PRESTRESSED PAVEMENT
VOL. 2, THICKNESS DESIGN

Research, Development, and Technology

Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101

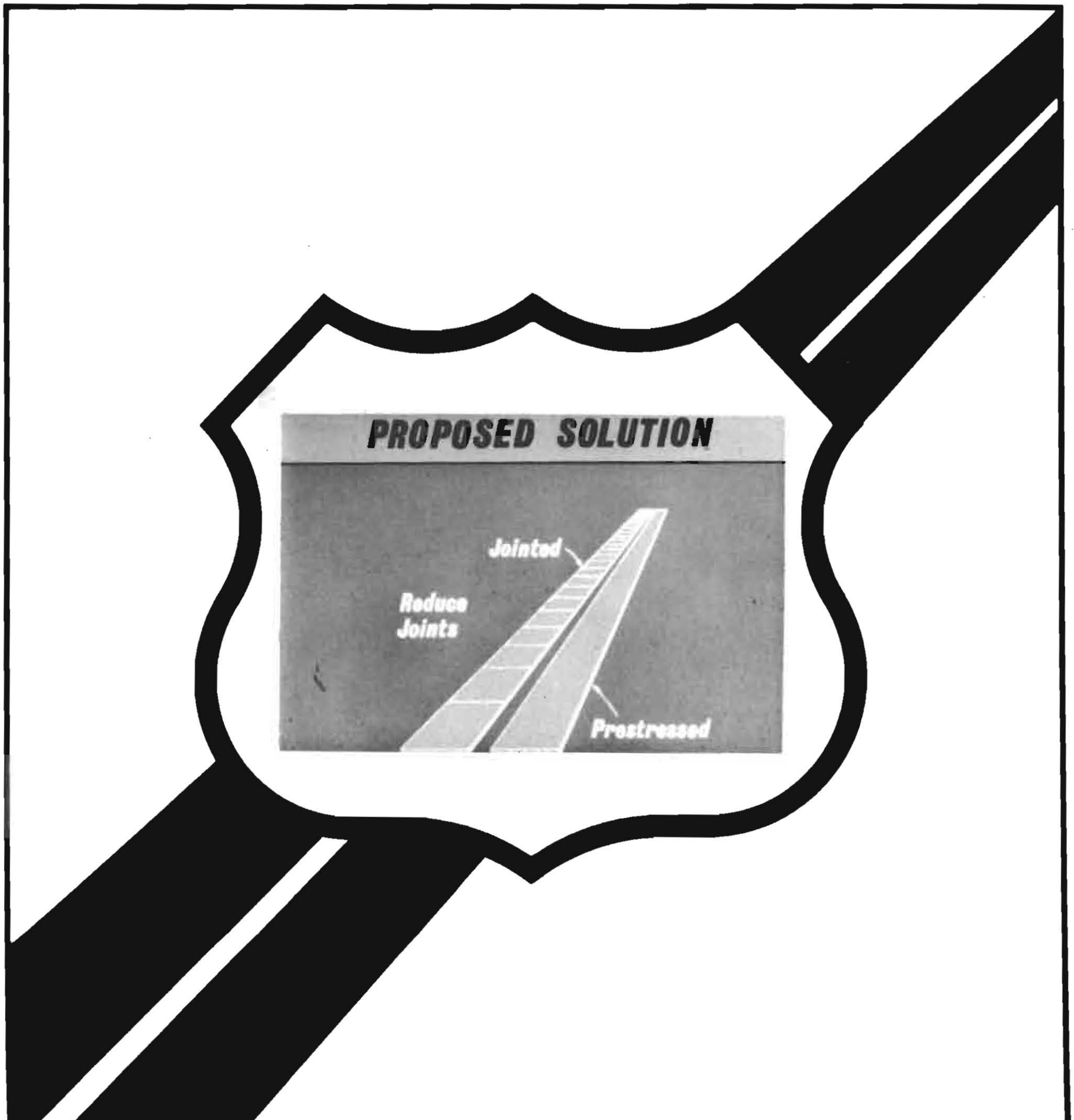
Report No.
FHWA/RD-82/091

U.S. Department of Transportation

Federal Highway Administration

Final Report

June 1983



FOREWORD

Highway administrators and engineers must select among alternative pavement investment and maintenance strategies. These decisions should be based upon economic analyses of the impacts expected for each pavement management strategy. Prestressed pavements offer an alternative type of strategy because of thinner slabs, fewer joints, and an expected reduction in maintenance costs.

In Volume 2, a computerized procedure for thickness design of prestressed pavements is presented. The other volumes are:

FHWA/RD-82/090, Volume 1, "Joint Designs"
FHWA/RD-82/092, Volume 3, "Construction Manual"
FHWA/RD-82/115, Volume 4, "Prestressed Pavement Accelerated Testing Program" (available only from NTIS)
FHWA/RD-82/114, Volume 5, "Evaluation of Innovative Concepts Relating to Prestressed Concrete Pavements" (available only from NTIS).

Richard E. Hay
Richard E. Hay, Director
Office of Engineering
and Highway Operations
Research and Development

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/RD-82/091		

4. Title and Subtitle	5. Report Date
Prestressed Pavement Thickness Design, Volume 2	June 1983
	6. Performing Organization Code
7. Author(s) Shiraz D. Tayabji, Bert E. Colley, and Peter J. Nussbaum	8. Performing Organization Report No.
9. Performing Organization Name and Address Portland Cement Association Research & Development Construction Technology Laboratories 5420 Old Orchard Rd., Skokie, IL 60077	10. Work Unit No. (TRAIS) FCP 35E3-032 11. Contract or Grant No. DOT-FH-11-8894
12. Sponsoring Agency Name and Address Federal Highway Administration Offices of Research and Development Washington, DC 20590	13. Type of Report and Period Covered Final Report 2-76 to 11-82 14. Sponsoring Agency Code

15. Supplementary Notes

Contract Manager: William J. Kenis, HNR-20 (HRS-14)
(T. F. McMahon, retired)

16. Abstract

A computerized procedure for the thickness design of "zero-maintenance" prestressed pavements is presented. Factors considered in developing the design procedure include traffic loading, temperature and moisture variations in concrete slab, loss of subbase support, properties of concrete, subbase and subgrade, and effective mid-slab prestress. The procedure is based on flexural stress analysis and prevention of bottom transverse cracking that may initiate from the longitudinal edge of the slab in the vicinity of mid-slab.

Input for the computer program include axle load distribution, wheel placement, traffic distribution during the day, temperature data, load transfer effectiveness, and effective prestress at mid-slab. Program output is in terms of total fatigue consumption at the end of design life. If the fatigue consumption is less than 100 percent, then the thickness meets design criteria.

A design example is presented for a rural four-lane highway in Illinois.

17. Key Words	18. Distribution Statement
concrete, concrete pavements, pavement design, prestressed pavements, temperature stresses, warping stresses	This document is available from the National Technical Information Service, Springfield, VA, 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	43	

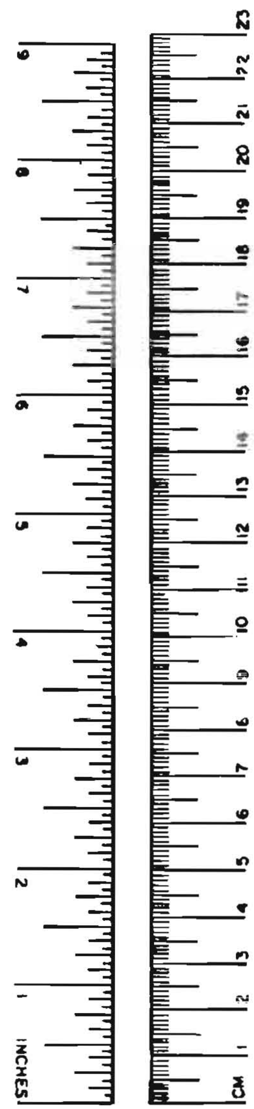
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

☆ U. S. GOVERNMENT PRINTING OFFICE : 1973 725-504/329

METRIC CONVERSION FACTORS

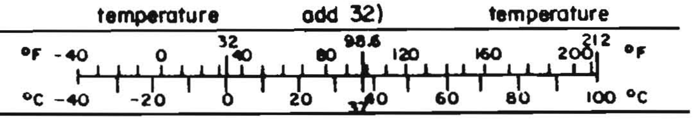
APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.6	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS FROM METRIC MEASURES

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	8.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This report has been prepared as part of a contract between FHWA and the Construction Technology Laboratories, Division of the Portland Cement Association.

It is the second of a five-volume series concerning design of prestressed concrete pavements. The series consists of the following reports.

1. Prestressed Pavement Joint Designs
2. Prestressed Pavement Thickness Design
3. Prestressed Pavement Construction Manual
4. Prestressed Pavement Accelerated Testing Program
5. Evaluation of Innovative Concepts Relating to Prestressed Concrete Pavements

LIST OF TABLES

LIST OF FIGURES

TABLE OF CONTENTS

INTRODUCTION

The objective of Federal Highway Administration's Research Project 5E, Premium Pavements for "Zero Maintenance" is to exploit modern materials and technology in developing "Zero Maintenance" pavements for warranted use.

