THE REVISION OF THE CONCRETE PAVEMENT THICKNESS DESIGN PROCEDURE OF CHINA

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The concrete pavement design specification currently used in China was issued by the Ministry of Communication in 1984. The thickness design procedure adopted in the specification is based on the prevention of fatigue cracking by limiting the maximum stress induced by the design axle load below the fatigue strength of concrete. In the meantime, a new thickness design procedure for considering the combined fatigue damage incurred by both traffic loads and temperature gradients was proposed (1), and research work on materialising this procedure was carreid on. Since then, nearly 10,000 kilometers of concrete roads has been built till 1991, and a lot of research results have obtained. In order to include the design experience and the research results accumulated during these years, it is decided to revise the concrete pavement design specification. The main adaption of the thicknes design procedure is focued on following aspeects:

1. the combined fatigue damage incurred by repeated traffic loads and fluctuating temperature gradients is considered instead of traffic loads alone.
2. a new fatigue equation based on flexural fatigue tests under various minimum stress level is developed for taking account of this combined fatigue damage.
3. stress reduction factor considering the load transfer efficiency of various joints is introduced based on deflection measurements and stress analysis along the joints.
4. the inner stress induced due to nonlinear distribution of temperature along slab section is considered, together with the thermal curling stress incurred by the maximum temperature gradients.
5. a fatigue thermal stress factor is introduced to take account of the cumulative fatigue effects of the daily and annually fluctuating temperature gradient.

In thispaper, an introduction of this newly revised thickness design procedure is presented.

DESIGN CRITERIA

The major distress mode of concrete pavements is the cracking of slabs, incurred by the fatigue damage due to repeated traffic loads and fluctuating temperature gradients. In order to prevent the fatigue cracking of concrete pavements during its design life, the design criteria adopted for determining the required thickness is to limit the sum of fatigue loading stress σ_p and fatigue thermal stress σ_t below the flexural strength of concrete σ_s, i.e.,

$$\sigma_p + \sigma_t < \sigma_s \quad (1)$$

The fatigue loading stress σ_p is an amplified loading stress which is determined by the maximum stress σ_{ps} induced by the design axle load P_s at the critical loading position and the fatigue factor k_f which considers the cumulative fatigue damage incurred by the traffic loads during the design life. Besides, two other factors, k_c and k_j, are introduced to consider the impacts of the unpredicted overload of vehicles and the load transfer efficiency of joints. Thus, the fatigue loading stres σ_p can be expressed as follows:

$$\sigma_t = k_f k_j \ k_c \sigma_{ps} \quad (2)$$

The fatigue thermal stress is determined by the maximum thermal stress σ_{tm} induced by the maximum temperature gradient and the fatigue factor k_t that considers the impact of the cumulative fatigue damage incurred by the fluctuating temperature gradients during the design life. That is,

$$\sigma_t = k_t \ \sigma_{tm} \quad (3)$$

LOADING STRESS ANALYSIS

The concrete pavement structure was idealized as a rectangular slab resting on semi-infinite foundation. The mechanical responses of this structure under traffic loads were solved with a computer program TJCONP developed by using finite element analysis.

For the convenience of engineering design, maximum loading stress charts for axle loads acting on inner, transverse edge and longitudinal edge center of slabs were developed by using TJCONP with various structural, material and traffic load parameters as inputs. The traffic load parameters used in this analysis are listed in Table 1. Figure 1 shows one of the stress charts, the maximum stresses for single axle load acting on the longitudinal edge center of the slab.

The computing results by finite element analtysis within the range of l=50-105cm have also been regressed as following expression (2):

$$\sigma_{ps} = A \frac{l^m p^n}{h^2} \tag{4}$$

where

σ_{ps}--maximum loading stress (MPa);
P -- single or tandem axle load (kN);
h -- thickness of pavement slab (cm);
l -- radius of relative rigidity of pavement structure (cm),

$$l = h \sqrt[3]{\frac{E_c(1-\nu_s^2)}{6E_c(1-\nu_s^2)}} \tag{5}$$

E_c and E_s -- elastic and resilient modulus of concrete and foundation (MPa);
ν_c and ν_s -- Poisson's ratio of concrete and foundation which are taken as 0.15 and 0.30;
A,m and n -- regression coefficients, depending on loading position and number of axles which are shown in Table 2.

