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基于累积损伤因子的水泥混凝土路面设计

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摘 要:考虑荷载疲劳应力和温度疲劳应力的综合疲劳方程,计算了单轴单轮及单轴双轮轴载的覆盖通行率,利用累积损伤因子替代标准轴载在交通量换算中的作用,提出了直接计算各级轴载对路面结构总的累积疲劳损伤方法和新的水泥混凝土路面设计方法,并采用两组交通量对轴载累积损伤量的计算方法的准确性与可行性进行了验证。分析结果表明:公路横断面上各点处轴载的作用次数是不同的,各级轴载的累积疲劳损伤峰值不一定在同一位置,利用基于累积损伤因子的水泥混凝土路面设计方法计算得到两组交通量下路面的最不利位置厚度均为22 cm,符合设计要求,其他位置厚度可按累积损伤曲线相应减小,此设计方法避免了现行规范基于标准轴载和疲劳耗损等效原则的水泥混凝土路面设计方法与路面实际损伤中存在的差异及轴载换算方法的局限性。

关键词:路面工程;路面设计;累积损伤因子;轴载换算;交通量;覆盖通行率
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Cement concrete pavement design based on cumulative damage factor

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Abstract: Based on the compositive fatigue equation of load fatigue stress and temperature fatigue stress, the coverage-to-pass ratios of single-axle-single-wheel load and single-axle-double-wheel load were calculated by adopting cumulative damage factor. A direct calculating method of total cumulative fatigue damage of pavement structure produced by multi-axle load and a new design method of cement concrete pavement were put forward by replacing design axle load with cumulative damage factor. The accuracy and application feasibility of calculating fatigue damage produced by multi-axle load were done through a design example with two types of traffic volumes. Analysis result indicates that the acting times of multi-axle load at all points on the cross section of highway are different, and the peak value of cumulative damage of each axle load may be not at the same location. The thicknesses of worst pavement places under the traffic volumes calculated by the design method based on cumulative damage factor are all 22 cm, which meets the design requirement, and the thicknesses of other places can reduce according to the cumulative damage curve. Thereby, it can avoid the differences and localizations of present specification design method of concrete pavement based on standard axle load and equivalent fatigue consumption principle. 1 tab, 8 figs, 12 refs.

Key words: pavement engineering; pavement design; cumulative damage factor; axle load conversion; traffic volume; coverage-to-pass ratio

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0 Introduction

The current specification of cement concrete pavement design adopts wheel trace horizontal distribution coefficients to calculate axle load times. In essence, it is assumed that axle load times on the driveway cross section subject to uniform distribution, and it takes the bottom stress as axle load index. According to standard axle load equivalent principle, it converts the fatigue damage resulted from various axle loads on pavement structure to the fatigue effect times of standard axle load. In fact, as the various types of vehicle's wheel trace distributions, treads, tyre spacings and tyre widths are different, axle load times on lane cross section are not uniform, so the damage that axle load acts on the cross section of pavement is displayed by a curve way. The peak values of cumulative fatigue damages at all levels of axle loads are not necessary at the same location. Adopting standard axle load conversion obscures the distinction, and the overlying fatigues of all levels of axle loads will directly result in the inaccurate calculation of the damage. In addition, as axle load conversion method has certain limitations and the parameters have their own applications, the conversion will inevitably lead to some errors. Therefore, it is necessary to make improvements.

In the past, the concept of aircraft design was adopted in airport pavement design, other aircraft traffic volume was converted into design aircraft traffic volume, which covered the fact that the cumulative damage distributions of different aircrafts on runway cross section were different, and made the traffic volume model relatively conservative. But in recent years, significant changes have taken place in the airport pavement traffic volume model in foreign countries. In 2008, the United States revised the pavement design standard by adopting the National Pavement Laboratory test results and the latest research results and abolished the concept of aircraft design[1-2]. Cumulative damage factor (C_{DF}) was introduced as pavement damage evaluation index, and cumulative damage curves were applied on the basis of Miner rule for various types of aircraft's overlyings, which was regarded as a big step toward the development of pavement traffic volume models[2-3]. The new idea offers something for road traffic conversion. The paper no longer converts other axle loads based on standard axle load, instead, introduces the concept of cumulative damage factor to calculate the cumulative fatigue damages of all levels of axle loads acting on pavement structure. The paper elaborates the road traffic volume model in a new way and discusses the pavement design method based on cumulative damage factor too.

