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Study on crack extension of the AC layer of CRC+AC composite pavement

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1. Introduction

The early damage of the asphalt pavements of our country is very serious, and the service life of the asphalt pavement of the expressway is shorter than the designed purpose frequently. Therefore, it is urgent to improve the durability of the road works as well as promote the rapid and better development of the domestic transportation business. And, the continuously reinforced concrete and asphalt composite pavement (CRC+AC) is featured by high integral structure strength, superior driving comfort, long service life, and low maintenance cost, which is deemed as the development direction of the long-life asphalt pavement structure of the heavy-load transportation expressway [1-3]. Furthermore, the traditional road works analysis program can't solve the mechanical response problem of the composite pavement structure under the conditions of the CRC layer with cracks as well as fail to simulate the singularity of the stress and displacement field near the crack tip. Currently, there are few studies on the crack extension of the CRC+AC composite pavement d at home and abroad, especially, there is no study on the surface and base temperature-type cracks of the AC layer.

The paper, based on the fracture mechanics, elastic multilayer theory, and other fundamental theories, are applied with the finite element method and stress intensity factor to describe the crack extensions, establish the relationships among the stress intensity factor, structural layer thickness, modulus, crack length, and crack extension period, and study the crack mechanism of the AC layer of the CRC+AC composite pavement as well as the influence factors of the crack extension strength of the AC layer under the effects of the load and temperature as well. And, the study results can be made as the reference basis of the rational design of the CRC+AC composite pavement.

2. Relevant theory and model parameters

It shall be guaranteed that the pavement structure design has sufficient fatigue lives, which are composed of four stages of the crack generation, microcrack extension, macrocrack extension, and final fracture [4]. And, the crack extension has its own uncertain factor, and the crack generation and crack extension occupy the main part.

According to opinions of the fracture mechanics [5-7], the crack extension has 3 kinds of displacement modes: open mode (type I), shearing mode (type II), and tearing mode (type III). As it is hard to obtain the analytic solution of the stress intensity factor for the actual engineering problems, the finite element method is applied for the numerical calculation generally.

2.1. Relevant theory

Concerning the plane crack shown in the Fig. 1, the origin of coordinates O is selected to be located at the crack tip. the r and θ refer to polar coordinates, x, y refers to the rectangular coordinates, u, and ν refers to the displacement component x direction and y direction, respectively. And, the stress intensity factor can be defined by the corresponding stress field and displacement field [8]

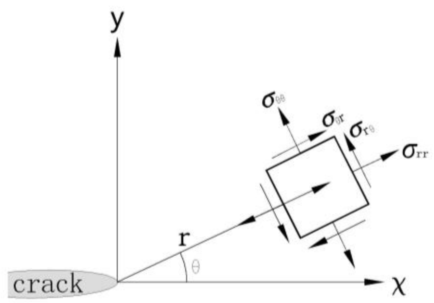

Fig. 1 Schema of crack tip

$$\sigma_{rr}=\frac{K_{\mathrm{I}}}{\sqrt{2\pi r}}cos\frac{\theta}{2}\left(1-sin\frac{\theta}{2}sin\frac{3\theta}{2}\right)-\\-\frac{K_{\mathrm{II}}}{\sqrt{2\pi r}}sin\frac{\theta}{2}\left(2+cos\frac{\theta}{2}cos\frac{3\theta}{2}\right)\quad(1)$$

$$\sigma_{y}=\frac{K_{\mathrm{I}}}{\sqrt{2\pi r}}cos\frac{\theta}{2}\left(1+sin\frac{\theta}{2}sin\frac{3\theta}{2}\right)+\\+\frac{K_{\mathrm{II}}}{\sqrt{2\pi r}}sin\frac{\theta}{2}cos\frac{\theta}{2}cos\frac{3\theta}{2}\quad(2)$$

$$\tau_{xy}=\frac{K_{\mathrm{I}}}{\sqrt{2\pi r}}cos\frac{\theta}{2}sin\frac{\theta}{2}cos\frac{3\theta}{2}+\\+\frac{K_{\mathrm{II}}}{\sqrt{2\pi r}}cos\frac{\theta}{2}\left(1-sin\frac{\theta}{2}sin\frac{3\theta}{2}\right)\quad(3)$$