LOAD TRANSFER EFFICIENCY OF JOINTS

The longitudinal or transverse joints of concrete slabs may have some contribution on transferring loads across the joints, thus it may reduce the maximum edge stresses obtained from the above computation which are based on free edge condition.

The load transfer effectiveness of joints is appropriately to be evaluated by deflection measurement of the opposite edges of the joints, and the test results may be interpreted as follows:

$$LTE = \frac{W_u}{W_l} \times 100\% \tag{6}$$

in which, W_u and W_l are the deflections of unloaded and loaded slabs respectively. It is defined as the deflection load transfer efficiency. The relevant stress load transfer efficiency is expressed in terms of stress reduction factor k_j , which is defined as the ratio of edge stress with the consideration of load transfer of joint σ_{ej} to the free edge stress σ_e, i.e.,

$$k_j = \frac{\sigma_{ej}}{\sigma_e} \times 100\% \tag{7}$$

Since extraordinary high subgrade stressess may develop in semi-infinite foundation model under edge and corner loading conditions (3), and the discontinuity of deflection profile at slab joints precludes the use of continuous semi-infinite foundation model, it is preferable to adopt the dense liquid (Winkler) foundation model for analysing the load transfer efficiency of joints. With the aid of finite element analysis, it is found that there exists close correlationship between the deflection load transfer efficiency LTE and stress reduction factor k_j for representative single or tandem axle loads (shown in Table 1). The structural rigidity of pavement has significant effect on the variation of this k_j - LTE relation for loads acting along transverse joint, but only has little effect for loads along longitudinal joint. Regression equations were then established separately with satisfaction (relative error less than 3%) for conventional pavement structures (radius of relative rigidity l_o varies within 65-100 cm)(4):

For axle load acting along longitudinal joint

$$k_j = 0.996-0.220LTE-0.125LTE^2 \quad \text{(single axle)} \tag{8}$$

$$k_j = 0.991-0.180LTE-0.115LTE^2 \quad \text{(tandem axle)} \tag{9}$$

For axle load acting along transverse joint

$$k_j = 0.987-0.055C-0.355C^2 \quad \text{(single axle)} \tag{10}$$

$$k_j = 0.993-0.130C-0.319C^2 \quad \text{(tandem axle)} \tag{11}$$

where

$$C = LTE + (\frac{100}{l_o} -1)(0.00815+0.9702LTE-1.0592LTE^2) \tag{12}$$

l_o -- radius of relative rigidity of pavement structure,

$$l_o = \frac{E h^3}{12(1-\nu^2)k} \tag{13}$$

k -- modulus of foundation reaction (MN/m^3).

Deflection measurements on various types of joints were conducted during early 1980's. The resultant deflection load transfer efficiency LTE for various types of joints are suggested based on these test results: 37-65% for longitudinal joints with tie bars, 30-60% for undoweled contraction joints, and over 70% for doweled contraction joints. Referring to the regression equations shown above, it is suggested that the stress reduction factor k_j for longitudinal joints with tie bars may be selected within the range of 0.80-0.90, the lower value is suitable for grooved joints and the higher one is for butt joints.

FATIGUE EQUATION AND LOAD EQUIVALENCY FACTOR

Flexural fatigue test on beam specimens under various minimum stress levels was conducted in laboratory. Based on the test results, a fatigue equation was regressed as follows (Figure 2) (5):

$$lg(\frac{\sigma_{max}}{\sigma_s}) = lgA - 0.0422\ (1-R)\ lgN \tag{14}$$

where

σ_{max}-- maximum stress applied, which is the sum of loading stress σ_p and thermal stress σ_t;
R -- stress ratio, $R=\sigma_{min}/\sigma_{max}$;
σ_{min}-- minimum applied stress, $\sigma_{min}=\sigma_t$;
σ_s -- flexural strength of concrete;
A -- regression coefficient, depending on

failure probability, as shown in Table 3.

