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Estimation of Critical Stress in Jointed Concrete Pavement

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Abstract

Pavements are subjected to repeated traffic loads along with temperature variation throughout their service life. In concrete pavement, critical stresses are developed due to the combined effect of wheel load and positive temperature differential leading to initiation of cracks. In this paper, a methodology has been presented for evaluating the critical stress in concrete pavement based on finite element technique. A generalized expression for estimating the critical stress has been developed considering various combinations of pavement configurations, axle loads and temperature differential. This equation can be effectively utilized to obtain the critical stress in concrete pavement for any combination of axle load and nonlinear positive temperature gradient without performing a rigorous finite element analysis. Based on the generalized expression, a modification on Bradbury's temperature stress coefficient (C) has been suggested.

Selection and peer-review under responsibility of International Scientific Committee.

Keywords: Concrete pavement; critical stress; wheel load stress; temperature differential; finite element analysis

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1. Introduction

Pavements are subjected to repeated traffic loads throughout their service life. In concrete pavements, the repeated application of traffic loads along with temperature variation may lead to initiation of cracks at the highly stressed locations. The cracks propagate through the pavement which may finally lead to failure of pavements due to fatigue. Due to temperature alone, cracks may also initiate in the newly-constructed pavements. Variation in temperature affects the stresses in concrete slab in two ways. The daily variation in temperature causes quick changes in thermal gradients through the depth of concrete slab, while the seasonal variation results into different average temperature in concrete slab. The concrete slab will tend to curl upward or downward when it is subjected to an increasing or decreasing temperature variation through its depth. Due to its self-weight, the slab is not allowed to curl, resulting in the development of curling stresses in the pavement. In concrete pavement, the combined effect of wheel load and temperature gradient is responsible for the development of critical stresses. In the guidelines of Indian Roads Congress (IRC: 58, 2002) for the analysis and design of concrete pavements, though the procedure for calculation of wheel load stress is now modified based on analytical approaches, the estimation of curling stress is still empirical in nature. The IRC approach of computing curling stress follows Bradbury's solutions with some modifications. However, these modifications are mostly empirical giving conservative results. Also the combined effect of wheel load stress and curling stress is not simply additive in nature. The variation of temperature through the depth of concrete slab is nonlinear in nature, which has been considered as linear in the Indian design code. Therefore, an attempt has been made in this study to develop a generalized expression for identifying and estimating the critical stress in the slab subjected to the combined action of wheel load and nonlinear temperature differential based on finite element method. This ready-to-use equation can be utilized conveniently by the practicing engineers for the design of concrete pavement. Finally, a modification on Bradbury's temperature stress coefficient has been suggested, which can now be used to estimate the curling stress on concrete pavement.

2. Methodology

In concrete pavement, the critical combination that gives the maximum tensile stress at the slab bottom is when axle load at the longitudinal edge of the pavement is combined with positive temperature gradient (Maitra et al., 2009a). In this paper, a methodology has been presented for evaluating the critical stress in concrete pavement due to the combined action of wheel load and positive temperature gradient based on finite element technique. A sensitivity analysis has been carried out in this work using a validated three-dimensional (3-D) finite element (FE) model for jointed concrete pavement (Maitra, 2011). The 3-D FE model was validated using a structural evaluation data of an in-service concrete pavement on the national highway in India. The details of the validation procedure are discussed elsewhere (Maitra, 2011). For the sensitivity analysis, different pavement configuration, axle load and positive temperature gradient have been considered and are discussed in the following sections.

2.1. Pavement Configuration

A three-panel concrete pavement system of dimension 4500 mm × 3500 mm, separated by transverse joints has been considered. The plain cement concrete (PCC) slab is supported over foundation, comprised of layers of base and granular subbase (GSB) over prepared (compacted) subgrade. In India, dry lean concrete (DLC) base and wet mix macadam (WMM) subbase are generally used (IRC: 58, 2002). The interface between concrete slab and DLC base is generally constructed as unbonded by providing a 125 micron polythene sheet as bond-breaker, which is the usual practice in India. Transverse joints for the pavement system are considered to be provided with 32 mm diameter dowel bars 600 mm in length and spaced at 300 mm center to center for transferring the applied wheel load to the adjacent panels. The slab panels are considered to be discontinuous beyond the width of the slab. Fig. 1 shows the schematic of the three-panel concrete pavement system. Various combinations of thicknesses and material properties for slab and foundation as considered in the sensitivity analysis are given in Table 1.