As a portion of this research project, an investigation has been conducted by the Construction Technology Laboratories, a Division of the Portland Cement Association, to develop design and construction techniques for prestressed concrete pavements. This work will be co-presented in reports covering the following:

(1) Transverse joint design
(2) Thickness design procedure
(3) Construction techniques
(4) Accelerated testing program
(5) Laboratory studies

Conventional concrete pavements are designed on the basis of concrete's relatively low modulus of rupture without effectively utilizing the natural advantage of its high compressive strength. In prestressed pavements, precompression in the concrete due to prestressing increases the allowable stress in the flexural zone. This permits a reduction or elimination of cracking and a large decrease in the number of transverse joints. Consequently, a more comfortable riding surface, and a reduction in maintenance costs results.

Prestressed pavement design includes determination of required pavement thickness and joint hardware selection based on anticipated slab movement and length. Figure 1 shows the basic steps involved in prestressed pavement design.

As shown in Figure 1, the design process is iterative and involves interaction of many factors. The process starts with selection of an initial slab thickness. Then, under joint design, trial main slab length and prestress tendon size, spacing, and force are selected. Effective mid-slab prestress is computed. A minimum of about 50 psi mid-slab prestress should

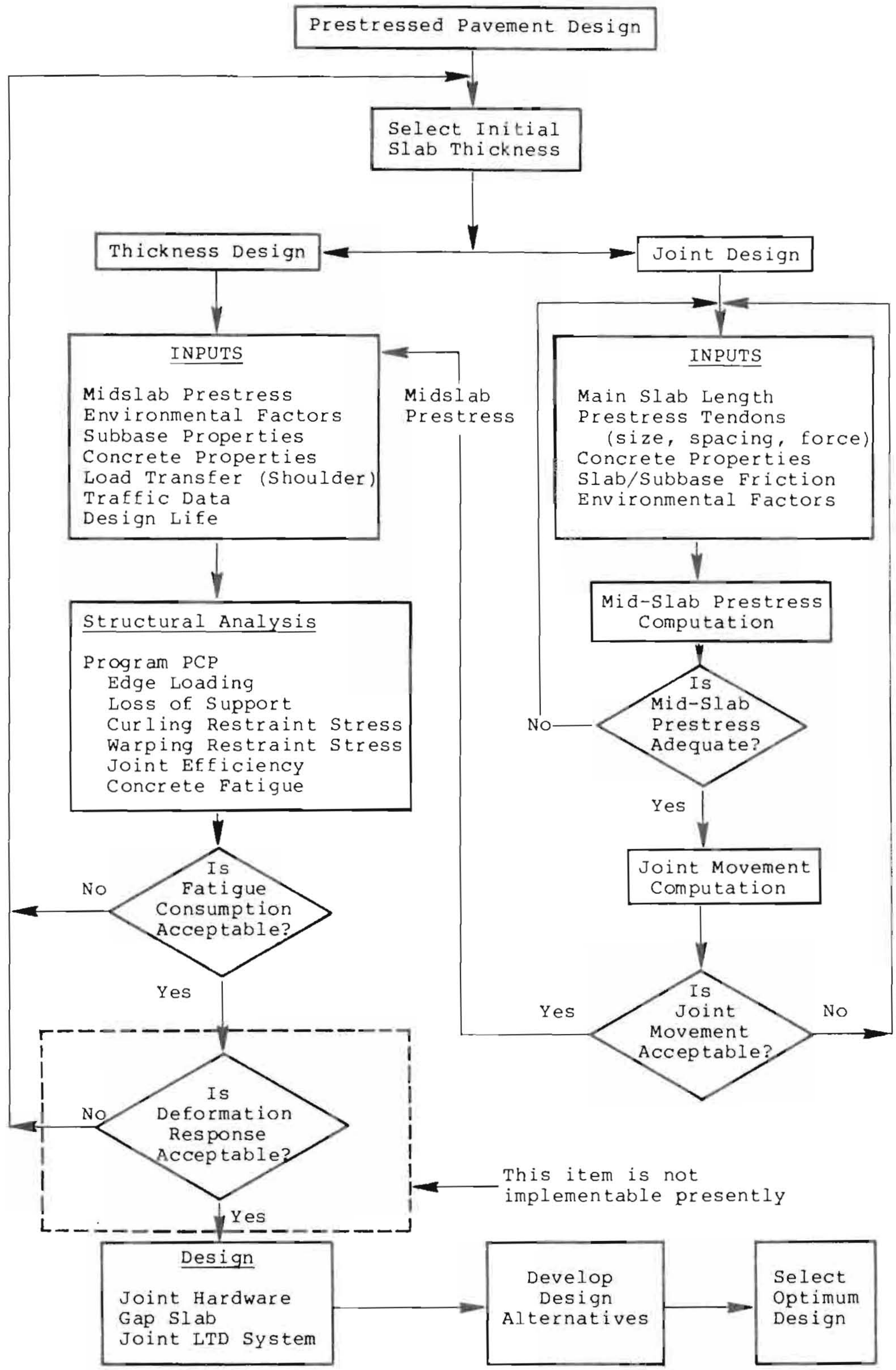


Figure 1 - Prestressed Pavement Design Process

be obtained. If not obtained, slab length, tendon size, spacing, or force is varied until the desired mid-slab prestress is obtained.

Once the mid-slab prestress criteria is met, anticipated maximum joint movement is computed. The selection of an infiltration prevention device such as a strip seal, compression seal, or steel cover plate depends on the magnitude of joint movement. Slab length is varied until the computed joint movement can be accommodated by the device selected. At this time a decision is made regarding use of a single active joint or two active joints between adjacent main slabs.

After an acceptable slab length, midslab prestress level, and joint hardware arrangement are established, a structural analysis is performed. The analysis requires the value of effective mid-slab prestress as an input. Alternatively, a minimum level of mid-slab prestress value may be assumed in the structural analysis. The structural analysis computes fatigue consumption due to edge stresses at mid-slab. If fatigue consumption is more than 100 percent, the design process is repeated using a larger slab thickness.

This report presents a thickness design procedure for prestressed concrete pavements. Factors considered in developing the procedure include traffic loading, temperature and moisture variations in concrete slab, loss of subbase support, properties of concrete, subbase and subgrade, and effective mid-slab prestress.

DESIGN PROCEDURE

A computerized program for thickness design of prestressed pavements is presented. Required pavement thickness is a function of stresses resulting from traffic loads, temperature and moisture variations, loss of subbase support, and mid-slab effective prestress. Summation of these stresses is balanced against fatigue consumed to obtain a pavement designed to resist bottom flexural cracking.

An acceptable criterion for design based on deflection is not available. Therefore, deflections are not computed. However, it is recognized that prestressed concrete pavements are thinner than conventional concrete pavements. For this reason, it is recommended that high quality stabilized subbases be specified for use with prestressed pavements.

Procedures used for computing stresses and decisions regarding inputs are discussed. A program users manual and program listing are presented in the Appendix.

Traffic Load Stresses

A finite element computer program for analysis of slabs on a Winkler (liquid) foundation was used to compute moments for the case of edge loading. These moments expressed as a function of the radius of relative stiffness (ℓ) are stored in this computer program. They are used together with a coefficient to determine edge stresses resulting from loads located at or inward from the pavement edge. The program also considers optional use of a tied concrete shoulder with a variable input for load transfer efficiency at the longitudinal joint.

Slab width is 12 ft (3.66 m) and length is sufficient to represent a very long slab. Either a single or a tandem axle load configuration may be selected as input. However, wheel imprint dimensions and wheel and axle spacings are constant. Dimensions selected for tandem axle loading are shown in Fig. 2. For single axle loading, wheel imprint size and spacings are the same.

Moments at the pavement edge due to loads at the edge are given by the following equations.

For a single-axle load,

$$M = 483.34 \frac{P}{18,000} (\ell)^{0.5711} \text{ in-lb} \qquad (1)$$

where: M = bending moment at edge

ℓ = radius of relative stiffness of pavement, in

$$\ell = \sqrt[4]{\frac{Eh^3}{12\,(1-\mu^2)\,k}} \qquad (2)$$

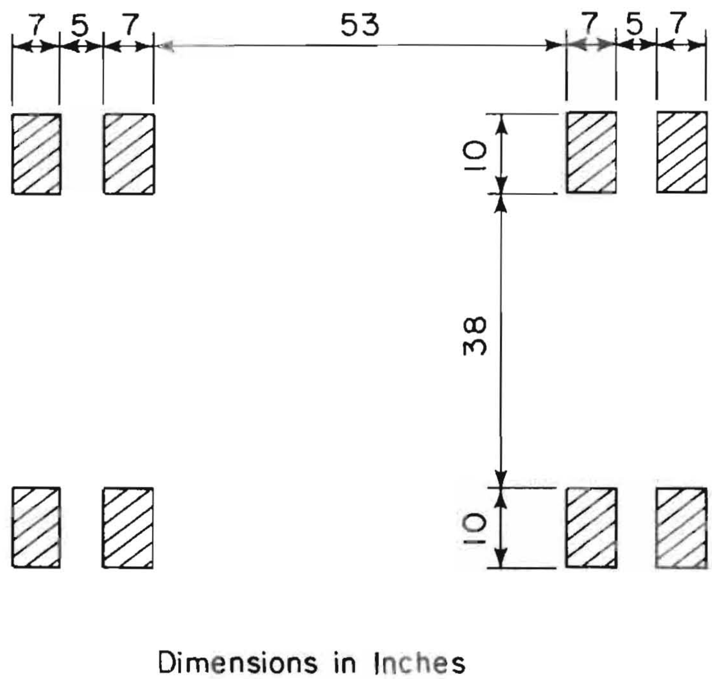


Figure 2 - Tandem Axle Load Configuration

where: E = Modulus of elasticity of concrete, psi

h = slab thickness, in

μ = Poisson's ratio = 0.15

k = modulus of subgrade reaction, psi

For a tandem-axle load:

$$M = 185.14 \frac{P}{36,000} (\ell)^{0.8197} \text{ in -lb} \tag{3}$$

Moment equations are based on the assumption of loss of subbase support for a 20-in (508 mm) distance inward from the pavement edge. This adjustment is made to recognize upward slab warping due to moisture differentials.

