TKUPAV: STRESS ANALYSIS AND THICKNESS DESIGN PROGRAM FOR RIGID PAVEMENTS

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(Reviewed by the Highway Division)

ABSTRACT: An alternative procedure for the determination of critical stresses and the thickness design of rigid pavements is presented. The effects of a finite slab size, different gear configurations, widened outer lane, tied concrete shoulder, second layer, and thermal curling are investigated. The well-known ILLI-SLAB finite-element program was used for the analysis. The program's applicability for stress estimation is further validated by reproducing very favorable results to the test sections of Taiwan's second northern highway, the AASHO road test, and the Arlington road test. Prediction models for stress adjustments are developed using a projection pursuit regression technique. A simplified stress analysis procedure is proposed and implemented in a user-friendly program (TKUPAV) to facilitate instant stress estimations at three critical locations of the slab; namely, the edge, corner, and interior. A modified Portland Cement Association stress analysis and thickness design procedure is also proposed and incorporated into the TKUPAV program. This program may be utilized for various structural analyses and designs of jointed concrete pavements in both the metric system and the U.S. customary system.

INTRODUCTION

Traditionally, Westergaard's closed-form stress solutions for a single wheel load acting on the three critical loading conditions (interior, edge, and corner) were often used in various design procedures of jointed concrete pavements. However, the actual pavement conditions are often different from Westergaard's ideal assumptions of infinite or semi-infinite slab size and full contact between the slab-subgrade interface. Besides the effects of different gear configurations, a widened outer lane, a tied concrete shoulder, or a second bonded or unbonded layer may result in very different stress responses from Westergaard's solutions. These effects may be more accurately and realistically accounted for through the use of a finite-element (FE) computer program. Nevertheless, the difficulties of the required run time, the complexity of FE analysis, and the possibility of obtaining incorrect results due to the improper use of the FE model often prevent it from being used in practical pavement design.

Currently, most concrete pavement thickness design procedures do not consider curling stress in fatigue analysis, but many researchers indicate that it should be considered to warrant a zero-maintenance thickness design. Darter and Barenberg (1977) surveyed the nontraffic loop of the AASHO road test and found that after 16 years most of the long slabs [12.2 m (40 ft)] had cracks, but there were no cracks in the 4.6-m (15-ft) slabs. They concluded that this is most likely because longer slabs have much greater curling stresses than shorter slabs. Darter and Barenberg have suggested the inclusion of curling stresses for pavement thickness design. Edge stress prediction models were developed using a stepwise regression technique to automatically select a list of arbitrary combinations of input parameters (Lee and Darter 1994b). Thompson et al. (1990) has further analyzed the same problem using the principles of dimensional analysis and the concept of equivalent single axle radius. Edge stress prediction models were developed in a similar fashion using a stepwise regression technique and have been implemented in the ILLI-CONC program. Nevertheless, "to estimate the combined stress due to load and temperature curling, some problems were encountered in analyzing the data using dimensional analysis."

This paper will summarize the final research findings of a series of continuous research projects sponsored by National Science Council, Taiwan (Lee and Lee 1995; Lee et al. 1996b). The ILLI-SLAB programs applicability for stress estimation will be further validated by reproducing very favorable results to the test sections of Taiwan's second northern highway, the AASHO road test, and the Arlington road test. The study will also enhance the approach adopted by Thompson et al. (1990) by resolving the dimensional analysis issue as well as providing a more complete treatment to the stress analysis of three loading conditions: (1) edge; (2) corner; and (3) interior. The ESAR concept will be replaced by stress reeduction adjustment factors, generally ranging from 0 to 1, to satisfy tentative boundary conditions in a stress estimation. A new modern regression technique [projection pursuit regression (PPR)] will be used to develop all of the prediction models for stress adjustments rather than the use of a conventional stepwise regression technique. A modified Portland Cement Association (PCA) equivalent stress calculation and thickness design procedure will be proposed and implemented in a highly user-friendly, Windows-based TKUPAV program for practical trial applications. Because all of the mechanistic variables used in the proposed models are dimensionally correct, the proposed approach is applicable to both the metric system (International System of Units) and the English system (U.S. customary system).

ILLI-SLAB PROGRAM AND ITS APPLICABILITY

The basic tool for this analysis is the ILLI-SLAB FE computer program, which was originally developed in 1977 and has been continuously revised and expanded at the University of Illinois over the years. The ILLI-SLAB model is based on a classical medium-thick plate theory, and employs the four-noded 12-degree-of-freedom plate bending elements. The Winkler foundation assumed by Westergaard is modeled as a uniform, distributed subgrade through an equivalent mass foundation. Curling analysis was not implemented until versions developed after June 15, 1987. The present version (Ko-

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rovesis 1990) was successfully compiled on available Unix-based workstations of the Civil Engineering Department at Tamkang University. With some modifications to the original codes, a microcomputer version of the program was also developed using Microsoft FORTRAN PowerStation (*Microsoft* 1994). To further investigate the applicability of the ILLI-SLAB program for stress estimation, comparisons of the resulting stresses and the actual field measurements from some test sections of Taiwan's second northern highway, the AASHO road test, and the Arlington road test, were conducted.