$$u=\frac{K_{\mathrm{I}}}{4G}\sqrt{\frac{r}{2\pi}}\left[\left(2\chi-1\right)cos\frac{\theta}{2}-cos\frac{3\theta}{2}\right]+\\+\frac{K_{\mathrm{II}}}{4G}\sqrt{\frac{r}{2\pi}}\left[\left(2\chi+3\right)sin\frac{\theta}{2}+sin\frac{3\theta}{2}\right]\quad(4)$$

$$\nu=\frac{K_{\mathrm{I}}}{4G}\sqrt{\frac{r}{2\pi}}\left[\left(2\chi+1\right)sin\frac{\theta}{2}-sin\frac{3\theta}{2}\right]-\\-\frac{K_{\mathrm{II}}}{4G}\sqrt{\frac{r}{2\pi}}\left[\left(2\chi-3\right)cos\frac{\theta}{2}+cos\frac{3\theta}{2}\right]\quad(5)$$

where G is shearing modulus, $G = \frac{E}{2(1+\nu_e)}$, E is expresses modulus of materials, ν_e is expresses Poisson's ratio of materials. $\chi = \frac{3-\nu_e}{4+\nu_e}$ (plane stress), $\chi = 3-4\nu_e$ (plane strain).

$$K_{\mathrm{I}} = \lim_{r\to 0}\left(\sigma_y\sqrt{2\pi r}\right)(r,0) \quad (6)$$

$$K_{\mathrm{II}} = \lim_{r\to 0}\left(\tau_{xy}\sqrt{2\pi r}\right)(r,0) \quad (7)$$

The power method is applied in FEM software ABAQUS For definition of K_{I} and K_{II}.

The prediction of fatigue life for pavement structure can be acquired by calculation of two stages, namely the crack generation and crack extension. We can use Paris formula to predict the crack propagation life of N_p.

$$N_p = \int_{C0}^{C1} \frac{1}{A(\Delta K)^n} dc \quad (8)$$

where ΔK is stress intensity factor variation, A, n is the material fracture parameters, (asphalt mixture with $A = 3.5\times10^{-6}$, $m = 3$); $C0$ is initial crack length; $C1$ is critical crack length, traffic loads usually adopts the structural layer thickness.

Because the pavement structure is assumed to be linear elastic model, so in the absence of external loads, pavement structure without stress field, of course, pavement crack stress intensity factor is 0, so the equation ΔK can be directly used to calculated pavement crack stress intensity factor.

Based on the Eq. (8), we can calculate the pavement crack fatigue life, namely the load cycle number.

2.2. Calculation model and parameters

The AC layer is with the thickness h = 8 cm, elastic modulus E = 1200 MPa, and ν_e = 0.3. The CRC layer is with the thickness h = 20 cm.When the Ø 16 mm deformed steel bar is used as the longitudinal bar, the reinforcement ratio ρ_1 = 0.6%.When the Ø10 mm deformed steel bar is used as the transverse bar, the reinforcement ratio ρ = 0.1%. And, the steel bar is set as the 1/2 place of the CRC layer, which is with the concrete modulus $E = 2.9\times10^4$ MPa, ν_e = 0.167, and coefficient of linear expansion of 1.0×10^{-5}. The steel bar is with the modulus $E = 2.0\times10^5$ MPa, ν_e = 0.28, and coefficient of linear expansion of 9.5×10^{-6}.The base material is the cement-stabilized macadam, which is with the thickness h = 20 cm, elastic modulus $E = 1.0\times10^3$ MPa, and Poisson's ratio of 0.25. The subgrade modulus is 50 MPa, and ν_e = 0.4.

3. Study on the load-type crack extension

No matter the type II stress intensity factor K_{II} is positive or negative; the crack extension will make contributions. Therefore, the calculation results of the paper will take the absolute value of the K_{II}. During the crack extension layer, under the effect of the shearing type stress intensity factor, the crack extension will make some angle changes. However, in the condition of the one-time driving load effect, it can be assumed that the crack is of the vertical and upward extension. In the paper, when the ratio between the crack length and the asphalt layer thickness is 0.5, it is defined as the medium term of the crack extension. Considering that the influence of the structural layer thickness and the modulus to the crack extension is not related to the crack extension period. Unless otherwise specified, the calculation results in the paper refer to the stress intensity factor in certain extension period (medium term of the crack extension).