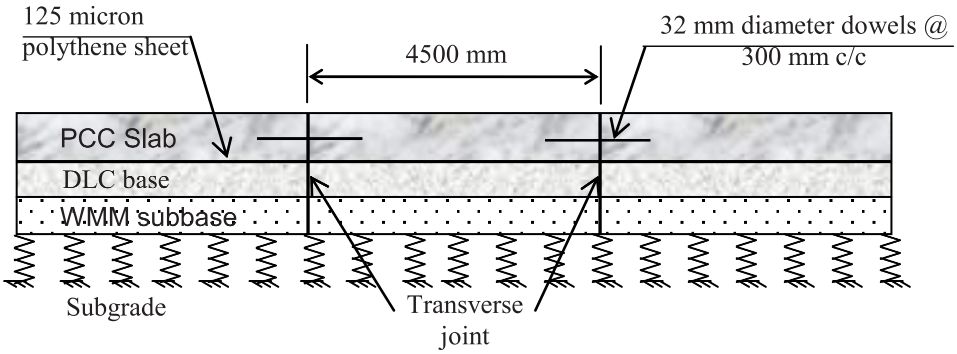

Fig. 1: Schematic Representation of the Three-Panel Concrete Pavement

Table 1: Properties of PCC, DLC, GSB & Subgrade Considered for the Sensitivity analysis

Parameters	Layers			
	PCC	DLC	GSB	Subgrade
Thickness (*h* in mm)	250, 300, 350, 400	100, 150	150	-
Density (γ in kN/m^3)	24	20	18	-
Coefficient of thermal expansion (α in mm/mm/°C)	1.0×10^{-5}	0.7×10^{-5}	-	-
Elastic Modulus (*E* in kPa)	25, 30, 35	10, 14, 17.5	0.5	-
Poisson's Ratio (υ)	0.15	0.15	0.35	-
Modulus of Subgrade Reaction (*k* in MPa/mm)	-	-	-	0.05, 0.08, 0.12, 0.15, 0.20

2.2. Details of Axle Load

Five different axle loads- 80 kN, 120 kN, 160 kN, 200 kN and 240 kN, were considered for the present analysis. The loads were selected as representatives of the typical axle load spectrum observed on Indian highways. The axle loads are placed with the outer wheel tangential to the longitudinal edge of the central panel (load position ‘A’, Ref. Fig. 2), For the purpose of the present analysis, the axle load was applied only on the middle panel. The figure also gives the details of the geometrical arrangement of the wheel loads on the axle. The stress will be critical below the outer wheel near the longitudinal edge of the pavement. Load transfer between the panels was assumed to be only through the dowel bars placed across the transverse joints and the contribution of aggregate interlocking has been neglected.

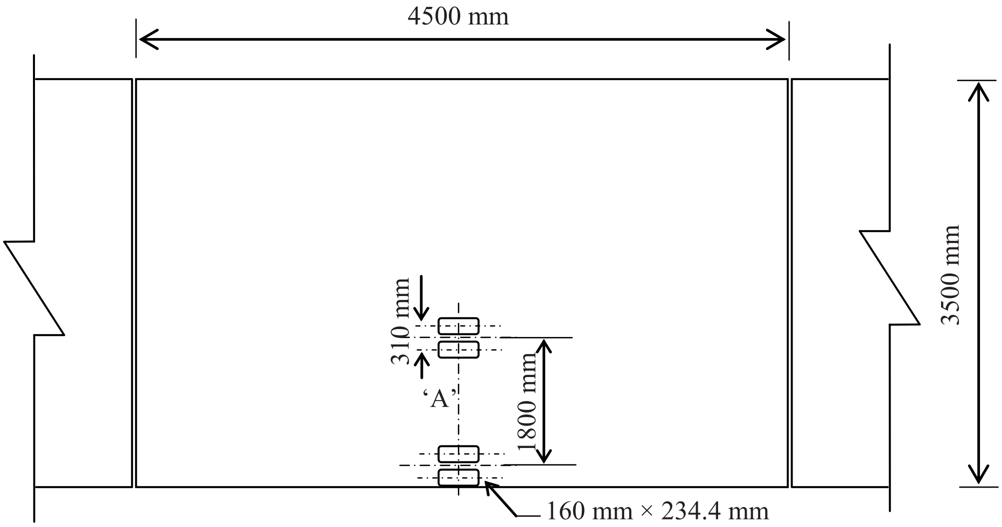

Fig. 2: Details of Axle Load and Critical Stress Location on the Pavement

2.3. Temperature Measurement in Laboratory

In the laboratory, experiments were performed to observe the variation of temperature within concrete specimens. Measurement of temperature was done on two concrete cylinders. Concrete cylinders of 150 mm diameter and 300 mm in height were cast in the laboratory for this purpose. The surface of the cylinder was covered and hot air was blown at one end of the cylinder. The other end was covered with soil. Five thermometers were inserted with equal intervals along the length of the cylinder to measure temperatures at different locations. Fig. 3 shows the photograph of the experiment performed in the laboratory for temperature measurement.