Test Sections of Taiwan's Second Northern Highway

The test sections of Taiwan's second northern highway (Yen et al. 1994; Lee and Lee 1996) were constructed as jointed concrete pavements with an unbonded lean concrete base. The cross section of highway pavement, gear configurations, and test layouts are given in Fig. 1(a). A fully loaded truck with three different levels, 270, 192, and 153 kN (60.7, 43.1, and 34.3 kip), of rear dual-tandem axle loads was placed near the slab corner. Concrete temperatures were measured by embedding thermocouples into the fresh concrete. Horizontal move-

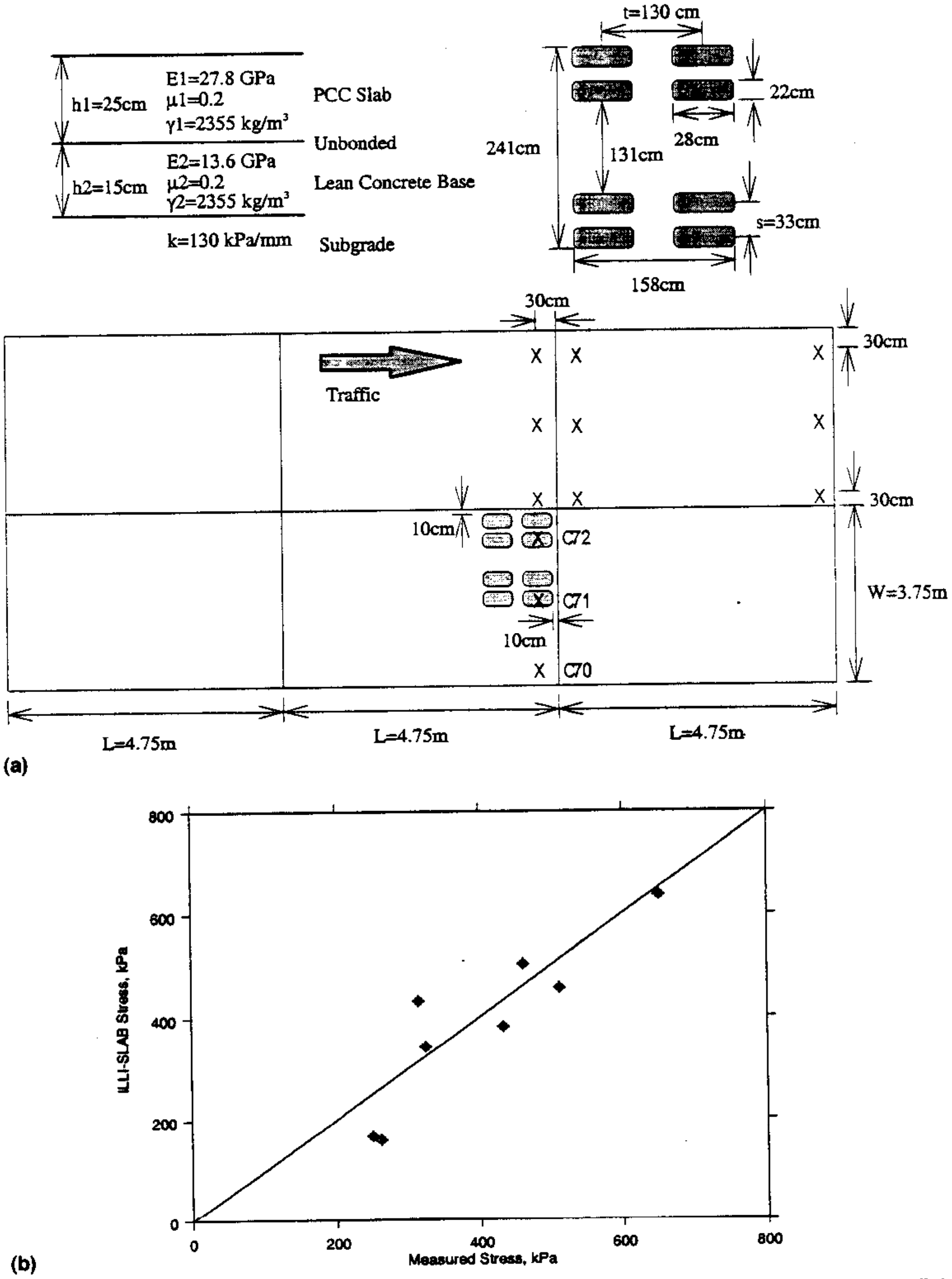

FIG. 1. Test Sections of Taiwan's Second Northern Highway: (a) Load Configurations and Test Layouts; (b) Predicted versus Measured Loading Plus Curling Stresses

ments of the slabs were measured using linear voltage displacement transducers. Strain gauges were used to measure surface concrete strains. At the time of testing, a positive temperature differential ΔT = 6°C (10.8°F) was measured across the slab thickness; the slab thermal coefficient α was assumed 9.9E-06/°F (5.5E-06/°F). The resulting horizontal stresses estimated by the ILLI-SLAB program were compared with the actual measured stresses. Note that the resulting ILLI-SLAB stresses must be adjusted accordingly because the strain gauge locations were actually placed 51 mm (2 in.) below the slab surface. As shown in Fig. 1(b), fairly good agreements were achieved.

AASHO Road Test

The following dynamic edge strain equation developed at the AASHO road test for single-axle vehicles was used to estimate the actual edge stress measurements (HRB 1962; Lee 1993):

$$\frac{\varepsilon_d}{L_1} = \frac{20.54}{10^{0.0031\Delta T} h^{1.278}} \tag{1}$$

where ε_d = dynamic edge strain ($\times 10^{-6}$); L_1 = nominal axle load of the test vehicle, kips; h = nominal thickness of the concrete slabs, in.; and ΔT = standard temperature differential as defined in the AASHO road test, °F.

By setting ΔT to zero, the above equation was used to estimate the measured edge stress due to an 80-kN (18-kip) single-axle load. The pertinent input parameters based on the AASHO road test condition were: E = 43.1 GPa (6.25E+06 psi); L_1 = 80 kN (18 kip); P = 40 kN (9,000 lb); μ = 0.28; L = 4.57 m (15 ft); W = 3.66 m (12 ft); and loaded area = 279 × 356 mm² (11 × 14 in.²). Six slab thickness values of 127, 165, 203, 241, 279, and 318 mm (5, 6.5, 8, 9.5, 11, and 12.5 in.) and three k values of 27.1 40.7, 54.3 kPa/mm (100, 150, and 200 pci) were assumed. The wheel load was not directly placed on the slab edge, and the offset distance between the outer face of the wheel and the slab edge was about 330 mm (13 in.). The resulting ILLI-SLAB loading stresses were compared with the measured ones and are shown in Fig. 2(a). Fairly good agreement was observed, especially for a k value of 40.7 kPa/mm (150 pci), which is very close to the in-field subgrade modulus of ~35.3 kPa/mm (130 pci) under the AASHO road test condition.