For the convenience of deriving formula for axle load converion, the above equation was reformed as follow (Figure 3):

$$\lg(\frac{\sigma_p}{\sigma_s-\sigma_t}) = \lg a - b\lg N \qquad (15)$$

in which, a and b are regression coefficients, also listed in Table 3.

According to the results shown above, following equation is adopted as fatigue criteria for the design procedure (Figure 3):

$$\frac{\sigma_p}{\sigma_s-\sigma_t} = N^{-0.0516} \qquad (16)$$

Consequently, the fatigue factor k_j can be defined as

$$k_f = N_e^{0.0516} \qquad (17)$$

in which, N_e is the accumulative repetition of standard axle loads during the design life of pavements.

An axle load of 100kN is adopted as standard axle load in the design procedure. Then, the number of repetitions applied by various axle loads are converted to those by the standard axle load. The expression of axle load conversion was derived by using the concept of equivalent fatigue damage and the fatigue equation (Equation 15) as follows:

$$LEF_i = \frac{N_s}{N_i} = (\frac{\sigma_{pi}}{\sigma_{ps}})^{1/b}$$

in which, LEF_i is the load equivalency factor for i th axle load to standard axle load, N_s and N_i are number of repetitions of standard axle load and i th axle load, and σ_{ps} and σ_{pi} are stresses induced by standard axle load and i th axle load. Substituting Equation (4) for the stresses, the above expression can be rewritten as:

$$LEF_i = \alpha_o(\frac{P_i}{P_s})^{16} \qquad (18)$$

in which, P_s and P_i are mass of standard axle load and i th axle load, and α_o is a coefficient, for single axle, α_o=1, and for tandem

$$\alpha_o = 4.74\times10^{-6}P_i^{-0.3767} \qquad (19)$$

THERMAL STRESS ANALYSIS

The temperature along slab section is nonlinearly distributed, which induces two parts of stresses in pavements. One is the thermal curling stress incurred by the temperature gradient between top and bottom side of the slab, and the other is the inner stress incurred due to the nonlinear distribution of temperature along the section.

The pavement structure was also idealized as a rectangular slab resting on semi-infinite foundation. The thermal curling stress was solved by using the same computer program TJCONP, and the computing results for variuos parameters of slab dimensions, relative stiffness and temperature gradients were regressed to formulate the following expressions (1):

$$\sigma_{tx} = \frac{E_c\alpha_t T_g h}{2(1-\nu_c^2)}(C_x+\nu_c C_y) \text{ (center of slab)} \qquad (20)$$

$$\sigma_{tx} = 0.5E_c\alpha_t T_g h\, C_x \text{ (edge center of slab)} \qquad (21)$$

in which, α_t is coefficient of thermal expansion of concrete (cm/cm°C), T_g is temperature gradient between top and bottom of the slab (°C/cm), and C_x (or C_y) is the curling stress coefficient along x (or y) axis which depends on the relative length or width of slab (L/l or B/l), as shown in Figure 4.

The inner stress induced by the nonlinear distribution of temperature can be derived according to the restraint strain at the bottom side of slab. The resultant thermal stress was then formulated by summing up the curling stress and the inner stress as follows (6):

$$\sigma_{tx} = \frac{E_c\alpha_t T_g h}{2(1-\nu_c^2)} D_x \text{ (center of slab)} \qquad (22)$$

$$\sigma_{tx} = 0.5E_c\alpha_t T_g h\, D_x \text{(edge center of slab)} \qquad (23)$$

in which, T_g is temperature gradient at h=22cm (°C/cm), and D_x is the thermal stress coefficient along x axis which is a function of curling stress coefficient C_x and slab thickness h, expressed as follows:

$$D_x = 2.08\, C_x'\, e^{-0.0448h} - 0.154\,(1-C_x') \qquad (24)$$

in which, $C_x' = (C_x + \nu_c C_y)/(1+\nu_c)$ for center of slab, and $C_x' = C_x$ for edge center of slab. D_x curves for the case of edge center of slab are also depicted in Figure 4.