Load stress, σ_L, is determined by the equation:

$$\sigma_L = \frac{6M}{h^2} \left(\frac{P}{18,000\ n} \right) C_e \text{ psi} \tag{4}$$

where: P = single-axle or tandem-axle load, lb

n = 1 for single-axle load

n = 2 for tandem-axle load

C_e = load placement coefficient

Load placement coefficients shown in Fig. 3 are provided as program input. These coefficients are used to reduce stress at the pavement edge when loads are applied in wheel paths located inward from the edge.

Equation 4 for load stress, σ_L, can be further modified to incorporate the contribution of a tied-shoulder. This is done by using the following equation:

$$\sigma_L = \frac{6M}{h^2} \left(\frac{P}{18,000\ n} \right) C_e \left(\frac{1}{1 + JE} \right) \text{ psi} \tag{4a}$$

where: JE = joint efficiency

$$JE = \frac{\text{deflection at shoulder side of joint}}{\text{deflection at main pavement side of joint}}$$

Traffic Characteristics

Axle-loads and lateral placement of loads across the pavement during different periods of the day are program inputs.

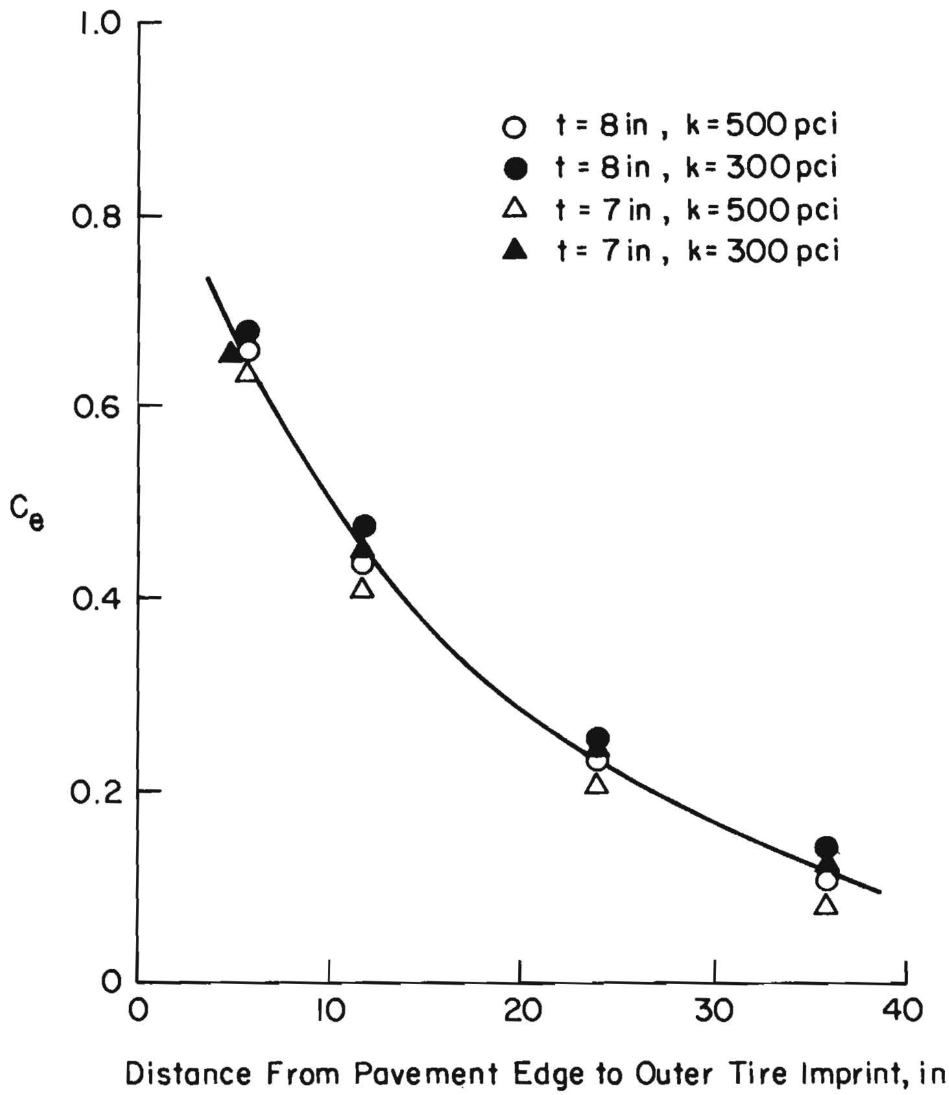


Figure 3 - Load Placement Coefficient , C_e

Curling stresses vary during the day and maximum curling stresses exist for only short durations. Therefore, traffic distribution during the day is required to equate maximum stresses to number of load applications during selected time periods. Time periods and traffic during the selected periods are program inputs.

States accumulate traffic loadometer data in the format used in Federal Highway Administration W4 loadometer tables. These tables tabulate number of axles observed within load groups, and are generally reported for 2,000 lb (18 kN) increments. Traffic projections are made for design periods that usually range from 20 to 40 years for concrete pavements.

A recommended lateral distribution of traffic is shown in Table 1. These values were selected based on information obtained by Emery.[1] Traffic volume is subdivided with respect to time of day. A recommended distribution is given in the users manual.

TABLE 1 - LATERAL LOAD DISTRIBUTION

Distance from Outside Wheel to Pavement Edge, in	Truck Traffic, %
0- 6	20
6-12	20
12-18	25
18-24	15
24-30	10
30-36	5

Temperature Effects

Curling stresses develop in a slab when temperatures vary with depth. During daytime, when the top surface is warmer than the bottom, tensile stresses develop at the slab bottom. During nighttime, when temperature gradients are reversed, tensile stresses develop at slab top. For stress calculations, it is generally assumed that the temperature gradient is linear. Maximum gradient is assumed about 3 F/in (0.07 C/mm) during daytime and about 1 F/in (0.02 C/mm) during nighttime. In practice, the temperature distribution is usually non-linear and constantly changing. Also, maximum daytime and nighttime temperature differentials exist for short time durations. Temperature distributions measured at the AASHTO Road Test[2] are shown in Fig. 4.

Since daily variation of air temperature follows an approximate sinusoidal cycle, temperature variations at the slab surface can be assumed sinusoidal. This variation can be represented as[3,4]

$$\theta_T = \theta_o \sin\left(\frac{2\pi t}{T}\right) \tag{5}$$

where: θ_T = temperature at surface of slab

θ_o = constant = amplitude of the temperature cycle at slab surface

t = time of day (24-hour clock)

T = 24 hr

This equation represents daytime conditions well but gives an incorrect distribution for nighttime conditions. For nighttime, the amplitude is about one-third of that computed using this equation. Therefore, for nighttime conditions, θ_o is replaced by θ_o' which is equal to $\theta_o/3$. Accuracy of night-time temperature distribution is not as critical because these stresses are subtracted from load stresses.

For homogeneous semi-infinite solids whose surface temperature varies sinusoidally, the temperature, θ_z, at any time t on a plane at depth z below the surface is given by

$$\theta_z = \theta_o e^{-\beta} \sin\left(\frac{2\pi t}{T} - \beta\right) \tag{6}$$