3.1. Study on the load-type crack extension of the AC layer surface

It is intended to completely analyze the crack extension of the AC layer surface under the deviatoric load effect, calcualte and analyze the relationships among the stress intensity factor K_{II} of the type II, crack extension period, crack length (length of the crack along the vertical depth direciton of the pavement), structural layer thickness, and modulus, as well as study the influence factor and impacting the crack extension of the AC layer surface.

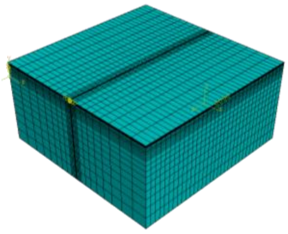

Fig. 2 Schema of 3D model

3.1.1. Analysis on the impact of the crack extension length and the structural layer thickness on the crack extension

The above calculation results show that:

1. It can be seen from the Fig. 3 that, under the effect of the deviatoric load, K_{II} increases to the peak value and slowly reduces along with the constantly downward extension of the crack. When the surface crack extends downwards to the place where the surface layer is with the thickness of about 0.6, the extension strength will be the maximum.

2. It can be seen from the Fig. 4 that, when the crack length is kept fixed, the thicker the AC layer is, the distance between the crack tip and the CRC layer support is farther, and the extension strength is larger. When the AC layer thickness is increased by 1cm, the crack extension strength will be increased by 3.5% approximately. However, as the extension path will also be increased, the increased AC layer thickness will delay the time required by the surface crack to run through the AC layer. It can be seen from the Fig. 4 that such delay effect is much larger than the effect caused by the increased extension strength.

3. It can be seen from the Fig. 5 that, in certain extension period, with the increased AC layer thickness, the distance between the crack tip and the CRC layer will increase too. Accordingly, the extension strength will be linearly increased and the extension path will be increased as well. The influence relationship between the increased extension strength and extension path and the crack exten-

sion of the AC layer surface is that: the delay effect of the increased extension path to the crack extension is 2-3 times of the increase effect of the increased strength factor.

4. It can be seen from the Fig. 6 that, as the impact of the CRC layer thickness on the crack extension strength of the type II crack of the AC layer surface is minor; the impact of the base thickness on the type II crack extension strength of the surface can be neglected. Therefore, no calculation will be made in the paper.

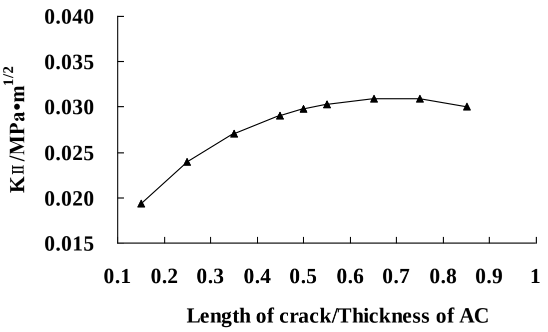

Fig. 3 Relationship of K_{II} and the crack extension

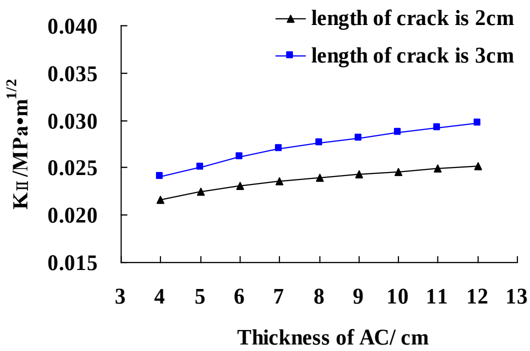

Fig. 4 Relationship of K_{II} and the thickness of AC layer under certain crack length

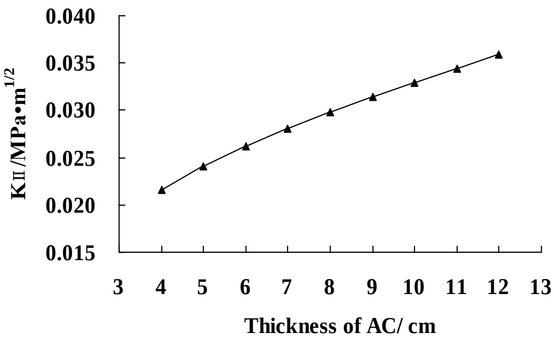

Fig. 5 Relationship of K_{II} and the thickness of AC layer under certain crack extension period