The thermal stress reaches maximum as the temperature gradient turns to the maximum. The maximum temperature gradient is found to be related to two major determinant climatic factor: daily solar radiation and daily air temperature difference, and regression equation for predicting the maximum temperature gradient from the weather reports in slab with 22 cm thickness has been developed on the basis of correlating the temperature gradient data surveyed from test with the climate data of relevant weather stations:

$$T_g = 0.001344\frac{Q}{t_d} + 0.00348\, T_a + 0.086 \qquad (25)$$

in which, Q is daily solar radiation (Kcal/m²), T_a is daily air temperature difference (°C), and t_d is sunshine time daily (h). This equation is found to be in fair agreement with the prediction formula derived on theorectical basis.

The whole country is divided into 7 regions with different geographic and climatic features, as shown in Table 4. With the representative climate data of each region, recommended maximum temperature gradients can be offered by using the prediction equation (Equation 25), which are also shown in Table 4.

Thetemperature gradient varies daily and annually. The accumulative fatigue damage incurred by the fluctuating temperature gradients is considered by introducing a fatigue thermal stress factor k_t which is defined as a ratio of equivalent fatigue temperature gradient to maximum temperature gradient, or correspondingly, as a ratio of equivalent fatigue thermal stress to maximum thermal stress. The equivalent fatigue temperature gradient will have the same fatigue damage effect as the accumulated one incurred by actual fluctuating temperature gradients.

Bassed on this equivalent fatigue concept and the fatigue equation, the daily equivalent fatigue temperature gradient expession was derived with the assumption of semi-sine curve distribution of temperature gradient in daytime, and then the annual equivalent fatigue temperature gradient expression was also derived with the sine curve (regions 3 and 6) or broken line (regions 2,4,5 and 7) distribution of maximum daily temperature gradient in sunny days. It is found that the fatigue thermal stress factor k_t is a function of the ratio of maximum thermal stress σ_{tm} to flexural strength of concrete σ_s, the proportion of sunshine, and the proportion of traffic in daytime. With the representative sunshine data collected from every climatic region, recommended values of fatigue thermal stress factor k_t for various clamatic regions are offered, as shown in Table 5 (7).

DESIGN INPUTS

The design inputs required for thickness determination are: (1) traffic, (2) flexural strength of concrete, (3) composite resilient modulus of subgrade and subbase, and (4) maximum temperature gradient.

Traffic

Traffic is one of the primary inputs in the design procedure. The traffic of design lane is estimated in terms of the total number of repetitions of the standard axle loads during the design life of pavements which can be projected with following expression:

$$N_e = \frac{N[(1+r)^t-1]}{r}\,\eta \qquad (26)$$

where

N--average daily repetitions of standard axle loads in the first year which is derived from estimates of average daily truck traffic and axle load distribution, and by converting various axle loads to standard axle load with LEF in Equation 18;

r--annual rate of traffic growth during design life;

t--design life of pavements which may vary from 20 to 40 years, depending on traffic intensity class of highway, defined in Table 6;

η--lateral distribution coefficient of wheel track which is recommendedas 0.18-0.23 for the case of adopting the longitudinal joint edge as critical loading position.

A load safety factor k_c is introduced to multiply the load stress induced by standard axle load for considering unpredicted truck overloads and dynamic impacts of traffic loads, as well as normal constuction variations in material properties and layer thickness. The recommended factor varies from 1.05 to 1.55 which depends on traffic intensity class, and is listed in Table 6.

A comparison of combined fatigue damage incurred by axle loads acting on various positions of slabs and temperture gradients has been conducted. It is shown that the most severe damage occurs when the axle load is acted along the center of longitudinal joint. Therefore, it is suggested to choose this position as the critical loading position for calculating the stresses in pavements.

Flexural Strength of Concrete

The flexural strength of concrete is determined by third point loading tests on beam specimens. The 28-day test results are recommended for use in thickness design, but 90-day results can be selected if the pavement will begin to experience design loads after 90 days.

The required design flexural strength of concrete is 5.0MPa for very heavy, heavy and medium traffic, and 4.5 MPa for light and very light traffic.