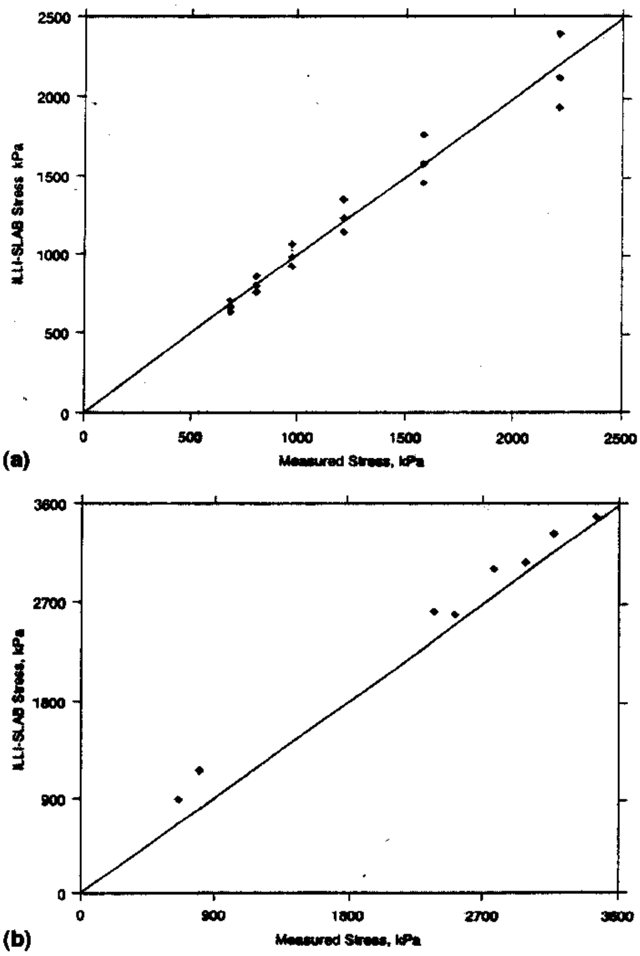

FIG. 2. AASHO Road Test Results: (a) Predicted versus Measured Stresses for Loading Only; (b) Predicted versus Measured Stresses for Loading Plus Curling

In addition, Lee (1993) has also demonstrated that fairly good agreement was achieved under a loading plus curling condition. The analysis was based on a 165-mm (6.5-in.) pavement slab under standard temperature differentials of −5.6, 5.6, 8.3, and 11.1°C (−10, 10, 15, and 20°F), and k values of 27.1 and 40.7 kPa/mm (100 and 150 pci). The coefficient of thermal expansion was assumed to be 9.0E-06/°C (5.0E-06/°F), and the self-weight of the slab was 2,410 kg/m³ (0.087 pci). The results of this comparison are shown in Fig. 2(b). Also note that the resulting ILLI-SLAB edge stresses were slightly higher than the estimated actual stress measurements.

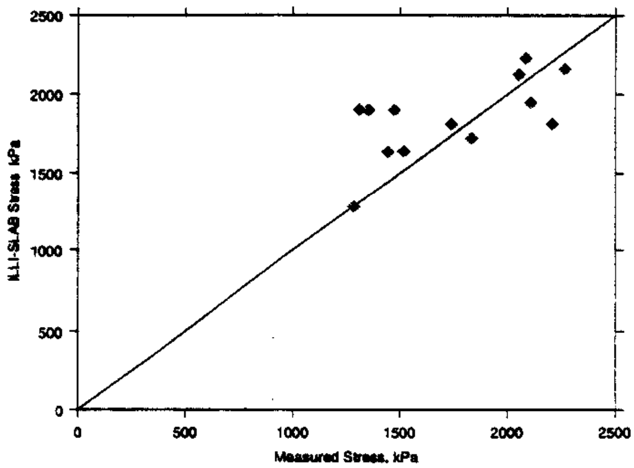

FIG. 3. Arlington Road Test Results for Curling Only

Arlington Road Test

The observed longitudinal curling stresses at the edge of the pavement slabs during the Arlington road test were obtained for the curling-only condition (Teller and Sutherland 1943; Lee 1993). The pertinent input parameters were E=34.5 GPa (5.0E+06 psi), k = 54.3 kPa/mm (200 pci), L = 6.1 m (20 ft), W = 3.05 m (10 ft), α = 8.64E-06/°C (4.8E-06/°F), and ΔT = 7.8–18.3°C (14–33°F). The measured curling stresses and the resulting ILLI-SLAB stresses for a slab thickness of 152 mm (6 in.) and 229 mm (9 in.) are plotted in Fig. 3. Even though the results of this comparison have shown some variabilities, the curling stress estimations are generally acceptable, especially when considering the difficulties involved in measuring curling strains and the scatterness of the Arlington road test data obtained.

IDENTIFICATION OF MECHANISTIC VARIABLES

Westergaard's closed-form solutions (Westergaard 1926; Ioannides et al. 1985) were based on ideal assumptions of an