1 Conversion method of standard axle load

There are a variety of vehicles on the road. In order to simplify the calculation, different kinds of vehicles should be converted in accordance with the principle of conversion. The current road design specifications use the concept of standard axle load to standardize different levels of axle loads. With the tensile stress at the bottom of the plate as an indicator, a variety of axle load fatigue damages to the pavement structure are converted into standard axle load times according to the principle of equivalence conversion method. Fatigue equivalence principle is that when the same pavement structure under different axial loads achieves the same degree of fatigue damage, the times of function are considered to be equivalent. In addition, for the same kind of traffic composition, no matter which axle load standard for conversion should be adopted, the pavement thicknesses calculated by the times of conversion are same.

Standard axle load has generally greater road response, at the same time, it reflects the overall levels of axle loads of national road transportation vehicles. In order to unify design standards and facilitate the management of transport sectors, many countries have clearly defined standard axle loads. Chinese road design specifications adopt the vehicle axle load of 100.0 kN (uniaxial load) as design standard axle load, 80.1 kN for the United States, 110.0 kN for Germany, 50.0 kN for Indonesia, 140.0 kN for Lebanon, and so on. Chinese axle load conversion formula of cement concrete pavement is

$$N = \sum_{i=1}^{n} \alpha_i N_i \left(\frac{P_i}{100}\right)^{16} \tag{1}$$

where P_i is axle load; N_i is axle load times; N is standard axle load times; n is the rating number of axle loads; α_i is the coefficient of axle load i.

It can be shown from Eq. (1) that the total standard axle load times can be concluded by the direct summation when all levels of axle loads are converted into standard axle load times. The computing process will bring about at least two errors. The conversion process itself is an approximate equivalence. The coefficients in Eq. (1) are applicable only within a specified range of axle load conversion. When they are out of the range, the computing error is even greater. In addition, if it is not considered that the function times that all levels of axle loads have produced to the pavement structure are in a lateral distribution on lane cross section and the peak values may not be at the same location at the time of calculating the summation of overall standard axle load times, the direct summation may lead to the fact that the summation does not reflect the actual situation of pavement fatigue damage, which may also cause certain unexpected errors.

2 Concept of cumulative damage factor

Cumulative damage factor, which is the value of C_{DF}, is calculated by certain tire width on the road. The Miner principle is used to linearly superpose the damage of each bandwidth in consideration of the damages calculated on the basis of different axle load characteristics and wheel traces of vehicle on the two sides of lane midlines, as well as the overall cumulative damages determined by superposing the damages of all levels of axle loads[2]. Through calculating C_{DF} of the bandwidth, different values take on a curve on the road cross section, and the curve is called the curve of cumulative damage. When the peak value equals 1, the pavement is damaged. C_{DF} is

$$C_{DF} = \sum_{i=1}^{n} \frac{n_i}{N'_i} \tag{2}$$

where N'_i is fatigue life; n_i is coverage times of axle load.

Eq. (2) shows that in the design of highway pavement, the coverage times of axle load are the main factor affecting the structure thickness, which is also a problem that should be firstly solved. Abroad usually uses pass-to-coverage ratio (P_C) to calculate the coverage times.

When an axle load passes a point on the road each time, this point is imposed by a coverage[4]. P_C is a ratio of overall passage times to the maximum passage times for single-axle load of a point on the road cross section[5-6]. In order to simplify the calculation, the paper introduces the concept of coverage-to-pass ratio (C_P), which indicates the ratio of the maximum passage times for single-axle load of a point on the road cross section to overall passage times.