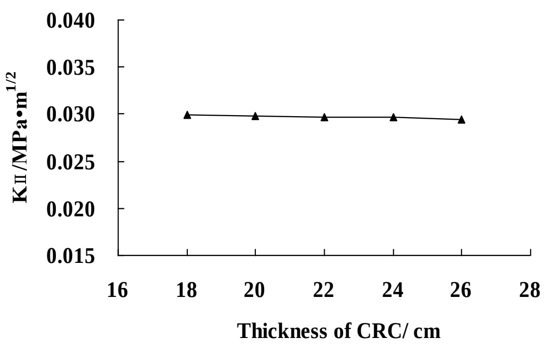

Fig. 6 Relationship of K_{II} and the thickness of CRC layer

3.1.2. Analysis on the modulus impact on the crack extension

The above calculation results show that:

1. It can be seen from the Fig. 7 that, the increased modulus of the AC layer will increase the K_{II} value, however, the influence is minor.

2. It can be seen from the Fig. 8 that, the modulus of the CRC layer will not impact the type II crack extension strength of the surface fundamentally. Accordingly, it is not necessary to consider the impact of the modulus of the base and soil base on the crack extension strength of the surface.

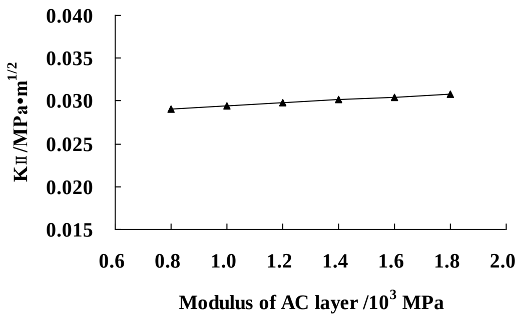

Fig. 7 Relationship of K_{II} and the modulus of AC layer

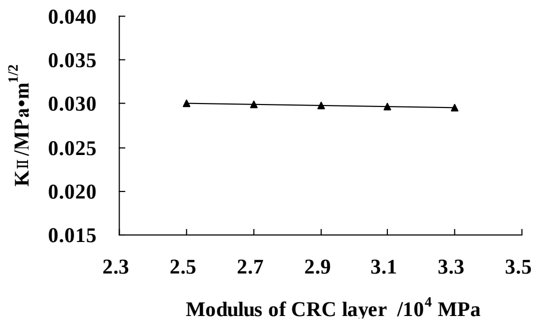

Fig. 8 Relationship of K_{II} and the modulus of CRC layer

3.2. Study on the load-type crack extension of the AC layer base

In the CRC+AC composite pavementstructure, transverse cracks of the CRC layer will appear in the AC layer base due to the concentrated stress. In addition to the above, under the effect of the exterior factor, cracks will constantly develop upwards. Finally, reflection crack will appear, which will seriously impact the durability of the CRC+AC composite pavement. Accoridngly, it is significant to study factors and affecting the crack extension of the AC layer base.

3.2.1. Analysis on the impact of the crack extension length and the structural layer thickness on the crack extension

The above calculation results show that:

1. It can be seen from the Fig. 9 that, under the effect of the deviatoric load, the strength factor K_{II} of the crack extension of the AC layer base will increase along with the upward extension of cracks, and the increase amplitude of the K_{II} of the crack extension in the later stage is obviously larger than that in the earlier stage.

2. It can be seen from the Fig. 10 that, when the

crack length is kept fixed, the increased thickness of the AC layer will reduce the crack extension strength. In addition to the above, along with the increased extension path, the increased AC layer thickness will delay the time required by the surface crack to run through the AC layer.

3. It can be seen from the Fig. 11 that, in certain extension period, with the increased AC layer thickness, the extension strength of cracks will be linearly increased and the extension path will be increased as well. The influence relationship between the increased extension strength and extension path and the crack extension of the AC layer base is that: the delay effect of the increased extension path to the crack extension is 4-6 times of the increase effect of the increased strength factor.

4. It can be seen from the Fig. 12 that, as the impact of the CRC layer thickness on the crack extension strength of the type II crack of the AC layer base is minor; the impact of the base thickness on the type II crack extension strength of the base can be neglected. Therefore, no calculation will be made in the paper.

