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# Subgrade-Associated Factorial Influences on Fatigue Cracking of Cement Concrete Pavement

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***Abstract***- Cracking is a kind of normal distress of cement concrete pavement, which occurs frequently under cyclic loads and reduces the pavement performance and shortens the pavement life substantially. In this paper, a general numerical model for cracking damage of cement concrete pavement under traffic loads is established, a series of analyses were carried out based on the general model with tailored parameters to analyze the influences of subgrade and associated factors on cracking index and sensitivity. The results show that subgrade stiffness has a great influence on fatigue cracking of cement concrete pavement, the damage accumulated in periods with low subgrade stiffness plays a pivotal role in fatigue cracking. The axle types and the subgrade stiffness have correlated influences on the destructive effect of the cement slab and the adaptability of different axle types. The combined effect of increasing the cement slab thickness and the modulus of rupture of cement concrete, reducing axle weight, load cycles and improving subgrade modulus result in an apparent increase of the fatigue cracking life. However, the sensitivity of the fatigue cracking life on the slab thickness, the modulus of rupture of cement concrete and the single-axle weight become weaker with the improvement of subgrade modulus. The increase of the base layer thickness can improve the fatigue cracking life definitely, but has no obvious influence on the relative change rate of CI varying with the subgrade stiffness. The interaction between the subgrade stiffness and the base thickness on the sensibility of fatigue cracking under traffic loads is very slight.

***Keywords-*** *Cement Concrete Pavement, Influence Evaluation, Fatigue Cracking, Subgrade Stiffness*

## I. INTRODUCTION

Cement concrete pavements have been used all over the world due to many advantages. However, crack of cement concrete slab occurs frequently under cyclic loads, which substantially reduces the pavement performance and shortens the pavement life. Many factors affect the crack while subgrade plays an important role as a support for the cement concrete slab [1-2]. To ensure a good performance of cement concrete pavement, the Ministry of Transport of China specified requirements on subgrade including durability, stiffness, and uniformity [3]. However, subgrade is not always in ideal status because of different moisture, compaction degree, variety and quantity of the fillers, etc. Extensive research regarding subgrade as the support of pavement has been conducted, which include the impact of subgrade stiffness or non-uniformity on mechanical response of cement concrete slab [4-7], methods of predicting or determining subgrade modulus [8-17], and how to improve the bearing capacity of subgrade [18-19].

All above research showed the importance of subgrade for cement concrete pavement. However, the axle types, pavement design parameters including cement slab thickness, load repetitions, the weight of axel, the modulus of rupture of cement concrete, the base layer, and the subgrade are associated with each other to have influences on fatigue slab cracking instead of working independently. This paper aims to meet this need to present a study on subgrade-associated influencing factors and sensitivity on the fatigue cracking of cement concrete pavement. Firstly, the background of a computer program KENSLABS [20] is introduced, a general numerical model is established, and a series of analyses were carried out to analyze the factorial influences and sensitivity on the damage of cement concrete pavement under traffic loads. The details of the results are presented and discussed. It is concluded that subgrade stiffness has a great influence on fatigue cracking of cement concrete pavement, the damage accumulated in periods with a low subgrade stiffness plays a more pivotal role in fatigue cracking. Both the destructive effect of axle types for cement slab and the adaptability of axle types on subgrade stiffness loss have a high correlation with subgrade modulus. The base layer can improve the fatigue cracking life definitely but no obvious influence found on the relative change rate of CI varying with subgrade stiffness, the interaction between subgrade stiffness and base thickness on the sensitivity of fatigue cracking of concrete pavement is very slight.

## II. BACKGROUND OF KENSLABS COMPUTER PROGRAM FOR FATIGUE CRACKING DAMAGE ANALYSIS

### A. Fatigue criteria

KENPAVE, a two-dimensional finite element program, is developed specifically for the design of both rigid and flexible pavements [21-23]. As a subprogram of KENPAVE, KENSLABS can be used for cement concrete pavement design. Damage analysis in this program can be performed by dividing each year into a maximum of 12 periods, each with a different set of material properties. Each period can have a maximum of 12 loading groups, either single or multiple. The damage caused by a fatigue crack in each period over the load groups is summed up to evaluate the design life. Because only the properties of foundation vary with the seasons, a foundation seasonal adjustment factor (FSAF) is assigned to each period to reflect the variation of subgrade properties with the season. Through foundation reaction module or stiffness matrix multiplying by the factor, the seasonal change of the subgrade stiffness is simulated. Cracking index (CI, non-dimensional) and the design life (DL, in a unit of the year) are reciprocal, which are used to represent the fatigue cracking damage.