where: $\beta = \frac{z}{\psi}\sqrt{\frac{\pi}{T}}$

ψ^2 = diffusivity of the material, in ^{2}/hr

$= \frac{\lambda}{\gamma c}$

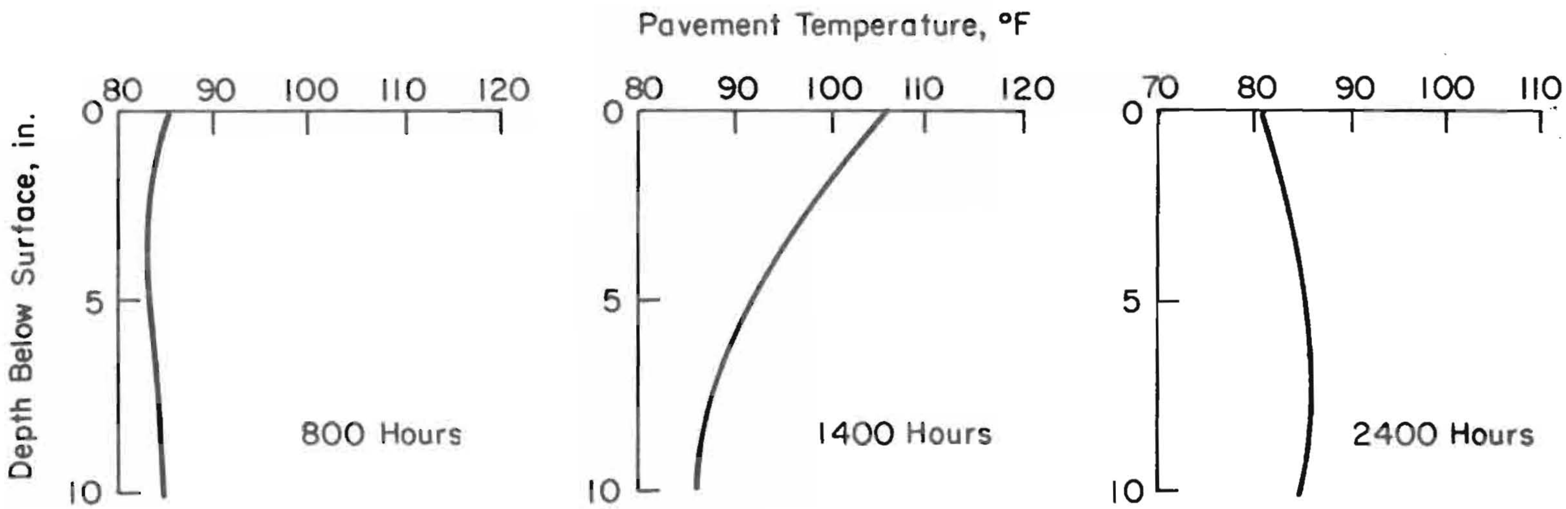


Figure 4 - Measured Changes in Temperature Distribution

λ = thermal conductivity of the material, Btu/hr-ft-F

γ = weight per unit volume of the material, lb/ft

c = specific heat of the material, Btu/lb-F

For a concrete slab resting on earth or subbase, Eq. 6 is applicable, as diffusivities of the materials are similar.

For concrete:

λ = 1.20 Btu/hr-ft-F

γ = 145 lb/ft^3

c = 0.22 Btu/lb-F

ψ^2 = 5.4168 in ^{2}/hr

Using this procedure, calculated variations in temperature distribution with time for concrete pavement thicknesses of as much as 10 in (254 mm) are shown in Fig. 5. These data are more representative of measured field data than the assumption of a linear temperature distribution.

Average slab temperature, θ_M, at time t is obtained by integrating Eq. 6 for θ_z between 0 and slab thickness, H, and dividing by H. The difference, θ_D, between average slab temperature and slab bottom temperature, θ_B, is given by:

$$\theta_D = \theta_M - \theta_B \qquad (7)$$

Curling stress at the bottom of the edge of a long slab is given by:

$$\sigma_C = \alpha E\, \theta_D \qquad (8)$$

where: α = coefficient of thermal expansion.

This non-linear temperature distribution formulation is used in the computerized design procedure to calculate curling stresses.

Its use requires an input value for θ_O shown in Eq. 5. For United States conditions a recommended value is 30 F; however, other values may be substituted where local information is available and conditions are substantially different.

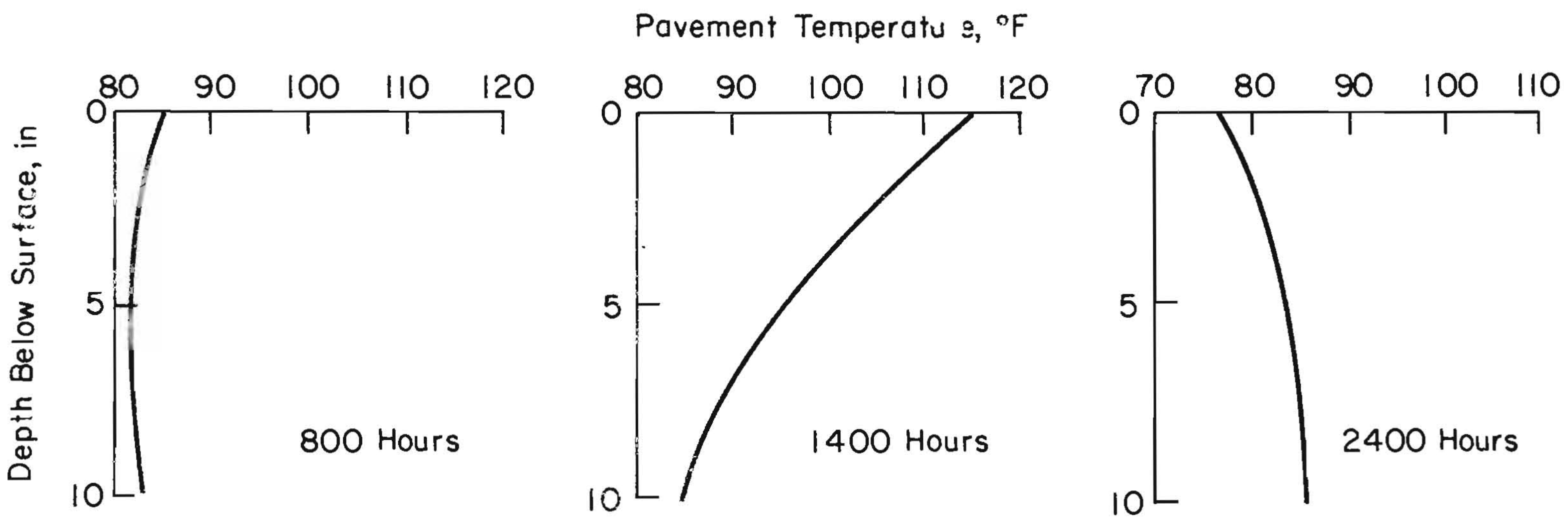


Figure 5 - Calculated Changes in Temperature Distribution

Moisture Effects

Top to bottom variations in pavement moisture content result in bottom fiber compressive stresses. Ideally, these stresses would be calculated for cyclical seasonal changes in moisture content. Calculated stresses would then be used in the thickness design procedure in the same manner as temperature stresses. However, only limited data are available regarding top to bottom moisture distribution, seasonal moisture variation, or stress magnitude. Friberg(5) and Nagataki(6) report that restrained warping strain at slab bottom may be about 150 millionths. These data are valuable and serve to direct future research. However, for the present it is being assumed that warping stresses for 7- and 8-in (178 and 203 mm) thick pavements are 190 and 220 psi (1,310 and 1,517 kPa), respectively.

Warping also results in a loss of support along the pavement edge. Loss of support causes an increase in edge stress due to traffic loading. Effects of upward warping on load stress calculations are included in Eqs. 1 and 3.

Subbase Support

Pavement performance is related to the quality of subbase and subgrade support. Ideally, as shown in Figure 1, the thickness design procedure should also incorporate allowable subbase and subgrade deformations as limiting criteria. However, sufficient data are not available to develop such criteria for concrete pavements. Measured concrete pavement deformations are influenced by the temperature gradient in the concrete at time of testing. Therefore, concrete pavement deformation data have to be correlated with pavement temperatures.

Prestressed concrete pavements are thinner than conventional concrete pavements. Thus, subbase support requirements are more critical. For zero-maintenance projects it is recommended that high quality subbase be used with prestressed pavements. Modulus of subgrade reaction at the top of the subbase should be about 500 pci (1357 kPa/cm).

Fatigue of Concrete

Flexural fatigue research on concrete has shown that as the ratio of flexural stress to modulus of rupture decreases, the number of stress repetitions to failure increases.(7) Allowable load repetitions for stress ratios between 0.50 and 0.85 are shown in Table 2.(8) These values are used in the program fatigue model. However, at the designer's option other fatigue models may be used as program input.

Mid-Slab Prestress

Mid-slab prestress is computed by accounting for prestress losses due to tendon friction, concrete shrinkage, concrete creep, steel relaxation, and subbase friction restraint.

Tendon Friction

Tendon friction results from curvature and wobble. Curvature is due to intentional and wobble to unintentional tendon profile variations. Tendon friction, σ_t, is determined from the equation:

$$\sigma_t = \sigma_{pe} \left(1 - e^{-\left(ux + \frac{KL}{2}\right)} \right) \text{psi} \qquad (9)$$

where: σ_{pe} = end prestress, psi,

u = curvature friction coefficient

x = angular change of tendon from jacking end to mid-slab, radians

K = wobble friction coefficient per foot

L = slab length, ft

For straight portions of pavements, intentional angular changes are negligible. Therefore, tendon friction can be obtained from

$$\sigma_t = \sigma_{pe} \left(1 - e^{-\left(\frac{KL}{2}\right)} \right) \text{psi} \qquad (10)$$

TABLE 2 - STRESS RATIOS AND ALLOWABLE LOAD REPETITIONS

Stress* ratio	Allowable repetition	Stress* ratio	Allowable repetition
0.51**	400,000	0.69**	2,500
0.52	300,000	0.70	2,000
0.53	240,000	0.71	1,500
0.54	180,000	0.72	1,100
0.55	130,000	0.73	850
0.56	100,000	0.74	650
0.57	75,000	0.75	490
0.58	57,000	0.76	360
0.59	42,000	0.77	270
0.60	32,000	0.78	210
0.61	24,000	0.79	160
0.62	18,000	0.80	120
0.63	14,000	0.81	90
0.64	11,000	0.82	70
0.65	8,000	0.83	50
0.66	6,000	0.84	40
0.67	4,500	0.85	30
0.68	3,500		

* Load stress divided by modulus of rupture.
** Unlimited repetitions for stress ratios of 0.50 or less.