3 Concept of coverage-to-pass

Coverage times and axle load times in the conversion formula are different. The current axle load conversion formula is based on the assumption of uniform distribution on the driveway. Due to the variety of vehicles on the road, the tests on the road traffic volume are relatively ambiguous, and there is no distinction among the wheel trace distributions of vehicles. However, based on the test results of moving vehicles at home and abroad, it can be approximately concluded that the cross-sectional distribution of each wheel trace of vehicle on the road is normal, it is $N(\mu, \sigma)$[7]. Single wheel trace distribution is shown in Fig. 1. The calculation of coverage times is based on the assumption that the wheel trace complies with normal distribution. It can be calculated as below

$$n_i = N_i C_P \tag{3}$$

$$C_P = c_i w_i \tag{4}$$

where w_i is effective tire width; c_i is trace distribution probability density of wheel center point.

C_P has the relationship with such factors as the type of axle load, tread, the effective width of tire and the parameters of normal distribution curve[8]. The paper can use tracking test technology to observe the distribution of wheel trace[9] and use simulation technology to determine the horizontal traffic distribution of lane[10]. Then the paper can calculate the C_P of any position. For the same type of vehicle with single-axle load or double-axle load, the C_P is same. When calculating the coverage-to-pass ratio, the paper need superpose all wheel traces on the same axle to get the overall distribution curves of wheel traces and to determine the probability density of trace distribution of wheel central point. The C_P of double wheels is shown in Fig. 2.

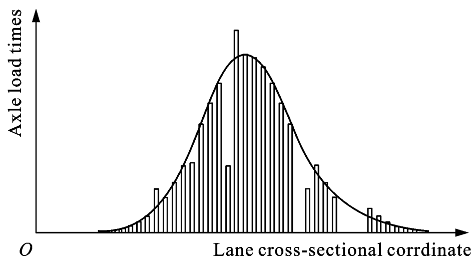

Fig. 1 C_P curve of one tire

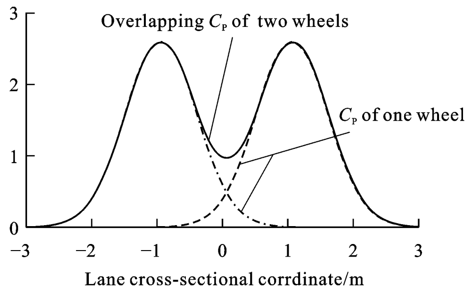

Fig. 2 C_P curves of two near wheels

In general, for the same axle load acting on rigid pavement or flexible pavement, C_P is usually different. The paper studies the calculation method for C_P on rigid pavement at driving time. Taking single-axle-single-wheel load and single-axle-double-wheel load as examples, the paper introduces the calculation method of C_P when they act on cement concrete pavement.

3.1 C_P of single-axle-single-wheel load

The arrangement of single-axle-single-wheel tires and the normal distribution curve of two tires' wheel trace at driving time are shown in Fig. 3. When the distance between left and right tires is longer, the distribution curves of wheel traces of two tires do not overlap. But most of the treads of vehicles are within 3 m. So parts of wheel traces of two tires overlap, and the overlapping range is related to tread and standard deviation σ.

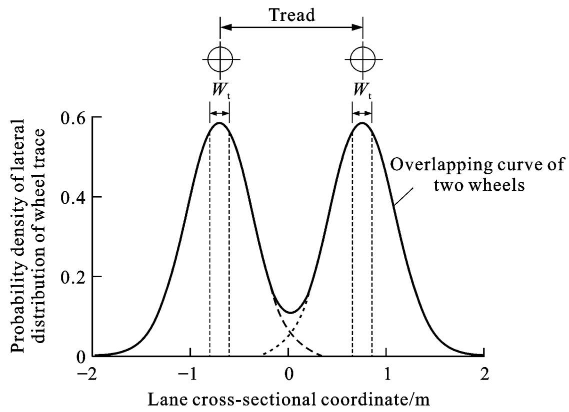

Fig. 3 Method for calculating C_P of single-axle-single-wheel load

Assuming that the width of tire contact area is W_t, for the central point that has the maximum probability, wheel within $W_t/2$ of centerline will cover the central point, the maximum probability density of normal distribution curve is C_x

$$C_x = \frac{1}{\sigma\sqrt{2\pi}}\left[e^{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2} + e^{-\frac{1}{2}\left(\frac{x-T_w}{\sigma}\right)^2}\right] \qquad (5)$$

where T_w is tread; σ is the standard deviation of normal distribution curve of vehicle's centerline (tires) when running; x is lane cross-sectional corrdinate.

