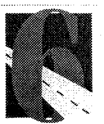
Sixth Int'l Purdue Conference on Concrete Pavement

DEVELOPMENT OF NEW STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURES FOR JOINTED CONCRETE PAVEMENTS



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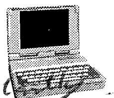
J. H. Bair, Y. M. Lee
Tamkang University
Taiwan, R.O.C.

#2

OBJECTIVES



- Develop an Alternative Stress Estimation Procedure to inst[illegible]
- Validate ILLI-SLAB Program's Applicability
- Modify PCA Stress Analysis & Thickness Design Procedure
- Develop a User-friendly TKUPAV Program for Automatic Stress Calc. & Thickness Design
- Applicable to Metric & English Systems

4. Incorporate
— Dimensional [illegible]
— F.E Runs
— Prediction eq.

1. This study focused. on
2. The well-known ILLI-SLAB was used.
3. The Program's applicability — reproducing favorable agreements to AASHO. Arlington Taiwan's second northern highway.

RESEARCH APPROACH

- Westergaard's Closed-Form Solutions
- Effects of Curling & Warping
- ILLI-SLAB Solutions and Its Applicability
- Identification of Mechanistic Variables
- Development of Stress Prediction Models
- Modified PCA Stress Analysis and Thickness Design Procedure
- Development & Verification of TKUPAV Program

CLOSED-FORM SOLUTIONS / ILLI-SLAB F. E. MODEL

- Westergaard/Bradbury
  - Loading Only
  - Thermal Curling
  - Loading Plus Curling
- ILLI-SLAB F. E. Model
  - Dimensional Analysis
  - Identification of Mechanistic Variables

#4

#5

EFFECTS OF CURLING & WARPING

day-time

- Thermal Curling Stress
  (Positive ΔT => Additional Stress)

- Moisture Warping Stress
  (Negative ΔM => Stress Reduction)
  (But Not Easy to Measure)
- Suggest to Include the Effect of Positive ΔT

ILLI-SLAB Program

- Originally Developed by Tabatabaie, 1977
- Continuously Revised by Wong, Conroyd, Ioannides, 1980-1985
- Included Curling Analysis by Korovesis, 1986-1989
- Re-Compiled by Lee, 1995
  (Microsoft FORTRAN PowerStation)

DEVELOPMENT OF NEW STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURES FOR JOINTED CONCRETE PAVEMENTS

Ying-Haur Lee[1], Shao-Tang Yen, Chao-Tsung Lee, Jean-Hwa Bair, and Ying-Ming Lee

ABSTRACT

Slide #2

This study focused on the development of an alternative stress estimation procedure to instantly calculate the critical stresses of jointed concrete pavements. Thus, the primary components for stress analysis including gear configurations, total wheel load, tire pressure, a widened outer lane, a tied concrete shoulder, and thermal curling due to a linear temperature differential have to be considered. The well-known ILLI-SLAB finite element program was used for the analysis. The program's applicability for stress estimation was further validated by reproducing very favorable results to the test sections of the Taiwan's second northern highway, the AASHO Road Test, and the Arlington Road Test. With the incorporation of the principles of dimensional analysis and experimental design, a series of finite element factorial runs over a wide range of pavement designs was carefully selected and conducted. Consequently, prediction equations for stress adjustments were developed using a modern regression technique (Projection Pursuit Regression). Subsequently, a simplified stress analysis procedure was proposed and implemented in a user-friendly computer program (TKUPAV) to facilitate instant stress estimations. Together with PCA's cumulative fatigue damage equation, a modified PCA stress analysis and thickness design procedure was also proposed and incorporated into the TKUPAV program. This computer program will not only instantly perform critical stress calculations, but it may also be utilized for various structural analyses and designs of jointed concrete pavements.

INTRODUCTION

Slide #4

Traditionally, the 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, a second bonded or unbonded layer may result in very different stress responses from the Westergaard's solutions. These effects may be more accurately and realistically accounted through the use of a finite element (F.E.) computer

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program. Nevertheless, the difficulties of the required run time, the complexity of F.E. analysis, and the possibility of obtaining incorrect results due to the improper use of the F.E. model often prevent it from being used in practical pavement design. Thus, the main objectives of this study were to develop an alternative procedure to more conveniently calculate the critical stresses of jointed concrete pavements with sufficient accuracy for design purposes [1].