Concrete Shrinkage

Prestress loss due to concrete shrinkage, σ_s, is given by the following equation:

$$\sigma_s = \varepsilon_s E_s \frac{A_s}{A_c} \text{ psi} \tag{11}$$

where: ε_s = concrete shrinkage strain

E_s = modulus of elasticity of tendon steel, psi

A_s = area of tendon per unit width of slab, in ^{2}

A_c = area of slab per unit width of slab, in ^{2}

Concrete Creep

Prestress loss due to concrete creep, σ_{cr}, is given by the following equation:

$$\sigma_{cr} = C_u \frac{E_s}{E_c} \sigma_{pe} \frac{A_s}{A_c} \text{ psi} \tag{12}$$

where: C_u = ultimate creep coefficient

E_c = modulus of elasticity of concrete, psi

Steel Relaxation

Prestress loss due to steel relaxation, σ_r, is given by the following equation:

$$\sigma_r = \rho\sigma_{pe} \text{ psi} \tag{13}$$

where: ρ = relaxation coefficient for appropriate stress level

Subbase Friction

Prestress loss due to subbase friction, σ_f, is given by the following equation:

$$\sigma_f = \frac{\mu s \gamma L}{288} \text{ psi} \tag{14}$$

where: μ_s = slab to subbase friction factor

γ = concrete unit weight, lb/ft^3

L = slab length, ft

Effective mid-slab prestress, σ_p, is given by the following equation:

$$\sigma_P = \sigma_{pe} - \sigma_t - \sigma_{cr} - \sigma_r - \sigma_f \qquad (15)$$

Example calculations for computing prestress losses and mid-slab prestress are given in Table 3. Coefficients and other values used for the computations are listed in Table 4.

PROGRAM FORMULATION

Total flexural stress at mid-slab edge is computed using the following equation.

$$\sigma_{T_{ijkl}} = \sigma_{L_{ijkl}} + \sigma_{C_{jkl}} - \sigma_P - \sigma_{W_{kl}} \qquad (16)$$

where: $\sigma_{T_{ijkl}}$ = total flexural stress for the ith axle group at the jth period of the day of kth month of lth year,

$\sigma_{L_{ijkl}}$ = traffic load stress due to the ith axle group at the jth period of day of kth month of lth year,

$\sigma_{C_{jkl}}$ = curling stress at the jth period of day of kth month of lth year,

σ_P = effective prestress at mid-slab at the jth period of day of kth month of lth year,

$\sigma_{W_{kl}}$ = warping stress during kth month of lth year.

TABLE 3 - PRESTRESS CALCULATIONS

Slab Thickness, in	7	8
Slab Length, ft	250	350
Strand Diameter, in	0.6	0.6
Strand Force, kip	41	41
Strand Spacing, in	24	18
End of Slab Prestress, psi	244	285
Prestress Losses		
Shrinkage, psi	6	6
Creep, psi	4	6
Relaxation, psi	20	23
Strand Friction, psi	39	62
Subbase Friction, psi	100	140
Total Losses, psi	169	237
Mid-Slab Prestress, psi	75	48

1 in = 25.4 mm
1 ft = 0.30 m
1 kip = 4.448 kN
1 psi = 6.894 kPa

TABLE 4 - PRESTRESS LOSS COMPUTATION COEFFICIENTS

Item	Magnitude
Tendon Ultimate Strength, psi	270,000
Area 0.6 in diameter tendon, in^2	0.217
Concrete Creep Coefficient	2.5
Concrete Shrinkage Strain, millionths	150
Strand Relaxation Coefficient 70 percent of Ultimate Stress 75 percent of Ultimate Stress	 0.08 0.10
Wobble Friction Coefficient per foot	0.0014
Subbase Friction Factor	0.8
Modulus of Elasticity of Steel, million psi	28
Modulus of Elasticity of Concrete, million psi	5

1 psi = 6.894 kPa
1 in = 25.4 mm
1 ft = 0.30 m

Anticipated number of repetitions, N_i, of stress of magnitude $\sigma_{T_{ijkl}}$ is determined. Then, the allowable number of stress repetitions, NN_i, of magnitude $\sigma_{T_{ijkl}}$ is calculated using the fatigue model. Fatigue consumption, F_i, due to repeated stress applications of magnitude $\sigma_{T_{ijkl}}$ is obtained as follows:

$$F_i = \frac{N_i}{NN_i} \tag{17}$$

Total fatigue consumption, F_{TOT}, during the design period is obtained by summing fatigue consumed by load repetitions for each stress level, and is given by

$$F_{TOT} = \Sigma F_i \tag{18}$$

If total fatigue consumption at the end of the design period is less than 100 percent, the thickness obtained meets design criteria.

DESIGN EXAMPLE

Thickness design of a prestressed pavement for a heavily trafficked highway in central Illinois is presented. The high volume of heavy loads used is representative of traffic at locations where the concept of zero-maintenance pavements is applicable. The concept of "zero-maintenance" implies use of a premium pavement at locations where higher first costs is justified by a reduction in future costs due to repairs, user travel delays, and accidents.

The design procedure may be used to determine pavement thickness for any traffic mix. However, use of a thickness less than 6-in (152 mm) may not be practical as the space necessary for placing joint hardware such as anchors, seal holders, load transfer devices, reinforcement, and positioning bars may not be available.

Project Traffic Data

Traffic distribution used was determined from data obtained from field surveys and interviews by Darter and Barenberg.(9) Average daily traffic for the design period was selected as 6000 vehicles per day.

Design life = 20 years

Single axle load distribution during design period:

Axle load, kips	Number
18-20	80,422
20-22	62,144
22-24	25,589
24-26	8,530
26-28	3,656
28-30	1,219
30-32	609
32-34	183

Tandem axle load distribution during design period:

Axle load, kips	Number
38-40	29,244
40-42	11,576
42-44	4,874
44-46	3,656
46-48	1,828
48-50	1,219
50-52	1,219
52-54	609
54-56	183

Material Properties

Concrete modulus of elasticity = 5,000,000 psi

Concrete modulus of rupture = 700 psi

Modulus of subbase reaction = 500 pci

Diffusivity of concrete = 5.24 in ^{2}/hr

Coefficient of thermal expansion of concrete = 0.000005 in /in /F

Prestress

Effective mid-slab prestress = 50 psi

Warping Restraint Stress

Stress for 7-in thick slab = 190 psi

Stress for 8-in thick slab = 220 psi

Results

Results obtained using the computer program are presented below:

Slab Thickness, in.	Joint Efficiency, percent	Fatigue Consumed, percent
7	0	2,070
7	60	1
8	0	36

Based on above results a 7-in (178 mm) thick concrete pavement with a tied concrete shoulder or an 8-in (203 mm) thick pavement without a tied concrete shoulder may be used.

SUMMARY

A computerized design procedure for prestressed concrete pavement is presented. The procedure is based on flexural stress analysis and prevention of bottom transverse cracking at slab edge. At present, only limited data are available to determine values for temperature cycle amplitude, θ_o, and warping restraint stress. Therefore, recommended design values may be used. The design procedure is simple to use and can be implemented immediately.

REFERENCES

1. Emery, Jr., D. K., "Paved Shoulder Encroachment and Transverse Lane Displacement For Design Trucks on Rural Freeways," A report presented to the Committee on Shoulder Design, Transportation Research Board, January 13, 1974.

2. "The AASHO Road Test," Special Report 61E, Transportation Research Board, 1962.

3. Thomlinson, J., "Temperature Variations and Consequent Stresses Produced by Daily and Seasonal Temperature Cycles in Concrete Slabs," Concrete and Construction Engineering, June, 1940.

4. Bergstrom, S. G., "Temperature Stresses in Concrete Pavements," Swedish Cement and Concrete Research Institute, Royal Institute of Technology, Stockholm, 1950.

5. Friberg, B. F., "Investigations of Prestressed Concrete for Pavements," Bulletin 332, Highway Research Board, 1962.

6. Nagataki, S., "Shrinkage and Shrinkage Restraints in Concrete Pavements," Journal of the Structural Division, American Society of Civil Engineers, July 1970.

7. Murdock, J. W., "A Critical Review of Research on Fatigue of Plain Concrete," Bulletin 475, Engineering Experiment Station, University of Illinois, 1965.

8. "Thickness Design for Concrete Pavements," Portland Cement Association, 1966.

9. Darter, M. I., and Barenberg, E. J., "Design of Zero Maintenance Plain Jointed Concrete Pavement, Vol. II-Design Manual," Report No. FHWA-RD-77-112, Federal Highway Administration, June 1977.

APPENDIX

USER'S MANUAL AND PROGRAM LISTING

PROGRAM PCP (Prestressed Concrete Pavement)

USER'S MANUAL

Data Card 1

NPROB
I5

NPROB = number of problems

The following set of cards are repeated NPROB times.

Data Card 2

TITLE (20)
20A4

TITLE (1) to TITLE (20) = problem title

Data Card 3

AL	ALPHA	H	U	DIFUS
F10.2	F10.2	F10.2	F10.2	F10.2

AL = slab length, ft
ALPHA = coefficient of thermal expansion, in /in /F
H = initial slab thickness. If NSUBPR (data card 10) is greater than one, slab thickness is incremented by 1.0 inch.
U = Poisson's ratio for concrete
DIFUS = diffusivity of concrete, in ^{2}/hour (see text for explanation)

Data Card 4

TRAFIC	GROWTH	NYEARS	NAXLE	NTAXLE	NPOS	NPROP	NTEMP	NLOC
F10.2	F10.2	I5	I5	I5	I5	I5	I5	I5

TRAFIC = 1.0
GROWTH = percent traffic growth per year
NYEARS = design period, years. NYEARS equals one if NPROP = 1
NAXLE = number of single axle load types
NTAXLE = number of tandem axle load types
NPOS = number of lateral positions for wheel loads
NPROP = 0 if different material properties and temperature values are used for each month of the year
= 1 if material properties and temperature values are same for each month of the year

NTEMP = number of periods during the day. If each period is 4 hours, then NTEMP equals 6. This option is used to compute the appropriate curling stress for each period.