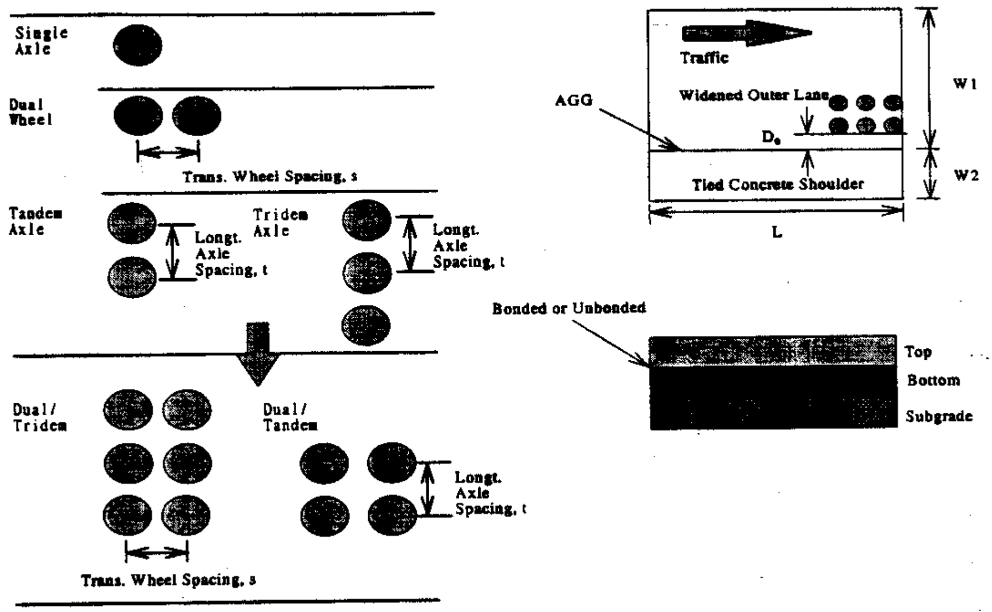

FIG. 4. Various Loading Conditions of Jointed Concrete Pavements

infinite or semi-infinite slab size, full contact between the slab-subgrade interface, and a single loaded area over a dense liquid (Winkler) foundation. In reality, jointed concrete pavements consist of many single finite concrete slabs jointed by aggregate interlock, dowel bars, or tie bars. As shown in Fig. 4, traffic loading may be in forms of dual wheel, tandem axle, or tridem axle. A widened outer lane may also shift the wheel loading away from Westergaard's critical loading locations. A tied concrete shoulder or a second bonded or unbonded layer may also result in different degrees of stress reductions. To account for these effects under a loading-only condition, the following relationship has been identified through many intensive FE studies for a constant Poisson's ratio (usually $\mu \approx 0.15$) (Lee 1993):

$$\frac{\sigma h^2}{P}, \frac{\delta k \ell^2}{P}, \frac{q \ell^2}{P} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{s}{\ell}, \frac{t}{\ell}, \frac{D_0}{\ell}, \frac{AGG}{k\ell}, \left(\frac{h_{eff}}{h_1}\right)^2\right) \quad (2)$$

where σ and q = slab bending stress and vertical subgrade stress, respectively (FL^{-2}); δ = slab deflection (L); P = wheel load (F); h = thickness of the slab (L); a = radius of the applied load (L); $\ell = (E \cdot h^3/(12 \cdot (1 - \mu^2) \cdot k))^{0.25}$ = radius of relative stiffness of the slab-subgrade system (L); k = modulus of subgrade reaction (FL^{-3}); L and W = length and width of the finite slab, respectively; s = transverse wheel spacing (L); t = longitudinal axle spacing (L); D_0 = offset distance between the outer face of the wheel and the slab edge (L); AGG = aggregate interlock factor (FL^{-2}); $h_{eff} = (h_1^2 + h_2^2 \cdot (E_2 \cdot h_2)/(E_1 \cdot h_1))^{0.5}$ is the effective thickness of two unbonded layers (L); h_1 and h_2 = thickness of the top slab and the bottom slab, respectively (L); and E_1 and E_2 = concrete modulus of the top slab and the bottom slab, respectively (FL^{-2}). Note that variables in both sides of the expression are all dimensionless. Primary dimension for force is represented by (F), and length is represented by (L).

In addition, Westergaard (1927) has also developed equations for curling stresses caused by a linear temperature differential between the top and bottom of the slab. Nevertheless, there is no explicit closed-form solution to account for the combination effect of loading plus curling on a concrete slab. The following relationship, which concisely defines the effects of loading plus thermal curling, has been identified (Lee and Darter 1994a,b):

$$\frac{\sigma}{E}, \frac{\delta h}{\ell^2}, \frac{qh}{k\ell^2} = f\left(\frac{a}{\ell}, \alpha \Delta T, \frac{L}{\ell}, \frac{W}{\ell}, \frac{\gamma h^2}{k\ell^2}, \frac{Ph}{k\ell^4}\right) \quad (3)$$

where E = slab modulus (FL^{-2}); α = thermal expansion coefficient (T^{-1}); ΔT = temperature differential through the slab thickness (T); γ = unit weight of the concrete slab (FL^{-3}); $D_\gamma = \gamma \cdot h^2/(k \cdot \ell^2)$; and $D_P = P \cdot h/(k \cdot \ell^4)$. Also note that D_γ was defined as the relative deflection stiffness due to self-weight of the concrete slab and the possible loss of subgrade support, whereas D_p was the relative deflection stiffness due to the external wheel load and the loss of subgrade support. The primary dimension for temperature is represented by (T).

DEVELOPMENT OF STRESS PREDICTION MODELS

The effects of a finite slab size, different gear configurations, widened outer lane, tied concrete shoulder, second bonded or unbonded layer, and thermal curling due to a linear temperature differential were considered in this study. For the analysis of the loading-only condition, the full contact assumption between the slab-subgrade interface is valid. Thus, the relationship as given in (2) can be broken down to a series of simple analyses for each individual effect. The dominating mechanistic variables (dimensionless) identified for each individual effect are given in Table 1. Many series of FE factorial runs over a wide range of pavement designs were carefully selected and conducted using the principles of experimental design. Several BASIC programs were written to automatically generate the FE input files and summarize the desired outputs. The FE mesh was generated according to the guidelines established in earlier studies (Ioannides 1984).

Critical stresses at different locations, i.e., edge, corner, and interior, were determined to provide a more complete treatment of the study. Separate adjustment factors were introduced to account for the effect of stress reduction due to each individual effect. Consequently, prediction equations for stress adjustments (multiplication factors) were developed using a modern regression technique (PPR). The principle of superposition is then applied to account for the combination effects of other more complicated cases.