In addition, 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. Thus, a review of the most widely-adopted PCA design procedure was first conducted. Based on Westergaard's closed-form edge stress solution and several prediction models for stress adjustments for a variety of loading and environmental conditions, a modified PCA equivalent stress calculation and thickness design procedure was proposed and implemented in a highly user-friendly, window-based TKUPAV program for practical trial applications.

WESTERGAARD'S CLOSED-FORM SOLUTIONS

In the analysis of a slab-on-grade pavement system, Westergaard has presented closed-form solutions for three primary structural response variables, i.e., slab bending stress, slab deflection, and subgrade stress, due to a single wheel load based on medium-thick plate theory and the assumptions of an infinite or semi-infinite slab over a dense liquid (Winkler) foundation [2]. In addition, Westergaard has also developed equations for curling stresses caused by a linear temperature differential between the top and the bottom of the slab [3, 4]. Nevertheless, there exists no explicit closed-form solutions to account for the combination effect of loading plus curling on a concrete slab.

EFFECTS OF CURLING AND WARPING

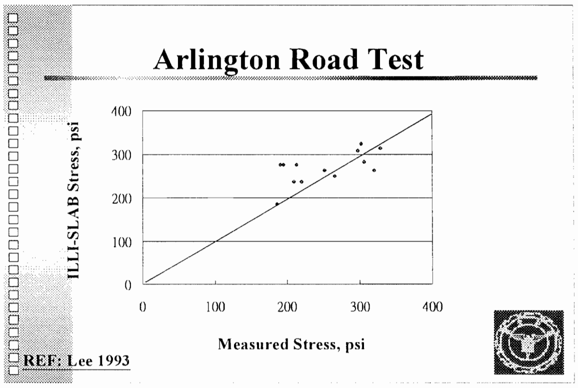
Whether curling and warping stresses should be considered in concrete pavement thickness
11.5 design is quite controversial. The temperature differential through the slab thickness and the self-weight of the slab induces additional thermal curling stresses. For day-time curling condition, compressive curling stresses are induced at the top of the slab whereas tensile stresses occur at the bottom; or vice versa for night-time curling condition. The moisture gradient in concrete slabs also results in additional warping stresses. Since higher moisture content is generally at the bottom of the slab, compressive and tensile stresses will occur at the bottom and at the top of the slab, respectively. A totally different situation will happen if the moisture content at the top of the slab is higher than that at the bottom right after raining.

Even though the effects of thermal curling and moisture warping have been discussed in the PCA design guide, curling stresses were not considered in the fatigue analysis due to the compensative effect of most heavy trucks driving at night and only quite limited number of day-time curling combined with load repetitions. Furthermore, since moisture gradient highly depends on a variety of factors such as the ambient relative humidity at the slab surface, free water in the slab, and the moisture content of the subbase or subgrade, which are very difficult to measure accurately, thus it was also ignored in the PCA's fatigue analysis [5].

To further investigate the applicability of ILLI-SLAB for stress.

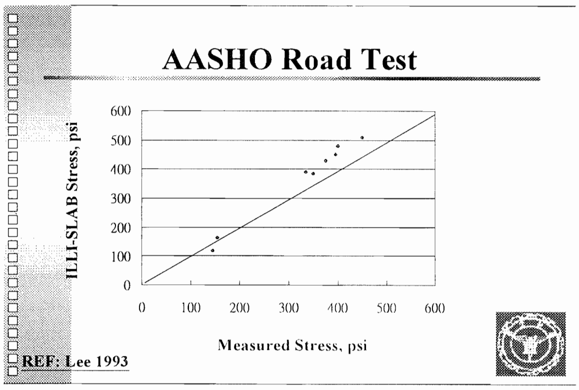
RESULTS OF ACTUAL FIELD MEASUREMENTS

- Arlington Road Test
  - Edge Stress (Curling Only)
- AASHO Road Test
  - Edge Stress (Loading + Curling)
- Taiwan's Second Northern Highway
  - Corner Stress (Loading + Curling)
- Compared to ILLI-SLAB Results
- Validated Its Applicability