From the experiment, typical nonlinear variation of temperature was observed within the concrete specimens. Fig. 4 shows some typical variations obtained from the experiment. Similar variations of temperature through the depth of slab were also observed by other researchers on model concrete pavements (Venkatasubramanian, 1964; Balbo and Severi, 2002; Beckemeyer et al., 2002).

Fig. 3: Temperature Measurement in the Laboratory

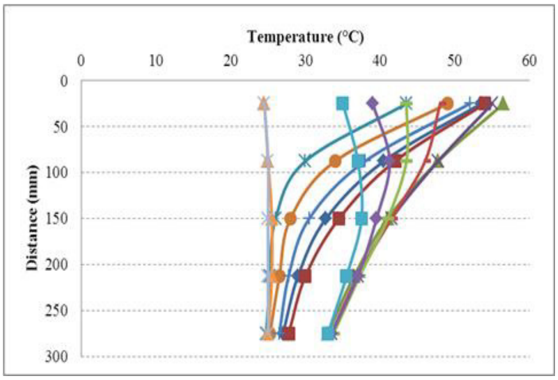

Fig. 4: Typical Variations of Temperature within Concrete Specimen

2.4. Temperature Differential

Based on the laboratory experiment, a non-linear temperature variation within the slab depth was considered for the sensitivity analysis. The temperature difference (T_D) between the top and the bottom surface of the slab was varied from 0 to 30° C. To simplify the analysis, the non-linear temperature variation was approximated by a bilinear variation, as shown in Fig. 5. In the figure, T_{top}, T_{bottom} and T_{mid} are the temperatures at the top fiber, bottom fiber and at the mid-depth of the concrete slab respectively. From the trends of temperature variations presented in Fig. 4, the following relationship can be considered among T_{top}, T_{mid} and T_{bottom}.

$$T_{mid} = T_{bottom} + \frac{1}{3}\left(T_{top} - T_{bottom}\right) \tag{1}$$

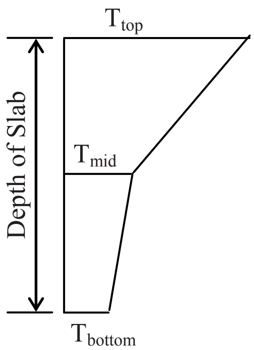

Fig. 5: Bilinear Variation of Temperature in the Slab

Dry lean concrete (DLC) layer was assumed to have uniform temperature throughout its depth. Temperature at the bottom fiber of the concrete slab was assigned to the DLC layer.

2.5. Finite Element Modeling of the Pavement

The three-panel concrete pavement sections were analyzed using a comprehensive three-dimensional finite element model (Maitra, 2011). The model has been developed using the commercial structural analysis software *ANSYS*.

Plain cement concrete (PCC) slab, dry lean concrete (DLC) base and granular subbase (GSB) were modeled as linear, elastic and isotropic materials. Eight-noded solid brick elements (SOLID45) were used to model these layers. Two elastic constants, the Young's modulus (E) and the Poisson's ratio (υ) were used to represent the material characteristics of each of these layers. The density (γ) of the layers and coefficient of thermal expansion (α) of concrete slab and DLC layer were the other input parameters used in the analysis. The subgrade was modeled as Winkler foundation (Westergaard, 1926). Winkler model is the idealization of the soil medium as a bed of closely spaced, independent, linear springs. Two-noded linear spring elements (COMBIN14) of *ANSYS* package were used to model the Winkler foundation. The effective normal stiffness of the spring element was obtained by multiplying the modulus of subgrade reaction (k) with the influencing area of that element. The interface between concrete slab and DLC base was modeled as either bonded or unbonded by using contact elements (CONTA178). The interface coefficient of friction between PCC slab and DLC base is taken as 0.5 for unbonded interface due to the presence of polythene sheet. For bonded interface, the friction between the two layers is very high and the coefficient of friction is taken as 20. These values were selected on the basis of the results of the push-off tests of concrete slabs on different types of base and subbase with different interface conditions reported by Maitra et al. (2007). Dowel bars along the transverse joints were modeled as 3-D beam elements (BEAM4). The beam elements representing the dowel bars are connected with the solid brick elements of concrete slab. One end of the dowel bars are generally covered with plastic sheets (a common practice in India). To represent this, a series of contact elements (CONTA178) are used to connect the beam elements of dowel bars with the concrete slab (Maitra et al., 2009b). It is assumed that the dowel bars have zero looseness around them. The properties of the steel dowel bars considered for the analysis are: elastic modulus (E) = 200,000 MPa and Poisson's ratio (υ) = 0.3. The modulus of dowel support (K) between dowel bars and concrete was taken as 450 MPa/mm for the sensitivity analysis. Fig. 6 shows the finite element model of the three panel concrete pavement system drawn in *ANSYS* software. Concrete slab, DLC base and granular subbase are shown as brick elements, while the Winkler foundation representing subgrade is shown as series of linear springs. The axle load at the critical location is also shown at the middle slab panel.