CI also represents the damage ratio. Damage ratio is the ratio between the predicted and allowable number of load repetitions, is computed for each load group in each period and summed over the year by Equation (1):

$$CI = \sum_{i=1}^{p}\sum_{j=1}^{m}\frac{n_{i,j}}{N_{i,j}} \tag{1}$$

where p denotes the number of periods in each year, m denotes the number of load groups, CI denotes damage ratio, $n_{i,j}$ denote the predicted cyclic numbers for load j in period i, and $N_{i,j}$ denotes the allowable number of cyclic numbers of loads based on Equation (2):

$$\log N_f = f_1 - f_2(\frac{\sigma}{S_c}) \tag{2}$$

Where $N_f$ denotes allowable number of load repetitions, $\sigma$ denotes the flexural stress in the slab, $S_c$ is the modulus of rupture of cement concrete.$f_1$ and$f_2$ are constants determined from fatigue tests. Base on the design target of zero maintenance for jointed plain cement concrete pavement, $f_1$=16.61 and $f_2$ =17.61[24] are used in the damage analysis of this study.

### B. Multiple axles

The following steps are used to analyze the damage for the tandem-axle case. First, check the tensile stress at three points under the dual tandem wheels, as shown in Figure 1(a), and find out which point results in the maximum tensile stress. The maximum tensile stress is then used with Equations (1) and (2) to obtain the allowable number of load repetitions and primary CI. Secondly, check the tensile stress at the corresponding points that lies in the midway between the two axles, as shown in Figure 1(b). The stress for damage analysis due to the second axle load is $\sigma_a$-$\sigma_b$, where $\sigma_a$ is the stress due to the loading that is shown in Figure 1(a), and $\sigma_b$ is the stress due to the loading that is shown in Figure 1(b). Figure 1(c) is an illustration of the above process.

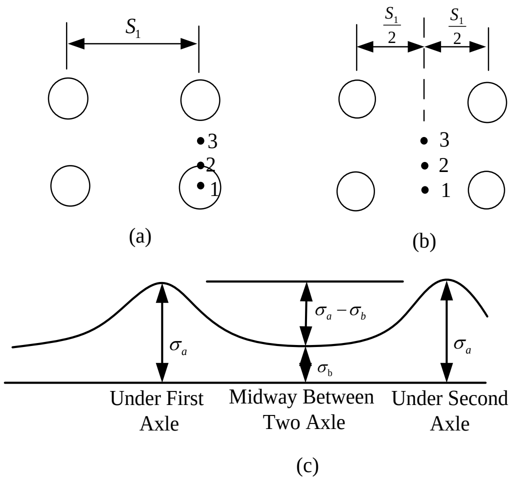



Figure 1. Damage analysis of biaxial loads

Damage analysis under tridem-axle loads is similar to above process with minor adjustments. Firstly, the maximum tensile stress $\sigma_a$ can be obtained by comparing the stress at three points as shown in Figure 2(a). Then, determine the corresponding tensile stress $\sigma_b$as shown in Figure 2(b). The stresses are then available for damage analysis under tridem-axle loading case with Equations (1) and (2), respectively.