Arlington Road Test

REF: Lee 1993



AASHO Road Test

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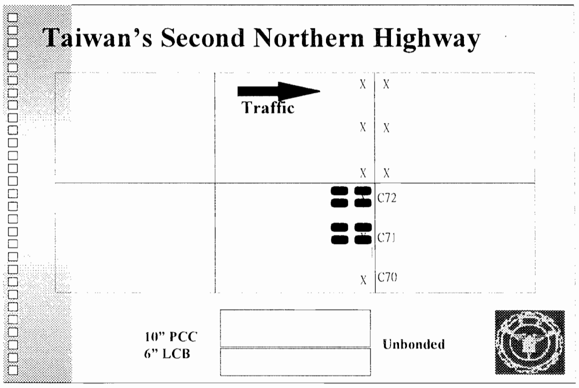
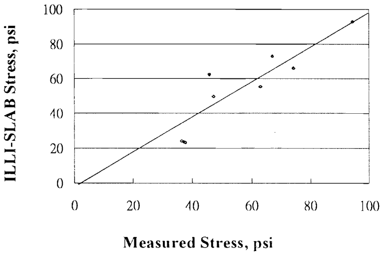


Taiwan's Second Northern Highway

1993-94

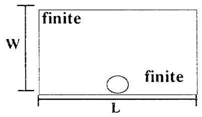
Taiwan's Second Northern Highway



As we mentioned before, slide #16

Identification of Mechanistic Variables (Loading Only)

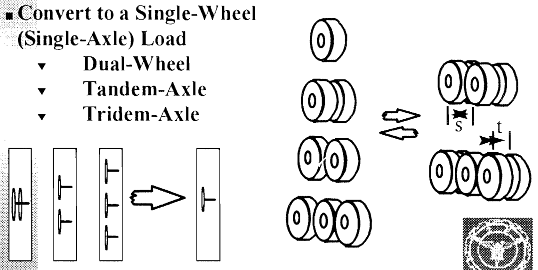
$$\frac{\sigma h^2}{P}, \frac{\delta k\ell^2}{P}, \frac{q\ell^2}{P} = f\left(\frac{a}{\ell}, \frac{L}{\ell}, \frac{W}{\ell}, \frac{s}{\ell}, \frac{t}{\ell}, \frac{D_0}{\ell}, \frac{AGG}{k\ell}, \left(\frac{h_{efft}}{h_1}\right)^2\right)$$



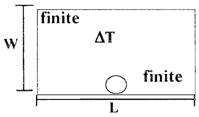
~~To account for these~~ effects, the ~~following relationship~~ :

Effect of Wheel and Axle Spacing

- Convert to a Single-Wheel (Single-Axle) Load
  - Dual-Wheel
  - Tandem-Axle
  - Tridem-Axle



Identification of Mechanistic Variables (Loading + Curling)



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 13 in. The resulting ILLI-SLAB loading stresses were compared to the measured ones and were shown in Figure 2 (a). Apparently, fairly good agreement was observed, especially for a k value of 150 pci, which is very close to the in-field subgrade modulus of about 130 pci under the Road Test condition.

In addition, for a 6.5-in. pavement slab under standard temperature differentials of -10, 10, 15, and 20 °F and k values of 100 and 150 pci, Lee [*13*] has also demonstrated that fairly good agreement was achieved under loading plus curling condition. The coefficient of thermal expansion was assumed to be 5.0 E-06 /°F and the self weight of the slab was 0.087 pci. The results of this comparison were shown in Figure 2 (b). Also note that the resulting ILLI-SLAB edge stresses were slightly higher than the estimated actual stress measurements.

