimated analysis data.

The amount of data points in the single-factor analysis above is not enough to support the prediction model, and enough data points can be obtained by designing the orthogonal table of influencing factors. The orthogonal table of influencing factors designed in this paper and the calculation results are shown in Table 10.

**Table 10.** Data of prediction model for reflection crack propagation.

| | Middle Course Thickness, m | Bottom Course Thickness, m | Base Thickness, m | Surface Modulus MPa | Amplitude of Temperature Drop, °C | Fatigue Extended Life |
|---|---|---|---|---|---|---|
| 1 | 0.06 | 0.08 | 0.18 | 500 | 8 | 748 |
| 2 | 0.06 | 0.12 | 0.36 | 1000 | 10 | 238 |
| 3 | 0.06 | 0.16 | 0.54 | 2000 | 12 | 76 |
| 4 | 0.06 | 0.24 | 0.72 | 3000 | 14 | 21 |
| 5 | 0.06 | 0.32 | 0.90 | 4000 | 16 | 9 |
| 6 | 0.12 | 0.08 | 0.36 | 2000 | 10 | 84 |
| 7 | 0.12 | 0.12 | 0.54 | 3000 | 12 | 30 |
| 8 | 0.12 | 0.16 | 0.72 | 4000 | 14 | 11 |
| 9 | 0.12 | 0.24 | 0.90 | 500 | 16 | 364 |
| 10 | 0.12 | 0.32 | 0.18 | 1000 | 8 | 510 |
| 11 | 0.18 | 0.08 | 0.54 | 4000 | 10 | 21 |
| 12 | 0.18 | 0.12 | 0.72 | 500 | 12 | 636 |
| 13 | 0.18 | 0.16 | 0.90 | 1000 | 14 | 233 |
| 14 | 0.18 | 0.24 | 0.18 | 2000 | 16 | 101 |
| 15 | 0.18 | 0.32 | 0.36 | 3000 | 8 | 186 |
| 16 | 0.24 | 0.08 | 0.72 | 1000 | 16 | 247 |
| 17 | 0.24 | 0.12 | 0.90 | 2000 | 8 | 219 |
| 18 | 0.24 | 0.16 | 0.18 | 3000 | 10 | 163 |
| 19 | 0.24 | 0.24 | 0.36 | 4000 | 12 | 49 |
| 20 | 0.24 | 0.32 | 0.54 | 500 | 14 | 821 |
| 21 | 0.30 | 0.08 | 0.90 | 3000 | 12 | 39 |
| 22 | 0.30 | 0.12 | 0.18 | 4000 | 14 | 64 |
| 23 | 0.30 | 0.16 | 0.36 | 500 | 16 | 799 |
| 24 | 0.30 | 0.24 | 0.54 | 1000 | 8 | 751 |
| 25 | 0.30 | 0.32 | 0.72 | 2000 | 10 | 274 |

3. Regression results

Nonlinear regression was carried out according to Formula (6). The prediction model of the reflected crack propagation life under the action of temperature is as follows:

$$N = 160863000 \times \frac{h_{p2}^{0.699} + h_{p3}^{2.944}}{h_b^{0.223}} \times E_p^{-1.296} \times \Delta T^{-1.283}\ R^2 = 0.756 \quad (8)$$

Formula (8) shows that under the action of temperature gradient cycling, the fatigue extension life of semi-rigid asphalt pavement has a good nonlinear correlation with the thickness of the middle and bottom courses, the thickness of the base course, the modulus of the surface course, and the decrease in temperature. Formula (8) defines the law of the thermal reflection crack propagation life as changing with the thickness of the structure course and the modulus of the structure course. The structure combination of heat-resistant reflective crack pavement can be put forward by Formula (8), which provides a new method for slowing down the temperature-based reflective crack of semi-rigid base asphalt pavement.

The service life of asphalt pavement in areas with large daily temperature differences will be greatly reduced under the action of temperature gradient cycling, but the existing asphalt pavement design methods do not consider the effect of temperature gradient cycling on the service life of asphalt pavement. In some alpine areas with large daily temperature differences, the asphalt pavement structure designed according to the existing pavement design method may not meet the requirements of service life. Formula (8) provides a prediction model for the reflection crack propagation life under the action of temperature gradient cycling, which can assist in the structural design of asphalt pavement in areas with large daily temperature differences and provide theoretical supplement and reference for the design of asphalt pavement in areas with large daily temperature difference.

## 8. Conclusions

In this paper, based on the building materials from the Guilin–Huangshahe section of National Highway 322 province and the climatic characteristics of Guilin City, the stress intensity factor analysis at the crack tip and the reflection crack propagation life analysis are carried out according to the theory of fatigue fracture mechanics. The conclusions are as follows:

1. At the same crack length, the amplitude of the stress intensity factor increases with an increase in the base course modulus, surface course modulus, base course thickness, and air temperature drop and decreases with an increase in the middle course thickness and bottom course thickness. The influence of the subgrade modulus on the amplitude of the stress intensity factor is basically negligible.
2. Under the action of temperature, within the range of influencing factors consistent with the actual condition of the pavement, the propagation life of temperature-type reflective cracks increases with an increase in the thickness of the middle course and bottom course and decreases with an increase in the surface course modulus, base course modulus, base course thickness, and temperature decrease. After sensitivity analysis, the significant order of influence factors on the propagation life of temperature reflection cracks is as follows: middle course thickness > bottom course thickness > temperature drop range > surface course modulus > base course thickness > base course modulus.
3. Sensitivity analysis was used to eliminate the influential factors with low influence on reflection crack propagation—base course thickness and base course modulus—and orthogonal design was carried out on the influential factors with high influence. The extended life of the reflection crack under the influence of multiple factors was calculated. Finally, a prediction model for the extended life of the reflection crack under the action of a temperature gradient was established. It provides a theoretical supplement and reference for the design and calculation of asphalt pavement structures in areas with large daily temperature differences in China.

**Author Contributions:** Methodology, A.Y.; Validation, A.Y.; Resources, F.C. and A.Y.; Writing—review & editing, F.C.; Supervision, F.C. and A.Y.; Project administration, A.Y.; Funding acquisition, F.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

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