The elastic modulus of concrete is adopted within $3.0\text{-}2.8\times10^4$ MPa, depending on the flexural strength of concrete.

Subgrade and Subbase Support

The idealized model of pavement structure used for stress analysis is a slab resting on semi-infinite foundation. Thus, the subgrade and subbase support is then defined in terms of composite resilient modulus of subgrade and subbase E_{cr}.

The composite resilient modulus E_{cr} can be determined by plate-loading test, and expressed as:

$$E_{cr} = \frac{\pi p D}{4l}(1-\nu_s) \qquad (27)$$

in which, p is the pressure applied on the plate (MPa), D is the diameter of the plate (cm), 28cm in common use, l is the resilient deflection measured corresponding to p (cm), and ν_s is Poisson's ratio of the foundation.

E_{cr} can also be determined by deflection measurement with truck having rear axle of 100 kN, and expressed as:

$$E_{cr} = 13739\, d_o^{-1.04} \qquad (28)$$

in which, d_o is representative resilient deflection measured (10^{-2}mm).

Experiment verification of loading and thermal stress results by finite element analysis were performed, and it is found that the resilient modulus of foundation have to be adjusted for matching the computed deflection and stress results to the measured ones. The rectified factor n for the composite resilient modulus is then suggested as:

$$n_c = 0.35 \qquad \text{(for thermal stress)} \qquad (29)$$

$$n_c = 0.75\times10^{-2.64}\left(\frac{hE_c}{E_{cr}}\right)^{0.8} \qquad \text{(for loading stress)} \qquad (30)$$

in which, h is the thickness of slab (cm), E_c is the elastic modulus of concrete (MPa).

Thus, the design composite resilient modulus of subgrade and subbase E_s is determined as follow:

$$E_s = n_c E_{cr} \qquad (31)$$

DESIGN PROCEDURE

The design procedure to determin pavement thick ness discussed herein may be summarized step by step as follows:

1. Collect traffic data (AADT and axle load composition), convert into numbers of standard axle load N with the load equivalency factor LEF (Equations 18 and 19), define traffic intensity class and design life (Table 6), calculate accumulative number of repetitions of standard axle load N_e in design lane during the design life by Equation 26.
2. Assume a concrete pavement structure with subgrade type, subbase type and thickness, slab size and thickness, and joint type.
3. Prepare concrete mix design, determine design flexural strength σ_s and elastic modulus E_c of concrete.
4. Determine the composite resilient modulus of subgrade and subbase by plate-loading test or deflection measurement, and adjust this value into design composite resilient modulus E_s by Equations 29, 30 and 31.
5. Estimate the maximum loading stress σ_{ps} by means of Figure 1 or Equation 4, select the stress reduction factor k_j according to the joint type, calculate the fatigue stress factor k_f with N_e and Equation 17, define the load safety factor k_c from Table 6, then multiply the maximum loading stress by these factors to get the fatigue loading stress σ_p.
6. Use Figure 4 to estimate the thermal stress coefficient D_x, select maximum temperature gradient T_g from Table 4, calculate the maximum thermal stress σ_{tm} by Equation 23, adopt the fatigue thermal stress factor k_t from Table 5 with the stress ratio σ_{tm}/σ_s, and then multiply the maximum thermal stress σ_{tm} by the factor k_t to get the fatigue thermal stress σ_t.
7. Sum up the fatigue loading stress σ_p and the fatigue thermal stress σ_t and compare it with the design flexural strength of concrete σ_s. If the difference is 3% over or 5% less than σ_s, repeat this process by assuming a new pavement structure until the sum of the fatigue stress is about the same as the flexural strength of concrete.