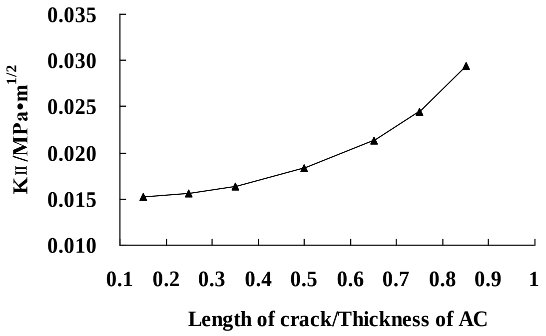

Fig. 9 Relationship of K_{II} and the crack extension

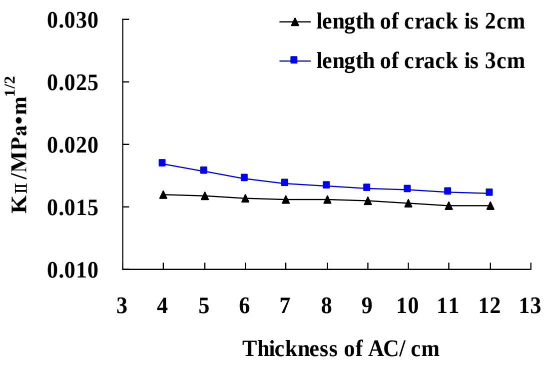

Fig. 10 Relationship of K_{II} and the thickness of AC layer under certain crack length

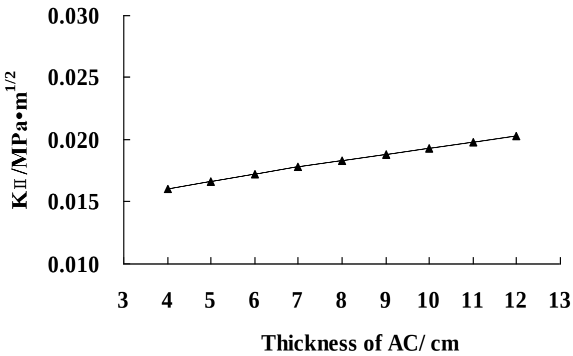

Fig. 11 Relationship of K_{II} and the thickness of AC layer under certain crack extension period

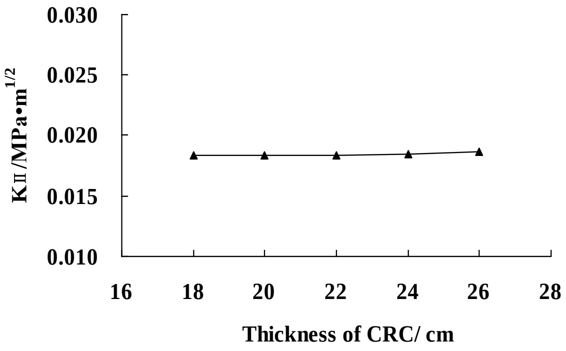

Fig. 12 Relationship of K_{II} and the thickness of CRC layer

3.2.2. Analysis on the modulus impact on the crack extension

The above calculation results show that:

1. It can be seen from the Fig. 13 that, the increased modulus of the AC layer will increase the K_{II} value. However, the influence is minor. Along with each additional 200 MPa of the modulus, the strength factor K_{II} of the base crack extension will be increased by 4% approximately.

2. It can be seen from the Fig. 14 that, the modulus of the CRC layer will not impact the type II crack extension strength of the base fundamentally. Accordingly, it is not necessary to consider the impact of the modulus of the base and soil base on the type II crack extension strength.