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 [*13, 14*]. The pertinent input parameters were: E=5.0 E+06 psi, k=200 pci, L=20 ft, W=10 ft, α=4.8 E-06 /°F. The measured curling stresses and the resulting ILLI-SLAB stresses for a slab thickness of 6 in. and 9 in. were summarized as follows and were also plotted in Figure 3: (Note: 1 in. = 2.54 cm, 1 psi = 0.07 kg/cm^2, 1 pci = 0.028 kg/cm^3, 1 kip = 454 kg, 1 °F = 5/9 °C)

h = 6 in.			h = 9 in.		
ΔT (°F)	Measured (psi)	ILLI-SLAB (psi)	ΔT (°F)	Measured (psi)	ILLI-SLAB (psi)
18	220	238	25	191	276
14	186	186	30	298	308
21	195	276	26	306	283
18	209	238	33	302	324
20	252	263	31	329	313
20	320	263	25	213	276
19	266	250	---	---	---

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 Road Test data obtained.

IDENTIFICATION OF MECHANISTIC VARIABLES

Slide #16

Westergaard's closed-form solutions were based on ideal assumptions of an infinite or semi-infinite slab size, full contact between the slab-subgrade interface, and a single loaded area. In reality, jointed concrete pavements consist of many single finite concrete slabs jointed by aggregate interlock, dowel bars, or tie bars. As shown in Figure 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, a second bonded or unbonded layer may also result in different degrees of stress reductions. To account for these effects under loading only condition, the following relationship has been identified through many intensive F.E. studies for a constant Poisson's ratio (usually $\mu \approx 0.15$) [*1*, *13*]:

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

Where σ, q are slab bending stress and vertical subgrade stress, respectively, $[FL^{-2}]$; δ is the slab deflection, [L]; P = wheel load, [F]; h = thickness of the slab, [L]; a = the radius of the applied load, [L]; $\ell=(E*h^3/(12*(1-\mu^2)*K))^{0.25}$ is the radius of relative stiffness of the slab-subgrade system [L]; k = modulus of subgrade reaction, $[FL^{-3}]$; L, W = length and width of the finite slab, [L]; 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, $[FL^{-2}]$; hefft = $(h_1^2 + h_2^2 * (E_2*h_2)/(E_1*h_1))^{0.5}$ is the effective thickness of two unbonded layers, [L]; h_1 , h_2 = thickness of the top slab, and the bottom slab, [L]; and E_1 , E_2 = concrete modulus of the top slab, and the bottom slab, $[FL^{-2}]$. Note that variables in both sides of the expression are all dimensionless and primary dimensions are represented by [F] for force and [L] for length.

Since no thermal curling effect was considered in the above relationship, the full contact assumption between the slab-subgrade interface and the principle of superposition may be applied to the analyses. Thus, the above relationship can be broken down to a series of simple analyses for each individual effect. The adjustment factors can be separately developed to account for the effect of stress reduction due to each different loading condition.

Furthermore, the following concise relationship has been identified by Lee and Darter [*15*] for the effects of loading plus thermal curling:

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

Where E is the slab modulus, $[FL^{-2}]$; α is the thermal expansion coefficient, $[T^{-1}]$; ΔT is the temperature differential through the slab thickness, [T]; γ is the unit weight of the concrete slab, $[FL^{-3}]$; $D_\gamma=\gamma*h^2/(k*\ell^2)$; and $D_P=P*h/(k*\ell^4)$. 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

A series of F. E. factorial runs were performed based on the dominating mechanistic variables (dimensionless) identified. Several BASIC programs were written to automatically

DEVELOPMENT OF STRESS PREDICTION MODELS

- Factorial F.E. Runs Based on the Dimensionless Mechanistic Variables
- Two-Step Modeling Approach
  - Projection Pursuit Regression (PPR)
  - Piece-wise Linear Regression
- S-PLUS Statistical Package
- Lee & Darter (TRR 1449)