3.2 C_P of single-axle-double-wheel load

When the maximum probability density of single-axle-double-wheel load is calculated, it is necessary to superimpose the curves of the normal distributions of two single-wheel traces on the same side of an axis. The superposed distribution curves are shown in Fig. 4. The upper part of the curves is the overlapping result of normal distribution curves of four tires' wheel traces. Its C_P is still calculated by Eq. (4), and the maximum probability density on the normal distribution curve is C_x

$$C_x = \frac{1}{\sigma\sqrt{2\pi}}\left[e^{-\frac{1}{2}\left(\frac{x}{\sigma}\right)^2} + e^{-\frac{1}{2}\left(\frac{x-s_t}{\sigma}\right)^2} + \right.$$

$$e^{-\frac{1}{2}\left(\frac{x-T_w}{\sigma}\right)^2}+e^{-\frac{1}{2}\left(\frac{x-s_t-T_w}{\sigma}\right)^2}\Bigg] \quad (6)$$

where s_t is distance of wheels.

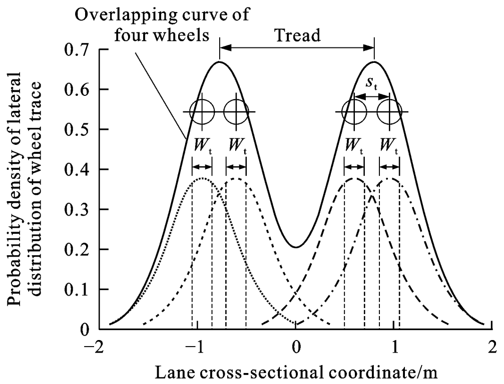

Fig. 4 Method for calculating C_P of single-axle-double-wheel load

The maximum probability density C_x of superimposed normal distribution curve by single-axle-single-wheel load and single-axle-double-wheel load does not appear at the central point of single axle, but moves to a certain point of dual axle. By adopting excel's calculating and painting functions, it is easy to determine the maximum probability density C_x of wheel trace on the normal overlapping distribution curves of single-axle-single-wheel load and single-axle-double-wheel load. Besides, it is also easy to determine its appearance location.

Cement concrete pavement generates some deflections when it withstands the loads. In general, no matter whether it is single-axle-single-wheel load or single-axle-double-wheel load, there is only one maximum deflection when it passes a certain point on the pavement. Similarly, double-axle-double-wheel load and three-axle-double-wheel load generate only one maximum deflection when they pass a certain point on the rigid pavement, so only a stress peak is considered in calculating load repetition. Other types of C_P can be determined by referring to the methods of single-axle-single-wheel load and single-axle-double-wheel load.

4 Cumulative damage calculation

In order to calculate the coverage times N'_i at the critical point, it is necessary to analyze the fatigue stress and temperature stress of pavement structure with axle load, and to adopt the appropriate concrete fatigue equation to determine the fatigue life of the structure by combining the effects of all levels of axle loads and temperature stresses.

4.1 Fatigue equation and stress calculation

Currently, there are many concrete fatigue equations. In order to put temperature stress caused by fatigue damage into the cumulative fatigue damage, the cement concrete fatigue equation considering the stress ratio is

$$\lg\left[\frac{S(1-R)}{1-SR}\right]=\lg(a)-b\lg(N'_i) \quad (7)$$

$$S=\sigma_{max}/f_r$$

$$R=\sigma_{min}/\sigma_{max}$$

where σ_{max} is the high stress under cyclic loading; f_r is the bending tensile strength of cement concrete; σ_{min} is the low stress under cyclic loading; a, b are fatigue equation regression coefficients, a is 1, b is 0.056 6.