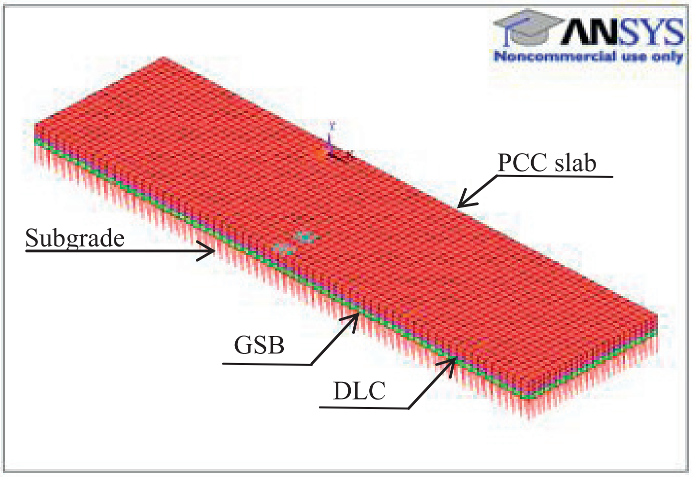

Fig. 6: Finite Element Model for the three-panel Concrete Pavement

3. Estimation of Critical Stress

Concrete pavement, with various configurations, axle loads and nonlinear temperature differentials were analyzed using the 3-D FE model and the critical stress due to the combined effect of wheel load and positive temperature gradient were determined. A regression analysis is carried out using all these results. Based on the regression analysis, a generalized expression for estimating the critical stress due to the combined action of axle load and nonlinear positive temperature gradient has been developed. The relationship was developed as a function of pavement parameters, axle load and temperature differential. The generalized expression for estimating the critical stress (σ_{cr}) is given as equation 2. The critical stress occurs at the bottom of the slab below the outer wheel at the longitudinal edge of the pavement (Ref. Fig. 4). In this work, the pavement combinations have been represented by a single parameter, 'radius of relative stiffness' expressed by equation 3. In equation 3, effective slab thickness (h_e) was considered to take care of the effect of bonded or unbonded dry lean concrete (DLC) base layer of the pavement (Zollinger et al., 2005).

$$\sigma_{cr} = 1.35 \times \left(\frac{P_A}{h_e^{\,2}} \right) + 13.5 \times \left(\alpha \frac{T_D}{h_c} \right) \times \left(k l^2 \right) \quad (2)$$

($R^2 = 0.89$, $F_{stat} = 111 > F_{critical} = 4.93$, t_{stat} of $(P/h_e^{\,2})$ and $(\alpha T_D / h_c) \times (k l^2) > t_{critical} = 1.94$)

where,

σ_{cr} = Critical stress due to wheel load and positive temperature gradient in MPa
P_A = Total axle load in N
h_e = Effective slab thickness with bonded or unbonded interface condition in mm
α = Coefficient of thermal expansion of concrete in mm/mm/°C
T_D = Temperature difference between top and bottom fiber of concrete slab in °C
h_c = Thickness of concrete slab in mm
k = Modulus of subgrade reaction in MPa/mm

$$l = \sqrt[4]{\frac{E_c h_e^3}{12(1-\mu^2)k}} \quad (3)$$

= Radius of relative stiffness (RRS) in mm

E_c = Elastic modulus of PCC layer in MPa
υ = Poisson's ratio of PCC layer
h_e = Effective thickness of PCC layer in mm

The expressions for the effective thickness of PCC layers are given by equations (4) to (6) (Ioannides et al., 1992).