BASIC program

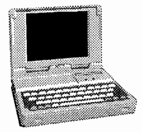
Proposed Stress Prediction Models (Edge, Corner, Interior)

$$\sigma_{cr} = \sigma_W \cdot R_1 \cdot R_2 \cdot R_3 \cdot R_4 \cdot R_5 + R_T \cdot \sigma_c$$

$$\sigma_W = \frac{P}{h^2} \times f_1\left(\frac{a}{\ell}\right)$$

$$\sigma_c = \frac{1}{2} E\alpha\Delta T \times f_2\left(\frac{W}{\ell}\right)$$

$R_1 \sim R_5, R_T$ = Prediction Models



Slide #22

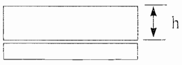
MODIFIED PCA STRESS ANALYSIS & THICKNESS DESIGN PROCEDURES

- Review PCA Thickness Design Procedure
  - Equivalent Stress Calculation
  - Fatigue Analysis
- PCA's Simplifications and Limitations
- Modified Equivalent Stress Calculation
- Modified PCA Fatigue Analysis & Thickness Design Procedures

(July 97) TRR

PCA THICKNESS DESIGN

- J-SLAB Program (Edge Stress)
- Equivalent Stress Calculations
- Fatigue Analysis (& Erosion Analysis)
- But Did NOT Consider Curling Stress
- PCAPAV Program



$$D_r = \sum_{i=1}^{m} \frac{n_i}{N_i}$$

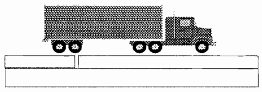
—PCA most well-known

PCA's Equivalent Stress Calculation

$$\sigma_{eq} = \frac{6M_e}{h^2} \bullet f_1 \bullet f_2 \bullet f_3 \bullet f_4$$

$Me = f(\ell, k)$ (in English System)

SA/NS , TA/NS , SA/WS , TA/WS



PCA's Fatigue Analysis

The proposed prediction models for interior stress adjustments are given in Table 3. Also Note that the effect of a tied concrete shoulder and a widened outer lane may be neglected in interior stress analysis or in other words $R_3 = R_4 = 1$. More detailed descriptions of the development process can be found in Reference [*1*].

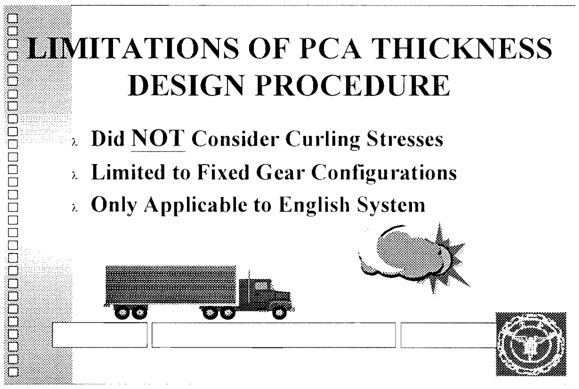
MODIFIED PCA STRESS ANALYSIS AND THICKNESS DESIGN PROCEDURE

Slide #22

The Portland Cement Association'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 [*5*]. Based on the results of J-SLAB [*22*] finite element (F.E.) analysis, the PCA method uses design tables and charts and a PCAPAV personal computer program to determine the minimum slab thickness required to satisfy the following design factors: design period, the flexural strength of concrete (or the concrete modulus of rupture), the modulus of subbase-subgrade reaction, design traffic (including load safety factor, axle load distribution), with or without doweled joints and a tied concrete shoulder [*23*]. The PCA thickness design criteria are to limit the number of load repetitions based on both fatigue analysis and erosion analysis. Cumulative damage concept is used for the fatigue analysis to prevent the first crack initiation due to critical edge stresses, whereas the principal consideration of erosion analysis is to prevent pavement failures such as pumping, erosion of foundation, and joint faulting due to critical corner deflections during the design period. Since the main focus of this study was to develop an alternative stress analysis procedure for thickness design of concrete pavements, the erosion analysis was not within the scope of this study.