Based on the actual stress of cement concrete pavement, the temperature stress σ_t is taken as low cyclic stress σ_{min}, and the combined stress of temperature stress and load stress σ_p are taken as the high cyclic stress σ_{max}, then they are put into Eq. (5), the single value of fatigue damage under the combined effects of temperature stress[11] and repetitive load stress can be calculated according to

$$\frac{1}{N'_i}=\left[\frac{\sigma_p}{a(f_r-\sigma_t)}\right]^{\frac{1}{b}} \quad (8)$$

Considering the effect factors of the pavement fatigue damage, which include seams load transfer, partial load, dynamic load and others, the fatigue stress of critical location of single wheel load can be calculated by

$$\sigma_p=k_r k_c A r^m P_i^k h^{-2} \quad (9)$$

where k_r is the reduction factor considering the joint load transfer stress; k_c is the comprehensive factor considering the coefficient of partial and dynamic load factors on pavement fatigue damage; h is the thickness of cement concrete slab; r is the radius of relative stiffness of concrete slab; A, m and k are the regression coefficients and shown in Tab. 1 [12].

Tab. 1 Regression coefficients

Axle-wheel	$A/10^{-3}$	m	k
Single-single	1.800	0.490	0.881
Single-double	1.190	0.597	0.905
Double-double	0.599	0.585	0.893
Three-double	0.395	0.493	0.892

Referring to the cement concrete pavement design specifications of highway, the temperature fatigue stress is calculated by

$$\sigma_t = k_t \sigma_{tm} = k_t \frac{\alpha_c E_c h T_g}{2} B_x \qquad (10)$$

where k_t is the coefficient of thermal stress; σ_{tm} is the temperature warping stress; α_c is linear expansion coefficient of cement concrete; E_c is the bending modulus of elasticity of cement concrete; T_g is the maximum temperature gradient; B_x is the temperature stress coefficient considering integrated temperature warping stress and internal stress.

4.2 Cumulative damage in pavement design

Based on the Miner principle and the coverage-to-pass ratio of axle load, the maximum coverage times n_i of the pavement stress critical points for all levels of axle loads within the pavement service life can be calculated. The allowable coverage times N_i is calculated by the fatigue equation based on the critical point's load stress and the concrete fatigue strength. The ratio n_i/N'_i is the pavement fatigue damage value of a certain level axle load. Then all fatigue damage values of different axle loads are accumulated linearly, and the accumulative fatigue damage factor is obtained. The value of C_{DF} is used to judge the fatigue damage stage of pavement[2].

When $C_{DF}=1$, the pavement just lives up to the damage standard in the expected service life, and the initially drafted thickness meets the design requirements. When $C_{DF}<1$, the pavement fails to live up to the damage standard in the expected service life, and the initially drafted thickness further reduces. When $C_{DF}>1$, the pavement lives up to the damage standard before the expected service life is due, and the initially drafted thickness should be further intensified.

To adopt the paper's design method, the first step is to calculate the coverage-to-pass ratios of axle loads and the total coverage times in the expected service life. Secondly, in accordance with the initially drafted pavement structural composition design, the biggest flexural stress at the critical point's bottom and the temperature stresses of axle loads are respectively calculated in considering the reliability coefficient. The allowable coverage-to-pass times of axle loads are obtained by using the comprehensive fatigue equations of load stress and temperature stress. Thirdly, the fatigue damage factor of the pavement is calculated. Lastly, the thickness of the pavement is calculated by using the fatigue damage factor. Through intensifying or deducing the thickness of the pavement, the value of the thickness is calculated repeatedly until C_{DF} is equal to 1. The final calculation result meets the requirements of the design.

4.3 Application of cumulative damage for axle load

Taking the cement concrete pavement as example, the cumulative damage of the pavement structure under the effect of axle loads is calculated. The length of road plate is 5.0 m, the standard value of the bending strength is 5.0 MPa, the elastic modulus is 31 000 MPa; the thickness of cement stabilized granular base is 0.18 m, the resilient modulus is 1 300 MPa; the cushion thickness is 0.15 m, the resilient modulus is 600 MPa; subgrade resilient modulus is 30 MPa. The seam is located rod flat seam, k_r is 0.87, k_c is 1.2, T_g is 88 ℃ • m^{-1}, α_c is 1.0×10^{-5}, and the reliability coefficient is 1.14.