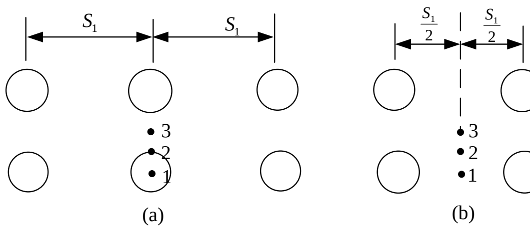



Figure 2. Damage analysis of triaxial loads

### C. General numerical model for analyses

The subgrade was modeled as a solid foundation. To simulate the seasonal change of the foundation stiffness, one year was divided into 6 uniform periods, the FSAF for each period was 1.0, 0.9, 0.8, 0.7, 0.6 and 0.5, respectively. For each foundation stiffness case, three different but typical axle configurations were considered, i.e., single-axle, tandem-axle and tridem-axle. Each individual axle was assumed carrying a 100 kN load with each wheel having a rectangle contact area with tire contact aspect ratio (b/a) 0.8712/0.6 for an assumed 0.7 MPa contact pressure. The number of load repetitions of every axle type was 200 in one day. The slab was placed directly on the top of the subgrade with full interaction but with no consideration for the moment in the base. In order to determine the most unfavorable conditions, the wheel load was placed in the middle of two transverse edges along with the free edge strictly. Because of the symmetry of slab and the wheel loads, a semi-structure was modeled to calculate the stresses in the slab to save the computation efforts. Figure 3 shows that there are 11 nodes that have been set along the X and Y direction, respectively, which are less than the maximum of 15 nodes required by the program. The node setting results in a total of 100 rectangular finite elements with KENSLABS. Meanwhile, the maximum aspect ratio of the element also meet the software requirements (120 cm/24.84 cm=4.83＜5, Huang 1993). The input parameters for the variables in KENSLABS are summarized in Table 1.

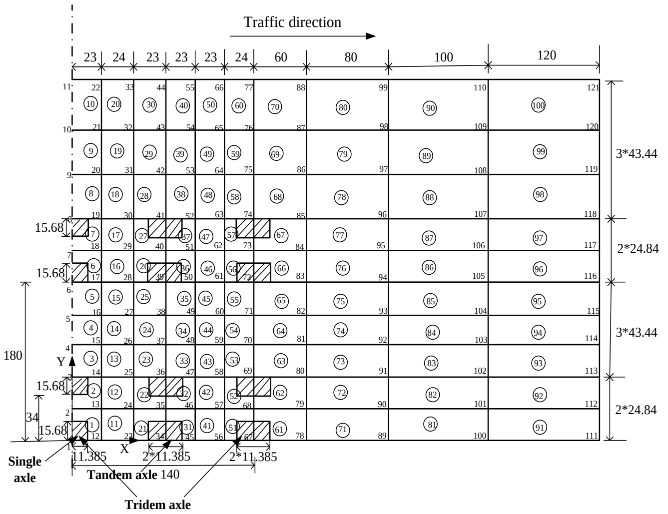



Figure 3. Model of damage for cement concrete pavement under traffic loads (unit: cm)

TABLE I. FIXED FINITE ELEMENT ANALYSIS INPUTS

| **Variables** | **Value** |
|---|---|
| Slab size | 10×3.6 m |
| Slab thickness | 21 cm |
| Slab elastic modulus | 28 GPa |
| Slab Poisson ratio | 0.2 |
| Modulus of rupture of concrete | 4.1MPa |
| Subgrade resilient modulus | 60 MPa |
| Subgrade Poisson ratio | 0.35 |
| Tire contact pressure | 0.7 MPa |
| Tire contact size | 22.77×15.68 cm |
| Wheel spacing | 34 cm |
| Wheel gap center spacing | 180 cm |
| Axle spacing(tandem-axle) | 140 cm |
| Axle spacing (tridem-axle) | 140 cm and 280 cm |

The above model was used as a general model for this study, and a series of analyses were carried out using the general model with tailored parameters based on the analysis focus.

## III. ANALYSES AND DISCUSSIONS

### A. *Influence of subgrade stiffness loss on CI*

In the analyses, 6 periods were adopted to make FSAF's gradient obvious. The CI of cement concrete pavement in the 6 periods of one year under different axle configurations is shown in Figure 4. The CI under tandem-axle or tridem-axle is the sum of primary and secondary CI. For tandem-axle loads, the primary CI is the damage ratio caused by the stress $\sigma_a$ due to the passage of the first axle, the secondary CI is the damage ratio caused by the stress $\sigma_a$-$\sigma_b$ due to the passage of the second axle, as illustrated in Figure 1. For tridem-axle loads, the primary CI is based on the loading position shown in Figure 2(a), while the secondary CI is based on two passages of the loading shown in Figure 2(b). CI of per period is obtained by summing over all damage ratios in this period, and CI of per axle type is summed over all damage ratios caused by this axle type. The total CI of this year 0.451 is obtained by adding up all these values, and the cement concrete pavement fatigue cracking life under the specific condition would be 1/CI= 2.22 years.