Application of New Predictive Modeling Technique

PPR techniques introduced by Friedman and Stuetzle (1981) strive to model the response surface y as a sum of nonpara-

TABLE 1. Variables Used in Proposed Prediction Models for Stress Adjustments

Model (1)	Dimensionless Mechanistic Variables $\frac{a}{\ell}$ (2)	$\frac{L}{\ell}$ (3)	$\frac{W}{\ell}$ (4)	$\frac{s}{\ell}$ (5)	$\frac{t}{\ell}$ (6)	$\frac{D_0}{\ell}$ (7)	$\frac{AGG}{k\ell}$ (8)	$\left(\frac{h_{eff}}{h_1}\right)^2$ (9)	$\alpha\Delta T$ (10)	D_γ (11)	D_P (12)
Finite slab length	✓	✓									
Finite slab width	✓		✓								
Dual wheel	✓			✓							
Tandem axle	✓				✓						
Tridem axle	✓				✓						
Widened outer lane	✓					✓					
Tired concrete shoulder	✓						✓				
Unbonded second layer	✓							✓			
Bonded second layer	✓							✓[a]			
Curling only		✓	✓						✓	✓	
Load plus curling	✓	✓	✓						✓	✓	✓

[a]For effect of bonded second layer, use following equations to convert to unbonded second layer: $\alpha = [(1/2)h_1(h_1 + h_2)/h_1 + h_2(E_1/E_2)]$, $\beta = (1/2)(h_1 + h_2) - \alpha$, $h_{1f} = \sqrt[3]{h_1^3 + 12h_1\beta^2}$, $h_{2f} = \sqrt[3]{h_2^3 + 12h_2\beta^2}$, $h_{eff} = \sqrt{h_{1f}^2 + (h_{2f}/h_{1f})h_{2f}^2}$

metric functions of projections of the predictor variables x through the use of local smoothing techniques. Assuming there is a true model

$$y = \bar{y} + \sum_{m=1}^{M_0} \beta_m \phi_m(a_m^T x) + \varepsilon \tag{4}$$

where $\mathbf{x} = (x_1, x_2, \ldots, x_p)^T$ denotes the vector of predictor variables; $\bar{y}$ = expected (or mean) value of response variable; β_m = regression coefficient, and ε = residual or random error. The PPR algorithm strives to minimize the mean squared residuals over all possible combinations of β_m, ϕ_m, and a_m values. Conceptually, the explanatory variables x are projected onto the direction vectors $\mathbf{a}_1, \mathbf{a}_2, \ldots, \mathbf{a}_m$, to get the lengths of the projections $a_m^T x$, where $m = 1, \ldots, M_0$. An optimization technique is also used to find the best combinations of nonlinear transformations $\phi_1, \phi_2, \ldots, \phi_m$ for the multidimensional response surface. The $\phi_m(a_m^T x)$ represents the unknown nonparametric transformation functions of the projected lengths $a_m^T x$ to be estimated.

As proposed by Lee and Darter (1994b), the two-step modeling approach using the PPR technique was utilized for the development of prediction models. Through the use of local smoothing techniques, the PPR attempts to model a multidimensional response surface as a sum of several nonparametric functions of projections of the explanatory variables. The projected terms are essentially 2D curves that can be graphically represented, easily visualized, and properly formulated. Piecewise linear or nonlinear regression techniques were then used to obtain the parameter estimates for the specified functional forms of the predictive models. This algorithm is available in the S-PLUS statistical package (*S-PLUS*, 1995). A practical predictive modeling example using this approach can be found in the literature (Lee and Darter 1994b).

Proposed Edge Stress Prediction Models

To account for the effects of different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), the following equation was proposed for edge stress estimations (Lee et al. 1996b, 1997):

$$\sigma_e = \sigma_{we} \cdot R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 + R_T \cdot \sigma_{ce} \tag{5a}$$

$$\sigma_{we} = \frac{3(1+\mu)P}{\pi(3+\mu)h^2}\left[\ln\frac{Eh^3}{100\,ka^4} + 1.84 - \frac{4}{3}\mu + \frac{1-\mu}{2} + 1.18(1+2\mu)\frac{a}{\ell}\right] \tag{5b}$$

$$\sigma_{ce} = \frac{CE\alpha\Delta T}{2} = \frac{E\alpha\Delta T}{2}\left\{1 - \frac{2\cos\lambda\cosh\lambda}{\sin 2\lambda \sinh 2\lambda}(\tan\lambda + \tanh\lambda)\right\} \tag{5c}$$

where σ_e = edge stress prediction (FL^{-2}); σ_{we} = Westergaard's closed-form edge stress solution (FL^{-2}); σ_{ce} = Westergaard/Bradbury's edge curling stress (Fl^{-2}); C = curling stress coefficient ($\lambda = W/((8^{0.5}) \cdot \ell)$); R_1 = adjustment factor for different gear configurations including dual-wheel, tandem axle, and tridem axle; R_2 = adjustment factor for finite slab length and width; R_3 = adjustment factor for a tied concrete shoulder; R_4 = adjustment factor for a widened outer lane; R_5 = adjustment factor for the combined effect of loading plus daytime curling.

The model given in (5) has the following advantages: (1) It is theoretically sound, dimensionally correct, and applicable to any unit system; (2) adjustment factors range from 0 to 1 to satisfy tentative boundary conditions for the loading-only condition; (3) the coefficient of determination (R^2 value) for each individual adjustment factor is generally in the high range of 0.98–1.0; and (4) for the most difficult condition of loading plus curling, the value for R_T is in the range of 0–1.2 with a high R^2 value >0.95. More detailed descriptions of the proposed prediction models and development process can be found in the literature (Lee et al. 1996b).