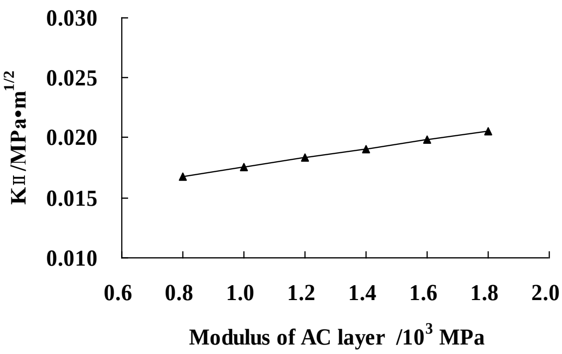

Fig. 13 Relationship of K_{II} and the modulus of AC layer

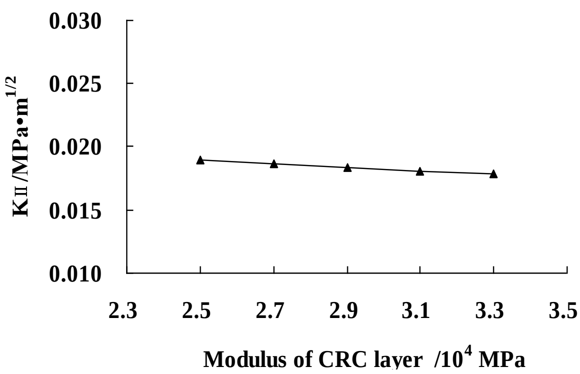

Fig. 14 Relationship of K_{II} and the modulus of CRC layer

4. Study on the temperature-type crack extension

The temperature-type crack of the AC layer is mainly composed of the open mode (type I). Along with the temperature changes, the temperature gradient has been formed in the CRC+AC composite pavement structure. Owing to the effect of the temperature gradient, certain temperature stress will be generated inside the structural layer. And, the asphalt mixture is a kind of typical temperature sensitive material, under the long-term effect of the temperature stress, the temperature-type crack will appear in the AC layer of the CRC+AC composite pavement, which will extend along the crack tip. The extension strength can be shown by the stress intensity factor K_I. Currently, the domestic design theories and methods concerning the composite pavement are insufficient [9], and there are few studies on the crack extension of the CRC+AC composite pavement at home and abroad. Therefore, the paper will study and analyze the extension strength of the temperature-type crack of the AC layer surface by applying the finite element method.

It is intended to completely analyze the crack extension of the AC layer surface under the temperature effect, calcualte the max. stress intensity factor K_I of the CRC+AC composite pavement under the continuous temperature change conditions, establish the relationships among the stress intensity factor K_I, crack extension period, crack length, structural layer thickness, and modulus, and study the influence factors of the crack extension of the AC layer surface as well.

4.1. Analysis on the impact of the crack extension length and the structural layer thickness on the crack extension

The above calculation results show that:

1. It can be seen from the Fig. 15 that, under the effect of the temperature, the K_I will increase along with the downward extension of cracks, and the increase amplitude of the K_I of the crack extension in the earlier stage is obviously larger than that in the later stage.

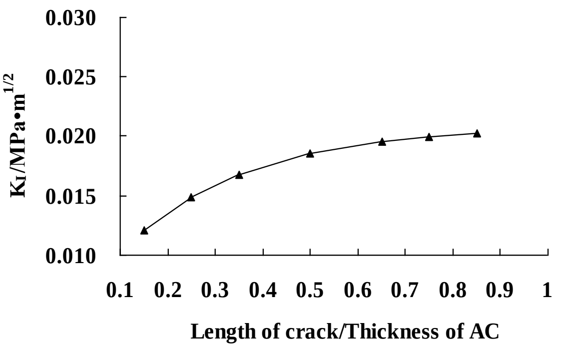

Fig. 15 Relationship of K_I and the crack extension

2. It can be seen from the Fig. 16 that, when the crack length is kept fixed, the thicker the AC layer is, and the extension strength is smaller. In addition to the above, along with the increased extension path, the increased AC layer thickness will delay the surface crack extension.

3. It can be seen from the Fig. 17 that, when the extension period is kept fixed, along with the increased thickness of the AC layer, the surface crack extension strength will be of small changes. However, as the extension path will also be increased, the increased AC layer thickness will delay the temperature-type crack extension of the surface.

4. It can be seen from the Fig. 18 that, as the impact of the CRC layer thickness on the temperature-type crack extension strength of the AC layer surface is minor, the impact of the base thickness on the temperature-type crack extension can be neglected, and therefore, no calculation will be made in the paper.

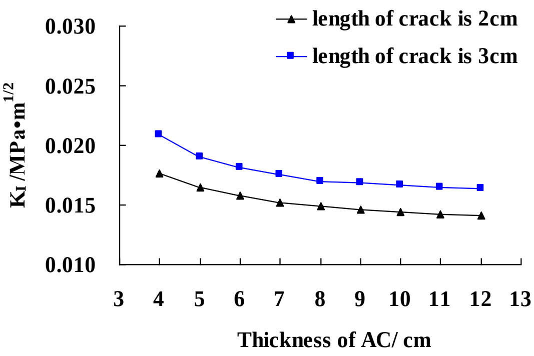

Fig. 16 Relationship of K_I and the thickness of AClayer under certain crack length