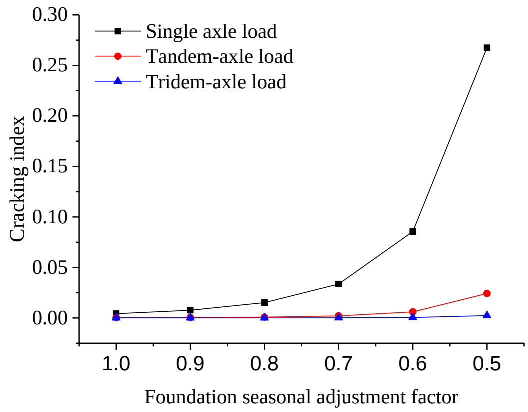



Figure 4. Influence of subgrade stiffness on cracking index with different axle types

Since subgrade stiffness is simulated by using basic stiffness matrix multiplying by the FSAF, the smaller the FSAF, the smaller the subgrade stiffness is. Figure 4 shows that the CI increased with the reducing of FSAF, i.e., the loss of subgrade stiffness for all axle types. Moreover, the curves show that the slopes become steeper with a decrease of FSAF, which implies that the smaller the subgrade stiffness was, the CI increases faster. It also found that for the same FSAF, the slope of curve for the tridem-axle is the flattest, which implies that the influence of the subgrade stiffness loss on the variation of CI for tridem-axle load case is the smallest; the slope of curve for the single-axle is the steepest, which implies that the influence of the subgrade stiffness loss on the variation of CI for the single-axle load case is the biggest. The findings show that the crack is related to both subgrade stiffness and the axle types.

The CI of 6 periods is obtained respectively by summing up all CI in a period caused by different axle loads. Figure 5 shows the CI of per period and its percentage in the total CI of this year. As shown in Figure 5, the smaller the FSAF is, the bigger the CI will be. As for the contribution of CI for certain period, the CI of period No. 6 whose FSAF is 0.5 accounted for 65.25% of the total CI, which demonstrates the importance of the subgrade stiffness on pavement fatigue cracking, and the damage accumulated in periods with relatively low subgrade stiffness plays a pivotal role in fatigue cracking and DL.

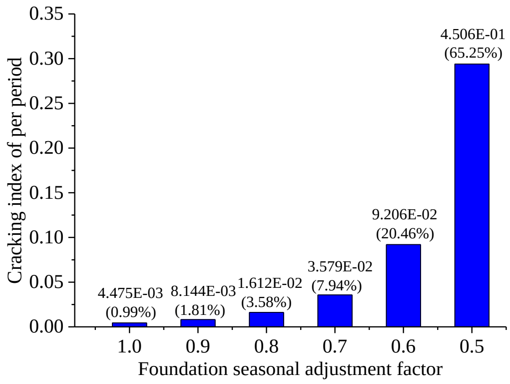



Figure 5. Cracking index of per period in one year

*B. Influence of the pavement design parameters on the fatigue cracking life*

To explore the influence of the pavement design parameters on fatigue cracking of cement concrete pavement, different cement slab thickness $h_s$ (using 20 cm, 20.5 cm, 21 cm, 21.5 cm, 22 cm), single-axle load cycles in one day $n$ (using 200, 250, 300, 350, 400), single-axle weight $T$ (using 90 kN, 100 kN, 110 kN, 120 kN, 130 kN) and the modulus of rupture of cement concrete $S_c$ (using 4.0 MPa, 4.1 MPa, 4.2 MPa, 4.3 MPa, 4.4 MPa) are considered in the research. The combinations of these parameters used in simulation analyses are as follows:

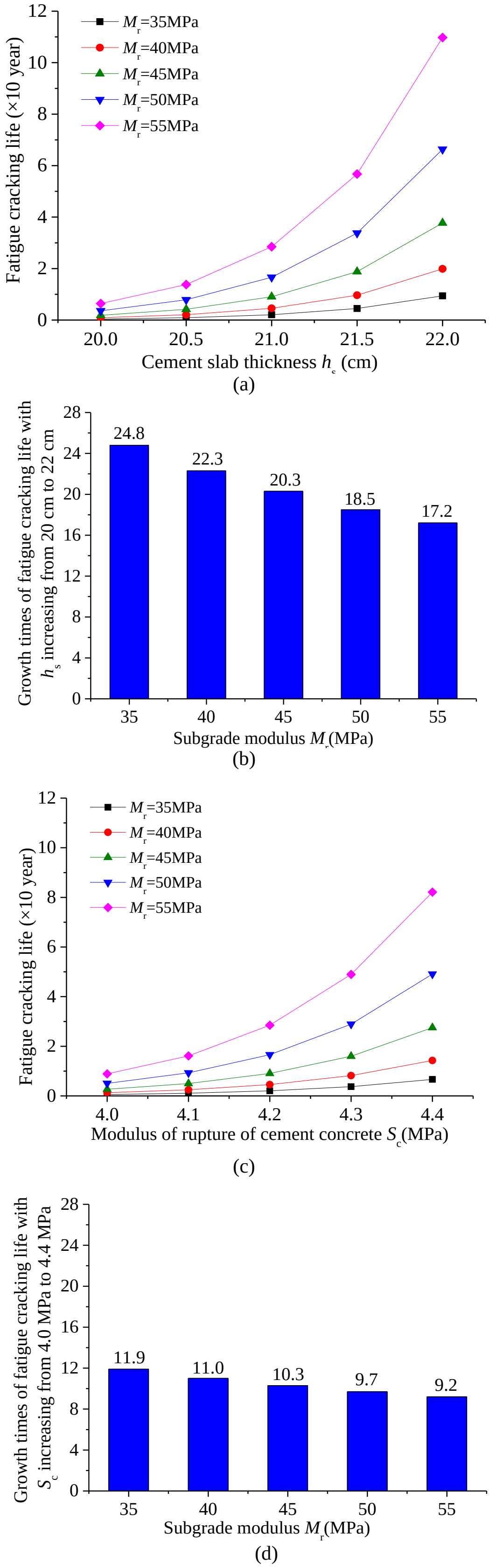
1) $S_c$=4.2 MPa, $T$=100 kN, $n$=300 and $h_s$ =20 cm, 20.5 cm, 21 cm, 21.5 cm, 22 cm;

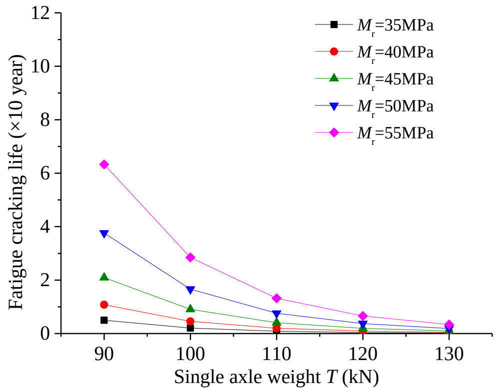
2) $h_s$=21 cm, $T$=100 kN, $n$=300 and $S_c$=4.0 MPa, 4.1 MPa, 4.2 MPa, 4.3 MPa, 4.4 MPa;

3) $h_s$ =21 cm, $S_c$=4.2 MPa, $n$=300 and $T$=90 kN, 100 kN, 110 kN, 120 kN, 130 kN;

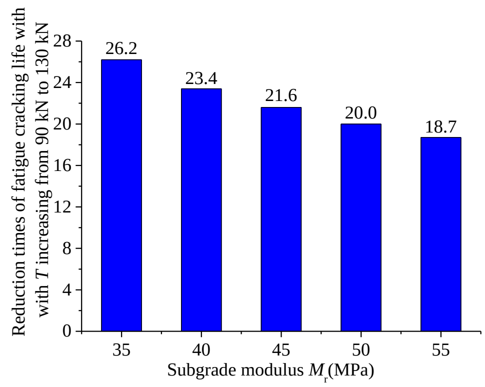
4) $h_s$ =21cm, $S_c$=4.2 MPa, $T$=100 kN and $n$=200, 250, 300, 350, 400.

In the analyses, only the single-axle load is considered and one year is used as one period with FSAF=1.0. Changes of the single-axle weight are simulated by changing the corresponding tire-pavement contact pressure while the loading area remains the same. The analysis results are shown in Figure 6.