NLOC = 0 (zero)

Data Card 5 (Repeat for I=1 to NPOS times)

PPP(I)	COEFF(I)
F10.2	F10.2

PPP(I) = fraction of traffic along lateral position I. For example, if first lateral position between edge and 6 in inward from edge has 20 percent of traffic, then PPP(1) equals 0.20.

COEFF(I) = coefficient to compute edge stress for wheel position inward from edge. For example, for first lateral position between edge and 6 in inward from edge, coefficient equals 1. For the second lateral position between 6 in and 12 in inward from edge, coefficient equals 0.75. See text for more details.

Data Card 6 (Repeat for I=1 to NAXLE times)

P(I)	PP(I)
F10.2	F10.2

P(I) = single axle load type I, lb

PP(I) = total number of axle loads of type I per year
= total number of axle loads of type I for the design period if NYEARS equals 1.

Data Card 7 (Repeat for I=1 to NTAXLE times)

T(I)	TT(I)
F10.2	F10.2

T(I) = tandem axle load type I, lb

II(I) = total number of axle loads of type I per year
= total number of axle loads of type I for the design period if NYEARS equals 1.

Data Card 8 (If NTEMP (data card 4) is greater than eight, continue on second card)

TRTEMP (1) to TRTEMP (NTEMP)
8F10.2

TRTEMP(I) = fraction of truck traffic during period I of the day. If each period is 4 hours long, then the first period would be from mid-night to 4 hours (on the 24-hour clock). TRTEMP(1) is the fraction of traffic that is on the road during that period. TRTEMP(2) is the fraction of traffic on the road between 4 hours and 8 hours. An example of the traffic breakdown during a day is given below.

Period, I	Time (24-hour clock)	TRTEMP(I)
1	0 to 4	0.05
2	4 to 8	0.20
3	8 to 12	0.25
4	12 to 16	0.25
5	16 to 20	0.20
6	20 to 24	0.05

Data Card 9 (Repeat for each month of the year if NPROP (data card 4) is equal to 0. If NPROP equals 1, only one card is needed.)

RM(I)	E(I)	AK(I)	SIGW(I)	THETA(I)	TMAX(I)	DTEMP(1,I)	DTEMP(2,I)
F10.2	F10.2	F10.2	F10.2	F10.2	F10.2	F10.2	F10.2

RM(I) = modulus of rupture of concrete, psi

E(I) = modulus of elasticity of concrete, psi

AK(I) = modulus of subgrade reaction for the Ith month, psi

SIGW(I) = warping restraint stress for the Ith month, psi

THETA(I) = amplitude of temperature cycle at slab surface in degrees Fahrenheit if non-linear temperature distribution is used. See text for details.

TMAX(I) = time on 24-hour clock when maximum temperature occurs at slab top for month I. If maximum temperature occurs at 2 p.m., then TMAX(I) equals 14.0.

DTEMP(1,I) = Maximum daytime temperature difference in degrees Fahrenheit between slab top and slab bottom during month I of the year if linear temperature distribution is used.

DTEMP(2,I) = Maximum nighttime temperature difference in degrees Fahrenheit between slab top and slab bottom during month I of the year if linear temperature distribution is used. DTEMP(2,I) is a negative value.

NOTE: If linear temperature distribution is considered, then NSUBR (data card 10) should equal 1. The solution is found individually for each slab thickness as DTEMP(1,I) and DTEMP(2,I) would vary with thickness.

Data Card 10

PRESTR	FATIGE	AA	BB	NSUBPR	NFAT	NPST	NLNR
F10.2	F10.2	F10.2	F10.2	I5	I5	I5	I5

PRESTR = initial value of effective prestress at mid-slab, psi. If NPST is greater than 1, the prestress value is incremented by 10 psi.

FATIGE = 1.0 if a fatigue model is input (see Note 1 below)
= 2.0 if program dependent fatigue model is used (see Note 2 below)

AA = constant described below

BB = constant described below

NSUBPR = number of different slab thickness values to be considered. Thickness value is incremented by 1.0 in each time if NSUBPR is greater than 1.

NFAT = 1.0

NPST = number of different mid-slab prestress values to be considered. Prestress value is incremented by 10 psi each time if NPST is greater than 1.

NLNR = 1 if non-linear temperature distribution in the slab is considered.
= 2 if linear temperature distribution is considered.

NOTES:

(1) The fatigue model is of the following form:
log N = AA + BB (Combined Stress/Modulus of Rupture)
where N = allowable number of stress applications equal in magnitude to the combined stress
AA, BB = constants determined from laboratory fatigue tests

(2) Program dependent fatigue model is as follows:
log N = 11.829 - 12.195 (Combined Stress/Modulus of Rupture)

Data Card 11

YJE	DECYJE	
F10.2	F10.2	

YJE = initial joint efficiency when tied-shoulder is considered

DECYJE = percent decrease in joint efficiency per year if NYEARS is greater than 1.

Typical input and output are given in the following pages. The output contains a listing of the input and fatigue consumption at end of each month for the design period. If NYEARS in the input equals one, then fatigue consumption is given at end of each month for one year. A satisfactory slab thickness is one that produces fatigue consumption which is less than 100%.

SAMPLE OUTPUT

```
1CONCRETE PAVEMENT DESIGN - BASED ON EDGE STRESS

 PRESTESSED PAVEMENT DESIGN EXAMPLE
 *****NON-LINEAR TEMPERATURE**********


 *****SLAB PROPERTIES*****
 SLAB LENGTH,FT=350.00      SLAB THICKNESS,IN= 8.00
 ALPHA,IN/IN/OF= .0000050     POISSON RATIO= .15
 DIFFUSIVITY OF CONCRETE= 5.41680
 NO. OF MATERIAL PROPERTIES= 1

 *****TRAFFIC DATA*****
 ANNUAL TRAFFIC OR FACTOR=       1.00      ANNUAL TRAFFIC GROWTH=    0
 DESIGN PERIOD,YR= 1
 NO.OF SAL TYPES= 8      NO. OF TAL TYPES= 9
 LATERAL POSITIONS= 4      DAILY TRAFFIC PERIODS= 6

 LATERAL POSITION   FRACTION OF TRAFFIC   STRESS COEFFICIENT
        1                   .20                 1.00
       2                   .20                 .75
       3                   .25                 .50
       4                   .15                 .40


 SAL,LBS        NO OF AXLES(FRACTION)
 34000.00                 183.00
32000.00                 609.00
30000.00                1219.00
28000.00                3656.00
26000.00                8530.00
24000.00               25589.00
22000.00               62144.00
20000.00               80422.00
```

TAL,LBS	NO OF AXLES(FRACTION)
56000.00	183.00
54000.00	609.00
52000.00	1219.00
50000.00	1219.00
48000.00	1828.00
46000.00	3656.00
44000.00	4874.00
42000.00	11576.00
40000.00	29244.00

TRAFFIC DISTRIBUTION DURING DAY= .05 .20 .25 .25 .20 .05

JOINT EFFICIENCY ALONG LONG JOINT= 0
DECREASE IN JE ALONG LONG JNT /YEAR= 0

MONTH	RM	E	K	SIGW	THETA	TMAX	DTEMP(DAY)	DTEMP(NGT)
1	700.0	5000000.0	500.0	220.0	30.0	14.0	18.0	-6.0

*****FATIGUE CURVE DATA*****
FATIGUE MODEL= 2.0
CONSTANT AA= 11.82900 CONSTANT BB= -12.19500

LONGITUDINAL PRESTRESS AT MIDLENGTH= 50.00

*****WHEEL LOADS AT MIDSLAB*******

YEAR NUMBER= 1 ANNUAL TRAFFIC OR FACTOR= 1.0
PERCENT FATIGUE CONSUMED= 3.0 6.0 9.0 11.9 14.9 17.9 20.9 23.9 26.9 29.8 32.8 35.8