To illustrate the problem, the two kinds of traffic volumes A and B are used for calculation and analysis. Traffic volume A is the standard single-axle-double-wheel load of 100 kN. Considering 0.39 that is the transverse distribution coefficient of wheel trace, the cumulative function times are 9.885×10^6. With reference to the method for current cement concrete pavement design, the thickness of the pavement under the effect of traffic volume A is calculated. The initially drafted pavement thickness is 0.22 m. Then the load fatigue stress is 3.29 MPa, and the temperature fatigue stress is 1.13 MPa. Considering the reliability coefficient, the fatigue stress is 5.04 MPa. It is very close to the standard value of the bending strength of road concrete 5.0 MPa, which is the allowable value of pavement concrete, so the thickness meets the design requirements. σ_p is 1.31 MPa, which is also obtained by Eq.(9). Based on Eq.(10), σ_t is 1.13 MPa. Considering the reliability coefficient of 1.14, the load fatigue stress and the temperature fatigue stress are put into Eq.(8), the fatigue damage generated by the standard single-axle-double-wheel load is 1.019×10^{-7} under the combined effect of repeated loading stress and temperature stress. According to the fact that the cumulative function times are 9.885×10^{6}, C_{DF} is 1.007, quite close to 1, which indicates that the road lives up to the damage standard when it completes the scheduled traffic volume, so it can be seen that the method in the paper is feasible.

Traffic volume B includes single-axle-single-wheel load and double-axle-double-wheel load. Without considering the lateral distribution coefficient, the total operation times are used to show it. Single-axle-single-wheel load is 65 kN, the tread is 2.02 m, and the total operation times are 1.228×10^{7}; double-axle-double-wheel load is 245 kN, the tread is 1.80 m, and the total operation times are 3.860×10^{6}. Their wheel traces' standard deviations of normal distributions are 0.5, wheel widths are 0.279 m, and the wheel space of double-axle-double-wheel load is 0.379 m. In the light of cement concrete pavement design specifications, traffic volume B is converted into the total operation times of standard axle load based on Eq.(1), and the calculation equation is

$$N=\sum_{i=1}^{2}\alpha_i N_i\left(\frac{P_i}{100}\right)^{16}=\alpha_1 N_1\frac{65}{100}+\alpha_2 N_2\frac{245}{100}=2.534\times10^{7} \qquad (11)$$

Considering that the lateral coefficient of wheel trace is 0.39, the total operation times of traffic volume B is equivalent to the cumulative acting times of standard axle load, $N_e=2.534\times10^{7}\times0.39=9.885\times10^{6}$. It can be seen that according to the current specifications, the effects of traffic volume A and traffic volume B on the pavement are totally equivalent, so the obtained pavement thicknesses should be same.

The pavement thickness under the effect of traffic volume B is calculated by using the method in the paper. The initially drafted pavement thickness is 0.22 m. The structure fatigue stress under single-axle-single-wheel load is 1.354 MPa. It is 1.399 MPa under double-axle-double-wheel load. The temperature fatigue stress is 1.13 MPa. After the reliability coefficient 1.14 is put into Eq.(8), the fatigue damage value under the combined effect of repeated loading stress and temperature stress is 1.756×10^{-7} for single-axle-single-wheel load, 3.111×10^{-7} for double-axle-double-axle load. The coverage times can be easily calculated by Eqs.(3)-(6) and excel. For instance, the coverage times of double-axle-double-wheel load are shown in Fig.5. The C_{DF} value of each strip under single-axle-single-wheel load and double-axle-double-wheel load can be calculated by Eq.(2), and the fatigue curves of single-axle-single-wheel load and double-axle-double-wheel load are shown in Figs.6, 7 respectively. The superimposed cumulative fatigue damage curve of single-axle-single-wheel load and double-axle-double-wheel load is shown in Fig.8. The greatest damage point is the most dangerous point. Its damage value is 0.986 4, which is quite close to 1, so the pavement structure just lives up to the damage standard when it completes the scheduled

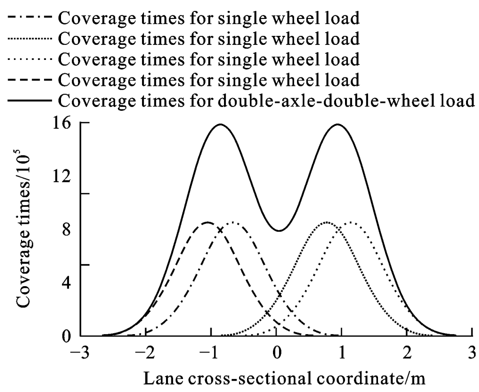

Fig. 5 Coverage times for double-axle-double-wheel load

traffic volume. The pavement thickness is 0.22 m, and meets the design requirements. The analysis result verifies the effects of traffic volume A and traffic volume B on the pavement are equivalent, therefore, the method in the paper is feasible.