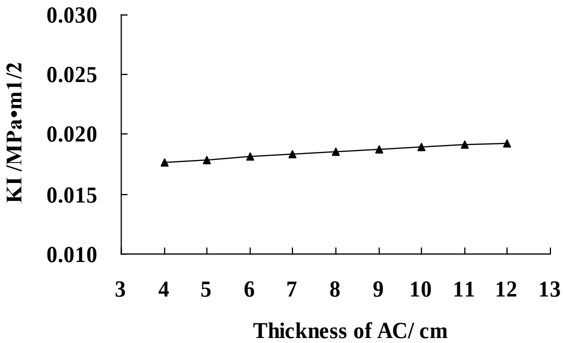

Fig. 17 Relationship of KI and the thickness of AC layer under certain crack extension period

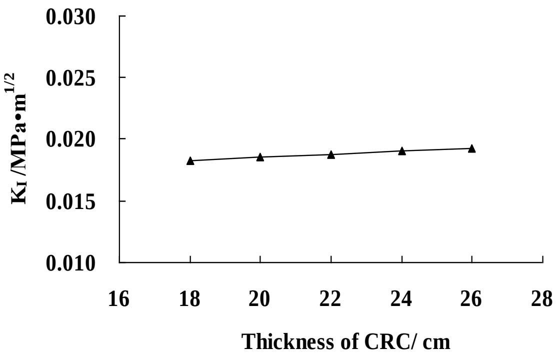

Fig. 18 Relationship of KI and the thickness of CRC layer

4.2. Analysis on the modulus impact on the crack extension

The above calculation results show that:

1. It can be seen from the Fig. 19 that, the increased modulus of the AC layer will linearly increase the K_I value of the temperature-type crack of the AC layer surface. Along with each additional 200 MPa of the modulus, the base crack extension strength will be increased by 18% approximately.

2. It can be seen from the Fig. 20 that, the modulus of the CRC layer will not impact the temperature-type crack extension strength fundamentally. Accordingly, it is not necessary to consider the impact of the modulus of the base and soil base on the temperature-type crack extension strength of the AC layer surface.

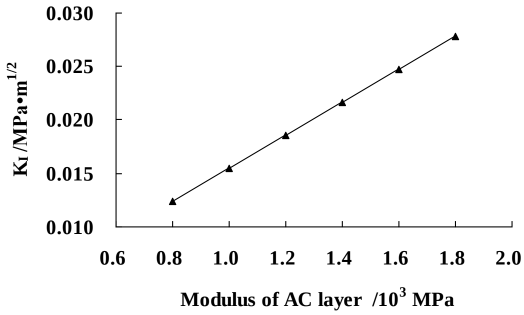

Fig. 19 Relationship of KI and the modulus of AC layer

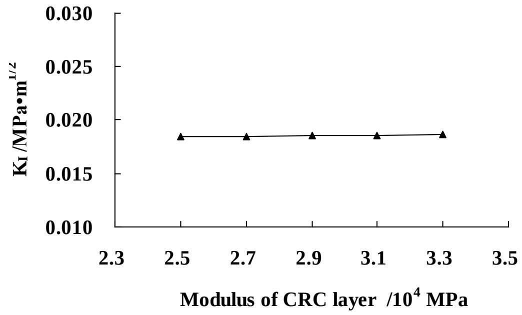

Fig. 20 Relationship of KI and the modulus of CRC layer

5. Conclusions

As the fatigue life of the AC layer of the CRC+AC composite pavement is depended on the service life of the crack extension stage, the study on the crack extension of the AC layer can be made as the reference basis of the rational design of the CRC+AC composite pavement. The main study conclusions of the paper are as follows:

1. Under the effect of the deviatoric load, the surface load-type crack of the AC layer will increase to the peak value and slowly reduces along with the constantly downward extension of the crack. When the surface crack extends downwards to the surface layer thickness of about 0.6, the extension strength will be the maximum. The strength factor K_{II} of the crack extension of the AC layer base will increase along with the upward crack extension, and the increase amplitude of the K_{II} of the crack extension in the later stage is obviously larger than that in the earlier stage.

2. The load-type crack extension strength of the AC layer will linearly increase or slightly reduce along with the increased thickness of the AC layer. However, as the increased thickness of the AC layer will increase the extension path and delay the crack extension, and such delay effect is much larger than the effect caused by the strength factor changes. Obviously, the increased thickness of the AC layer will delay the load-type crack extension of the AC layer, especially the load-type crack extension of the AC layer base.