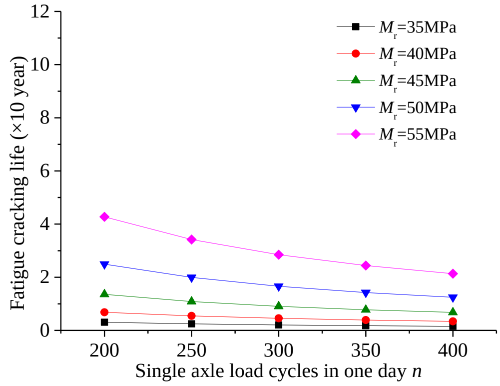




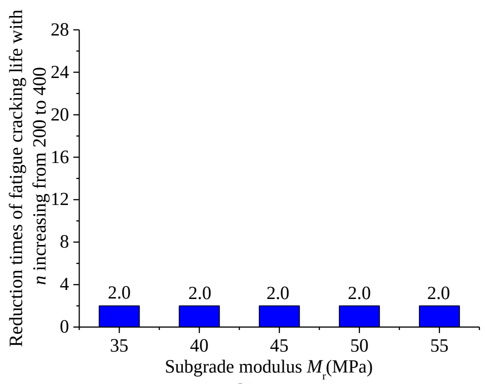

(e)




(f)




(g)




(h)

Figure 6. Influence of core pavement design parameters on fatigue cracking life of cementconcrete pavement with different subgrade modulus

Fig.6(a) shows that the fatigue cracking life increases nonlinearly with the increase in cement slab thickness $h_s$ for all cases with a different resilient modulus of the subgrade. The curves show that the slopes become steeper with an increase in the slab thickness, which implies that the larger the slab thickness is, the fatigue cracking life increases faster. Moreover, the curve slopes become steeper with an increase in the resilient subgrade modulus for a fixed slab thickness, which implies that the larger the subgrade modulus is, the faster fatigue cracking life increase with an increase of the slab thickness, and a larger subgrade modulus enhances the influence of the slab thickness on the fatigue cracking life. The combined effect of the increase in the slab thickness and the improving subgrade modulus result in an apparent increase in the fatigue cracking life. In addition, Fig.6(b) shows the growth rates of the fatigue cracking life with the cement slab thickness $h_s$ increasing from 20 cm to 22 cm with different resilient subgrade modulus. It is found that the relative growth rate of the fatigue cracking life decreases with an increase in subgrade modulus. It means that the sensitivity of the fatigue cracking life on the slab thickness becomes weaker with the improvement of subgrade modulus.

Fig.6(c) shows that the fatigue cracking life increases nonlinearly with an increase in the modulus of rupture of cement concrete $S_c$. The slopes of the curves become steeper with an increase in the modulus of rupture of cement concrete, which implies that the larger the modulus of rupture of cement concrete is, the fatigue cracking life increases faster. Moreover, the slopes of the curves become steeper with an increase in the subgrade modulus as well as an increase in the modulus of rupture of cement concrete, which implies that the larger the subgrade modulus is, the faster the fatigue cracking life increases with an increase of the modulus of rupture of cement concrete, and a larger subgrade modulus enhances the influence of the modulus of rupture of cement concrete on the fatigue cracking life. The combined effect of an increase of the modulus of rupture and improving subgrade modulus results in a significant increase in the fatigue cracking life. Moreover, Fig.6(d) shows the growth rates of the fatigue cracking life when the modulus of rupture $S_c$ increases from 4.0 MPa to 4.4 MPa for different resilient subgrade modulus. It is found that the growth rate of the fatigue cracking life decreases with an increase in subgrade modulus. The finding implies that the sensitivity of fatigue cracking life on the modulus of rupture of cement concrete becomes weaker with the improvement of subgrade modulus.