For fully-bonded layers,

$$h_e = h_{e-b} = \left\{ h_1^{\,3} + \frac{E_2}{E_1} h_2^{\,3} + 12 \left[\left(x_{na} - \frac{h_1}{2} \right)^2 h_1 + \frac{E_2}{E_1} \left(h_1 - x_{na} + \frac{h_2}{2} \right)^2 h_2 \right] \right\}^{1/3} \quad (4)$$

where,

x_{na} = Neutral axis distance from top of PCC layer in mm

$$x_{na} = \frac{E_1 h_1 \frac{h_1}{2} + E_2 h_2 \left(h_1 + \frac{h_2}{2} \right)}{E_1 h_1 + E_2 h_2} \tag{5}$$

For unbonded layers,

$$h_e = h_{e-u} = \left[\left(h_1^{\ 3} + \frac{E_2}{E_1} h_2^{\ 3} \right) \right]^{1/3} \tag{6}$$

where,

E_1 and E_2 = Elastic moduli of PCC and DLC layers respectively in MPa
h_1 and h_2 = Thicknesses of PCC and DLC layers respectively in mm

Equation 2 shows that the critical stress (σ_{cr}) depends significantly on pavement configuration (expressed in terms of effective thickness and radius of relative stiffness), and the strength of the supporting soil, along with the magnitude of axle load and the temperature differential. This ready-to-use equation can be conveniently utilized to obtain the critical stress in concrete pavement with various configurations for any combination of axle load and nonlinear positive temperature gradient without performing a rigorous finite element analysis.

4. Comparison with IRC Method

The critical stress, obtained from the generalized expression (equation 2), has been compared with that recommended by IRC method (IRC: 58, 2002) for a given pavement system. The design example given in IRC: 58 (2002) has been considered for this purpose. Salient features of the pavement system are given below.

Flexural strength of concrete = 4.5 MPa
Elastic modulus of concrete = 30,000 MPa
Poisson's ratio of concrete = 0.15
Coefficient of thermal expansion of concrete = 1.0×10^{-5} mm/mm/°C
Effective modulus of subgrade reaction with DLC base = 0.08 MPa/mm
Thickness of slab = 330 mm
Axle load = 240 kN (single axle)
Temperature differential = 21°C

The wheel load stress is estimated using the stress charts given in IRC: 58 (2002) based on IITRIGID computer program. The load stress works out to be 2.41 MPa.

The temperature stress is computed using Bradbury's equation (IRC: 58, 2002) as given in equation 7. For 21°C temperature differential, the curling / temperature stress is estimated as 1.73 MPa.

$$\sigma_{tc} = \frac{E_c \alpha T_D C}{2} \tag{7}$$

where,

σ_{tc} = Temperature / curling stress

C = Bradbury's coefficient, the values of which can be obtained from Bradbury's chart by knowing the L/l values of the pavement
L = Pavement dimension, along which the temperature stress is to be calculated

The other parameters were previously defined.

Therefore, the total critical stress (σ_{cr}) is the summation of the load stress and the temperature stress and is equal to 4.14 MPa (= 2.41 + 1.73) as per IRC: 58 (2002).

Considering the present analysis, the corresponding critical stress (σ_{cr}) for the pavement system given in IRC: 58, 2002, as estimated from equation 2 is 3.71 MPa. This value is found to be less (about 11.6%) as compared to that obtained from the IRC method. It is thus observed that IRC: 58 (2002) overestimates the critical stress for the combined action of wheel load and temperature gradient in a concrete slab.

5. Modification of Bradbury's Coefficient

Based on the relationship developed for estimating the critical stress at the edge of the jointed concrete pavement (equation 2), an attempt has been made in the present study to modify Bradbury's coefficient for estimating the temperature stress (σ_{tc}).

By comparing the critical stress (σ_{cr}) obtained from the regression analysis (equation 2) with that obtained by adding the wheel load stress and the temperature stress using IRC method, a modified Bradbury's coefficient (C_m) as given by equation 8 is proposed.

$$C_m = 27\frac{kl^2}{E_c h_e} \tag{8}$$

The parameters were previously defined.

Bradbury's equation can, thus, be utilized with the modified coefficient (C_m) considering the effective thickness of slab with the corresponding radius of relative stiffness values for estimating temperature stress for any pavement configuration.

6. Conclusion

This paper presents a methodology for estimating the critical stress in concrete pavement due to the combined action of wheel load and positive temperature gradient using a comprehensive three-dimensional finite element model. A generalized expression has been proposed to evaluate the critical stress in concrete slab. This equation can be effectively utilized in the design of concrete pavement to obtain the critical stress for any combination of axle load and nonlinear positive temperature gradient without performing a rigorous finite element analysis. A comparison with IRC: 58 (2002) method shows that the critical stress, particularly the temperature stress is overestimated using the IRC method. Based on the generalized expression, a modification on Bradbury's temperature stress coefficient has been suggested, which can now be used to estimate the curling stress on concrete pavement.

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