SUMMARY

The new thickness design procedure developed for revising the concrete pavement design specification of China is reviewed. Design criteria adopted is to prevent the fatigue cracking of slab incurred by the combined fatigue damage of traffic loads and temperature gradients. The thickness design is based on the estimation of the fatigue damage induced by repeated loading stresses and the fluctuating thermal stresses with newly developed fatigue equation which can take account of variable low stresses levels. The pavement structure is idealized as a rectangular slab testing on semi-infinite foundation, and the stress due to traffic loads and temperature gradients are determined with a finite element computer program TJCONP. The effects of load transfer efficiency of joints and the inner stress induced due to nonlinear distribution of temperature along slab section have been considered. The equivalent fatigue damage concept has been used to derive the load equivalent factor and the fatigue thermal stress factor for considering the accumulative effects of various traffic loads and temperature gradients.

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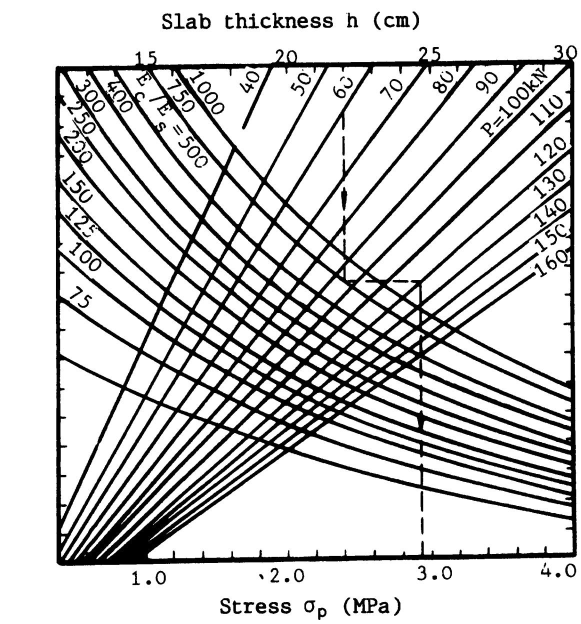

Figure 1. Maximum stress chart for single axle load acting on longitudinal edge center of slab.

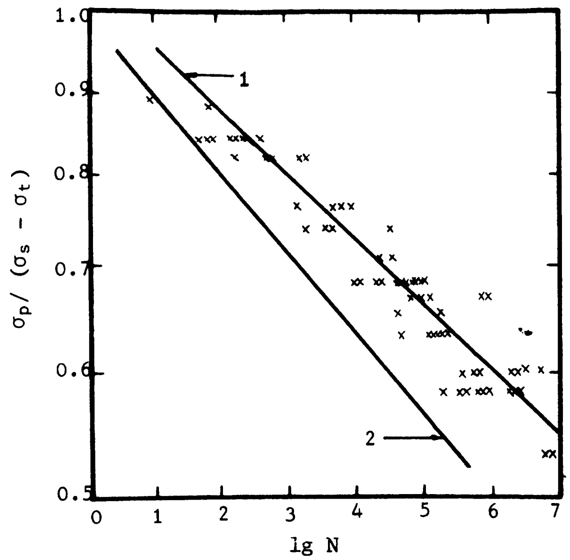

Figure 3. Fatigue equations (1--Equation 15, 2--Equation 16)

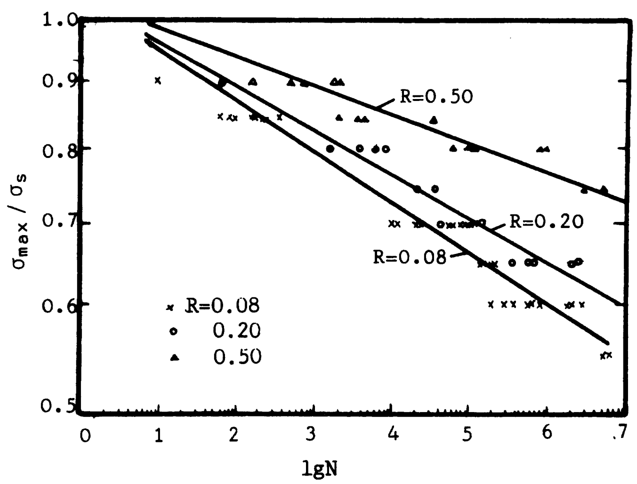

Figure 2. Fatigue test results under various R ($R = \sigma_{min}/\sigma_{max}$).