Fig. 6(e) shows that the fatigue cracking life decreases nonlinearly and the slopes become flattered gradually with an increase in the single-axle weight $T$. This implies that the larger the single-axle weight is, the fatigue cracking life decreases but the decreasing rate becomes slower. Moreover, the curve slopes become steeper with an increase in the subgrade modulus for the cases with the same single-axle weight change. It implies that the larger the subgrade modulus is, the faster the fatigue cracking life decreases with an increase in the single-axle weight, larger subgrade modulus enhances the influence of the single-axle weight on the fatigue cracking life. The combined effect of reducing single-axle weight and improving subgrade modulus may result in an apparent increase of fatigue cracking life. Furthermore, Fig.6(f) shows the reduction times of fatigue cracking life with single-axle weight *T* increasing from 90 kN to 130 kN for different resilient subgrade modulus. It shows that the relative reduction rate of fatigue cracking life decreases with an increase in the subgrade modulus, it implies that the sensitivity of fatigue cracking life on the single-axle weight become weaker with the improvement of subgrade modulus.

Fig.6(g) shows that the fatigue cracking life decreases almost linearly with an increase in the single-axle load cycles in one-day*n*, and the slopes of curves become steeper with the increase in subgrade modulus for the cases with the same single-axle load cycles in one-day change, which implies that the larger the subgrade modulus is, the faster the fatigue cracking life decreases with an increase in the single-axle load cycles in one day, a larger subgrade modulus enhances the influence of the single-axle load cycles in one-day on the fatigue cracking life. The combined effect of reducing the single-axle load cycles in one-day and improving subgrade modulus result in an apparent increase in the fatigue cracking life. Moreover, Fig.6(h) shows the reduction rates of the fatigue cracking life with single-axle load cycles in one-day *n* increasing from 200 to 400 for different resilient subgrade modulus. As Fig.6(h) shown, the relative reduction rates of the fatigue cracking life are nearly same for the cases with different resilient subgrade modulus. It implies that the enhancement of the subgrade modulus definitely enhances the fatigue cracking life, but does not have any influence on the relative reduction rate caused by an increase in the single-axle load cycles.

### *C. Combined effect of the subgrade stiffness and the base thickness*

The base also has an influence on cracking of cement concrete pavement, especially under the situation with a subgrade stiffness loss. To study the influence of the base on cracking, a new analysis is carried out by adding the cement stabilized base layer into the general numerical model shown in Figure 3. The base thickness uses 0 cm, 5 cm, 10 cm, 15 cm, 20 cm and 25 cm, respectively. When the base thickness is 0 cm, it is equivalent to the general model, otherwise, the base is regarded as the second slab layer, whose resilient modulus $M_b$=2000MPa, Poisson ratio $\mu_b$=0.3, modulus of rupture $S_b$=0.8MPa, the size and the node layout of the base are the same with the cement slab. The interface between the base layer and the cement slab is unbounded. Other model parameters including cement slab thickness, axle configurations, etc., remain the same with the original numerical model shown in Figure 3.

Figure 7 shows the fatigue cracking life of cement concrete pavement for the cases with different base thickness. It is found that the fatigue cracking life increases nonlinearly with an increase in the base thickness, and the greater the base thickness is, the larger the growth percentage is, i.e., the faster the fatigue cracking life increases.