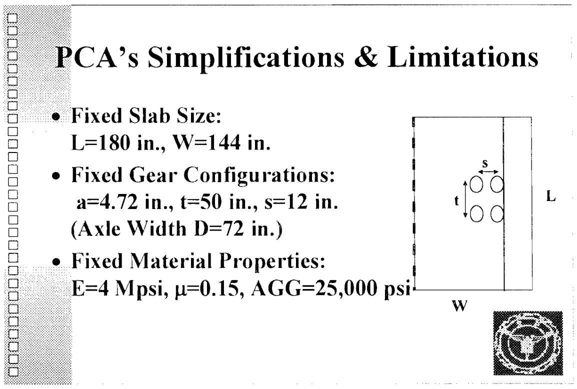
Equivalent Stress Calculations

In the PCA thickness design procedure, the determination of equivalent stress is based on the resulting maximum edge bending stress of J-SLAB F.E. analysis under a single axle (SA) load and a tandem axle (TA) load for different levels of slab thickness and modulus of subgrade reaction. The basic input parameters were assumed as: slab modulus $E = 4$ Mpsi, Poisson's ratio $\mu = 0.15$, finite slab length $L = 180$ in., finite slab width $W = 144$ in. A standard 18-kip single axle load (dual wheels) with each wheel load equal to 4,500 lbs, wheel contact area = $7*10$ in.^{2} (or an equivalent load radius $a = 4.72$ in.), wheel spacing $s = 12$ in., axle width (distance between the center of dual wheels) $D = 72$ in. was used for the analysis, whereas a standard 36-kip tandem axle load (dual wheels) with axle spacing $t = 50$ in. and remaining gear configurations same as the standard single axle was also used. If a tied concrete shoulder (WS) was present, the aggregate interlock factor was assumed as AGG = 25000 psi. PCA also incorporated "the results of computer program MATS, developed for analysis and design of mat foundations, combined footings and slabs-on-grade" to account for the support provided by the subgrade extending beyond the slab edges for a slab with no concrete shoulder (NS). Together with several other adjustment factors, the equivalent stress was defined as follows: [*24*]



LIMITATIONS OF PCA THICKNESS DESIGN PROCEDURE

- Did <u>NOT</u> Consider Curling Stresses
- Limited to Fixed Gear Configurations
- Only Applicable to English System



PCA's Simplifications & Limitations

- **Fixed Slab Size:**
  L=180 in., W=144 in.
- **Fixed Gear Configurations:**
  a=4.72 in., t=50 in., s=12 in.
  (Axle Width D=72 in.)
- **Fixed Material Properties:**
  E=4 Mpsi, μ=0.15, AGG=25,000 psi

Modified Equivalent Stress Calculation (I)

Modified Equivalent Stress Calculation (II)

$$\sigma_w = \frac{P}{h^2} \times f_1\left(\frac{a}{\ell}\right)$$

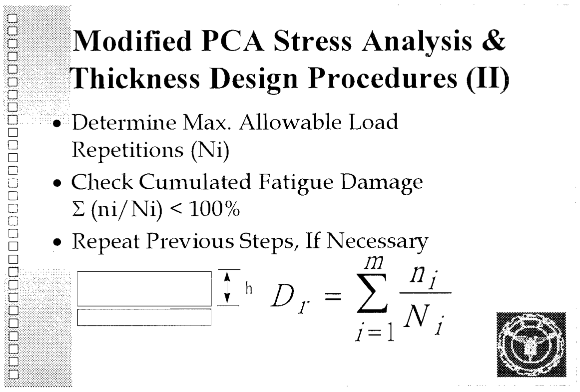
$$\sigma_c = \frac{1}{2} E\alpha\Delta T \times f_2\left(\frac{W}{\ell}\right)$$

$R_1 \sim R_5$, R_T = Prediction Models

Tables 1 ~ 3

Modified PCA Stress Analysis & Thickness Design Procedures (I)

- Calculate Expected Load Repetitions (ni)
- Calculate Modified Equivalent Stress (σ_{eq})
  $\sigma_{eq} = \sigma_{cr} * f_3 * f_4$
  - Loading Only
  - Loading + Curling ($\Delta T>0$)
- Calculate Stress Ratio (σ_{eq} /Sc)



Modified PCA Stress Analysis & Thickness Design Procedures (II)

- Determine Max. Allowable Load Repetitions (Ni)
- Check Cumulated Fatigue Damage
  Σ (ni/Ni) < 100%
- Repeat Previous Steps, If Necessary