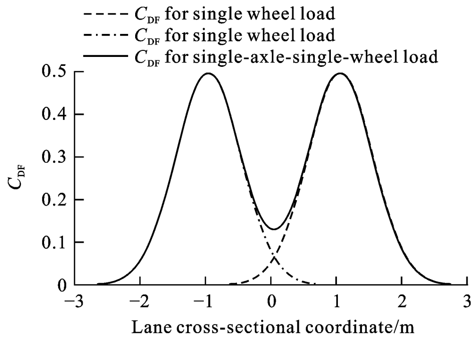

Fig. 6 C_{DF} for single-axle-single-wheel load

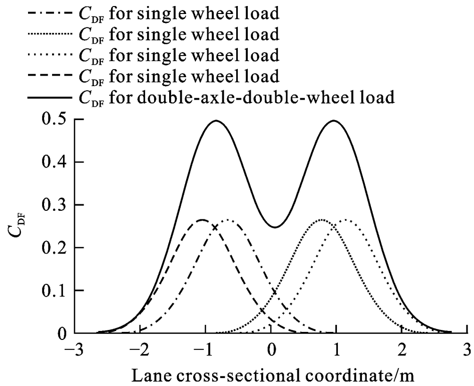

Fig. 7 C_{DF} for double-axle-double-wheel load

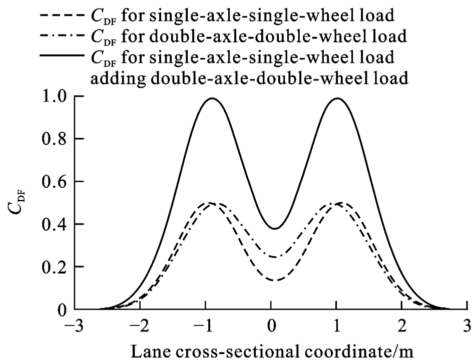

Fig. 8 Summation C_{DF} of traffic volume B

5 Conclusions

The current design method of concrete pavement should be improved because it converts the fatigue damage that multi-axle load has done to the pavement structure into the fatigue acting times of standard axle load, which covers up the differences of wheel trace distributions of axle loads and leads to some errors. Besides, as the conversion equation has its own applications and the conversion itself will produce some errors. Based on the concept of cumulative damage factor, the paper calculates the coverage times of each axle load, adopts the comprehensive fatigue equations of load fatigue stress and temperature fatigue stress to directly calculate the cumulative fatigue damage that multi-axle load has done to the pavement structure and analyzes the traffic volume. Through examples, the paper elaborates the method for calculating the cumulative damages of single-axle-single-wheel load and single-axle-double-wheel load. The result indicates that the design method of concrete pavement based on cumulative damage factor is feasible.

The advantage of the design method is that it can directly calculate the cumulative damage of each axle load without conversion, and by superimposing, the total cumulative damage curve can take shape. It is of great significance to the pavement design that is beyond the range of the conversion equation of axle load. It is also adaptive to the design of the pavement with heavy traffic as the overloading problem is growing more and more serious. For the axle loads with large tread differences, the peaks of cumulative damage curves may not be at the same location, and the total superimposed damage will be less than the sum of all axle load peaks, so the method is more accurate.

At present, as the test on wheel trace distribution is too general, the separate test data of wheel trace distributions of various types of vehicles can not be obtained, thus the standard deviation σ of the normal distribution curve of wheel trace has no measured data. In addition, the stress regression equation under standard axle load is accurate, but the pavement stress equation under other levels of axle loads still has some errors, so further research should be made.

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