OK
>

```
C     ! PROGRAM THICK  (KEYBRD,CONSOL,TAPE5=KEYBRD,TAPE6=CONSOL)
C  PRESTRESSED PAVEMENT THICKNESS DESIGN
       DIMENSION FF(12),TITLE(20),SIGW(12)
C
      COMMON/ONE/AK(12),E(12),RM(12),H,U,P(10),COEFF(10),SIGL(12,10,10),
     1 NAXLE,T(10),SIGT(12,10,10),NTAXLE,TT(10),NPOS,COEF2(10)
      COMMON/TWO/SIGCC(12,12),NTEMP,DTEMP(2,12),ALPHA,DIFUS,THETA(12),
     1   TMAX(12),NLNR
      COMMON/FOUR/SIGDAY  ,PP(10),TRAFIC,GROWTH
       COMMON/FIVE/PPP(10),FATIGE,AA,BB,TRAF,TRTEMP(12)
      COMMON/SIX/NYEARS,NPROP
C
C     READ(5,*) NPROB
       READ(5,501) NPROB
  501  FORMAT(I5)
      DO 100  NPR=1,NPROB
       READ(5,196) (TITLE(I),I=1,20)
 196   FORMAT(20A4)
      WRITE(6,35)
      WRITE(6,101)
 101  FORMAT('1','CONCRETE PAVEMENT DESIGN - BASED ON EDGE STRESS',/)
C     READ(5,*) AL,ALPHA,H,U,DIFUS
(S,C OR RETURN)>
       READ(5,502) AL,ALPHA,H,U,DIFUS
  502  FORMAT(8F10.2)
C     READ(5,*) TRAFIC,GROWTH,NYEARS,NAXLE,NTAXLE,NPOS,NPROP,NTEMP,NLOC
      READ(5,503)TRAFIC,GROWTH,NYEARS,NAXLE,NTAXLE,NPOS,NPROP,NTEMP,NLOC
  503  FORMAT(2F10.2,8I5)
       DO 14  I=1,NPOS
C     READ(5,*)  PPP(I),COEFF(I),COEF2(I)
       READ(5,502) PPP(I),COEFF(I),COEF2(I)
  14   CONTINUE
      DO  5  I=1,NAXLE
C     READ(5,*)  P(I),PP(I)
       READ(5,502) P(I),PP(I)
   5  CONTINUE
      DO 8 I=1,NTAXLE
C     READ(5,*) T(I),TT(I)
       READ(5,502) T(I),TT(I)
   8  CONTINUE
C      READ(5,*) (TRTEMP(I),I=1,NTEMP)
       READ(5,502) (TRTEMP(I),I=1,NTEMP)
      DO  10  I=1,12
       IF(NPROP.EQ.1.AND.I.GT.1) GO TO 11
C     READ(5,*) RM(I),E(I),AK(I),SIGW(I),THETA(I),TMAX(I),DTEMP(1,I),
(S,C OR RETURN)>
```

```
C     *   DTEMP(2,I)
        READ(5,502)RM(I),E(I),AK(I),SIGW(I),THETA(I),TMAX(I),DTEMP(1,I),
      *   DTEMP(2,I)
        GO TO 10
 11       RM(I)=RM(1)
        E(I)=E(1)
         AK(I)=AK(1)
         SIGW(I)=SIGW(1)
         THETA(I)=THETA(1)
         TMAX(I)=TMAX(1)
        DTEMP(1,I)=DTEMP(1,1)
         DTEMP(2,I)=DTEMP(2,1)
  10   CONTINUE
C      READ(5,*) PRESTR,FATIGE,AA,BB,NSUBPR,NFAT,NPST,NLNR
        READ(5,504)PRESTR,FATIGE,AA,BB,NSUBPR,FAT,NPST,NLNR
  504   FORMAT(4F10.2,4I5)
C       READ(5,*) YJE,DECYJE,XJE,DECXJE
        READ(5,502) YJE,DECYJE,XJE,DECXJE
C
        WRITE(6,197)(TITLE(IK),IK=1,20)
 197    FORMAT(' ',20A4)
C        NONL=1
(S,C OR RETURN)>
C        IF(NLNR.EQ.3) NONL=2
C        DO   410   NNLNR=1,NONL
C        IF(NNLNR.EQ.1.AND.NONL.EQ.2) NLNR=1
C        IF(NNLNR.EQ.2.AND.NONL.EQ.2) NLNR=2
         IF(NLNR.EQ.1)  WRITE(6,411)
  411    FORMAT(' ','*****NON-LINEAR TEMPERATURE***********'/)
         IF(NLNR.EQ.2) WRITE(6,412)
  412    FORMAT(' ','*****LINEAR TEMPERATURE***************'/)
C
        DO  311 NPS=1,NPST
        DO 211 NFT=1,NFAT
        DO  210  NSUB=1,NSUBPR
        IF(NFT.EQ.1.AND.NPS.EQ.1)WRITE(6,3) AL,H,ALPHA,U,DIFUS,NPROP
  3     FORMAT(' ',/' ','*****SLAB PROPERTIES*****'/
      1 ' ','SLAB LENGTH,FT=',F6.2,5X,'SLAB THICKNESS,IN=',F5.2/
      2 ' ','ALPHA,IN/IN/OF=',F9.7,5X,'POISSON RATIO=',F4.2/
      3  ' ','DIFFUSIVITY OF CONCRETE=',F8.5/
      4 ' ','NO. OF MATERIAL PROPERTIES=',I2/)
        IF(NSUB.EQ.1.AND.NFT.EQ.1.AND.NPS.EQ.1)GO TO 903
        GO TO 901
 903     WRITE(6,9) TRAFIC,GROWTH,NYEARS,NAXLE,NTAXLE,NPOS,NTEMP
  9    FORMAT(' ','*****TRAFFIC DATA*****'/
(S,C OR RETURN)>
```

```
     1 ' ','ANNUAL TRAFFIC OR FACTOR=',F10.2,5X,
     2 'ANNUAL TRAFFIC GROWTH=',F4.1/' ','DESIGN PERIOD,YR=',I2/
     3 ' ','NO.OF SAL TYPES=',I2,5X,'NO. OF TAL TYPES=',I2/
     4 ' ','LATERAL POSITIONS=',I2,5X,'DAILY TRAFFIC PERIODS=',I2/)
      WRITE(6,16)  (I,PPP(I),COEFF(I),I=1,NPOS)
  16  FORMAT(' ','LATERAL POSITION   FRACTION OF TRAFFIC',3X,
     1 'STRESS COEFFICIENT'/' ',(6X,I2,16X,F5.2,15X,F4.2))
      WRITE(6,35)
  35 FORMAT(' ',/)
     WRITE(6,4) (P(I),PP(I),  I=1,NAXLE)
   4  FORMAT(' ','SAL,LBS',7X,'NO OF AXLES(FRACTION)',/
     1 ' ',(F8.2,13X,F12.2))
     WRITE(6,44) (T(I),TT(I),  I=1,NTAXLE)
  44  FORMAT(' ','TAL,LBS',7X,'NO OF AXLES(FRACTION)',/
     1 ' ',(F8.2,13X,F12.2))
      WRITE(6,622) (TRTEMP(I),I=1,NTEMP)
 622  FORMAT(' ','TRAFFIC DISTRIBUTION DURING DAY=',10(F4.2,4X))
     WRITE(6,231) YJE,DECYJE
 231  FORMAT(' ',/,' ','JOINT EFFICIENCY ALONG LONG JOINT=',F5.2/
     1  ' ','DECREASE IN JE ALONG LONG JNT /YEAR=',F5.2/)
901   CONTINUE
     WRITE(6,35)
(S,C OR RETURN)>
      II=12
      IF(NPROP.EQ.1)  II=1
     IF(NFT.EQ.1.AND.NPS.EQ.1)   WRITE(6,6)(I,RM(I),E(I),AK(I),SIGW(I),
     *  THETA(I),TMAX(I),DTEMP(1,I),DTEMP(2,I),I=1,II)
   6  FORMAT(' ','MONTH',4X,'RM',11X,'E',11X,'K',9X,'SIGW',8X,'THETA',
     *  8X,'TMAX',5X,'DTEMP(DAY)',3X,'DTEMP(NGT)'/
     2 ' ',(I3,5X,8(F9.1,3X)))
      IF(FATIGE.EQ.2.0)  AA=11.829
      IF(FATIGE.EQ.2.0)  BB=-12.195
      IF(FATIGE.EQ.3.0)  AA=14.428
      IF(FATIGE.EQ.3.0)  BB=-14.286
      IF(NSUB.GT.1) GO TO 902
     IF(NSUBPR.EQ.1.AND.NPS.EQ.1)WRITE(6,107) FATIGE,AA,BB
 107 FORMAT(' ',/,' ','*****FATIGUE CURVE DATA*****'/
     1 ' ','FATIGUE MODEL=',F4.1/
     2 ' ','CONSTANT AA=',F10.5,5X,'CONSTANT BB=',F10.5/)
      WRITE(6,117) PRESTR
 117  FORMAT(' '/' ','LONGITUDINAL PRESTRESS AT MIDLENGTH=',F6.2/)
C
902   CONTINUE
C
     WRITE(6,35)
(S,C OR RETURN)>
```

```
        DO  300  III=1,2
       FFF=0.0
        IF(III.EQ.1) PRES=PRESTR
        IF(III.EQ.1) WRITE(6,302)
 302    FORMAT(' ','*****WHEEL LOADS AT MIDSLAB*******'/)
        IF(III.EQ.2.AND.NLOC.EQ.0) GO TO 300
        IF(III.EQ.2)  PRES=0.0
        IF(III.EQ.2)  WRITE(6,301)
 301    FORMAT(' ','*****WHEEL LOADS AT TRANSVERSE JOINT(CRACK)**'/)
        IF(NPS.GT.1.OR.NFT.GT.1) GO TO 555
        CALL  SIGLD(III)
        CALL SIGCRL
  555   CONTINUE
C
       DO  20  II=1,NYEARS
        XXJE=XJE*(1-DECXJE/100*(II-1))
        YYJE=YJE*(1-DECYJE/100*(II-1))