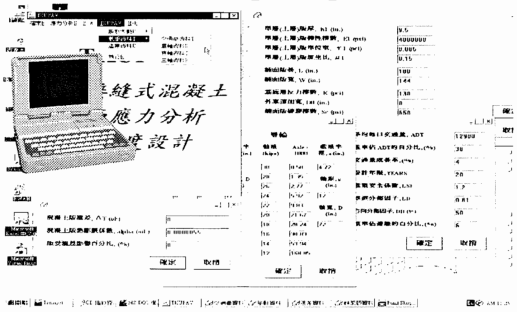
$$D_r = \sum_{i=1}^{m} \frac{n_i}{N_i}$$

To facilitate practical trial application of the proposed.—

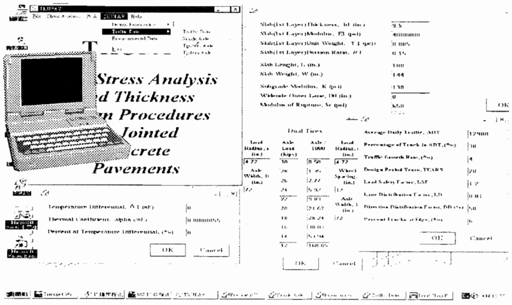
DEVELOPMENT OF TKUPAV PROGRAM

- Using Visual Basic Program (Ver. 4.0)
- Highly User-Friendly Interfaces
- Basic Features of TKUPAV Program
  - Different Slab Size, Axle Configurations, Material Properties, Temperature Differentials
  - Metric and English Systems
  - English & Chinese Versions

TKUPAV Example Input Screens



TKUPAV Example Input Screens



Slab(1st Layer)Thickness, h1 (in.) 9.5
Slab(1st Layer)Modulus, E1 (psi) 4000000
Slab(1st Layer)Unit Weight, γ1 (pci) 0.085
Slab(1st Layer)Poisson Ratio, μ1 0.15
Slab Lenght, L (in.) 180
Slab Weight, W (in.) 144
Subgrade Modulus, K (pci) 130
Widende Outer Lane, D0 (in.) 0
Modulus of Rupture, Sc (psi) 650

Dual Tires

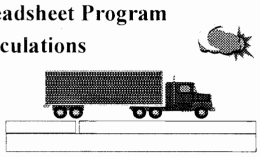
Load Radius, a (in.)	Axle Load (kips)	Axle / 1000	Load Radius, a (in.)
4.72	30	0.50	4.72
Axle Width, D (in.)	28	[illegible]	Wheel Spacing, (in.)
	26	2.77	
72	24	[illegible]	12
	22	[illegible]	Axle Width, D (in.)
	20	21.62	
	18	26.24	72
	16	[illegible]	
	14	[illegible]	
	12	[illegible]	

Average Daily Traffic, ADT 12900
Percentage of Truck in ADT,(%) 10
Traffic Growth Rate,(%) 4
Design Period Years, YEARS 20
Load Safety Factor, LSF 1.2
Lane Distribution Factor, LD 0.81
Direction Distribution Factor, DD (%) 50
Percent Trucks at Edge, (%) 6

Temperature Differential, ΔT (oF) 0
Thermal Coefficient, alpha (/oF) 0.0000055
Percent of Temperature Differential, (%) 0

TKUPAV PROGRAM VALIDATION

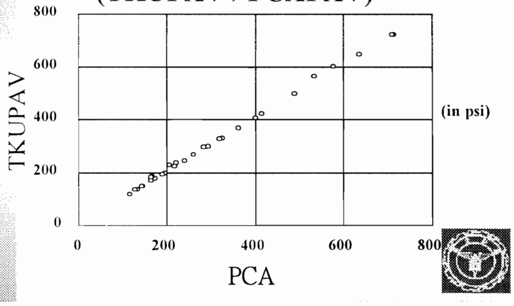
- Comparing the Results of PCAPAV, TKUPAV, and a Spreadsheet Program
- Equivalent Stress Calculations
  - TKUPAV / PCAPAV
- Fatigue Analysis
  - Loading Only
  - Loading + Day-time Curling