Proposed Corner Stress Prediction Models

A similar approach was adopted to develop separate prediction models for corner stress adjustments. To account for the effects of different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), the following equation was proposed for corner stress estimations (Lee and Lee 1995, 1996; Lee et al. 1996b):

$$\sigma_c = \sigma_{wc} \cdot R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 + R_T \cdot \sigma_{c0} \tag{6a}$$

$$\sigma_{wc} = \frac{3P}{h^2}\left[1 - \left(\sqrt{2}\,\frac{a}{\ell}\right)^{0.6}\right] \tag{6b}$$

$$\sigma_{c0} = \frac{E\alpha\Delta T}{2(1-\mu)} \tag{6c}$$

where σ_c = corner stress prediction (FL^{-2}); σ_{wc} = Westergaard's closed-form corner stress solution (FL^{-2}); σ_{c0} = Westergaard's interior curling stress for an infinite slab (FL^{-2}); R_1, R_3, R_4 and R_5 = same definitions as shown in (5); $R_2 = R_{2a}$ or R_{2b}; R_{2a} = adjustment factor for finite slab length and width for the loading-only condition; R_{2b} = adjustment factor for finite slab length and width for the condition of loading plus curling, but $\Delta T = 0$ to allow partial contact between the slab-subgrade interface; and R_T = adjustment factor for the combined effect of loading plus nighttime curling; also note that the adjustment factors R_T and R_{2b} should be used together for higher accuracy.

This model has similar advantages to those described in the previous section. The proposed prediction models for corner stress adjustments and more detailed descriptions of the development process can be found in the literature (Lee and Lee 1995, 1996; Lee et al. 1996b). The maximum minor principal stress on top of the slab corner and the effect of loading plus nighttime curling were used in this analysis.

Proposed Interior Stress Prediction Models

To account for the effects of different material properties, finite slab sizes, gear configurations, and environmental effects (e.g., temperature differentials), the following equation was proposed for interior stress estimations (Lee and Lee 1996):

$$\sigma_i = \sigma_{wi}\cdot R_1\cdot R_2\cdot R_3\cdot R_4\cdot R_5 + R_T\cdot\sigma_{c0} \quad (7a)$$

$$\sigma_{wi} = \frac{3}{2\pi}(1+\mu)\frac{P}{h^2}\left[\left\{\ln\frac{2\ell}{a}\right\} - 0.0772 + \frac{\pi}{32}\left(\frac{a}{\ell}\right)^2\right] \quad (7b)$$

$$\sigma_{c0} = \frac{E\alpha\Delta T}{2(1-\mu)} \quad (7c)$$

where σ_i = interior stress prediction (FL^{-2}); σ_{wi} = Westergaard's closed-form interior stress solution (FL^{-2}); σ_{c0} = Westergaard's interior curling stress for an infinite slab (FL^{-2}); and R_1, $R_2(R_{2a}$ or $R_{2b})$, R_3, R_4, R_5, and R_T = same definitions as shown in (5).

This model also has similar advantages to those described in the previous section. The proposed prediction models for interior stress adjustments and more detailed descriptions of the development process can be found in other literature (Lee and Lee 1996). The effect of a tied concrete shoulder and a widened outer lane may be neglected in interior stress analysis, or in other words, $R_3 = R_4 = 1$.

MODIFIED PCA STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURE

The PCA's thickness design procedure (or PCA method) is the most well-known, widely adopted, and mechanically based procedure for the thickness design of jointed concrete pavements (*A design* 1984). Based on the results of J-SLAB (Tayabji and Colley 1986) FE analysis, the PCA method uses the concept of equivalent stress and fatigue analysis to determine the minimum slab thickness required. PCA's fatigue analysis concept was to avoid pavement failures (or first initiation of crack) by fatigue of concrete due to critical stress repetitions. Based on Miner's cumulative fatigue damage assumption, the PCA thickness design procedure first lets the users select a trial slab thickness, calculates the ratio of equivalent stress versus concrete modulus of rupture (stress ratio, σ_{eq}/S_c) for each axle load and axle type. The procedure then determines the maximum allowable load repetitions N_f based on the following $\sigma_{eq}/S_c - N_f$ relationship:

$$\log N_f = 11.737 - 12.077\cdot(\sigma_{eq}/S_c) \quad \text{for } \sigma_{eq}/S_c \geq 0.55 \quad (8a)$$

$$N_f = \left(\frac{4.2577}{\sigma_{eq}/S_C - 0.4325}\right)^{3.268} \quad \text{for } 0.45 < \sigma_{eq}/S_c < 0.55 \quad (8b)$$

$$N_f = \text{Unlimited} \quad \text{for } \sigma_{eq}/S_c \leq 0.45 \quad (8c)$$

The PCA thickness design procedure then uses the expected number of load repetitions, dividing by N_f to calculate the percentage of fatigue damage for each axle load and axle type. The total cumulative fatigue damage must be within the specified 100% limiting design criterion, or a different trial slab thickness must be used and previous calculations again repeated.

Modified Equivalent Stress Calculations

PCA's equivalent stress was determined based on the assumptions of a fixed slab modulus, a fixed slab length and width, a constant contact area, wheel spacing, axle spacing, and aggregate interlock factor, which may influence the stress occurrence, to simplify the calculations. Thus, the required minimum slab thickness will be the same based on the PCA thickness design procedure, disregarding the fact that a shorter or longer joint spacing, a better or worse load transfer mechanism, a different wheel spacing and axle spacing, and environmental effects are considered. The equivalent stress equation is currently only applicable to the English system (U.S. customary system) (Lee et al. 1997).