        IF(III.EQ.1) XYJE=YYJE
        IF(III.EQ.2) XYJE=XXJE
        IF(XYJE.LE.0.0) XYJE=0.0
        XYJE=1/(1.0+XYJE)
        TRAF=TRAFIC*(1.0+GROWTH/100.0)**II
(S,C OR RETURN)>
       WRITE(6,105) II,TRAF
 105   FORMAT(' ','YEAR NUMBER=',I3,5X,'ANNUAL TRAFFIC OR FACTOR=',F9.1)
        TRAF=TRAF/12.0
       DO 21  I=1,12
        DO 621  ITEMP=1,NTEMP
C    CALCULATE FOR SINGLE AXLE LOADS
C
       DO 30  J=1,NAXLE
       DO 30  K=1,NPOS
        SIGDAY=SIGL(I,J,K)*XYJE+SIGCC(I,ITEMP)-PRES-SIGW(I)
       IF(SIGDAY.LT.1.0)  SIGDAY=1.0
C
       CALL  MINER(II,I,J,K,F,1,ITEMP)
        FFF=FFF+F
C
  30   CONTINUE
C
C    CALCULATE FOR TANDEM AXLE LOADS
C
       DO  31  J=1,NTAXLE
       DO 31  K=1,NPOS
        SIGDAY=SIGT(I,J,K)*XYJE+SIGCC(I,ITEMP)-PRES-SIGW(I)
(S,C OR RETURN)>
```

```
       IF(SIGDAY.LT.1.0)  SIGDAY=1.0
C
       CALL  MINER(II,I,J,K,F,2,ITEMP)
        FFF=FFF+F
C
  31   CONTINUE
C
 621    CONTINUE
        FF(I)=FFF*100.0
C
 21       CONTINUE
        WRITE(6,110)  (FF(MN),MN=1,12)
 110    FORMAT(' ','PERCENT FATIGUE CONSUMED=',12(F7.1,1X))
  20   CONTINUE
C
       WRITE(6,35)
 300    CONTINUE
        H=H+1.0
        DO 6211 I56=1,12
        IF(NPROP.EQ.1.AND.I56.GT.1) GO TO 6210
       IF(NLNR.EQ.2.AND.NSUB.LT.NSUBPR)READ(5,*)DTEMP(1,I56),DTEMP(2,I56)
C      IF(NLNR.EQ.2.AND.NSUB.LT.NSUBPR)READ(5,502)DTEMP(1,I56),DTEMP(2,I5
(S,C OR RETURN)>
C    *6)
        GO TO 6211
 6210   DTEMP(1,I56)=DTEMP(1,1)
        DTEMP(2,I56)=DTEMP(2,1)
 6211   CONTINUE
 210    CONTINUE
        H=H-1.0*NSUBPR
        IF(NFT.EQ.1) FATIGE=2.0
        IF(NFT.EQ.2) FATIGE=3.0
 211    CONTINUE
        PRESTR=PRESTR+10.0
311     CONTINUE
          PRESTR=PRESTR-10.0*NPST
  410     CONTINUE
 100   CONTINUE
C
       END
       SUBROUTINE  SIGLD(III)
C
C
       COMMON/ONE/AK(12),E(12),RM(12),H,U,P(10),COEFF(10),SIGL(12,10,10),
     1 NAXLE,T(10),SIGT(12,10,10),NTAXLE,TT(10),NPOS,COEF2(10)
(S,C OR RETURN)>
```

```
      COMMON/SIX/NYEARS,NPROP
C
C     WRITE(6,55)
C 55  FORMAT(' ',/' ','MONTH',2X,'AXLE LOAD',2X,
C    *  'STRESS DISTRIBUTION ACROSS PAVEMENT',/)
C
     DO  10  I=1,12
     RADL=(E(I)*(H**3.0)/(12.0*(1.0-U**2.0)*AK(I))) **0.25
C  EQN BELOW IS FOR EDGE STRESS, 20 IN. LOSS OF SUPPORT
      IF(III.EQ.1) AMOM=483.34*(RADL**0.5711)
C  EQN BELOW IS FOR JOINT STRESS, FLAT SLAB
      IF(III.EQ.2) AMOM=133.91*(RADL**0.8107)
     SIGMA=6.0*AMOM/(H**2.0)
C
C   FOR TANDEM AXLES
C  EQN BELOW IS FOR EDGE STRESS, 20 IN. LOSS OF SUPPORT
      IF(III.EQ.1) BMOM=185.14*(RADL**0.8197)
C  EQN BELOW IS FOR JOINT STRESS, FLAT SLAB
      IF(III.EQ.2) BMOM=110.32*(RADL**0.9090)
     SIGMB=6.0*BMOM/(H**2.0)
C
C  CALCULATE FOR SINGLE AXLES
(S,C OR RETURN)>
     DO  11  J=1,NAXLE
     SIGJ=SIGMA*(P(J)/18000.0)
C
     DO  30  K=1,NPOS
      IF(III.EQ.1)  COEF=COEFF(K)
      IF(III.EQ.2)  COEF=COEF2(K)
 30  SIGL(I,J,K)=COEF*SIGJ
C     IF(I.GT.1) GO TO 11
C     WRITE(6,20) I,P(J),(SIGL(I,J,K),K=1,NPOS)
C 20  FORMAT(' ',I5,5X,10F10.1)
 11  CONTINUE
C
C  CALCULATE FOR TANDEM AXLES
     DO  12  J=1,NTAXLE
     SIGJ=SIGMB*(T(J)/36000.0)
     DO  31  K=1,NPOS
      IF(III.EQ.1)  COEF=COEFF(K)
      IF(III.EQ.2)  COEF=COEF2(K)
 31  SIGT(I,J,K)=COEF*SIGJ
C     IF(I.GT.1) GO TO 12
C     WRITE(6,20) I,T(J),(SIGT(I,J,K),K=1,NPOS)
 12  CONTINUE
(S,C OR RETURN)>
```

```
C
   10  CONTINUE
C       WRITE(6,35)
C
        RETURN
        END
        SUBROUTINE  SIGCRL
C
        COMMON/ONE/AK(12),E(12),RM(12),H,U,P(10),COEFF(10),SIGL(12,10,10),
       1NAXLE,T(10),SIGT(12,10,10),NIAXLE,TI(10),NPOS,COEF2(10)
        COMMON/TWO/SIGCC(12,12),NTEMP,DTEMP(2,12),ALPHA,DIFUS,THETA(12),
       1  TMAX(12),NLNR
C
         IF(NLNR.EQ.2) GO TO 900
         DO 500 I=1,12
         DO 500 ITEMP=1,NTEMP
          DIFS=DIFUS**0.5
         TPRIOD=(ITEMP-1)*24.0/NTEMP
         TIME=TPRIOD-(TMAX(I)-6.0)
         IF(TIME.LT.0.0) TIME=TIME+24.0
         ALB=(H/DIFS)*0.361801
         THETDD=-100.0
(S,C OR RETURN)>
         NTIMES=24.0/NTEMP
         DO  20  NTIME=1,NTIMES
         A1=THETA(I)/(2.0*ALB)
         A2=EXP(-ALB)*(COS(0.2618*TIME-ALB)-SIN(0.2618*TIME-ALB))
         A3=COS(0.2618*TIME)-SIN(0.2618*TIME)
         THETAM=A1*(A2-A3)
         THETAB=THETA(I)*EXP(-ALB)*SIN(0.2618*TIME-ALB)
         THETAD=THETAM-THETAB
         IF(THETAD.GT.THETDD)  THETDD=THETAD
         TIME=TIME+1.0
         IF(TIME.GT.24.0) TIME=TIME-24.0
   20    CONTINUE
         SIGCC(I,ITEMP)=ALPHA*E(I)*THETDD
  500    IF(TIME.GT.12.0)  SIGCC(I,ITEMP)=SIGCC(I,ITEMP)/3.0
         GO TO 901
  900    CONTINUE
         DO 600 I=1,12
         DO 600 ITEMP=1,NTEMP
         DIFF=(DTEMP(1,I)-DTEMP(2,I))/(NTEMP/2.0)
         TEMP=DTEMP(2,I)+(ITEMP-1)*DIFF
         IF(ITEMP.GT.(NTEMP/2)) TEMP=DTEMP(1,I)-(ITEMP-(NTEMP/2)-1)*DIFF
  600    SIGCC(I,ITEMP)=ALPHA*E(I)*TEMP*0.5
(S,C OR RETURN)>
```

```
 901    CONTINUE
C       WRITE(6,902)(SIGCC(1,ITEMP),ITEMP=1,NTEMP)
C902    FORMAT(' ',/,' ','CURLING STRESS WITH TIME FOR FIRST MONTH',
C     *   /,' ',12F10.1//)
        RETURN
        END
       SUBROUTINE  MINER(II,I,J,K,F,NUM,ITEMP)
C
       COMMON/ONE/AK(12),E(12),RM(12),H,U,P(10),COEFF(10),SIGL(12,10,10),
      1 NAXLE,T(10),SIGT(12,10,10),NTAXLE,TT(10),NPOS,COEF2(10)
       COMMON/FOUR/SIGDAY   ,PP(10),TRAFIC,GROWTH
       COMMON/FIVE/PPP(10),FATIGE,AA,BB,TRAF,TRTEMP(10)
C
        IF(NUM.EQ.1) AN=TRAF*PP(J)*PPP(K)*TRTEMP(ITEMP)
        IF(NUM.EQ.2) AN=TRAF*TT(J)*PPP(K)*TRTEMP(ITEMP)
C
       IF(SIGDAY .LE.(0.5*RM(I)))  F=0.0
       IF(SIGDAY .LE.(0.5*RM(I)))  GO TO 10
       IF(SIGDAY .GT.(0.85*RM(I)))  SIGDAY =0.85*RM(I)
       ANNDAY=       (AA + BB*(SIGDAY /RM(I)))
       ANNDAY=10.0**ANNDAY
        F=AN/ANNDAY
(S,C OR RETURN)>
C
 10     CONTINUE
       RETURN
       END
>
```