A Case Study for Validation

Basic Assumptions: Same as PCA Method

Comparison of Equivalent Stress (TKUPAV / PCAPAV)



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Fatigue Analysis for Loading Only

Fatigue Analysis for Loading + Day-time Curling

slide #39

the proposed

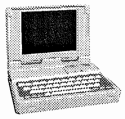
DISCUSSIONS

- Followed Similar Approach Adopted by NCHRP 1-26 Project
  - ILLI-CONC Program for Edge Stress Only
- Resolved the Dimensional Analysis Issue for Loading + Curling Condition
- Provided More Complete Treatment
  - Edge, Corner, and Interior Stress Analysis
- ESAR Concept Was Replaced by Stress Reduction Adjustment Factors (R's =0~1)

CONCLUSIONS AND RECOMMENDATIONS (I)

- Validated ILLI-SLAB's Applicability
- Developed an Alternative Procedure for Critical Stress Estimation
  - Edge, Corner, & Interior L+C Stress
- Modified PCA's Equivalent Stress Calculation & Fatigue Analysis
- Developed a Highly User-Friendly TKUPAV Program

CONCLUSIONS AND RECOMMENDATIONS (II)



- Expanded PCA Thickness Design for:
  - Different Slab Size, Axle Configurations, Material Properties, Temperature Differentials
  - Metric and English Systems
- Validated the TKUPAV Program
- Illustrated the Effect of Loading + Curling Should be Considered
- Further Verifications & Trial Applications

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  - NSC85-2211-E032-010

cumulative fatigue damage calculated by the TKUPAV program is very close to that determined by the PCAPAV program (63.4%). Apparently, very good agreement to the equivalent stress and fatigue damage calculations was obtained.

(2) TKUPAV Fatigue Analysis Example (Loading Plus Curling):

Now if we assume a very small portion (10%) of the load repetitions was affected by day-time curling, and $\Delta T = 20$ °F, $\alpha = 5.5E\text{-}06$ /°F, $\gamma = 0.087$ pci. Thus, $\alpha\Delta T = 0.00011$, $W/\ell = 3.873$, $L/\ell = 4.648$, $a/\ell = 0.1219$, $DG = 4.0274$, $\lambda = 1.370$, and $\sigma_c = 88.5$ psi. The results of this example are summarized in Table 5. The possible detrimental effect of loading plus day-time curling has been clearly observed by the fact that a total of 64.2% fatigue damage was caused by 90% of load repetitions, whereas a total 138.84% of fatigue damage could be induced by only 10% of loading plus curling. In this case, an additional 1/2 inch of slab thickness which may reduce the total cumulative fatigue damage from 203.0% to an acceptable level of 41.3% is required.

DISCUSSIONS

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The proposed stress analysis procedures follow similar approach adopted by the NCHRP 1-26 report [7]. The ILLI-CONC program completed at the University of Illinois in 1992 can be used to calculate the slab edge stress for different axle load configurations. Nevertheless, "to estimate the combined stress due to load and temperature curling, some problems were encountered in analyzing the data using dimensional analysis" [7]. This study enhanced the approach by resolving the dimensional analysis issue as well as providing a more complete treatment of the stress analysis of three loading conditions, i.e., interior, edge, and corner. In addition, the Equivalent Single Axle Radius (ESAR) concept was replaced by stress reduction adjustment factors (R's), ranging from 0 to 1, to satisfy tentative boundary conditions in stress estimation. Since all the mechanistic variables used in the proposed models are dimensionally correct, both English and metric (SI) systems can be used by the TKUPAV program.

This study also 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. Thus, this deficiency and the associated inherent biases in determining fatigue damage should be cautioned and further investigated.

CONCLUSIONS AND RECOMMENDATIONS

An alternative procedure for the determination of the critical stresses of jointed concrete pavements was developed under this study. The effects of a finite slab size, different gear configurations, a widened outer lane, a tied concrete shoulder, a second bonded or unbonded layer, and thermal curling due to a linear temperature differential were considered. The ILLI-SLAB program's applicability for stress estimation was further validated by reproducing very