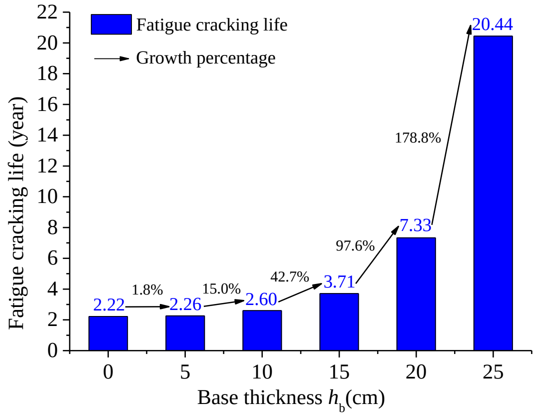



Figure 7. Fatigue cracking life varying with base thickness

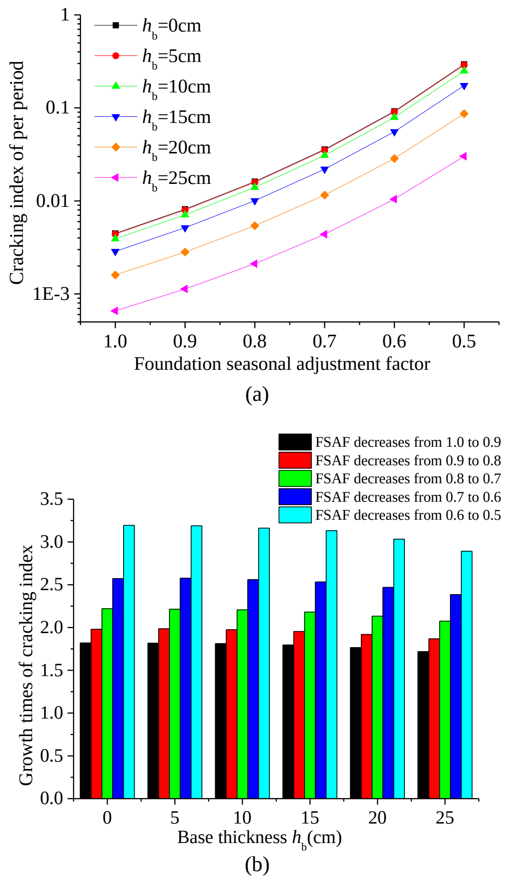



Figure 8. (a) Cracking indexvarying with FSAF, (b) Growth times of cracking index with the reduction of FSAF - Influence of subgrade stiffness on cracking index for the caseswith different base thickness and

The influence of subgrade stiffness on cracking index for the cases with different base thickness is shown in Figure 8. Figure 8(a) shows that the cracking index increases with the reduction of FSAF for all cases with different base thickness, and the curve shapes are similar to each other, which can be clarified further by Figure 8(b). Figure 8(b) shows that the smaller the subgrade stiffness, the bigger the relative growth rates is, but the disparity between the relative growth rates of CI with same subgrade stiffness loss for the different base thickness case are negligible. It means that the change rates of CI with the subgrade stiffness loss are similar to each other for the cases with different base thickness, which implies that base thickness has no obvious influence on the change rate of CI with subgrade stiffness loss. The base thickness and the subgrade stiffness playsnearly an independent role on the sensibility of fatigue cracking of concrete pavement under traffic loads.

## IV. CONCLUSIONS

This paper explored the influences and sensitivity of the subgrade stiffness, the axle types, the pavement design parameters including the cement slab thickness, the single axle load cycles in one day, the single axle weight, the modulus of rupture of cement concrete and the base thickness on fatigue cracking of cement concrete pavement. A series of numerical analyses were carried out. Conclusions based on the analysis results are concluded as follows:

1) With the reduction of the subgrade stiffness, the fatigue crack damage is easier to occur on the cement concrete slab. The damage accumulated in periods with low subgrade stiffness played a pivotal role in fatigue cracking and the design life of cement concrete pavement.
2) The influences of different axle types on crack are highly correlated with the subgrade stiffness. The destructive effect of axle types for cement slab varies with the subgrade stiffness, and the subgrade stiffness affects the adaptability of different axle types on subgrade stiffness loss as well.
3) The fatigue cracking life increases nonlinearly with the increase in the cement slab thickness and the modulus of rupture of cement concrete. The larger the slab thickness and the modulus of rupture of cement concrete are, the fatigue cracking life increases faster. Fatigue cracking life decreases nonlinearly with the increase in the single-axle weight, but the decreasing rate becomes slower. The fatigue cracking life decreases almost linearly with the increase of the single-axle load cycles in one-day.
4) Larger subgrade modulus enhances the influence of the pavement design parameters including the cement slab thickness, the modulus of rupture of cement concrete, the single-axle weight and single-axle load cycles in one-day on fatigue cracking life. The combined effect of the increasing cement slab thickness, modulus of rupture of cement concrete, reducing axle weight, load cycles, and the improving subgrade modulus would result in an apparent increase of fatigue cracking life. However, the sensitivity of the fatigue cracking life on the slab thickness, modulus of rupture of cement concrete and single-axle weight become weaker with the improvement of subgrade modulus.
5) Cement stabilized base layer can improve the fatigue cracking life directly. The greater the base thickness is, the faster the fatigue cracking life increases. However, the base thickness has no obvious influence on the relative change rate of CI varying with subgrade stiffness, the interaction between the subgrade stiffness and the base thickness on the sensibility of the fatigue cracking life of concrete pavement under traffic loads is very slight.

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