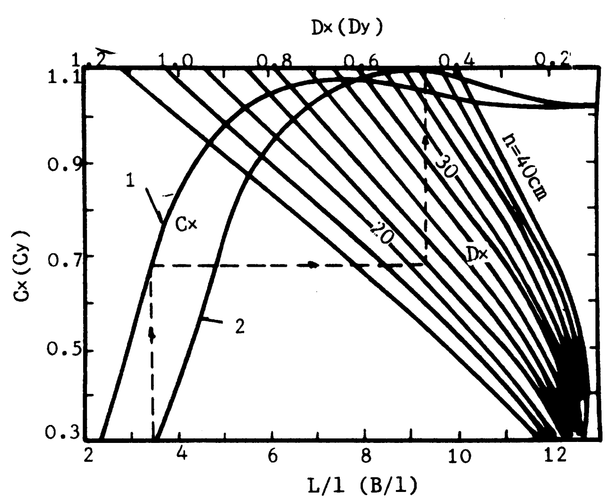

Figure 4. Thermal stress coefficient C_x and D_x curves for edge center of slab (1--Semi-infinite foundation, 2--Winkler foundation).

Table 1. Representative parameters of traffic loads

Axle	Axle load (kN)	Tyre Pressure (MPa)	Dual Wheel Spacing(cm)	Tread (cm)	Tandem Wheel Spacing(cm)
Single	40-50	0.45	25	165	
	60-70	0.50	29	174	
	80-90	0.60	32	177	
	100-110	0.60	32	182	
	120-140	0.70	34	182	
Tandem	80-100	0.35	29	174	112
	120-180	0.60	34	180	122
	200-220	0.60	34	186	132
	240-320	0.65	34	186	132

Table 2. Regression coefficients A,m and n

Loading Position	Axle	A	m	n
Longitudinal edge center	Single	0.8738	0.7381	0.8263
	Tandem	0.2577	0.8818	0.8068
Transverse edge center	Single	0.8425	0.7016	0.8482
	Tandem	0.2490	0 8709	0.8362

Table 3. Coefficients A, a and b for various failure probability

Failure probability	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
A	0.9611	0.9843	0.9957	1.0067	1.0131	1.0190	1.0242	1.0288	1.0330	1.0380
a	0.9340	0.9713	0.9935	1.0094	1.0218	1.0319	1.0405	1.0481	1.0546	1.0606
b	0.0391	0.0403	0.0409	0.0412	0.0413	0.1412	0.0414	0.0414	0.0414	0.0413

Table 4. Recommended maximum temperature gradient T_g(°C/cm) for 22cm slab thickness

Region	1	2	3	4	5	6	7
Features	Permafrost	Seasonal frost east	Loess plateau	Hot and wet, south east	Warm & humid, south west	Arid, northwest	Tsinghai-Tibet plateau
T (°C/cm)	---	0.83-0.88	0.90-0.95	0.86-0.92	0.83-0.88	0.86-0.92	0.93-0.98

Table 5. Recommended fatigue thermal steess factor k_t

	Climatic region					
σ_{tm} / σ_s	2	3	4	5	6	7
0.20	0.350	0.358	0.287	0.273	0.338	0.354
0.25	0.427	0.439	0.378	0.374	0.415	0.436
0.30	0.485	0.502	0.447	0.449	0.476	0.497
0.35	0.533	0.554	0.502	0.508	0.527	0.546
0.40	0.574	0.598	0.548	0.556	0.570	0.587
0.45	0.609	0.637	0.588	0.598	0.608	0.621
0.50	0.641	0.672	0.622	0.634	0.643	0.652
0.55	0.669	0.703	0.654	0.665	0.674	0.679
0.60	0.695	0.732	0.682	0.694	0.704	0.703

Table 6. Recommended design life and load safety factor k_c

Traffic intensity class	Very heavy	Heavy	Medium	Light	Very light
Average daily repetitions of standard axle in design lane	>1500	501-1500	101-500	6-100	<6
Design life (year)	40	30	30	20	20
Load safety factor k_c	1.55	1.45	1.30	1.10	1.05