To expand the applicability of the PCA's equivalent stress for different material properties, finite slab sizes, gear configurations, environmental effects (e.g., temperature differentials), and any unit system, the following equation was proposed (Lee and Lee 1996; Lee et al. 1997):

$$\sigma_{eq} = (\sigma_{we}\cdot R_1\cdot R_2\cdot R_3\cdot R_4\cdot R_5 + R_T\cdot\sigma_{ce})\cdot f_3\cdot f_4 = \sigma_e\cdot f_3\cdot f_4 \quad (9)$$

$$f_3 = 0.894 \quad \text{for 6\% truck at the slab edge}$$

$$f_4 = 1/[1.235\cdot(1 - CV)]$$

where σ_{eq} = modified equivalent stress (FL^{-2}); σ_{we}, σ_{ce}, σ_e, R_1, R_2, R_3, R_4, R_5, and R_T = same definitions as given in (5); f_3 = adjustment factor to account for the effect of truck placement on the edge stress (PCA recommended a 6% truck encroachment, f_3 = 0.894); and f_4 = adjustment factor to account for the increase in concrete strength with age after the 28th day, along with a reduction in concrete strength by one coefficient of variation (CV); (PCA used CV = 15%, f_4 = 0.953).

Modified Thickness Design Procedure

A new thickness design procedure was developed based on the above "modified equivalent stresses," and the PCA's cumulative fatigue damage concept. Thompson et al. (1990) has suggested the inclusion of thermal curling by separating traffic repetitions into three parts: (1) Loading with no curling; (2) loading combined with daytime curling; and (3) loading combined with nighttime curling. Nevertheless, based on practical considerations of the difficulty and variability in determining temperature differentials, a more conservative design approach was proposed by neglecting possible compensative effects due to nighttime curling. Thus, only the conditions of loading with no curling, and loading combined with daytime curling were considered under this study. Separated fatigue damages are then calculated and accumulated. The 100% limiting criterion of the cumulative fatigue damage is also applied to determine the minimum required slab thickness. A brief description of the proposed thickness design procedure is as follows.

1. Data input: assume a trial slab thickness; input other pertinent design factors, material properties, load distributions, and environmental factors (i.e., temperature differentials).
2. Expected repetitions n_i: calculated the expected repetitions for the case of loading with no curling and for the case of loading with daytime curling during the design period.
3. Modified equivalent stress σ_{eq}: calculate the "modified equivalent stresses" using (9) for each case.
4. Stress ratio σ_{eq}/S_C: calculate the ratio of the modified

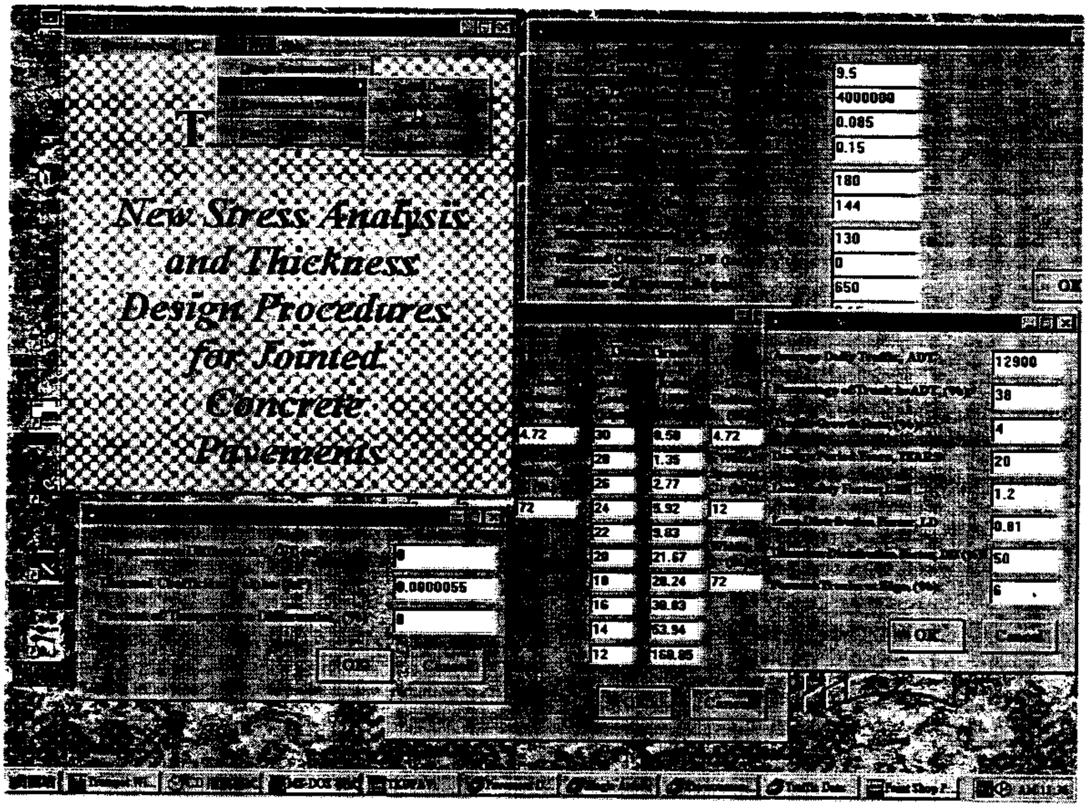

FIG. 5. Sample Input Screens of TKUPAV Program

equivalent stress versus the concrete modulus of rupture S_C for each case.

5. Maximum allowable load repetitions N_i: determine the maximum allowable load repetitions for different stress ratios based on the fatigue equation [(8)].
6. Calculate the percentage of each individual fatigue damage n_i/N_i.
7. Check if the cumulative fatigue damage Σ (n_i/N_i) < 100%.
8. If not, assume a different slab thickness and repeat Steps 1–7 again to obtain the minimum required slab thickness.

DEVELOPMENT AND VERIFICATION OF TKUPAV PROGRAM

To facilitate practical trial applications of the proposed stress analysis and thickness design procedures, a Windows-based program (TKUPAV) was developed using the Microsoft Visual Basic software package (*Microsoft* 1993). The TKUPAV program was designed to be highly user-friendly and thus came with many well-organized graphical interfaces, selection menus, and command buttons for easy use. Both English and Chinese versions of the graphical interfaces are available. Furthermore, because all of the mechanistic variables used in the proposed models are dimensionally correct, the proposed approach is applicable for both English and metric (SI) systems. Several example screens of the TKUPAV program are shown in Fig. 5.