3. The impact of the thickness of the CRC layer on the load-type crack extension strength of the AC layer is minor; the impact of the AC layer modulus on the load-type crack extension strength of the AC layer, and the modulus of other structural layers doesn't impact the load-type crack extension strength of the AC layer fundamentally.

4. The K_I value of the temperature-type crack of the AC layer surface will increase along with the constantly downward extension of cracks, and the increase amplitude of the K_I of the crack extension in the earlier stage is obviously larger than that in the later stage.

5. The temperature-type crack extension strength of the AC layer will reduce along with the increased thickness of the AC layer. And the extension path will be increased along with the increased thickness of the AC layer. Obviously, the increased thickness of the AC layer will reduce and delay the temperature-type crack extension of the AC layer.

6. The thickness of the CRC layer doesn't impact the extension strength of the temperature-type crack of the AC layer surface fundamentally.

7. Along with the increased modulus of the AC layer, the K_I value of the temperature-type crack will linearly increase, and the modulus of the CRC layer, base and soil base doesn't impact the temperature-type crack extension strength of the AC layer fundamentally.

Through the above-mentioned calculation and analysis, we find out that, under the deviatoric load effect, the AC layer mainly shows the type II open mode. However under the temperature effect, it mainly shows the type I open mode. Accordingly, under the coupled load and temperature effects, the crack extension strength has no changes fundamentally, and no further calculation and analysis will be made here.

Acknowledgment

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PLYŠIO PLITIMO CRC+AC GRINDINIO KOMPOZITO SLUOKSNYJE TYRIMAS

R e z i u m ė

Kadangi tolygiai įtempto betono (CRC) ir asfalto kompozito (AC) grindinio struktūros charakteristikos yra nepakankamai ištirtos, remiantis irimo mechanikos teorija ir taikant baigtinių elementų metodą atliktas plyšio susidarymo ir plitimo mechanizmo asfalto kompozito sluoksnyje tyrimas. Be to, atsižvelgiant įtempių plyšio viršūnėje intensyvumo faktorių, apkrovimo tipą ir temperatūrą asfalto kompozito sluoksnyje, buvo apskaičiuota plyšio plitimo periodo įtaka, plyšio ilgis, konstrukcijos sluoksnių storis, moduliai ir kiti veiksniai, turintys įtakos plyšio plitimui asfalto kompozito sluoksniuose. Tyrimo rezultatai parodė, kad plyšio plitimo greitis asfalto kompozito sluoksnyje turi įtakos plyšio plitimo jėgai. Didėjant asfalto kompozito sluoksnio storiui, plyšio plitimo greitis gali sumažėti. Tolygiai įtempto betono sluoksnio storio įtaka plyšio plitimo greičiui asfalto kompozito sluoksnyje yra minimali ir nereikšminga. Asfalto kompozito sluoksnio plyšio plitimo temperatūros įtaka tiesiškai didėja didėjant šio sluoksnio moduliui, plyšio apkrovimo tipas keičiasi minimaliai, o kitų sluoksnių modulių įtaka plyšio plitimo jėgai yra labai maža. Šio tyrimo rezultatai gali būti duomenų bazė siekiant racionaliai projektuoti tolygiai įtempto betono ir asfalto kompozito grindinį.

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STUDY ON CRACK EXTENSION OF THE AC LAYER OF CRC+AC COMPOSITE PAVEMENT

S u m m a r y

Focusing on the characteristics of structures of the CRC+AC composite pavement as well as the insufficient studies, the crack generation and extension mechanisms of the AC layer are studied by applying the fracture mechanics theory and finite element method. In addition to the above, the tip stress intensity factor of the load-type crack and temperature-type crack of the AC layer is calculated, the influence of the crack extension period, crack length, structural layer thickness, modulus, and other factors to the crack extension of the AC layer are analyzed and studied. And, the study results show that: the extension period of cracks of the AC layer has some impacts on the crack extension strength. the increased thickness of the AC layer can well delay the crack expansion of the AC layer, the impact of the thickness of the CRC layer on the crack extension of the AC layer is minor or none fundamentally, The extension strength of the temperature-type crack of the AC layer will linearly increase along with the increased modulus of the AC layer, and the change of the load-type crack is minor, and the impact of the modulus of other structural layers on the crack extension strength of the AC layer is very minor. And, the study results can be made as the reference basis of the rational design of the CRC+AC composite pavement.

Keywords: road engineering, continuously reinforced concrete composite pavement, load-type crack, temperature-type crack, crack extension.

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