Lee et al. (1997) has further verified the proposed approach by comparing the results of equivalent stresses and fatigue damages using the PCAPAV program, Microsoft EXCEL spreadsheets, and the Windows-based TKUPAV program. Very good agreement to the equivalent stress and fatigue damage comparisons was achieved, which convincingly verified the applicability of the proposed procedure. The possible detrimental effect of loading plus daytime curling has also been illustrated in a case study, which indicated that the effect of thermal curling should be considered.

CONCLUSIONS

An alternative procedure for the determination of critical stresses and the thickness design of rigid pavements is presented in this paper. The effects of a finite slab size, different gear configurations, widened outer lane, tied concrete shoulder, second bonded or unbonded layer, and thermal curling due to a linear temperature differential at three critical locations of the slab, namely, edge, corner, and interior, have been investigated. The ILLI-SLAB program's applicability for stress estimation has been further validated by reproducing very favorable results to the test sections of Taiwan's second northern highway, the AASHO road test, and the Arlington road test. Prediction models for stress adjustments have been developed using a modern regression technique (PPR). A simplified stress analysis procedure has been proposed and implemented in a highly user-friendly, Windows-based program (TKUPAV) to facilitate instant stress estimations. A modified PCA stress analysis and thickness design procedure has also been proposed and incorporated in the TKUPAV program. This computer program may also be utilized for various analyses and designs of jointed concrete pavements.

The proposed approach for stress estimations has the following advantages: (1) It is theoretically sound, dimensionally correct, and applicable to any unit system; (2) adjustment factors range from 0 to 1, to satisfy tentative boundary conditions for a loading-only condition; (3) the coefficient of determination (R^2 value) for each individual adjustment factor is generally in the high range of 0.98–1.0; (4) for the most difficult condition of loading plus curling, the adjustment factor for the effect of loading plus curling is in the range of 0 to 1.2 with a high R^2 value >0.95 in general.

This study also enhanced the applicability of the PCA method to analyze any different material properties, finite slab sizes, gear configurations (such as additional effects of a single axle/single wheel, and a tridem axle/dual wheels), and environmental effects (e.g., temperature differentials). The proposed prediction models can be utilized for the U.S. customary system and the metric system because all of the mechanistic variables are dimensionless.

It should be noted, however, that this study adopted the PCA's approach to design reliability by reducing the concrete strength by a factor based on one coefficient of variation of concrete strength and by using a load safety factor. The variability of many other factors such as slab thickness, foundation support, slab modulus, etc., which may all affect fatigue analysis, was not considered in either the PCA method or the proposed modification procedures. This deficiency and the associated inherent biases in determining fatigue damage should be cautioned and further investigated.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

AGG = aggregate interlock factor (FL^{-2});
a = radius of applied load (L);
$\mathbf{a}_m$ = direction vectors;
$a_m^T x$ = length of projections;
C = curling stress coefficient ($\lambda = W/((8^{0.5})*\ell)$);
D_P = relative deflection stiffness due to external wheel load and loss of subgrade support;
D_γ = relative deflection stiffness due to self-weight of concrete slab;
D_0 = offset distance between outer face of wheel and slab edge (L);
E, E_1 = modulus of top slab (FL^{-2});
E_2 = modulus of bottom slab (FL^{-2});
f_3 = adjustment factor for effect of truck placement on edge stress;
f_4 = adjustment factor for increase in concrete strength with age after 28th day, along with reduction in concrete strength by one coefficient of variation;
h, h_1 = thickness of top slab (L);
h_{eff} = effective thickness of two unbonded layers (L);
h_2 = thickness of bottom slab (L);
k = modulus of subgrade reaction (FL^{-3});
L = length of finite slab (L);
L_1 = nominal axle load of test vehicle, kip;
ℓ = radius of relative stiffness of slab-subgrade system (L);
N_f = maximum allowable number of load repetitions;
n_i = expected number of repetitions;
P = wheel load (F);
q = vertical subgrade stress (FL^{-2});
R_T = adjustment factor for combined effect of loading plus daytime curling;
R_1 = adjustment factor for different gear configurations including dual-wheel, tandem axle, and tridem axle;
R_2, R_{2a} = adjustment factor for finite slab length and width for loading-only condition;
R_{2b} = adjustment factor for finite slab length and width for condition of loading plus curling but $\Delta T = 0$ to allow partial contact between slab-subgrade interface;

R_3 = adjustment factor for tied concrete shoulder;
R_4 = adjustment factor for widened outer lane;
R_5 = adjustment factor for bonded/unbonded second layer;
S_c = concrete modulus of rupture;
s = transverse wheel spacing (L);
t = longitudinal axle spacing (L);
W = width of finite slab (L);
$\mathbf{x}$ = vector of predictor variables;
$\bar{y}$ = expected (or mean) value of response variable;
α = thermal expansion coefficient (T^{-1});
β_m = regression coefficients;
γ = unit weight of concrete slab (FL^{-3});
ΔT = temperature differential through slab thickness (T);
δ = slab deflection (L);
ε = residual or random error;
ε_d = dynamic edge strain ($\times 10^{-6}$);
σ = slab bending stress (FL^{-2});
σ_c = corner stress prediction (FL^{-2});
σ_{ce} = Westergaard/Bradbury's edge curling stress (FL^{-2});
σ_{c0} = Westergaard's interior curling stress for infinite slab (FL^{-2});
σ_e = edge stress prediction (FL^{-2});
σ_{eq} = modified equivalent stress (FL^{-2});
σ_i = interior stress prediction (FL^{-2});
σ_{wc} = Westergaard's closed-form corner stress solution (FL^{-2});
σ_{we} = Westergaard's closed-form edge stress solution (FL^{-2});
σ_{wi} = Westergaard's closed-form interior stress solution (FL^{-2}); and
$\phi_m(a_m^T x)$ = nonparametric transformation functions of projected lengths $a_m^T x$.